National Park Service
U.S. Department of the Interior

Natural Resource Stewardship and Science

Montezuma Castle National Monument

Geologic Resources Inventory Report

Natural Resource Report NPS/NRSS/GRD/NRR—2019/2022

ON THE COVER
Photograph of Montezuma Castle (cliff dwellings). Early in the 12th century, ancestral Native American people called the "Southern Sinagua" by archeologists began building a five-story, 20-room dwelling in an alcove about 30 m (100 ft) above the valley floor. The alcove occurs in the Verde Formation, limestone. The contrast of two colors of mortar is evident in this photograph. More than 700 years ago, inhabitants applied the lighter white mortar on the top one-third. In the late 1990s, the National Park Service applied the darker red mortar on the bottom two-thirds. Photograph by Katie KellerLynn (Colorado State University).

THIS PAGE
Photograph of Montezuma Castle National Monument. View is looking west from the top of the Montezuma Castle ruins. Beaver Creek, which flows through the Castle Unit of the monument, is on the valley floor. NPS photograph available at https://www.nps.gov/moca/learn/photosmultimedia/photogallery.htm (accessed 22 November 2017).

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Geologic Resources Inventory Report

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

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

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

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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 (see Appendix A). 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.

On 8 December 1906, President Theodore Roosevelt proclaimed Montezuma Castle National Monument (referred to as the "monument" throughout this report) under the Antiquities Act of 1906. The monument is in Yavapai County, Arizona. The nearest town is Camp Verde. Since its designation, the boundary of the monument has changed six times, and the monument is now composed of two units, referred to as the "Castle Unit" and "Well Unit." The Castle Unit is located on the Camp Verde USGS 7.5-minute quadrangle; the Well Unit is located on the Lake Montezuma USGS 7.5-minute quadrangle. Coconino National Forest nearly surrounds both units of the monument.

The most distinguishing feature of the Castle Unit is Montezuma Castle—a well-preserved, five-story high, 20-room cliff dwelling that ancestral Native American people, called the "Southern Sinagua" by archeologists, built in the 1100s and 1200s. An alcove (recess formed in a cliff face) that developed in the Verde Formation, limestone (**Tvls**) houses the castle. The Castle Unit also encompasses "Elephant Hill"—a site that hosts groupings of fossil footprints, called "trackways," that were made by a variety of mammals, including early relatives of elephants, during the Pliocene Epoch (5.3 million–2.6 million years ago).

The most distinguishing feature of the Well Unit is Montezuma Well—a travertine-depositing spring and sinkhole in the Verde Formation, travertine (**Tvt**). The well is among the premier natural resources managed by the National Park Service and contributes to park significance due to its substantial scientific value and endemic species (National Park Service 1992, 2016). Levels of carbon dioxide, which are a result of volcanic degassing through a fracture system below the well, are too high to support fish, but amphipods (small shrimp-like animals) and leeches, which feed on them, have evolved within this isolated environment. These particular species occur nowhere else in the world (National Park Service 2016). An estimated 94 invertebrate species, including insects, mollusks, crustaceans, and annelids (worms), are present in the well. In addition, rare, freshwater bryozoans inhabit Swallet Cave (the cave system through which Montezuma Well drains) (National Park Service 2014).

The "Geologic Setting and Significance" chapter of this report discusses the Castle and Well Units in detail. That chapter summarizes connections between geologic resources and other park resources and describes the regional geologic setting of the monument, which is related to both the Colorado Plateau and Basin and Range physiographic provinces.

The "Geologic Features and Processes" chapter further discusses Montezuma Well. In addition, that chapter discusses the trackways at Elephant Hill and other paleontological resources. Furthermore, the monument's bedrock (Verde Formation), surficial deposits (terrace gravel and alluvium), and other rocks of significance for the monument's geologic story are highlighted; these include nearby Early Proterozoic rocks more than 1.7 billion years old, Paleozoic sedimentary strata, and lava flows (Hickey Formation) that cover mesa tops in the headwaters of Wet Beaver Creek. Figure 7 in the "Geologic Features and Processes" chapter is a geologic time scale based on the international chronostratigraphic chart (International Commission on Stratigraphy 2018). The figure shows geologic eras, periods, and epochs, which are referred to throughout this report, in the context of geologic time. Similarly, table 1 displays the map units of the GRI GIS data, which accompany this report, in a context of geologic time.

The "Geologic History" chapter provides a timeline, which begins in the Early Proterozoic Era (2.5

billion–1.6 billion years ago) and leads to the present day. The timeline makes a very long story short and highlights the major geologic events in the evolution of the monument's landscape, including deposition of the monument's bedrock (Verde Formation) and development of Montezuma Well.

The "Geologic Resource Management Issues" chapter discusses management issues related to the monument's geologic resources (features and processes). Because management priorities are constantly shifting (Matt Guebard, Montezuma Castle and Tuzigoot National Monuments, chief of Cultural Resources, written communication, 21 May 2019), these issues are ordered alphabetically, rather than with respect to management priority. These issues are cave and karst resource management; climate change; fluvial features and processes; geothermal resources; groundwater withdrawal; illegal rock collection; oil and gas reserve; paleontological resource inventory, monitoring, and protection; Quaternary faults and earthquakes; and slope movements. Information about these issues was compiled from the 2006 scoping summary (National Park Service 2006), a geologic resources foundation summary (National Park Service 2014), the monument's foundation document (National Park Service 2016), notes from the 2017 GRI conference call, and research associated with preparation of this report.

As explained in the "Geologic Map Data" chapter, GRI GIS data accompany this report. Writing of this report followed compilation of these data and was based on them. A poster (in pocket) displays a portion of these data. DeWitt et al. (2008) was the source map used in compiling the GRI GIS data for the monument (motu_geology.mxd). These data 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. These data include Tuzigoot National Monument and much of the Verde Valley between Tuzigoot and Montezuma Castle National Monuments. Thus, the GRI GIS data provide geologic mapping for both monuments, facilitating correlation (and resource management) between them. A separate GRI report for Tuzigoot National Monument is being prepared (KellerLynn 2019).

"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 may 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. The "Natural Hazards in Arizona" map viewer at https://azgs.arizona.edu/center-natural-hazards, which the Arizona Geological Survey (AZGS) maintains, is particularly noteworthy.

Appendix A of this report provides a list of people who participated in the scoping meeting for the monument in 2006 and/or in the follow-up conference call in 2017. The list serves as a legacy document and reflects participants' affiliations, positions, and names at the time of scoping or the conference call.

Finally, Appendix B of this report 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, developed the source map and NPS staff reviewed GRI content. This chapter describes GRI products and acknowledges contributors to this report.

GRI Products

The GRI team undertakes three tasks for each park in the Inventory and Monitoring program: (1) conduct a scoping meeting and provide a summary document, (2) provide digital geologic map data in a geographic information system (GIS) format, and (3) provide a GRI report (this document). These products are designed and written for nongeoscientists.

Scoping meetings bring together park staff and geologic experts to review and assess available geologic maps, develop a geologic mapping plan, and discuss geologic features, processes, and resource management issues that should be addressed in the GRI report. Following the scoping meeting, the GRI map team converts the geologic maps identified in the mapping plan to GIS data in accordance with the GRI data model. After the map is completed, the GRI report team uses these data, as well as the scoping summary and additional research, to prepare the GRI report. The GRI team conducts no new 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), 2006 National Park Service Management Policies, and the Natural Resources Inventory and Monitoring Guideline (NPS-75). The "Additional References" chapter and Appendix B provide links to these and other resource management documents and information.

Additional information regarding the GRI, including contact information, is available at http://go.nps.gov/gri.

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 US Geological Survey, which produced the source map (DeWitt et al. 2008) for the GRI GIS data of the monument, and the Arizona 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 creating many of the graphics in this report.

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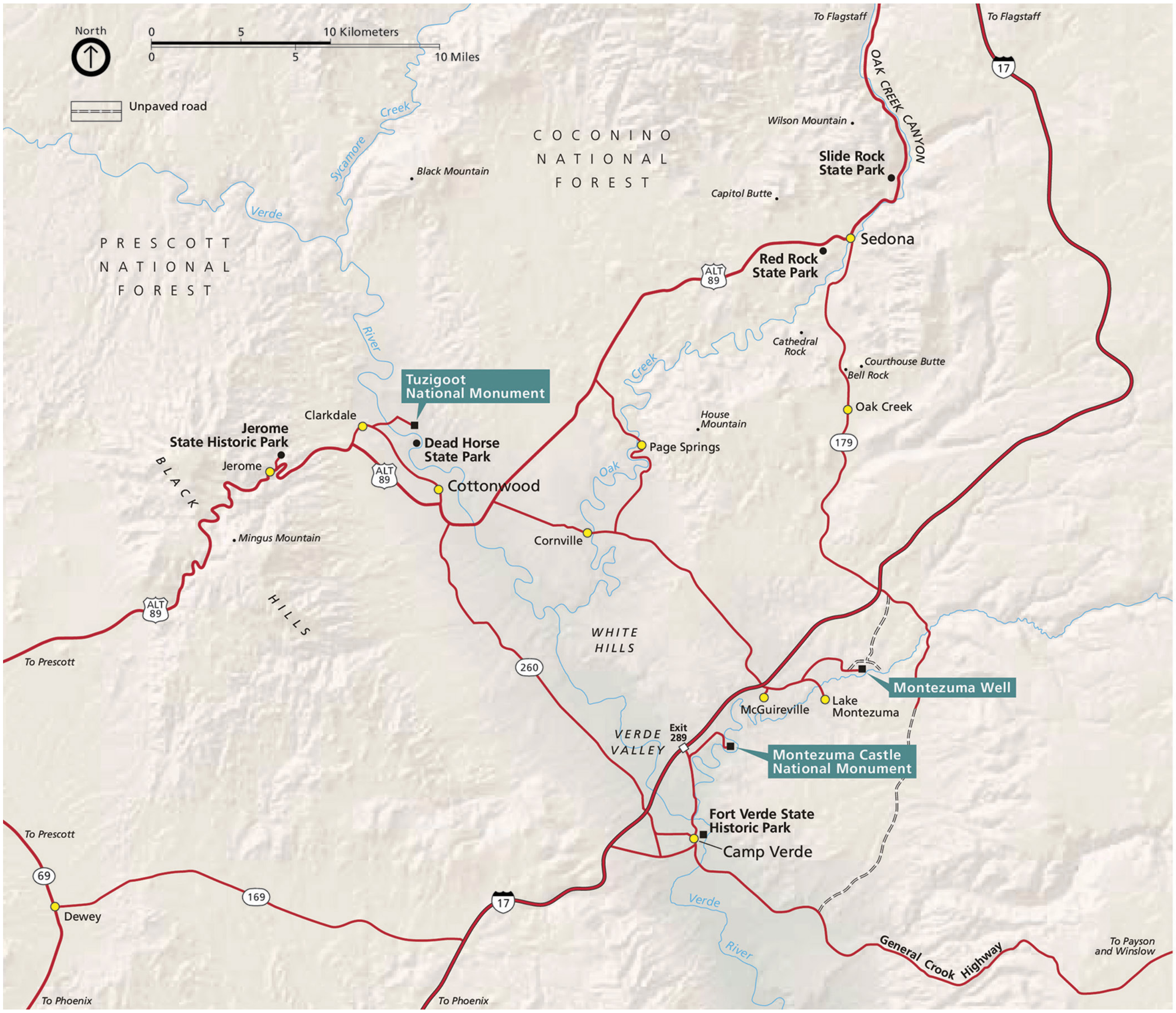

Figure 1. Location map for Montezuma Castle National Monument.
The monument lies in central Arizona. It is composed of two units: the Well Unit, which contains Montezuma Well, and the Castle Unit, which contains the Montezuma Castle cliff dwellings. Many national and state parks are in this scenic part of the state. Other National Park Service areas in the vicinity include Tuzigoot National Monument, which will receive a separate GRI report (KellerLynn 2019). 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 and Setting

On 8 December 1906, Montezuma Castle National Monument (referred to as the “monument” throughout this report) became one of the nation’s first national monuments designated under the Antiquities Act of 1906. It followed Devils Tower National Monument, which was designated on 24 September 1906, and was joined by El Morro National Monument and Petrified Forest National Monument (now Petrified Forest National Park), which also became national monuments on 8 December 1906. Since then, the boundary of the monument has expanded several times. In 1943, lands that contain Montezuma Well were added to the monument; that property was expanded again in 1959 to protect additional related resources. In 1978, another expansion incorporated the site known as “Elephant Hill” (see “Paleontological Resources”). In 1978 and 2003, expansions helped to better protect the areas adjacent to the Montezuma Castle cliff dwellings. The National Register of Historic Places listed archeological sites within the monument on 15 October 1966.

Today, two noncontiguous units compose the monument: the larger Castle Unit to the south and the Well Unit to the north (fig. 1). Beaver Creek flows through the Castle Unit whereas Wet Beaver Creek flows through the Well Unit. These creeks are tributaries of the Verde River (fig. 2).

The original proclamation and subsequent expansions brought the total size of the monument to 406 ha

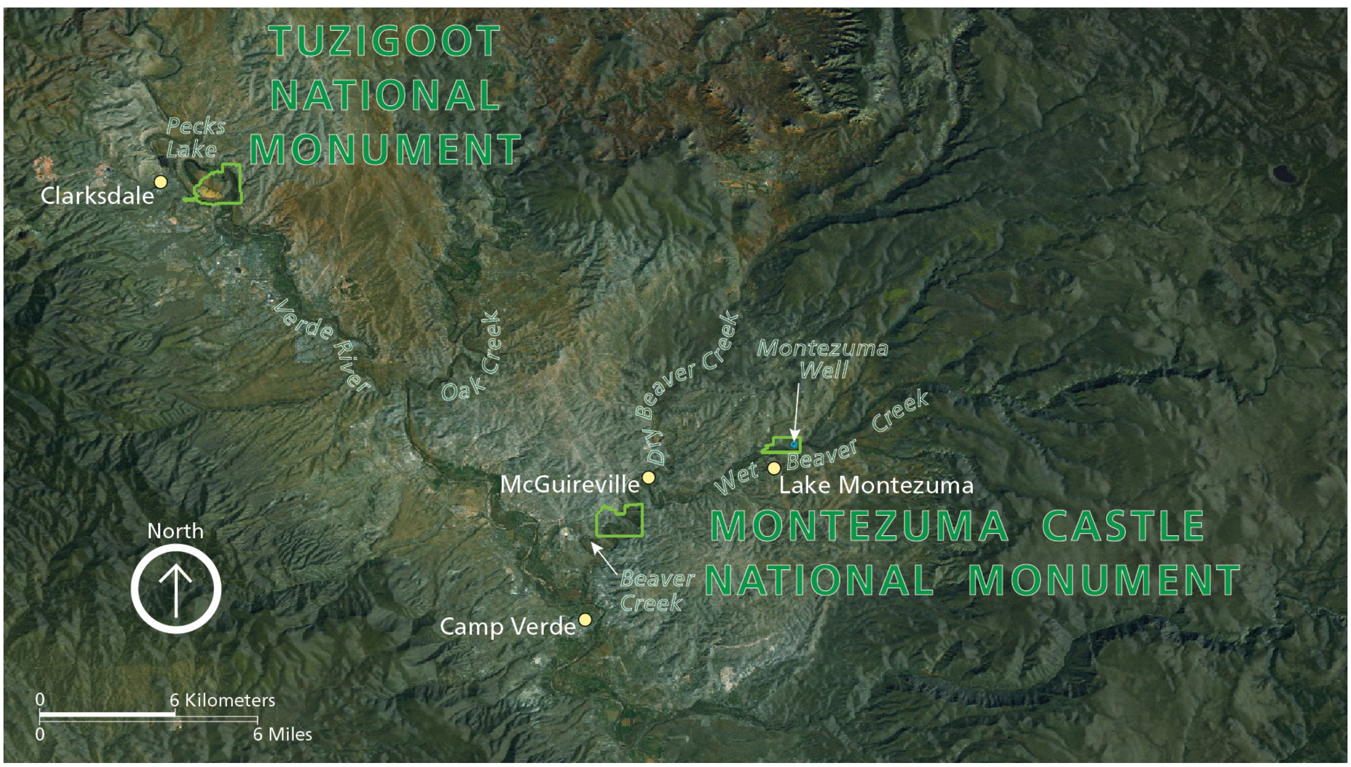

Figure 2. Satellite imagery of the Verde Valley and Mogollon Rim.
The Verde Formation, which makes up the bedrock of the monument, appears as a white “dusting” over much of the Verde Valley. Montezuma Castle National Monument is in a tributary valley (Beaver Creek and Wet Beaver Creek) of the Verde River. At about McGuireville, Wet Beaver Creek and Dry Beaver Creek converge, forming Beaver Creek, which drains into the Verde River. The monument consists of the Well Unit, which contains Montezuma Well, and the Castle Unit to the southwest of the Well Unit. Tuzigoot National Monument is in the Verde Valley, northwest of Montezuma Castle National Monument. Graphic by Trista Thornberry-Ehrlich (Colorado State University) using base imagery from ESRI ArcGIS World Imagery.

(1,004 ac) with 6.81 ha (16.83 ac) of nonfederal land (National Park Service 2016). The nonfederal land is a private inholding along Wet Beaver Creek; farming and livestock grazing take place on this inholding. The monument's land protection plan recommended acquisition of a scenic easement for the inholding (National Park Service 2016).

Castle Unit

Visitors typically access the monument through the visitor center at the Castle Unit and follow a path along Beaver Creek. After a short distance of walking along this path at the base of limestone cliffs composed of the Verde Formation (discussed below), Montezuma Castle is slowly revealed, nestled in an alcove (recess generally formed in a precipitous rock face) 30 m (100 ft) above the valley floor (fig. 3). The well-preserved castle is more than five stories high and contains 20 rooms. Many other structures and rooms share the cliff face with the castle. The path ends at the base of what was once a larger but now collapsed structure, called "Castle A" (National Park Service 2016).

Figure 3. Photograph of the Castle Unit. An ancient Southern Sinaguan ruin, Montezuma Castle sits high above the valley floor in an alcove that developed in the Verde Formation, limestone (Tvls). NPS photograph from Nauman (2010, cover).

Believing that the "castle" was Aztec in origin (a common mistake at the time; see GRI report about Aztec Ruins National Monument by KellerLynn 2016), early miners and soldiers who visited the area misnamed the prehistoric cliff house "Montezuma Castle" after the Aztec emperor, Montezuma (Protas 2002). Today, archeologists recognize the castle as a cliff dwelling built in early 1100 CE ("common era," preferred to AD) and inhabited for about 300 years, until around 1400 CE, by ancestral Native American people whom they call the "Southern Sinagua." These ancient builders were desert farmers who found the reliable waters of Beaver Creek, along with nearby fertile land, a suitable place to settle. The exact number of people who inhabited the castle and nearby structures is unknown, but researchers estimate that at least 150 to 200 people lived in the immediate area at the height of settlement (National Park Service 2016).

Built into the Verde Formation, limestone (map unit **Tvls**; table 1), Montezuma Castle is sheltered from the elements and was so well built that it has stood for 900 years. The castle is considered one of the best preserved prehistoric structures in the Southwest (National Park Service 2016), and it remains the most visible feature of a larger prehistoric community within the Verde Valley.

Well Unit

The Verde Formation, limestone (**Tvls**), lacustrine rocks (**Tvl**), and travertine (**Tvt**) make up the monument's bedrock. Table 1 of this report provides descriptions of these rocks. Definitions of geologic terms follow table 1. Montezuma Well formed in the travertine (**Tvt**). These travertine deposits of the Verde Formation are distinctive and occur only in the immediate vicinity of Montezuma Well (Johnson et al. 2012a).

The well is the eponymous feature of the Well Unit and is most assuredly "unique"—a term used during the 2006 scoping meeting to identify notable features such as those mentioned in a park's legislation, features of widespread geologic importance, geologic resources of interest to visitors, or geologic features worthy of interpretation (see National Park Service 2006). Lange (1957, p. 40) also referred to Montezuma Well as "unique," owing to its singular existence in the Verde Formation. Indeed, the well is "a single, isolated sinkhole [that] evokes a more compelling explanation than typical karstic processes" (e.g., the dissolution of soluble rock such as limestone) (National Park Service 2006, p. 9) (see "Montezuma Well").

The Well Unit is 10 km (6 mi) upstream from the Castle Unit (fig. 2). Water resources at the Well Unit consist of Montezuma Well, Wet Beaver Creek, and two drilled wells in the Verde Formation that supply water to resident NPS staff and visitors (National Park Service 1992).

Although Montezuma Well is the most distinctive feature, the Well Unit also contains significant groupings of cultural resources including cliff dwellings, pueblos, pithouses, historic and prehistoric irrigation canals, and 19th century ranch buildings (fig. 4). Initial construction of the canal predates the time of contact with European explorers (National Park Service 2016). The well has been crucial to several major Southwest cultures, as evidenced by a nearby pithouse (built about

Table 1. Geologic map units at Montezuma Castle National Monument.

Colors correspond to USGS suggested colors for geologic time periods.

Alluvium—Stream-deposited sediment.

Calcite—A carbonate (carbon + oxygen) mineral of calcium, CaCO3 (calcium carbonate). It is the most abundant cave mineral.

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.

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.

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

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

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

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

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

Terrace—Any long, narrow, relatively level or gently inclined surface (i.e., a bench or steplike ledge) that is bounded along one edge by a steeper descending slope and along the other edge by a steeper ascending slope, thus breaking the continuity of the slope; commonly occurs along the margin and above the level of a body of water, marking a former water level.

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

Era	Period (Epoch)	Map Unit (symbol)	Geologic Description
Cenozoic (the past 66 million years)	Quaternary (Holocene) 11,700 years ago to the present	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).
Cenozoic	Quaternary (Holocene and Pleistocene) 2.6 million years ago to the present	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).
Cenozoic	Tertiary (Pliocene) 5.3 million to 2.6 million years ago	Verde Formation, travertine (**Tvt**)	Coarse-grained, calcite-rich travertine mounds, especially abundant near Montezuma Well, in east-central part of outcrops of the Verde Formation. Thickness 10–35 m (30–110 ft).
Cenozoic	Tertiary (Pliocene and Miocene) 23.0 million to 2.6 million years ago	Verde Formation, lacustrine rocks (**Tvl**)	Includes claystone, siltstone, and silty limestone. Thickness variable.
Cenozoic	Tertiary (Pliocene and Miocene)	Verde Formation, limestone (**Tvls**)	Limestone and silty limestone. Thickness variable.

1100 CE). Moreover, from about 1125 to 1400 CE, the Southern Sinagua built large surface pueblos and approximately 50 rooms within the recesses at the well's edge (National Park Service 2016).

Regional Geologic Setting

The monument lies in a transition zone between two physiographic provinces: the Basin and Range and the Colorado Plateau (fig. 5). This transition zone has features of both provinces; for example, crystalline bedrock uplifted in ranges and basin-filling sediments characterize the Basin and Range whereas colorful, flat-lying sedimentary strata characterize the Colorado Plateau. Additionally, episodes of extension, indicative of the Basin and Range, and compression, indicative of the Colorado Plateau, have created a region severely deformed by faulting and uplift.

Figure 4. Photographs of the Well Unit. Montezuma Well is the eponymous feature of the Well Unit. Like the Castle Unit, the Well Unit also contains cliff dwellings, which are in an alcove at the edge of the well. The well formed in the Verde Formation, travertine (Tvt). NPS photographs by Lisa Norby (NPS Geologic Resources Division) taken in May 2006.

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 Basin and Range region started forming about 15 million years ago when Earth's crust began pulling apart (see "Geologic History"). In this part of the Basin and Range (i.e., central Arizona), extension is ongoing.

The Black Hills (on the western side of the Verde Valley and west of the monument; fig. 1) are an excellent example of a "range" in the Basin and Range. They are the first major range west of the Colorado Plateau. "Basins" are on either side of the Black Hills "range." Today's Verde Valley, on the east, and the Lonesome Valley, on the west, mark these basins.

In general, north–south-oriented structural basins, which dropped down along normal faults (fig. 6), separate adjacent, parallel uplifted mountain ranges. 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).

The uplifted Black Hills are bounded on the west by the Coyote fault and on the east by the Verde fault. Thus, these mountains are referred to as "fault-block" mountains or ranges; they also are referred to as "horsts" (fig. 6). As Earth's crust stretches apart, fault-block mountains lift up along normal faults while basins, referred to as "grabens," drop down along these same faults (fig. 6).

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." Sediment, including alluvial fans at the mouths of tributary drainages, that is shed from the surrounding highlands is deposited and not transported out of the basin by streamflow. The bedrock at the monument (Verde Formation) is an example of a basin-filling unit. The Verde Formation was deposited before the through-flowing Verde River cut its way into the basin floor and started transporting sediments out of the basin. In much of the Verde Valley, the Verde Formation consists of lacustrine deposits ("lake beds"), including limestone (**Tvls**), which is indicative of an ancient lake contained within the basin (see "Verde Formation").

Colorado Plateau

The Colorado Plateau is roughly centered on the Four Corners area of Arizona, Utah, Colorado, and New Mexico (fig. 5). Incorporating 35 National Park System units (organized into the Northern Colorado Plateau and Southern Colorado Plateau Inventory and Monitoring Networks), the Colorado Plateau physiographic province contains the highest concentration of parklands in North America (Kiver and Harris 1999). Most of these special areas are known for their spectacular scenery and geology. Many also celebrate fascinating cultural periods and an ancient North American civilization.

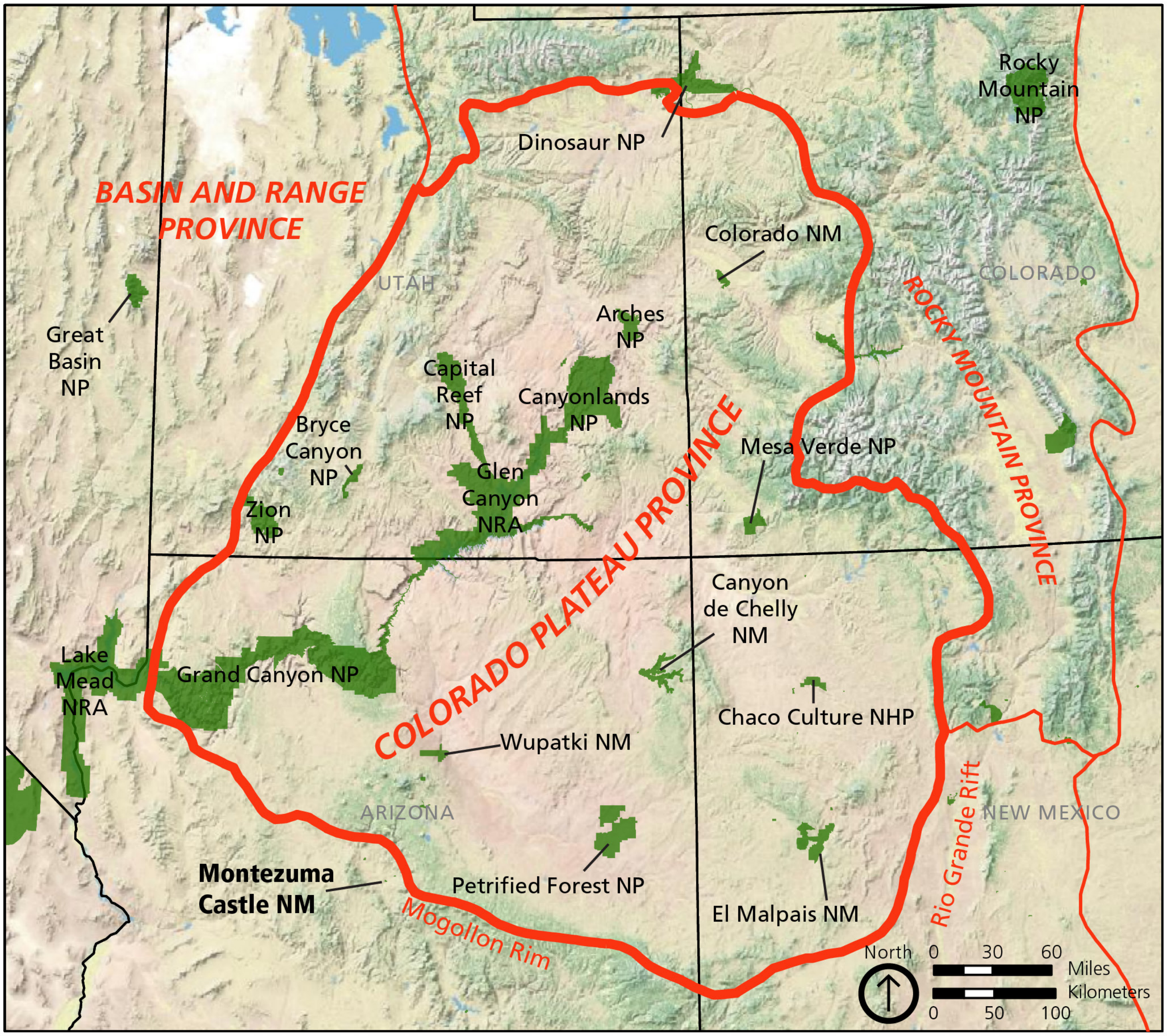

Figure 5. Graphic of the Four Corners Area of Utah, Colorado, Arizona, and New Mexico. Located in a transition zone between the Colorado Plateau and Basin and Range physiographic provinces, Montezuma Castle National Monument is one of many NPS areas in the region. The figure shows these areas in green; 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.

Bounded on the west by the Basin and Range, the Colorado Plateau is a high-elevation region of generally horizontal strata in multihued cliffs, broad mesas, steep-sided canyons, and badlands (Baars 1983). In the Montezuma Castle area, basalt flows commonly cover the flat-lying sedimentary rocks.

Compressional mountain building and erosional episodes, as well as periods of extension and volcanism, created the Colorado Plateau. Current elevations of land masses and associated pollen data suggest that the Colorado Plateau has risen approximately 330 m (1,080 ft) while the Verde basin has subsided about 660 m (2,200 ft) since the Miocene Epoch (i.e., the past 5 million years) (Nations et al. 1981).

Most (about 90%) of the Colorado Plateau is drained southward by the Colorado River, for which it was named, and its primary tributaries (i.e., the Green, Little Colorado, San Juan, and Virgin Rivers). A few rivers in the high plateau section (western edge) drain northward and then westward into the Great Basin (the huge

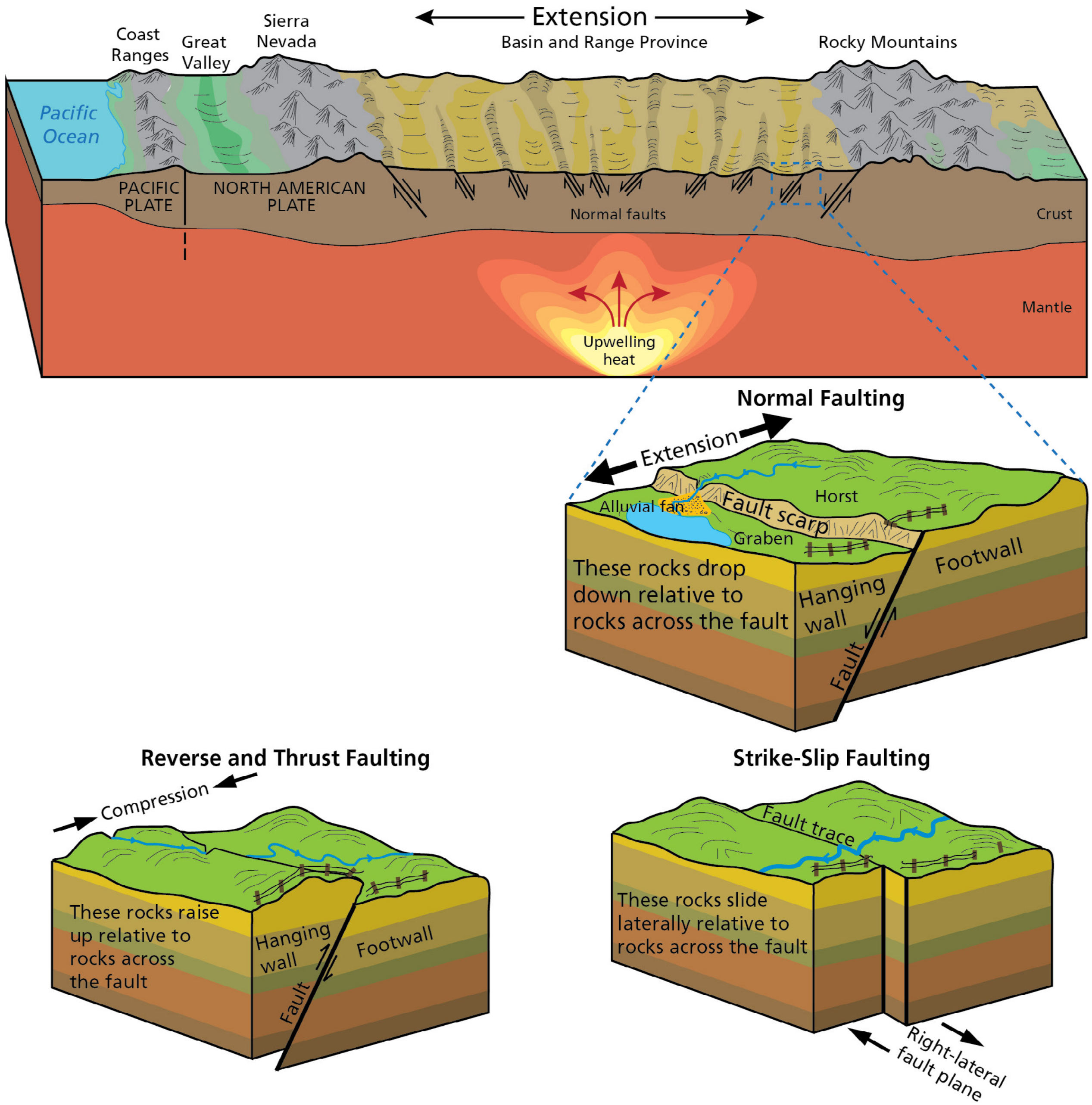

Figure 6. Graphic of Basin and Range extension, normal fault, and other fault types.
Extension (pulling apart of Earth's crust) affects the Basin and Range physiographic province. Extensional forces have stretched Earth's crust (and upper mantle) up to 100% of its original width. The crust thinned and cracked as it pulled apart, creating normal faults, which are generally oriented north to south in the Basin and Range. Mountains were 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"). Movement occurs along a fault plane. Footwalls are below the fault plane, and hanging walls are above. Normal faults, where crustal extension moves the hanging wall down relative to the footwall, characterize the Basin and Range. Faults mapped near the monument are normal faults. The other two principal types of faults are reverse and strike-slip. 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 Idaho Geological Survey (2011, p. 2).

"water trap" of the Basin and Range province). A small part of the eastern plateau drains into the Rio Grande.

Near the monument, an abrupt cliff known as the "Mogollon Rim" bounds the Colorado Plateau. The Mogollon Rim runs for 320 km (200 mi) and looms alongside the Verde Valley as a sheer precipice that ranges 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 due to youthful streams such as Beaver Creek, Oak Creek, and Sycamore Creek that have cut steep-walled canyons back into the tableland of the plateau. 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). Significantly, the Mogollon Rim serves as the groundwater recharge area for Montezuma Well (see "Montezuma Well").

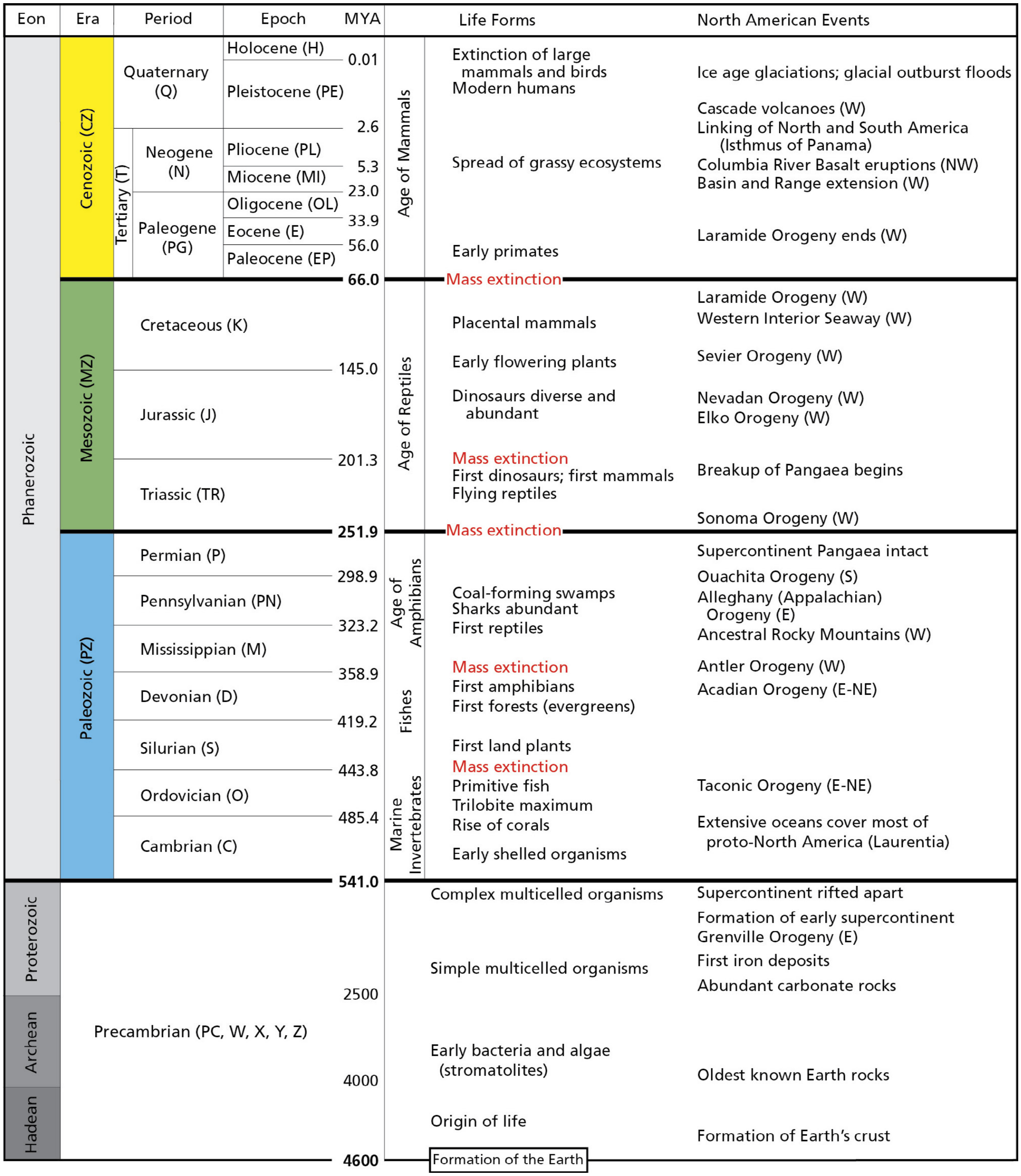

Figure 7. Geologic time scale.
The geologic time scale puts the divisions of geologic time in stratigraphic order, with the oldest divisions at the bottom and the youngest at the top. GRI map abbreviations for each time division are in parentheses. Rocks in the GRI GIS data for the monument are from the Proterozoic (X), Paleozoic (PZ), Tertiary (T), and Quaternary (Q). The Verde Formation (the monument's bedrock) is between 7 million and 2 million years old (Miocene–Pleistocene on this recent time scale; Miocene–Pliocene at the time the source map was created in 2008). Compass directions in parentheses indicate the regional lsocations of events. Boundary ages are millions of years ago (MYA). National Park Service graphic using dates from International Commission on Stratigraphy (2018).

Geologic Features and Processes

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

Early Proterozoic Rocks

The Verde Valley has a remarkable geologic history (see "Geologic History"), spanning back to the Early Proterozoic Era (also referred to as the "Paleoproterozoic" Era, 2.5 billion–1.6 billion years ago) (fig. 7). The oldest rocks mapped by DeWitt et al. (2008) are older than 1.76 billion years, though these rocks (gneiss) are not part of the GRI GIS data. Rhyolitic intrusive rocks (**Xr3**) are the oldest rocks in the GRI GIS data. These rocks are older than rhyolitic tuff (**Xr2**), which Anderson et al. (1971) dated at 1.75 billion years old.

The closest exposures of Early Proterozoic rocks to the monument are in Copper Canyon, 8.3 km (5.2 mi) southwest of the monument. These rocks are the Cherry Tonalite (**Xch**; see GRI GIS data), which is a newly named formation by DeWitt et al. (2008) for the exposures near Cherry, Arizona. Using the uranium-lead (U-Pb) method, Anderson et al. (1971) dated a sample of the Cherry Tonalite that yielded an age of 1.74 billion years. Tonalite, also known as quartz diorite, is a group of plutonic rocks having the composition of diorite but with an appreciable amount of quartz. These rocks would have been part of Earth's early crust.

Paleozoic Rocks

In the Montezuma Castle area, rocks from the Paleozoic Era (541.0 million–251.9 million years ago) make up a sequence of nearly flat-lying, consolidated, sedimentary units. Sediments that now compose these units were deposited along an ancient shoreline that stretched from Sonora, Mexico, to British Columbia, Canada (Tapeats Sandstone, **Ct**); in an ocean basin (Martin Formation, **Dm**); and in shallow, tropical ("near the equator") seas (Redwall Limestone, **Mr**). Beginning more than 300 million years ago (either during the Late Mississippian Period or Late Pennsylvanian Period), the Montezuma Castle area emerged from tropical seas, and sediments of the Supai Formation (**PNs**) accumulated first in coastal deltas that covered the earlier marine deposits then in a variety of primarily continental settings. Continental conditions continued in the Permian Period as the Hermit Formation (**Ph**) was deposited in fluvial mud flats, the Schnebly Hill Formation (**Psh**) was deposited in coastal dunes, and the Coconino Sandstone (**Ptc**) was deposited in inland dunes. The Toroweap Formation (part of **Ptc**) and Kaibab Limestone (**Pk**) originated farther west as marine sediments (fig. 8).

Exposures (outcrops) of many of these units are in the tributary canyons that cut the Mogollon Rim. From its headwaters on the Mogollon Rim, Wet Beaver Creek cuts into the Schnebly Hill (**Psh**) and Hermit (**Ph**) Formations (see poster, in pocket). Because the poster is focused on the immediate vicinity of the monument, the poster does not show all the Paleozoic rocks in the area; for example, the poster shows neither the Supai Formation (**PNs**) nor the Kaibab Limestone (**Pk**). However, figure 8 of this report, which provides a regional representation of Paleozoic rocks between the Verde Valley and Grand Canyon, shows these maps units. Moreover, the GRI GIS data show their locations in the monument area.

Hickey Formation

The Hickey Formation is widespread on both sides of the Verde Valley. Initially the unit accumulated as sedimentary rocks (**Ths**), but most of these sediments eroded away. Then several periods of volcanic activity ensued during the Miocene Epoch (23.0 million–5.3 million years ago) with basalt erupting onto the surface. Using the potassium-argon (K-Ar) dating method on the basalt (whole rock) of the Hickey Formation, McKee and Anderson (1971) acquired ages of 10.1 ± 0.4 to 14.0 ± 0.6 million 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 (west of the monument) represents a major eruptive center. Today, thick accumulations of Hickey Formation, basalt (**Thb**) compose the summit region of the Black Hills, including Lookout and Woodchute Mountains (see GRI GIS data). On the eastern side of the Verde Valley, mesa tops, including those at the headwaters of Wet Beaver Creek, are composed of the Hickey Formation, alkali basalt (**Thab**) (see poster, in pocket).

Verde Formation

The monument's bedrock consists of the Verde Formation, which makes up the cliffs at the Castle and Well Units, encloses Montezuma Well (see "Montezuma Well"), and underlies the Verde Valley. In addition, it holds up the hilltop pueblo at Tuzigoot National Monument (see the GRI report about Tuzigoot National Monument by KellerLynn 2019).

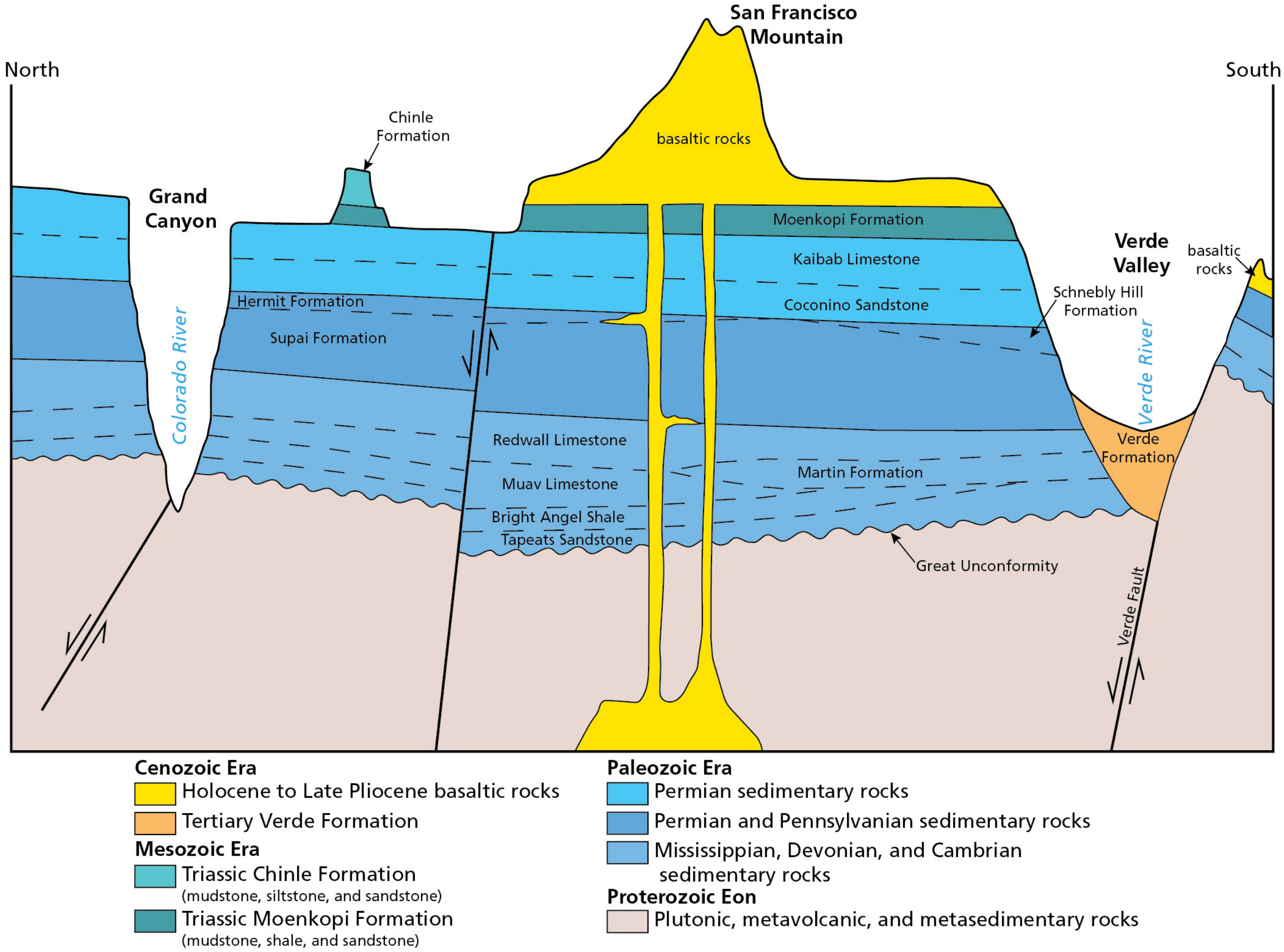

Figure 8. Generalized cross section between the Verde Valley and Grand Canyon. Investigators have correlated the rocks exposed in the Verde Valley with the rocks in the Grand Canyon region. The Great Unconformity—perhaps the world's most famous—is a distinctive feature in the Verde Valley's rock record. The Great Unconformity is commonly recognized by its appearance (and excellent exposure) at the bottom of the Grand Canyon. Five-hundred-million-year-old (Cambrian) Tapeats Sandstone is above the unconformity; 1.75-billion-year-old (Proterozoic) gneiss (a metamorphic rock with alternating bands of dark and light minerals) is below the unconformity. In the Verde Valley, the Great Unconformity represents a 1.2-billion-year-long "gap" in the geologic record. Montezuma Castle National Monument is in the Beaver Creek–Wet Beaver Creek tributary canyon of the Verde Valley. Wet Beaver Creek cuts into the Schnebly Hill, Hermit, and Verde Formations, as well as basalt upstream from the monument. The Redwall Limestone is a source of groundwater to Montezuma Well. Graphic by Trista Thornberry-Ehrlich (Colorado State University) after Blasch et al. (2005, figure 23).

The lithology and genesis of the Verde Formation is complex. Since its initial description and naming by Jenkins (1923), the formation's complexity has resulted in differences in interpretation and mapping by various investigators throughout the Verde Valley (for a comparison, see the GRI report about Tuzigoot National Monument by KellerLynn 2019). The source map for the monument (DeWitt et al. 2008) interpreted the formation as Pliocene and Miocene in age and divided it into the following informal members (from youngest to oldest):

- Travertine (**Tvt**, Pliocene)—coarse-grained, calcite-rich travertine mounds, especially abundant near Montezuma Well, in east-central part of outcrops of the Verde Formation. Hevly et al. (1992) classified the travertine deposits as "tufa" (hard, dense variety of travertine) and reported a uranium-thorium (U-T) date of 116,000 ± 2,000 years ago at Montezuma Well, which suggests that travertine accumulated during the Pleistocene Epoch.

- Undivided sedimentary rocks (**Tvs**, Pliocene and Miocene)—limestone, claystone, silty limestone, and siltstone.
- Lacustrine rocks (**Tvl**, Pliocene and Miocene)—claystone, siltstone, and silty limestone.
- Limestone (**Tvls**, Pliocene and Miocene)—limestone and silty limestone.
- Gravel (**Tvg**, Pliocene and Miocene)—silty limestone that contains pebbles and cobbles of Paleozoic sandstone and limestone and Tertiary basalt. Abundant on the northwest and southeast margins of the exposed-outcrop area of the Verde Formation.
- Evaporite beds (**Tve**, Miocene)—sulfate-rich strata interbedded with minor limestone and siltstone (Thompson 1983). Sulfate minerals include glauberite, gypsum, mirabillite, and thernardite.

Three of these informal members occur within the monument: (1) limestone (**Tvls**) in both the Castle and Well Units, (2) lacustrine rocks (**Tvl**) in the Castle Unit, and (3) travertine (**Tvt**) in the Well Unit (table 1). Montezuma Castle cliff dwellings are in limestone (**Tvls**). Montezuma Well and ruins are in travertine (**Tvt**). Undivided sedimentary rocks (**Tvs**) and gravel (**Tvg**) occur upstream of the Well Unit. Evaporite beds (**Tve**) occur south of the Castle Unit (see poster, in pocket).

The Verde Formation accumulated in a basin whose boundaries, according to Twenter and Metzger (1963), were about the same as those of the present-day Verde Valley. The Verde basin and Verde Valley are distinct, however, with the former being a down-dropped, structural basin that predates the latter erosional river valley. The Verde Valley formed when the modern, through-flowing Verde River began incising and transporting the basin-filling Verde Formation out of the drainage.

For much of its 5-million-year history, the Verde basin was a closed basin due to structural subsidence related to Basin and Range extension. Damming of drainage by lava flows at the southern end of the basin also may have played a role in the closed nature of the basin. Two basalt flows are interbedded with the basin-filling sediments (fig. 9). Some investigators (e.g., Lehner 1958) mapped these flows as part of the Verde Formation (see the GRI report about Tuzigoot National Monument by KellerLynn 2019). DeWitt et al. (2008), however, described these lava flows as separate map units, younger volcanic and sedimentary rocks (**Tby** and **Taby**). Younger volcanic and sedimentary rocks, basalt (**Tby**) caps much of the upland area north of the monument (see poster, in pocket, and GRI GIS data). Younger volcanic and sedimentary rocks, alkali basalt

Figure 9. Photographs of basalt.
As mapped by some investigators, though not DeWitt et al. (2008), the Verde Formation contains lava flows in parts of the Verde Valley. During formation of the Verde Valley, flowing lava filled paleochannels on top of Paleozoic rocks (i.e., Permian sandstone) and produced a series of basalt flows in the Verde Formation. Basalt flows within the Verde Formation are highly fractured and are probably conduits for groundwater flow within the less permeable Verde Formation, which is mostly composed of lake bed limestone that typically has a high clay content. The fault zones may also be quite permeable due to dissolution of limestone along these zones of weakness. However, basalt dikes that formed in fracture zones probably cooled quite slowly, not becoming fractured, and may be barriers to groundwater flow (Johnson et al. 2012a). "Float rocks" (shown in the top photograph) are displaced fragments of the overlying basalt flow. The basalt boulders in the bottom photograph eroded out of an outcrop of the Verde Formation at the monument. Top photograph from Johnson et al. (2012a, figure 5). Bottom photograph by Katie KellerLynn (Colorado State University).

(**Taby**) occurs north of the Well Unit within and on the mesa above Bias and Hog Canyons (see GRI GIS data).

As a geologic–cultural resource connection, the Southern Sinagua used basalt for manufacturing tools such as metates, manos, and hammerstones (Ladd 1964). The basalt is indicative of volcanic activity that took place at the same time as the Verde basin dropped down and began filling with sediment in conjunction with Basin and Range extension (see “Regional Geologic Setting”). Basalt was also significant for the development of Montezuma Well (see “Montezuma Well”).

With respect to the genesis of the Verde Formation, intermittent tributary streams, flowing into the basin from the surrounding highlands, carried loads of very fine to very coarse rock fragments. The coarse fragments (gravel and sand) collected along the margin of the basin, including in alluvial fans, while the fine fragments (silt) spread out into the lake and settled onto the lake floor. Limestone precipitated in the deeper waters of the lake. Mudstone developed in shallower water areas. Additionally, mudstone and evaporite (“salts” deposited from aqueous solution as a result of extensive or total evaporation) formed in isolated ponds bordering the restricted lake during dry periods (Twenter and Metzger 1963) (fig. 10). Travertine formed in parts of the basin where groundwater discharged onto the land surface, forming terraces or mounds (see “Montezuma Well”).

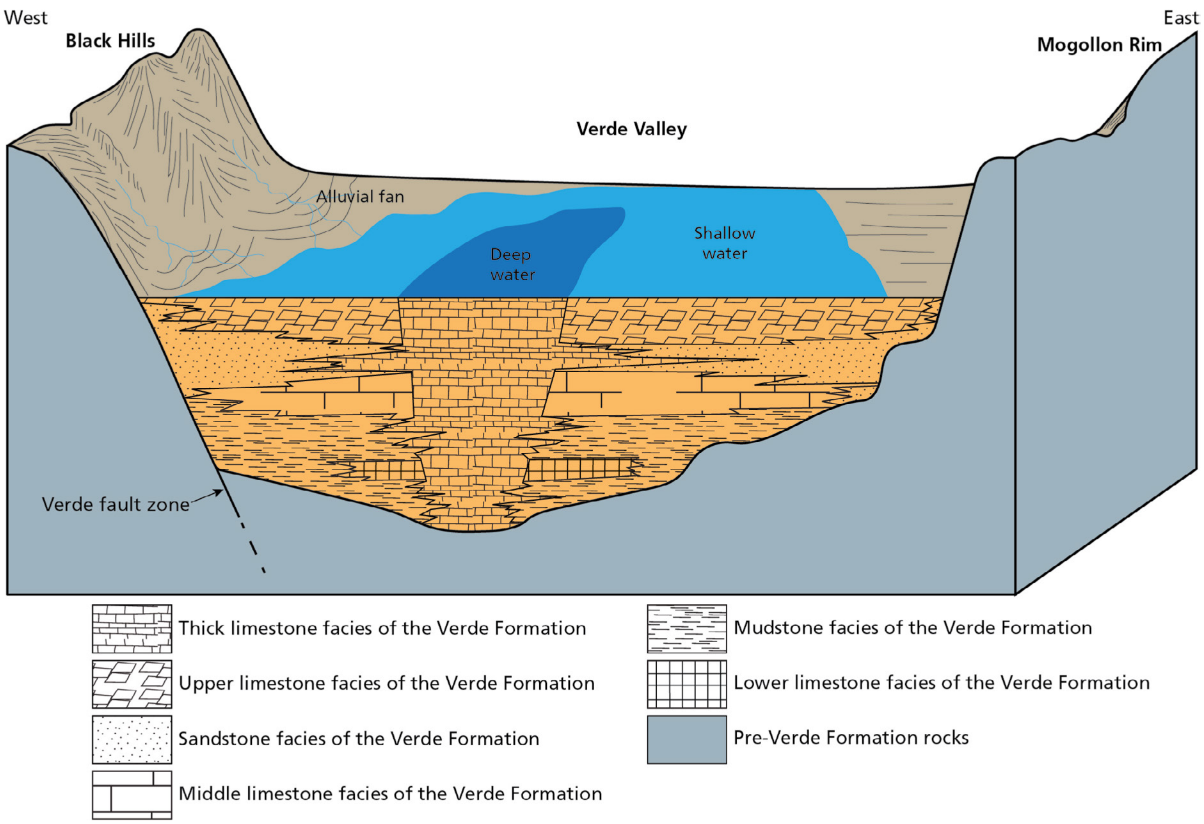

Figure 10. Graphic of Verde Formation facies.
Twenter and Metzger (1963) were the first to divide the Verde Formation into facies, which record changes within the depositional setting, particularly differences among adjacent units. Each facies has a characteristic set of properties (e.g., color, lithology [e.g., type and size of rock fragments], texture, and sedimentary structures) owing to its deposition in a particular environment. Twenter and Metzger (1963) defined six facies: (1) thick, undifferentiated limestone facies, which developed in deep water and includes undifferentiated upper, middle, and lower limestone faces; (2) upper, (3) middle, and (4) lower limestone facies, which extend laterally from the thick limestone faces; (5) sandstone facies, which consists of coarse grains of alluvial fans from tributary valleys; and (6) mudstone facies, which 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).

Terrace Gravel and Alluvium

Focusing on bedrock geology, DeWitt et al. (2008) mapped only two units—terrace gravel (**Qt**) and alluvium (**Qal**)—associated with the stream system at the monument. Terraces step upward from the modern floodplain, which in turn, is higher than the modern stream channel. During floods, water covers the modern floodplain. As such, terraces represent an abandoned floodplain, no longer covered in water during floods. Terrace gravel (**Qt**) represents fluvial activity leading up to the present day but predating the active channel. Alluvium (**Qal**) represents the active channel.

Terrace gravel (**Qt**) and alluvium (**Qal**) of DeWitt et al. (2008) are simplified units from surficial mapping by House and Pearthree (1993) (see GRI report about Tuzigoot National Monument by KellerLynn 2019) and House (1994). Notably, surficial mapping by House (1994) covers the Castle Unit of the monument, though this map is not part of the GRI GIS data.

Mapping by Cook et al. (2010a) provides a more detailed picture of the evolution of Wet Beaver and Beaver Creeks than the one provided by DeWitt et al. (2008). Additionally, mapping by Cook et al. (2010a) supersedes that of House (1994) (Arizona Geological Survey staff, GRI conference call, 6 December 2017). Focusing on surficial geology and the geomorphic evolution of the Verde River's tributaries, Cook et al. (2010a) divided the alluvium and floodplain deposits at the monument into eight "main channel" deposits and two "tributary" units (table 2). Table 2 of this GRI report shows the units mapped by Cook et al. (2010a) in the monument compared to those mapped by DeWitt et al. (2008). Mapping by Cook et al. (2010a) is not part of the GRI GIS data, but the map and report are available through the Arizona Geological Survey's website (http://repository.azgs.az.gov/) (see "Geologic Map Data"). The more detailed mapping and descriptions by Cook et al. (2010a) may be useful for resource managers in understanding the evolution of the stream system that flows through the monument as well as provide information pertinent to flooding potential. Another benefit for resource management (and interpretation) provided by Cook et al. (2010a) is correlation among National Park Service areas, including Casa Grande Ruins National Monument in southern Arizona (see GRI report by KellerLynn 2018) and Gila Cliff Dwellings National Monument in southern New Mexico (see GRI report by KellerLynn 2014).

Wet Beaver and Beaver Creeks

The stream system within the monument consists of Wet Beaver Creek (fig. 11) and Beaver Creek, which are tributaries to the Verde River (fig. 2). The headwaters of Wet Beaver Creek originate at springs in the Permian Coconino Sandstone (see "Paleozoic Rocks") on the Mogollon Rim (National Park Service 1992). The elevation of Wet Beaver Creek's riverbed ranges from 1,879 m (6,165 ft) above sea level at the headwaters in southern Coconino County to 937 m (3,073 ft) above sea level at the confluence with the Verde River in Yavapai County, where the stream is named "Beaver Creek." The total length of the channel, including both Wet Beaver and Beaver Creeks, is approximately 55 km (34 mi).

Figure 11. Photograph of Wet Beaver Creek. Wet Beaver Creek flows in the Well Unit of the monument. NPS photograph by A. Wondrak Biel from Gwilliam et al. (2017, cover).

The uppermost section of Wet Beaver Creek occurs in an extremely narrow canyon, commonly less than 15 m (50 ft) wall-to-wall, cut into Tertiary basalt (Cook et al. 2010a). This section of the creek is not included in the GRI GIS data, but Cook et al. (2010a) provided a description. Waterfalls, plunge pools, and extremely large in-channel boulders are common in the uppermost section. Downstream, the canyon remains narrow, and incision by the creek increases the height of the bedrock walls lining the canyon to more than 270 m (900 ft). Wet Beaver Creek cuts through Kaibab Limestone then into the Toroweap Formation (fig. 8).

As shown in the GRI GIS data (see poster, in pocket), above the Well Unit of the monument, Wet Beaver Creek incised the Schnebly Hill (**Psh**) and Hermit (**Ph**) Formations as well as flows through the undivided sediments (**Tvs**) and gravel deposits **Tvg**) of the Verde Formation. Within the Well Unit, the stream flows in the Verde Formation, limestone (**Tvls**). Under natural

Table 2. River and piedmont alluvium at Montezuma Castle National Monument.

*Estimated from table 1 in Cook et al. (2010a).

Notes: Geoarcheological studies by Cook et al. (2010a) provided the following dates: Qy3r developed from 1150 CE to arroyo cutting in 19th century. Qy2r developed from 1150–900 CE to 600–500 CE.

Period (Epoch)	Years Ago*	Map Unit DeWitt et al. (2008) (symbol)	Map Unit Cook et al. (2010a) (symbol)	Description from Cook et al. (2010a)
Quaternary (Holocene)	Present day	Alluvium (**Qal**)	Active river channel deposits (Qycr)	Active channel. Some of these deposits are submerged by the low-flow river channel; remaining areas are submerged during moderate to extreme flow events. Areas of Qycr are subject to deep, high velocity flow and lateral bank erosion.
Quaternary (Holocene)	Less than 2,000	Terrace gravel (**Qt**)	Flood channel and low terrace deposits (Qy4r)	Adjacent to active channel. These surfaces are commonly inundated under moderate to extreme flow events and can be subject to deep, high velocity flow and lateral bank erosion.
Quaternary (Holocene)	Less than 2,000	No piedmont alluvium mapped	Latest Holocene alluvium (Qy3)	Recently active piedmont (at the base of a mountain front) alluvium located primarily along active drainages including floodplain, low-lying terraces, and tributary channels.
Quaternary (Holocene)	Less than 2,000	Terrace gravel (**Qt**)	Historical river terrace deposits (Qy3r)	Terrace deposits that occupy elevations from 2 to 3 m (5 to 10 ft) above Qycr or Qy4r deposits. Correlates to terrace at Gila Cliff Dwellings National Monument (see GRI report KellerLynn 2014).
Quaternary (Holocene)	Less than 2,000	Terrace gravel (**Qt**)	Late Holocene to historical river terrace deposits (Qy2r)	Deposits are associated with broadly planar surfaces that locally retain the shape of past river meanders. Correlates to terrace at Gila Cliff Dwellings National Monument (see GRI report KellerLynn 2014).
Quaternary (Holocene)	About 2,000	No piedmont alluvium mapped	Holocene fine grained deposits (Qys)	Unconsolidated, very fine– to fine-grained piedmont alluvium located close to basin-fill deposits. Qys deposits are generally derived from erosion of fine-grained basin-fill deposits.
Quaternary (Pleistocene)	Less than 130,000	Terrace gravel (**Qt**)	Late Pleistocene river terrace deposits, undivided (Qi3r)	Qi3r mapped in the Castle Unit only. Correlates to surface at Casa Grande Ruins National Monument (see GRI report KellerLynn 2018).
Quaternary (Pleistocene)	About 130,000	Terrace gravel (**Qt**)	Middle to late Pleistocene river terrace deposits, undivided (Qi2r)	Qi2r mapped in the Castle Unit only. Qi2r deposits are similar to Qi3r deposits but occupy higher positions in the landscape. Terrace surfaces are slightly to moderately rounded.
Quaternary (Pleistocene)	About 760,000	Terrace gravel (**Qt**)	Middle Pleistocene river terrace deposits, undivided (Qi1r)	Qi1r mapped in the Castle Unit only. Qi1r deposits are associated with high-standing, well-rounded river gravel terraces.
Quaternary (Pleistocene)	Between 2.6 million and 760,000	Terrace gravel (**Qt**)	Early Pleistocene river terrace deposits, middle [of three members] (Qo2r)	Qo2r mapped in the Castle Unit only. Qo2r terraces range from 55 to 67 m (180 to 220 ft) above the modern river channel.

conditions, Montezuma Well would discharge into Wet Beaver Creek (see “Montezuma Well”).

Beginning at the western end of the Well Unit, the width of the Holocene river floodplain begins to increase dramatically, exceeding 900 m (3,000 ft) near the town of Lake Montezuma. Near the confluence with Dry Beaver Creek (an intermittent stream that flows primarily in response to precipitation and snowmelt), Wet Beaver Creek begins a series of many tight meanders with upward-stepping suites of Holocene to Pleistocene terraces preserved on inside meander bends (Cook et al. 2010a).

Below the confluence of Wet Beaver Creek and Dry Beaver Creek, the stream becomes Beaver Creek. Beaver Creek extends about 14 km (9 mi) from the confluence of Wet Beaver Creek and Dry Beaver Creek to the Verde River. About 2.4 km (1.5 mi) of Beaver Creek flows through the Castle Unit, which is located about 6 km (4 mi) above the confluence with the Verde River. Beaver Creek is perennial from the Wet Beaver Creek–Dry Beaver Creek confluence to the Castle Unit, though part or all of the flow is diverted for irrigation during the summer (National Park Service 1992). Near the confluence with the Verde River, the Beaver Creek floodplain is wide and flat. Extensive latest to early Pleistocene river terraces north of the modern confluence mark previous paths of Beaver Creek (Cook et al. 2010a).

Montezuma Well

Montezuma Well is a travertine-depositing spring and sinkhole (fig. 4). It occurs in the Verde Formation, travertine (**Tvt**) (fig. 12). Donchin (1983) mapped these travertine deposits in detail.

Travertine springs occur throughout the world and are generally associated with deep crustal rifting and faulting (Hancock et al. 1999). Faults or fractures are the upper crustal conduits for the deep fluids entering an aquifer. Montezuma Well and many springs in the western United States are located in crustal extension zones of the Basin and Range (see “Regional Geologic Setting”) that have geochemical signatures (e.g., CO_2 levels) associated with degassing magmas, even though they are not necessarily in active magmatic locations and have relatively cold water temperatures. Helium isotopes indicate that a significant component of the groundwater in travertine-depositing springs is from Earth’s deep crust (25%) and mantle (10%) (Crossey et al. 2009).

Since the early 1900s, scientists (e.g., Blake 1906; Colten and Baxter 1932; Henderson 1933; McKee et al. 1947; Schroeder 1948; Lange 1957) have speculated on the origin of Montezuma Well. Popular misconceptions of its origin included an extinct geyser, volcanic explosion, and meteorite impact (Hevly 1974). The results of a study by Johnson et al. (2011), which the National Park Service requested, determined how a combination of geologic and geochemical processes created the features found at Montezuma Well.

Figure 12. Photograph of the Verde Formation, travertine.
DeWitt et al. (2008) mapped travertine (Tvt) in the monument. Old travertine spring vents are preserved near Montezuma Well. Draped layering of travertine, which dips inwards toward what is interpreted to be a former locus of the spring discharge zone, distinguishes these vents The most dramatic vent is exposed in an eroded area near Montezuma Well above Wet Beaver Creek. At this location, the old water pathways can be clearly seen in the “porosity pattern.” Photograph by Raymond Johnson (US Geological Survey) from DeWitt et al. (2008, map).

Johnson and DeWitt (2009) provided the following description of the Montezuma Well system.
Recharge of the majority of groundwater eventually contained within Montezuma Well takes place in the topographically high area of the Mogollon Rim (northeast of the monument) at elevations greater than 2,100 m (7,000 ft) above sea level (fig. 13). The elevation of the water surface at Montezuma Well is 1,083 m (3,553 ft) (fig. 14). Recharge through the Mogollon Rim follows fractures in the cover basalt and the underlying sandstones and then flows rapidly through the karstic Redwall Limestone at depth. Geologic inferences indicate the presence of a basalt dike underneath Montezuma Well that affects groundwater flow and geochemistry. This basalt dike appears to be a barrier for regional groundwater flow and a locus for a component of deep-seated groundwater flowing upward along bedrock fractures (hence the formation and unique

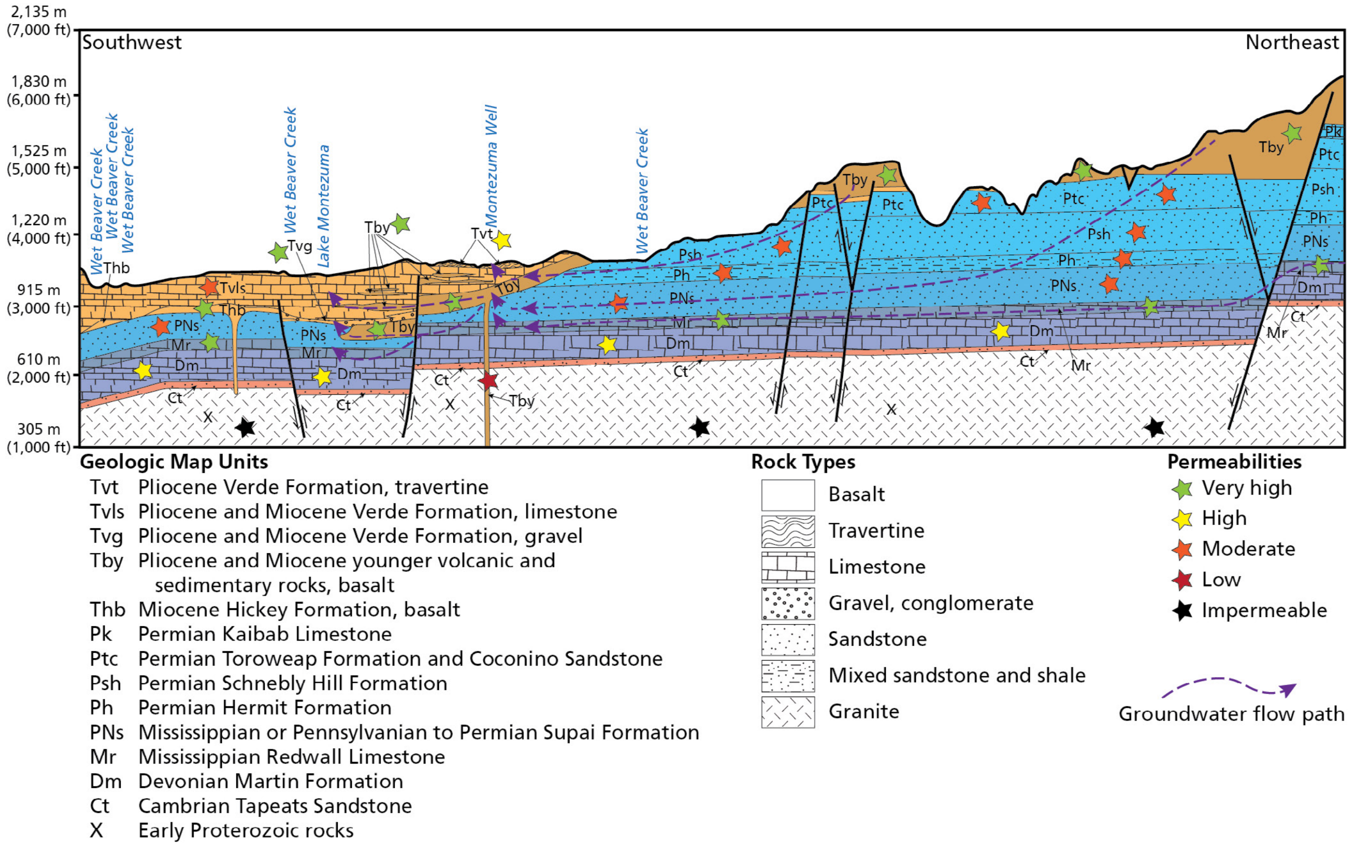

Figure 13. Generalized cross section of the Wet Beaver Creek drainage and Mogollon Rim. The cross section spans from the Mogollon Rim (northeast) to the confluence of Wet Beaver Creek and Dry Beaver Creek (southwest). It shows rock units, rock permeabilities, and groundwater flow paths. The higher ground—north and east of Montezuma Well—is the recharge zone. Groundwater in this area flows through the surface basalts (Tby) and underlying sedimentary rocks (Ptc, Psh, Ph, PNs, and Mr) before reaching the well along a low-permeability barrier (basalt dike, Tby) that intruded a fracture zone below the well. The main geologic features controlling groundwater flow (represented by the purple arrows on the graphic) at Montezuma Well are the permeable basalts (Tby) near the surface at the higher elevations; the permeable, karstic Redwall Limestone (Mr) at depth; and a low permeability basalt dike (Tby) underneath Montezuma Well. These features control groundwater flow by (1) rapid movement of groundwater through basalt flows, (2) the Redwall Limestone providing a very permeable pathway for groundwater flow at depth, and (3) the basalt dike creating a barrier for groundwater flow that forces groundwater to the surface. Note: The five labels of "Wet Beaver Creek" on the graphic illustrate the meandering nature of the creek, which repeatedly intersects the cross-section line. Geologic map unit symbols, ages, and names are from DeWitt et al. (2008). Graphic by Trista Thornberry-Ehrlich (Colorado State University) after Johnson et al. (2011, figures 3, 18, and 50).

geochemistry of Montezuma Well). The presence of this basalt dike and deep fracture system forces groundwater flowing at depth (less than 230 m [750 ft]) to the surface, resulting in groundwater discharge at Montezuma Well. Discharge has sufficient velocity to entrain sand-sized particles from the underlying bedrock and keep them in suspension within the pool (the "false bottom" [discussed below]). The fracture system appears to contribute a small amount of brine related to volcanic degassing. This brine contains carbon dioxide, salts, and trace elements such as arsenic, which mixes with water in the main groundwater system during discharge. The proportion of brine waters is probably quite small. The increased carbon dioxide dissolves limestone at depth, which subsequently helps to maintain open fractures; in addition, it probably created the Montezuma Well sinkhole. The water within Montezuma Well has high concentrations of carbon dioxide, calcium, and alkalinity. Subsequent degassing of the carbon dioxide at the surface causes travertine (calcium carbonate) deposition. This deposition currently occurs in prehistoric and historic irrigation ditches that transport

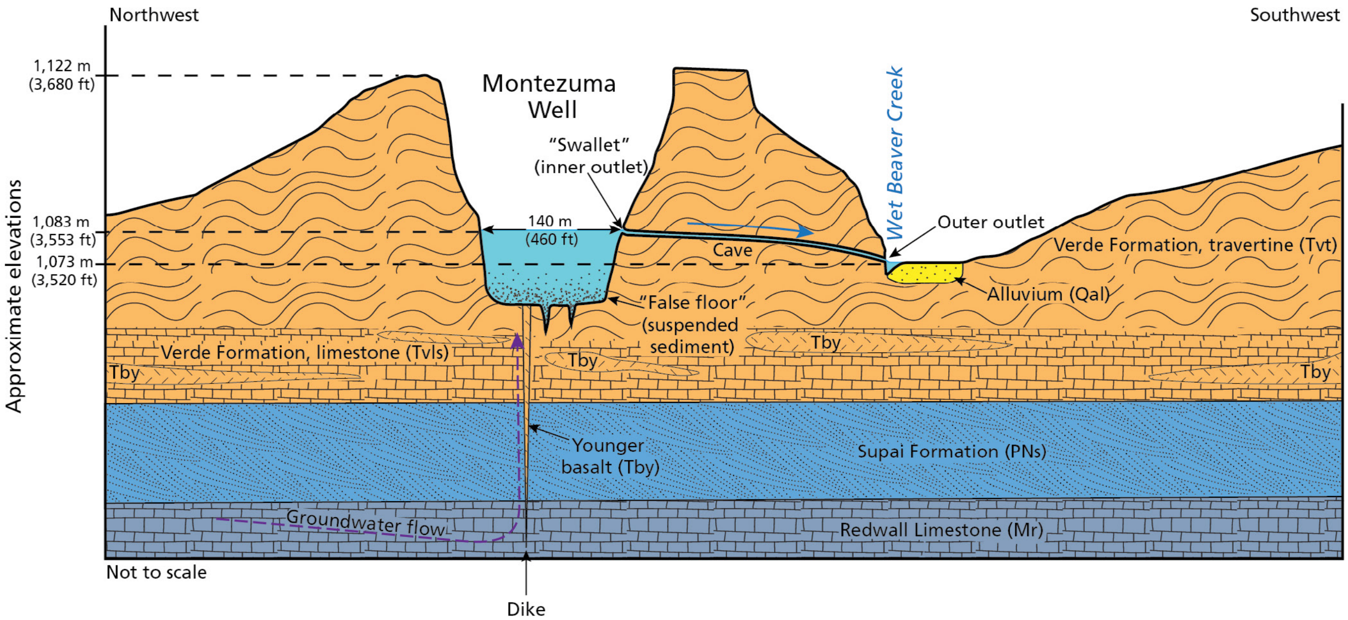

Figure 14. Generalized cross section through Montezuma Well.
Montezuma Well occurs in the Verde Formation, travertine (Tvt). Groundwater (represented by the purple arrow on the graphic) follows flow paths (shown in fig. 13) reaching permeable fractures along and above a basalt dike below the well. These fractures serve as conduits that carry groundwater and deep-sourced carbon dioxide (CO2) to the surface, which dissolves carbonate minerals along the transport path in response to the added CO2; this mechanism likely formed the cavity of Montezuma Well. At the surface, CO2 degasses, depositing travertine. As evidence, travertine coats the current irrigation ditch that transports water away from Montezuma Well. Groundwater enters Montezuma Well with such force to keep sand particles in suspension, creating the "false floor." At the surface, water flows through the swallet, cave, and outer outlet into an irrigation ditch. Under natural conditions, Wet Beaver Creek would transport this water away from the well. Graphic by Trista Thornberry-Ehrlich (Colorado State University) after Konieczki and Leake (1997, figure 15) and Johnson et al. (2012a, figure 9) with information from Lange (1957) and Lenihan (2011).

water away from Montezuma Well. Similar processes in the past have created extensive travertine deposits in the surrounding area.

Water pours out of the well at a point on the southeast border referred to as the "swallet" (an opening through which a stream disappears underground). Waters from Montezuma Well then "disappear" into a 90-m- (300-ft-) long cave (see "Cave and Karst Resource Management") for about a 7-minute flow before emerging at a natural outlet into an irrigation ditch, now thickly coated with lime (National Park Service 2016). The ditch is part of an extensive prehistoric and historic irrigation system. Under natural conditions, the outlet would pour into Wet Beaver Creek (Cole and Batchelder 1969; Cole and Barry 1973; Cole 1982). An estimated 5.7 million L (1.5 million gal) of water flows through the well daily (National Park Service 2016). Montezuma Well discharges at an average annual rate in excess of 0.06 m^3 per second (2 cfs) (National Park Service 1992).

A "false bottom" of Montezuma Well is a feature that has long intrigued explorers and investigators and inspired tales of the well as "bottomless." Lenihan (2011, p. 16) described the false bottom as "a layer of dense, suspended white stuff, like a thick cloud." The material also has been described as "oatmeal" or "churning" (Johnson et al. 2012a, p. 1831). The unusual churning nature of the sand is due to the hydraulic equilibrium attained between the upward velocity of the inflowing groundwater and the downward velocity of the sand grains (Johnson et al. 2012a). Images and videos of the false bottom are available at https://www.nps.gov/moca/learn/photosmultimedia/montezuma-well---nps-dive-images.htm and https://www.nps.gov/moca/learn/photosmultimedia/dive-to-the-bottom-of-the-well.htm. These images, taken in 2006, are from the most recent dive into Montezuma Well.

The depth from the surface of the pool to the false bottom is approximately17 m (55 ft). Flowing sands in two main vents, one east and one west, form the false bottom. Groundwater discharging through these vents creates a strong upward pressure that keeps the sediment in suspension. Johnson et al. (2012a) estimated the upward flow velocity of the water at 3.85 cm (1.52 in) per second, which is required to keep the quartz and magnetite grains (discussed below) in suspension. No current was detected throughout the rest of the pool (Konieczki and Leake 1997). Each vent has an estimated diameter of 1.02 m (3.35 ft), which is needed to maintain particle suspension (Johnson et al. 2012a). Measured with a probe, the west and east vents extend 21 m (69 ft) and 20 m (64 ft) beyond the false bottom, respectively (Lenihan 2011). The vents probably flare outward at the floor of the pool, which is where particles begin to fall out of suspension (Johnson et al. 2012a).

The suspended sediment in Montezuma Well is primarily sand between 0.105 mm (0.00413 in) and 0.420 mm (0.0165 in) in diameter. The mineral composition of the sediment is 97% quartz grains, 2% red sandstone grains, 1% carbonate aggregate, and 0.3% heavy minerals (i.e., magnetite, clinopyroxene, olivine, and zircon). The well-rounded, frosted, percussion-marked quartz grains are aeolian (windblown) material from the Supai Formation northeast of Montezuma Well. The rounded to subangular (free from sharp angles but not smoothly rounded) sandstone grains come from the water-transported part of the Supai Formation beneath Montezuma Well. The poorly rounded carbonate aggregate containing magnetite and rock debris comes from the Verde Formation limestone beneath the travertine. The heavy minerals come from the basalt dike that underlies the well. The dike is composed of a fine-grained groundmass and may even be glassy (Johnson et al. 2012a).

Age and Development of Montezuma Well

The exact age of Montezuma Well is unknown but is between about 5.5 million and 13,300 years old. Four pieces of evidence help to constrain the well's age. First, the well must be younger than the Verde Formation, travertine (**Tvt**), which contains it. As reported by DeWitt et al. (2008), the Verde Formation, travertine (**Tvt**) dates from the Pliocene Epoch (5.5 million to 2.6 million years ago). Second, the well must be younger than the basalt dike underlying the well, which the groundwater-flow model (Johnson et al. 2012a, 2012b) concluded aided in the well's formation. DeWitt et al (2008) reported an age of 6.2 million to 5.5 million years old for this basalt (**Tby**). Third, the well must be older than the water it contains; Johnson et al. (2012b) provided an age of between 13,300 and 5,400 years old for the well's water. Fourth, the well must be older than the diatoms it contains; Blinn et al. (1994) collected a record from the past 11,000 years.

According to Lange (1957), following the initial collapse of the well, which was not of the magnitude of the present well but probably a good proportion of it, the pool was shallow with a water level that stood at least 4 m (14 ft) higher than at present. This water level was required in order that the adjoining cave was submerged so that silt could be deposited in the cave and the existing speleogens (bedrock features that stand out in relief on the walls, ceiling, or floor of a cave) could form.

Studies by Davis and Shafer (1992) and Blinn et al. (1994) suggest the following timeline for the development of Montezuma Well:

- More than 9,000 years ago: Montezuma Well contained shallow water of constant depth.
- 9,000–5,000 years ago: Water levels underwent substantial fluctuations, and sediments were occasionally exposed to the air.
- After 4,000 years ago: Collapse in the travertine structure of the well resulted in a change in calcite deposition.
- After 3,000 years ago: Increased surface erosion occurred from steep slopes surrounding the Montezuma Well pool.
- After 1,500 years ago: Water levels rose steadily.

Paleontological Resources

"Elephant Hill" in the Castle Unit is the best-known fossil site within the monument (Santucci et al. 1998). The fossils at Elephant Hill consist of large footprints from extinct proboscideans (early relatives of elephants) (Hunt et al. 2005) and tracks of camelids (camel family), tapirids (herbivorous mammal with a short prehensile ["gripping"] trunk), antelope-like artiodactyls (cloven-hooved mammals), and other unidentified animals (McGeorge and Schur 1994). The tracks (fig. 15) occur in the Verde Formation, limestone (**Tvls**), which represent ancient lake sediments (fig. 10). The "squishing up" of the outer edges of the tracks indicates that the animals were walking in shallow water or in soft lakeshore mud (Shafer 1971).

Brady and Seff (1959) were the first to document the tracks at Elephant Hill in the scientific literature, but others previously knew of these fossils. For example, Myron Sutton, a Montezuma Castle ranger, made note of them in an unpublished NPS report, *Geology of the Verde Valley: An Interpretive Treatment* (Sutton 1953). Subsequently, paleontologists and other researchers (e.g., Twenter 1962) studied these rare tracks. At the

Figure 15. Photographs of fossils at Elephant Hill. The top photograph shows two proboscidean footprints. The bottom photograph shows a trackway made by artiodactyl (even-toed ungulates). The footprints and trackway occur in the Verde Formation, limestone (Tvls). Brady and Seff (1959, p. 80–82) wrote that the tracks "appear to be those of a small group of elephants. The length of stride is 82 inches; the diameter of the prints is about 17 inches." Metric conversion: 82 in = 208 cm; 17 in = 43 cm. Photographs by Vince Santucci (NPS Geologic Resources Division) taken in 2012.

time of these studies, the trackways of Elephant Hill were within Coconino National Forest; a boundary change in 1978 transferred the Elephant Hill parcel of land to the National Park Service.

In addition to tracks, which are trace fossils (evidence of past activity), the Verde Formation has also yields body fossils (remains of an actual organism), including plants, gastropods, fish, a camel ankle bone, some unidentified vertebrate remains, cricetid rodents (such as hamsters, voles, or lemmings, and their ancestors), equids (horses and their ancestors), and proboscideans. These fossils were documented by the Museum of Northern Arizona in Verde Formation fossil sites within or directly adjacent to the monument, as well as to other localities nearby (Santucci 2012).

In addition, the Quaternary lake deposits of Montezuma Well are fossiliferous and are the subject of several reports (Hevly 1974; Shafer and Davis 1987, 1988; Davis and Shafer 1992; Blinn et al. 1994). The two most extensive publications to date are Davis and Shafer (1992), primarily on pollen, and Blinn et al. (1994) on diatoms (a type of phytoplankton that secretes a cell wall made of silica). Both reports made use of an 11.25-m- (36.91-ft-) long core from the north-central part of the well that covers at least the last 12,000 years. Davis and Shafer (1992) also incorporated plant macrofossils (to provide radiocarbon dates) and mentioned the presence of macrofossils from aquatic organisms, including gastropods. Based on work by Davis and Shafer (1992), the area apparently changed from a piñon and juniper woodland to a steppe and desert scrub setting in the middle Holocene Epoch (9,000–6,000 years ago) with several rapid climate fluctuations during that time. Blinn et al. (1994) found evidence that the well had been very low or dry at several times in the middle Holocene Epoch, and that a period of wall collapses or other alterations to the geography of the well may have taken place about 4,000 to 2,000 years ago. The Southern Sinagua were present during a moderately dry period that occurred about 1,200 to 600 years ago.

Other Quaternary deposits (e.g., terraces) may contain isolated remains of fauna such as testudinids (e.g., turtles and tortoises), equids (member of the horse family), camelids, and proboscideans. In addition, Wet Beaver Creek may transport eroded fossils from nearby Paleozoic formations into the monument; the most likely are marine invertebrate fossils from the Permian Schnebly Hill Formation and secondarily from the Permian Toroweap Formation. In addition, packrat (*Neotoma* spp.) middens contain Quaternary fossils. Middens, which resemble piles or mounds of plant material with a dark glossy coating of crystallized packrat urine, provide important paleoecological information. Although middens are common within caves or rock crevices in the area, no study of middens at the monument has taken place to date.

Geologic History

This chapter highlights the chronology of geologic events that formed the present-day landscape of the monument. The "Geologic Features and Processes" chapter describes the geologic features mentioned in the timeline. As evidenced by the Early Proterozoic rocks in the area, evolution of the Montezuma Castle region took place over the past 1.7 billion years. The bedrock and surficial deposits in the monument represent the past 8.5 million years.

The following timeline makes a very long story short:

- Earth forms about 4.6 billion years ago (fig. 7).
- About 1.76 billion to 1.74 billion years ago, during the Early Proterozoic Era, plutonic rocks intrude below Earth's surface and volcanic rocks erupt onto it.
- During the Paleozoic Era (541.0 million–251.9 million years ago), sedimentary rocks of the Cambrian, Devonian, Mississippian, Pennsylvanian, and Permian Periods accumulate along ancient shorelines and in shallow seas and deeper marine basins. In the Montezuma Castle region, the oldest unit in the Paleozoic sequence is the Cambrian Tapeats Sandstone (**Ct**); the youngest is the Permian Kaibab Limestone (**Pk**). Exposures of Paleozoic rocks crop out in the tributary canyons that cut the Mogollon Rim, including the narrow canyon near the headwaters of Wet Beaver Creek.
- In the region, Basin and Range extension begins about 15 million years ago (Shafiqullah et al. 1980).
- The Hickey Formation (sedimentary and volcanic rocks, "**Th**" map units) accumulates and erupts between 14.5 million and 11 million years ago (McKee and Elson 1980). The Black Hills had not yet uplifted when basalt flows of the Hickey Formation spread across 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 ("**Tv**" map units) accumulates in the down-dropped Verde basin between about 8.5 million and 2.5 million years ago.
- Timing of the initial collapse of Montezuma Well is unknown but estimated to have taken place between about 5.5 million and 13,300 years ago. The well existed as a shallow pool starting about 9,000 years ago. Water levels began to rise steadily after about 1,500 years ago.
- About 2.5 million years ago, the Verde River begins to incise into the Verde Formation, creating today's Verde Valley. Incision by tributaries also began at this time. Terrace gravel (**Qt**) and alluvium (**Qal**) record the evolution of the Verde River valley and tributary drainages.
- Modern river and tributary-stream deposits (**Qal**) mark active channels. These deposits record ongoing geomorphic changes chiefly caused by flooding.

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 human 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 assistance for these issues.

During the 2006 scoping meeting (see National Park Service 2006), participants (see Appendix A) identified the following geologic features, processes, and resource management issues at the monument:

- Disturbed lands: urban development at Soda Springs, Arizona, and the potential for construction and sand-and-gravel mining on floodplains, groundwater withdrawal, and grazing.
- Hillslope features and processes: spalling of rock fragments in alcoves and rockfall (including boulders) from cliff faces onto trails.
- Cave and karst features and processes: archeological sites in alcoves, Montezuma Well, and Swallet Cave.
- Aeolian (windblown) features and processes: aeolian sand is a possible source of sediment in Montezuma Well.
- Fluvial features and processes: flash floods on Dry Beaver Creek, flooding and impacts on the irrigation system on Wet Beaver Creek, and bank failure along Wet Beaver Creek.
- Geothermal features and processes: a comparison of groundwater in Montezuma Well with Tavasci Marsh (in Tuzigoot National Monument) and other springs along the Verde River; Verde Hot Springs (a developed hot springs and former resort) illustrates the presence of geothermal activity in the area.
- Mineral resources: a travertine quarry on USDA Forest Service land northwest of Montezuma Well.
- Paleontological resources: the Verde Formation is fossiliferous. The Redwall Limestone (in the vicinity of the monument) may yield fossils.
- Unique geologic features: Montezuma Well is a "unique" geologic feature; its geochemistry and biology are distinctive.

In 2018, monument staff, an Arizona Geological Survey (AZGS) geologist, and GRI team members (see Appendix A) discussed the issues identified in 2006 and updated the list of issues to be addressed in this GRI report (tables 3–12). This chapter contains a table for each of the identified geologic resource management issues. The information following each of these tables may be useful for resource management actions. Appendix B, which summarizes laws, regulations, and policies that specifically apply to NPS minerals and geologic resources, also may be useful in planning for potential resource management actions.

Since scoping in 2006, the NPS Geologic Resources Division completed a geologic resources foundation summary (National Park Service 2014), which informed the foundation document for the monument (National Park Service 2016). Because the foundation document is a primary source of information for resource management within the monument, it was used in preparation of this report; it helped to draw connections between geologic features and "core components" of park significance such as "fundamental resources and values," "other important resources and values," and "interpretive themes." Core components and connections to geologic resources are highlighted in the tables included in this chapter.

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/geology). Staff from the geologic heritage emphasis area can assist monument managers with issues discussed in this chapter such as cave and karst resource management; illegal rock collection; and paleontological resource inventory, monitoring, and preservation. Staff from the active process and hazards emphasis area can assist with fluvial features and processes, geothermal resources, Quaternary faults and earthquakes, and slope movements. Staff from the energy and minerals management emphasis area can assist with issues associated with the monument's oil and gas reserve. Monument managers are encouraged to contact the NPS Geologic Resources Division (https://www.nps.gov/orgs/1088/contactus.htm) for assistance with the geologic resource management issues discussed in this chapter. Monument staff can formally request assistance via https://irma.nps.gov/Star/.

In addition, the NPS Geologic Resources Division administers the Geoscientists-in-the-Parks (GIP; http://go.nps.gov/gip) and Mosaics in Science (http://go.nps.gov/mosaics) programs. These internship programs place scientists (typically undergraduate students) in parks to complete geoscience-related projects. Many participants perform interpretive functions such as giving presentations, leading interpretive walks, writing site bulletins, and training staff members about the geology of a park. Program participants have used GRI reports in preparing interpretation, education, and training materials.

Resource managers may find *Geological Monitoring* (Young and Norby 2009) useful for addressing geologic resource management issues. The manual, which is available online at http://go.nps.gov/geomonitoring, 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. Where applicable, the following discussions highlight chapters in *Geological Monitoring*.

The Sonoran Desert Network is currently monitoring the following geologic features: groundwater, seeps, springs, tinajas (natural potholes), streams, and soils. The Sonoran Desert Network's website for the monument, https://www.nps.gov/im/sodn/moca.htm, posts the results of this work.

In addition, the Sonoran Desert Network is monitoring climate. Because of the potential disruption that climate change may cause to monument resources, including geologic resources, a brief 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 (see https://www.nps.gov/orgs/ccrp/index.htm).

Because management priorities are constantly shifting (Matt Guebard, Montezuma Castle and Tuzigoot National Monuments, chief of Cultural Resources, written communication, 21 May 2019), the following geologic resource management issues are ordered alphabetically, rather than with respect to management priority:

Cave and Karst Resource Management

The Federal Cave Resources Protection Act of 1988 requires the identification of "significant caves" in NPS areas, the regulation or restriction of use as needed to protect cave resources, and inclusion of significant caves in land management planning. For the National Park Service, the regulations stipulate that all caves on NPS properties are "significant." This act requires that land management planning considers caves and their use be regulated or restricted as needed to protect cave resources. The act also imposes penalties for harming a cave or cave resources and exempts park managers from releasing specific location information for significant caves in response to a FOIA request (see Appendix B). Other laws, such as the Archeological Resources Protection Act, also provide 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). Karst is a landscape that forms through the dissolution of soluble rock, most commonly carbonates such as limestone or dolomite (Toomey 2009). Caves, sinkholes, losing streams, springs, and internal drainage are characteristic features of karst landscapes. 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.

The NPS Geologic Resources Division can facilitate the development of a park-specific cave management plan. Such plans include a comprehensive evaluation of current and potential visitor use and activities, as well as a plan to study known and discover new caves.

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.

Table 3. Cave and karst resource management

Cave and Karst Resources	Explanation
Description	Both units of the monument contain cave resources: a large shelter cave or alcove houses the prehistoric cliff dwelling known as Montezuma Castle. Alcoves and associated archeological sites also occur around the perimeter of Montezuma Well. In addition, a 90-m- (300-ft-) long cave, referred to as "Swallet Cave," is associated with Montezuma Well; the cave is between the swallet (inner outlet) and the outer outlet of the well. The well itself is a significant karst feature, which formed via discharge of deep-seated, upward-flowing groundwater and collapse of a travertine-spring mound. Montezuma Well is one of four "collapse structures" (hazard feature lines) mapped in the GRI GIS data; the other three occur in limestone and are along Highway 17 outside the monument (see poster, in pocket).
Core components of park significance	Montezuma Well and cliff dwellings in alcoves have park significance and are a fundamental resource and value.
Associated map units or geologic features	• Verde Formation, limestone (**Tvls**) • Verde Formation, travertine (**Tvt**)
Threats	• Rockfall, including spalling, may damage archeological features (e.g., cliff dwellings). Rockfall events are frequently associated with wet periods. • Falling rocks (flakes from spalling in alcoves and larger pieces from cliff faces) are a safety hazard for visitors and staff. • Vandalism, including unintentional damage by visitors, and animals cause degradation of archeological resources in alcoves. • Urban growth and changes in water use could impact karst features such as Montezuma Well.
Potential research, planning, and data needs	• Interesting research would study why the alcove that houses Montezuma Castle is so large and competent compared to the other smaller caves near the monument. A possible hypothesis is that a depression above the castle pools water during large rainstorms, which could have facilitated erosion (National Park Service 2006). • National Park Service (2014) noted the need for regular monitoring and mitigation of spalling hazards. • National Park Service (2014) noted the need for a basic inventory of cave and karst features at the monument. • Investigators have used lidar and sonar bathymetry to document the well and its associated archeological resources. Monument managers plan to repeat these documentation efforts on a schedule to monitor and track changes over time (Matt Guebard, Montezuma Castle and Tuzigoot National Monuments, chief of Cultural Resources, written communication, 21 May 2019). • A potential source of data may be the NPS Submerged Resources group.

Climate Change

The monument has both weather and climate change information to support climate change planning. For example, in 2007, the Sonoran Desert Network completed a weather and climate inventory (Davey et al. 2007). Collection of weather data continues at a National Oceanic and Atmospheric Administration (NOAA) Cooperative Observer Program (COOP) weather station (MONTEZUMA CASTLE NM, ID#25635) in the monument. This station has been in operation since 1938, and the record provides a reliable, long-term climate dataset available for analysis. In 2014, the Sonoran Desert Network established Davis weather stations at both the Castle and Well Units. These stations are linked to the NOAA Citizen Weather Observer Program (CWOP) and accessible through the Climate Analyzer website (www.climateanalyzer.org), which creates custom graphs and tables from weather station data, satellite imagery, and other climate data sources.

Gonzalez (2014) is a climate change summary for the monument. It provided climate trends in temperature and precipitation, reporting that temperature has increased at a statistically significant rate of 1.2°C (2.2°F) since 1950. The summary found no statistically significant change in precipitation since 1950. In addition, the summary documented the following vulnerabilities: fire frequencies could increase up to 25% by 2100 (Moritz et al. 2012); recent drought and beetle infestations have killed piñon pines and other tree species, which may continue in areas experiencing drought in the future (Breshears et al. 2005); and past warming has reduced snowpack widely and rainfall in some areas, which may continue to reduce summer streamflow and water supplies (Garfin et al. 2013).

Monahan and Fisichelli (2014) is a climate change resource brief for the monument. These investigators analyzed temperature and precipitation and identified "extreme" conditions (exceeding 95% of the historical range). Five temperature variables were "extreme warm"; no temperature variables were "extreme cold." In short, temperature at the monument is pushing the limit of the historical range in five of the seven variables; two variables (mean temperature of the driest quarter and mean temperature of the wettest quarter) did not exceed the historical range. One precipitation variable (precipitation of the driest quarter) was "extreme dry"; no precipitation variable was "extreme wet." In short, precipitation is pushing the limit of the historical range in the driest quarter of the year. In addition, Monahan and Fisichelli (2014) noted that climate change will manifest itself not only as changes in average conditions but also as changes in particular climate events (e.g., more intense storms, floods, or drought).

Gwilliam et al. (2017) provided a status update of climate and water resources at the monument for water year 2016. Data collected and analyzed included precipitation, drought conditions, extreme weather events (e.g., days of extreme cold), mean daily discharge in streams, and water quality.

The Sonoran Desert Network monitors several vital signs that will likely show the effects of climate change (Sonoran Desert Network 2010); the following vital signs are also geologic indicators of change: seeps, springs, and tinajas; streams (e.g., channel morphology and stream discharge), washes (e.g., channel morphology and riparian vegetation), and groundwater.

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/.

Table 4. Climate change

Climate Change	Explanation
Description/ Threats	**Geologic features affected by climate change include the following:** ● A drier landscape due to climate change may result in dust storms and wind erosion, including "sand blasting" of cultural and natural resources. ● Changing precipitation patterns could affect Montezuma Well, causing a lower groundwater table and less discharge into the well. ● Greater frequency of slope movements may result from increasing wildland fire (see GRI report about Bandelier National Monument by KellerLynn 2015, which discusses fire as a driving force in an interconnected system of streamflow, sediment transport, stream channel morphology, and slope movements). ● More intense or frequent floods could increase the vulnerability of park infrastructure and resources along Wet Beaver and Beaver Creeks. ● An increase in storm frequency/intensity could accelerate current erosion rates, increasing the vulnerability of paleontological resources (e.g., fossil tracks) through exposure.
Core components of park significance	Climate change is a key issue because its impacts and those of changing weather patterns will have a lasting effect on the monument.
Associated map units or geologic features	● Flooding: alluvium (**Qal**) and terrace gravel (**Qt**) ● Montezuma Well: Verde Formation, travertine (**Tvt**) ● Slope movements: Verde Formation, limestone (**Tvls**) and Verde Formation, travertine (**Tvt**) ● Paleontological resources: Verde Formation, limestone (**Tvls**); and Quaternary sediments in Montezuma Well ● Aeolian (windblown) features and processes
Potential research, planning, and data needs	● Climate change scenario planning

Fluvial Features and Processes

To assist with planning, 36 USGS gaging stations record streamflow data in the Verde River watershed. One of these gaging stations, USGS 09505200 BEAVER CREEK NEAR RIMROCK, AZ, is about 18 km (11 mi) upstream from the confluence with Dry Beaver Creek. The drainage area for this gaging station is 287 km^2 (111 mi^2). Streamflow data (precipitation, daily discharge, and gage height) for this station are available at https://waterdata.usgs.gov/usa/nwis/uv?09505200. Arizona Department of Water Resources also provides data for the Verde River at http://www.azwater.gov/AzDWR/StatewidePlanning/WaterAtlas/CentralHighlands/Streams/VerdeRiver.htm.

Regarding the sewage treatment and disposal system, the National Park Service conducted a floodplain study defining the base and critical action floodplain boundaries of Beaver Creek for the sewage treatment and disposal system at the Castle Unit (National Park Service 1981). Elevations of the base and critical action floodplain boundaries were defined at 3,102.5 feet and 3,106.5 feet, respectively; metric conversions for these defined boundaries are 945.6 m and 946.9 m. As a result of that study, the National Park Service constructed new sewage lagoons on a site above 3,100 feet (or 945 m) and removed the older ones, which were occasionally flooded at a bend in the creek below 3,000 feet (or 914 m) (National Park Service 1992).

The *Geological Monitoring* chapter "Fluvial Geomorphology: Monitoring Stream Systems in Response to a Changing Environment" (Lord et al. 2009) provides an overview of river and stream dynamics, describes possible stressors that may lead to channel instability, and lists guidelines and methods for monitoring streams and rivers. The chapter discusses the following vital signs: (1) watershed landscape (vegetation, land use, surficial geology, slopes, and hydrology), (2) hydrology (frequency, magnitude, and duration of stream flow rates), (3) sediment transport (rates, modes, sources, and types of sediment), (4) channel cross section, (5) channel planform, and (6) channel longitudinal profile. Because differences exist in budget, staffing, and management needs and objectives, the chapter provides three levels of monitoring protocols. This information may be useful for monument managers in monitoring the creeks in the monument and planning for changes in floodplain stability.

The Sonoran Desert Network monitors the status and trends of six different parameters related to fluvial features and processes at the monument. These parameters are (1) water quality (e.g., core water quality parameters, nutrients, metals, and toxins), (2) water quantity (flow volume, flooding magnitude, and flooding frequency), (3) channel morphology (shape and habitat of the stream channel), (4) riparian vegetation (type, abundance, and communities of river-related plants), (5) macroinvertebrates (small crustaceans, mollusks, worms, and aquatic insects), and (6) fish (native and nonnative fish abundance and frequency).

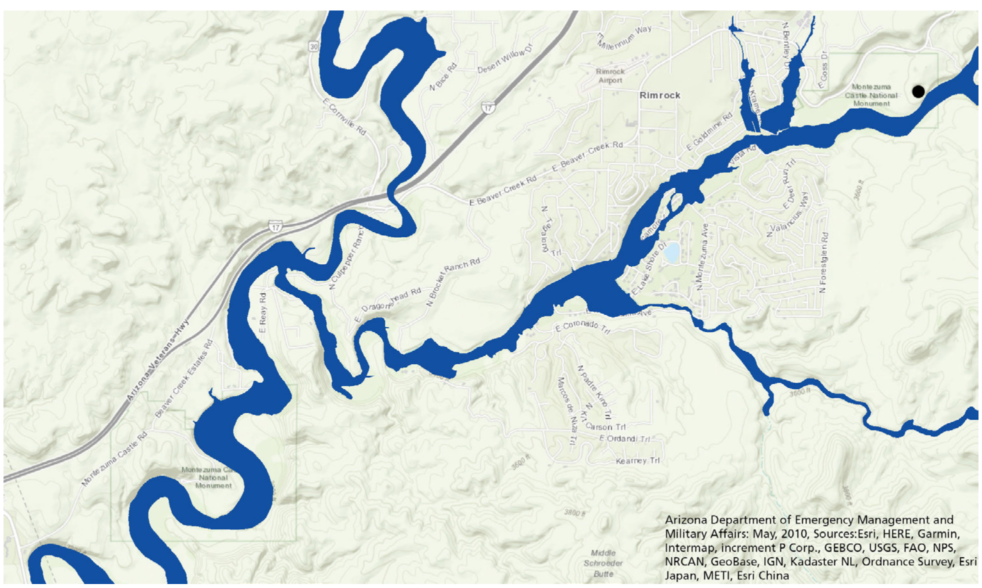

Figure 16. Map of flood potential.
The figure shows the Well (north) and Castle (south) Units of the monument. Blue areas indicate high flood potential. The black dot in the Well Unit marks Montezuma Well. Graphic generated from AZGS "Natural Hazards in Arizona" map viewer at https://azgs.arizona.edu/center-natural-hazards (accessed 16 April 2019).

Table 5. Fluvial features and processes

Fluvial Features and Processes	Explanation
Description	Fluvial features at the monument include Beaver Creek (in the Castle Unit) and Wet Beaver Creek (in the Well Unit) and their channels and floodplains. These creeks are tributaries of the Verde River. Ephemeral discharge in Dry Beaver Creek and perennial springs on the Mogollon Rim, which discharge into Wet Beaver Creek, feed Beaver Creek. In bedrock-lined reaches of Wet Beaver Creek, the floodplain may be confined to an area 20–100 m (60–400 ft) wide; in less confined reaches along Beaver Creek, the Holocene floodplain may be 300–900 m (1,000–3,000 ft) wide.
Core components of park significance	● The Verde River and its tributaries are part of the oral histories of native tribes. As such, these fluvial features have cultural connectivity, which is a fundamental resource and value. ● The channel features found in Beaver Creek and Wet Beaver Creek are associated with the historic setting and the rationale for early habitation at the site (National Park Service 1992). These features provide cultural connectivity, which is a fundamental resource and value. ● The Verde River and its tributaries serve as wildlife corridors thus they are linked to flora and fauna, which is an "other important resources and value." ● Water resources, including the Verde River and its tributaries, are an interpretive theme.
Associated map units or geologic features	● Alluvium (**Qal**) ● Terrace gravel (**Qt**)
Threats	● Flooding on Beaver Creek is eroding banks around the monument's housing area. During a flooding event in winter 2005, Beaver Creek damaged a historical 1930s gabion (levee-like structure) built by the Civil Works Administration. This gabion is protecting infrastructure (i.e., picnic area and sidewalks). ● Future flooding could threaten the sewage treatment and disposal system (see figs. 16 and 17). ● Dry Beaver Creek (outside the monument) has flash floods during the summer months. ● As illustrated by flooding in February 2019, flooding on Wet Beaver Creek can affect the irrigation canals and ditch gauging station, as well as scour vegetation during flood events and cause cut slopes along the stream to fail, resulting in a safety hazard for visitors walking along the stream (Matt Guebard, Montezuma Castle and Tuzigoot National Monuments, chief of Cultural Resources, written communication, 21 May 2019). ● Dissolution of carbonate rock causes the location of the well's outlet to shift, which results in periodic flooding on the nearby trail. ● Many tributaries of the Verde River, including Wet Beaver Creek, are incised into bedrock or consolidated basin fill for their entire lengths. As a result, the overall width of the Holocene floodplain is relatively stable. With shifts in channel position during large flood events, however, river or tributary deposits can become inundated and subsequently buried, undercut, and eroded away, or reshaped through partial erosion (Cook et al. 2010a). ● Scoping participants noted the potential for development in Soda Springs (upstream from the monument). Building within floodplains has the potential to affect water quality and increase flood-related hazards. ● Mining of sand and gravel used to take place along Wet Beaver Creek upstream from the monument; this operation is now closed. ● A local operator, B and B Materials, is mining gravel from the floodplain of Dry Beaver Creek. Scoping participants suspected that this operation may affect water quality. ● Part or all of the flow of Beaver Creek is diverted for irrigation during the summer. During the peak irrigation season (June), half of the 0.4 m^3 per second (15 cfs) streamflow gain in the Verde River at the mouth of Beaver Creek is attributable to subsurface irrigation return flows through the alluvium (Owen-Joyce and Bell 1984; National Park Service 1992).
Potential research, planning, and data needs	● Management decisions about water resources, including streams, are guided by *Water Resources Management Plan, Montezuma Castle and Tuzigoot National Monuments* (National Park Service 1992). This document is outdated. The monument does not have an updated version (Matt Guebard, Montezuma Castle and Tuzigoot National Monuments, chief of Cultural Resources, written communication, 21 May 2019). ● According to the monument's water resources management plan (National Park Service 1992), flood hazard of an unknown degree exists at the Castle and Well Units. Thus, a flood hazard assessment, including flash floods from Dry Beaver Creek, is a data need. The AZGS "Natural Hazards in Arizona" map viewer (**https://azgs.arizona.edu/center-natural-hazards**) may provide insight since 1992 (fig. 16).

Geothermal Resources

Since the 1970s, AZGS geoscientists have been engaged in evaluating and characterizing potential geothermal "hot spots" throughout central and southern Arizona. This effort has yielded dozens of reports, numerous well-hole data, and maps assessing the potential for geothermal energy. Derivative products include geothermal development plans for most of Arizona's counties; Yavapai County is part of the northern counties plan (Goldstone and White 1980). 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.

Existing reports about geothermal resources for the Verde Valley include a map showing the potential geothermal resource areas (Ross and Farrar 1980); USGS Water Resources Investigations Report 97-4156 (Konieczki and Leake 1997), which was prepared in cooperation with the National Park Service; and the 2006 scoping summary (National Park Service 2006), which noted the water temperature of Montezuma Well.

As reported by Konieczki and Leake (1997), divers from the US Geological Survey, who were conducting an underwater survey of Montezuma Well in May 1991, noticed that the water in the two fissures (at the bottom of Montezuma Well) was warmer than in the rest of the pond. The mean water temperature near the bottom of the well was at least 2°C (4°F) warmer than the mean water temperature of samples from stream alluvium, the Verde Formation, and the Supai Formation. The mean temperatures of water from the alluvium and Supai Formation were 17.6°C (63.7°F) and 17.9°C (64.2°F), respectively. The temperature in the pond ranged from 21.0°C (69.8°F) to 26.5°C (79.7°F). In most of the water profiles, the temperature dropped about 0.5°C (0.9°F) in the first 5 m (16 ft) below the surface and then remained constant for about 10 m (30 ft). The temperature rose about 1°C (2°F) in the suspended sand. The temperature remained constant horizontally except at the fissures where the temperature increased.

The 2006 scoping summary provided the following information: The water temperature of Montezuma Well is much more similar to Tavasci Marsh, in Tuzigoot National Monument, than Verde Hot Springs (Laurie Wirt, USGS-Denver, geologist, written communication, 23 June 2006). Verde Hot Springs has the highest measured temperature (39°C [102°F]) in the Verde Valley (Ross and Farrar 1980). In the 1920s, a resort developed around the hot springs but burned down in 1958. The resort did not have a significant impact on the landscape (Protas 2002). Soda Springs, which is 30 km (20 mi) north of Verde Hot Springs, was designated as a hot spring by Hahman et al. (1978), having a measured temperature of greater than 30°C (86°F).

During the scoping meeting, Laurie Wirt noted that many springs along the Verde River emerge from large faults or karst. These springs have the same water temperature of about 19°C (68°F). The largest one known to Wirt is at Page Springs, which is 10 km (6 mi) east of Tavasci Marsh (see GRI report about Tuzigoot National Monument by KellerLynn 2019). Fisheries operate at that location because the warm water encourages rapid fish growth. Water temperature of about 19°C (68°F) is fairly common for some of the other carbonate springs along the Verde River, for example, Bubbling, Lolomai, and Turtle Springs, which are upstream from Page Springs. Like Montezuma Well, the springs in the Verde Valley typically emerge through the Verde Formation, but probably come through the underlying Paleozoic section of rocks. Since scoping, Johnson et al. (2011, 2012a, 2012b) provided further evidence of this.

The Sonoran Desert Network monitors groundwater levels (see "Groundwater Withdrawal") as well as seeps, springs, and tinajas at the monument (Sonoran Desert Network 2018). Although seeps and springs are discharge areas of groundwater, the Sonoran Desert Network monitors seeps and springs as surface water features with vital signs that focus on water availability and water quality, not geothermal activity. 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 monitoring geothermal resources at the monument. The NPS Geologic Resources Division's Geothermal Systems Monitoring website, http://go.nps.gov/geomonitoring, provides additional information. The GRI reports about Petrified Forest National Park and El Morro National Monument by KellerLynn 2010 and 2012, respectively, provide information about tinajas, which may be of interest to monument managers.

Table 6. Geothermal resources

Geothermal Resources	Explanation
Description	The monument is not one of the 16 units within the National Park System that contain geothermal 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). Nevertheless, the "elevated" water temperatures in Montezuma Well are a clue for understanding the system. In 2006, scoping participant Laurie Wirt (USGS) noted that the water in Montezuma Well is about 3°C (5°F) warmer than expected, which could be evidence of a deep groundwater system (see "Montezuma Well").
Core components of park significance	The groundwater reservoir for Montezuma Well, which is a fundamental resource and value, would be affected by geothermal resource development in the area.
Associated maps units or geologic features	The Colorado Plateau has low geothermal potential whereas the Basin and Range has high geothermal potential; the monument is located in the transition zone of these two provinces.
Threats	• Ross and Farrar (1980) investigated the groundwater reservoir in the Verde Valley as a potential geothermal energy resource with associated desalinization project; no major groundwater reservoir suitable for supplying desalinated water exists in the Verde Valley. • The threat from geothermal development in the Verde Valley is low but could reoccur as a result of updated technologies and a national or regional emergency. Geothermal energy development is a means to supplement the nation's existing energy supply.
Potential research, planning, and data needs	• Monitor Montezuma Well as a geothermal feature using vital signs from Heasler et al. (2009).

Groundwater Withdrawal

Because of the increasing withdrawal of groundwater within the Verde Valley due to population growth, the National Park Service through the US Geological Survey initiated a research project to better understand and identify the source and flow paths of groundwater to Montezuma Well (see “Montezuma Well”). Three documents provide the results of this research: (1) Johnson et al. (2011) supplied the collected data and described the data-collection methods, (2) Johnson et al. (2012a) described the geologic controls and hydrogeologic framework for groundwater to Montezuma Well, and (3) Johnson et al. (2012b) described how the geochemistry of groundwater constrains the groundwater flow paths to Montezuma Well.

The Sonoran Desert Network monitors groundwater at the monument (Sonoran Desert Network 2018). Network staff collects data on depth-to-water and water-level elevation in order to (1) detect long-term changes in groundwater levels, (2) support interpretation of surface monitoring results, (3) extend regional groundwater data and regional groundwater trends to immediate park locales, (4) contribute to an understanding of water-balance dynamics at parks (including relationships between groundwater and surface water resources, biota, and climate), (5) support larger scale water balance efforts by other agencies, (6) assess site suitability for riparian habitat, and (6) document water-level elevations to support legal protection of the resource.

The National Park Service owns proprietary water rights to half the flow from Montezuma Well. Monument administrators oversee the water claims on the discharge from Montezuma Well and coordinate the distribution of this water through the network of prehistoric and historic irrigation ditches (National Park Service 1992; Protas 2002).

In addressing groundwater withdrawal at the monument, the Water Rights Branch (WRB) of the NPS Water Resources Division would be the lead at the national level, and the Sonoran Desert Network would be the lead at the local level. The role of the Water Rights Branch is to secure and protect water rights for the preservation and management of the National Park System through all available local, state, and federal authorities. A basic function of the Water Rights Branch is to measure and analyze groundwater and surface water data. The Water Rights Branch has provided assistance to many parks in the Sonoran Desert Network (see https://www.nps.gov/orgs/1439/wrb.htm). WRB staff members have expertise in hydrogeology, groundwater modeling, groundwater sustainability, and water rights (see https://www.nps.gov/orgs/1439/contactus.htm).

Table 7. Groundwater withdrawal

Groundwater Withdrawal	Explanation
Description	Work by Johnson et al. (2011, 2012a, 2012b) indicated that flow to Montezuma Well may be more susceptible to future groundwater withdrawal from the Redwall Sandstone (**Mr**) than from any other geologic unit. The source of water of the monument's domestic water well is an aquifer in the Verde Formation, limestone (**Tvls**).
Core components of park significance	• Montezuma Well [including the water it contains] is a fundamental resource and value.
Associated map units or geologic features	• Redwall Limestone (**Mr**) is the primary source of groundwater to Montezuma Well. • The Verde Formation (**Tvls** and **Tvl**) and Quaternary alluvium (**Qal**) are aquifers. • Via an interconnected system of fractured bedrock, water flows through surface basalts (**Tby**) in the recharge area on the Mogollon Rim then through the underlying Proterozoic sedimentary rocks (**Ptc**, **Psh**, **Ph, PNs**, and **Mr**) before reaching Montezuma Well along a low-permeability barrier (basalt dike, **Tby**) and associated fracture zone below the well.
Threats	• Development (groundwater withdrawal) in Soda Springs, Arizona, could impact features (e.g., water level, flows rates, and chemistry) of Montezuma Well. • The Rim Rock Bottling Company is pumping groundwater near Montezuma Well. The targeted aquifer is unknown. • New drilling upgradient from the well within the Redwall Limestone could potentially lower the water table. • Subsidence can occur as a result of groundwater withdrawal.
Potential research, planning, and data needs	• Study alternative flow paths for groundwater to Montezuma Well such as flow through the shallow basalts within the Verde Formation, the underlying Permian sandstone, and/or flow through the granitic basement rocks (see Johnson et al. 2012b). • Study the potential for subsidence to impact monument resources. • Since 1992, the water resources management plan developed for Montezuma Castle and Tuzigoot National Monuments (National Park Service 1992) has guided management. The plan takes into consideration the characteristics of the water resources, the legislative requirements, the various demands for water, the management goals and objectives for the monument (e.g., protection of the aquatic and riparian habitats), and the results of previous research on changes in the quantity and quality of the regional water resources. Nevertheless, this document is outdated, and the monument does not have an updated version (Matt Guebard, Montezuma Castle and Tuzigoot National Monuments, chief of Cultural Resources, written communication, 21 May 2019).

Illegal Rock Collection

Illegal rock and mineral collection may share similarities with illegal fossil collection, so Santucci et al. (2009) may be useful for this issue (see "Paleontological Resource Inventory, Monitoring, and Protection"). Collaborating with the USDA Forest Service for locating, inventorying, monitoring, and patrolling may be an option.

Table 8. Illegal rock collection

Illegal Rock Collection	Explanation
Description	A small travertine quarry with semi-precious (gem-grade) onyx (known as "poor man's marble") is located on USDA Forest Service land; monument staff suspects that the deposit extends into the monument (National Park Service 2006). The quarry used to be mined commercially for picture agate but is now only used by "rockhounds" (recreational collectors).
Core components of park significance	• Travertine encompasses Montezuma Well, which is a fundamental resource and value.
Associated map units or geologic features	Verde Formation, travertine (**Tvt**)
Threats	• The potential for illegal collection exists within the monument. • Typically, state geological surveys have information about and monitor activities in large mining districts; activities of rockhounds are rarely monitored, however.
Potential research, planning, and data needs	• Determine if travertine deposit with onyx extends within monument, and, if so, document (GIS and photographs) and evaluate it for past damage and recent illegal collection. Determine if additional resource management or protection actions are warranted. • Provide training for staff in rock and mineral resource protection. • Write a plan to increase public awareness of NPS regulations regarding rock and mineral resources.

Oil and Gas Reserve

Arizona is not a major oil and gas producing state (Arizona Geological Survey 2018). Most production stems from small oil fields in northeastern Arizona. Arizona Geological Survey Circular 29, *Arizona has Oil & Gas Potential* (Rauzi 2001), is an excellent starting point for learning about the state's oil and gas resources. The Arizona Oil and Gas Conservation Commission's webpage (http://www.azogcc.az.gov/), maintained by the Arizona Department of Environmental Quality (https://azdeq.gov/welcome-adeq), provides additional information about oil and gas in the state.

In the National Park Service Organic Act and the acts that established individual park units, Congress authorized the secretary of the Interior to develop regulations for managing and protecting park units. Based on these authorities, the National Park Service promulgated regulations at 36 CFR Part 9, Subpart B, which govern the exercise of nonfederal oil and gas rights in park units. The "9B" regulations require prospective operators to obtain NPS approval of an operations permit from the National Park Service before conducting any oil and gas activities within a park unit. The operations permit application outlines all proposed activities of the oil and gas development, describes how reclamation will be completed, and requires that appropriate financial assurance be provided to ensure that reclamation is conducted. The National Park Service uses the information to determine the effects of proposed operations on the environment, visitor uses, and park management.

The NPS Geologic Resources Division can assist monument managers with oil and gas–related issues. The NPS Geologic Resources Division's Energy and Minerals website, http://go.nps.gov/grd_energyminerals, provides additional information.

Table 9. Oil and gas reserve

Oil and Gas Reserve	Explanation
Description	The Castle Unit of the monument contains a 0.88-ha (2.17-ac) tract of land on which oil and gas were reserved when the National Park Service acquired the property.
Core components of park significance	None
Associated map units or geologic features	Of the rocks underlying the monument, four are of interest for oil and gas production: (1) Cambrian Tapeats Sandstone (**Ct**) is a reservoir rock (a permeable rock layer where hydrocarbons have migrated and are held underground); (2) Devonian Martin Formation (dolomite and limestone, **Dm**) is petroliferous (has a strong petroleum smell) and has a known oil seep (northwest of Payson); (3) Mississippian Redwall Limestone (**Mr**) produced oil in the Dry Mesa field (northeastern Apache County) from 1959 to 1998; and (4) Permian and Pennsylvanian Supai Formation (**PNs**) is petroliferous and shows an oily sheen on fresh fractures in the Sedona–Diamond Creek district (Coconino and Apache Counties).
Threats	• Potential impacts of oil and gas development 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.
Potential research, planning, and data needs	• Locate the reserve in the monument's GIS data for the purpose of park planning. Notably, the GRI GIS data do not include the reserve as a feature. • Determine how the reserve, which is a "special mandate," affects park planning. • Identify potential threats to natural and cultural resources at the monument.

Paleontological Resource Inventory, Monitoring, and Protection

In 2012, Vincent Santucci (NPS Geologic Resources Division) conducted a site visit at the monument. The associated trip report (Santucci 2012) documented and evaluated the condition of the trackway and provided recommendations for management (some of which are included in the table above). At present, the trackway is mostly covered over with dirt; this, and its location in the backcountry, are the primary means of protection (GRI conference call, 5 December 2017).

Monument staff should be aware of the following paleontological vital signs at the monument: erosion (both geologic and climatic factors), geohazards, human access and public use, and hydrology/bathymetry. The *Geological Monitoring* chapter about paleontological resources (Santucci et al. 2009) provides detailed methods for monitoring these vital signs.

Tweet et al. (2008)—a paleontological resource inventory and monitoring report about parks in the Sonoran Desert Network—provided park-specific information about the paleontological resources at the monument. During the conference call, Justin Tweet (NPS Geologic Resources Division, paleontologist), primary author of the aforementioned inventory and monitoring report, noted that the fossil specimens from the monument that are contained in the Western Archeology and Conservation Center (WACC) collection have been photographed. These include a brachiopod, a tabulate coral, and what appears to be a mushroom-shaped tooth.

Two other NPS publications provide information about paleontological resources in NPS settings; these are servicewide publications but may be of interest and use to monument managers. First, Santucci et al. (2001) is an inventory of paleontological resources associated with NPS caves. Second, Kenworthy and Santucci (2006) is an overview of NPS paleontological resources in cultural resource contexts. Significantly, any fossil within a cultural context may be a sensitive resource and subject to the Native American Graves Protection and Repatriation Act. In addition, documenting a fossil found in a cultural context requires both archeological and paleontological input. The NPS Geologic Resources Division and WACC can coordinate additional documentation/research of such material.

Monument managers are encouraged to contact the NPS Geologic Resources Division for paleontological resource management or interpretation assistance. If a staff member or visitor discovers a packrat midden in an alcove or rock crevice, the NPS Geologic Resources Division maintains a list of active researchers of packrat middens in the Southwest and can facilitate communication between monument managers and these researchers.

If funding allows, resource managers could consider obtaining quantitative information via photogrammetry (the science of making measurements from photographs), which could be useful in documenting the fossil tracks and monitoring their condition. The NPS 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, though a camera attached to a low-altitude unmanned vehicle is an option. The result is a 3D model. The NPS Geologic Resources Division's Photogrammetry website (http://go.nps.gov/grd_photogrammetry) provides more information and examples of applications of photogrammetry for resource management.

Table 10. Paleontological resource inventory, monitoring, and protection

Paleontological Resources	Explanation
Description	All paleontological resources are nonrenewable and subject to science-informed inventory, monitoring, protection, and interpretation as outlined by the 2009 Paleontological Resources Preservation Act (see Appendix B). As of August 2019, Department of the Interior regulations associated with the act were in the surnaming process.
Core components of park significance	Paleontological resources are an "other important resource and value."
Associated map units or geologic features	● The site known as "Elephant Hill" contains the well-known fossilized trackways and footprints of Pliocene mammals in the Verde Formation, limestone (**Tvls**) (fig. 15). ● The Verde Formation has the potential to yield body fossils (see "Paleontological Resources"). ● Quaternary sediments in Montezuma Well contain fossils. ● Investigators found older Pleistocene bird and rodent fossils (bones) in the wall of Swallet Cave in the 1950s; Lange (1957) reported on these. ● Wet Beaver Creek has the potential to transport eroded fossils from nearby Paleozoic rocks into the monument. ● Alcoves in the Verde Formation (**Tvls** and **Tvt**) have the potential to contain packrat (*Neotoma* spp.) middens, which are commonly found within caves or rock crevices. ● Quaternary deposits (**Qt**) such as terraces have the potential to contain Pleistocene mammal fossils.
Threats	● Over the years, monument managers have covered the tracks at Elephant Hill with soil to protect this resource (Protas 2002). The trackways are currently buried (GRI conference call, 5 December 2017). ● Natural erosional processes can leave fossil resources exposed and vulnerable, increasing the likelihood of theft or damage. ● Human-caused threats such as vandalism or theft of fossils are possible. ● After-hours trespassing may cause inadvertent damage.
Potential research, planning, and data needs	● Research to identify other potential locations of trackways is of interest but a low-priority data need. ● Periodic surface surveys for exposure of new tracks at Elephant Hill would help protect these features. Monument staff (as part of their regular field duties), trained volunteers, partners (e.g., local paleontologists), GRD staff (through a technical assistance request), or a Geoscientist-in-the-Parks (GIP) intern could conduct surveys. ● Through evaluation of the GRI GIS data, assess for other potential fossil localities within the Verde Formation in the monument and initiate surface surveys in these areas. ● Obtain and maintain GIS-based locality data for each of the known fossil tracks and trackways. Continue to capture GIS data for any tracks discovered in the future. Utilize GIS data to produce a paleontological resource locality map to support management and planning. ● Initiate long-term repeat photographic documentation and monitoring of fossil tracks. GRD staff can provide assistance with acquisition of 3D photogrammetric images. ● Work with GRD staff to develop a monitoring plan for the track site. ● Recruit a GIP intern to assist with the recommendations contained in Santucci (2012).

Quaternary Faults and Earthquakes

Earthquake monitoring in the state of Arizona occurs at seismograph stations throughout the state (fig. 17). Most of these stations are maintained by two seismograph networks: (1) the Northern Arizona Seismograph Network (NASN) and (2) the Arizona Broadband Seismograph Network (ABSN). 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 conduct research on earthquakes occurring in the state of Arizona (Arizona Earthquake Information Center 2010).

The *Geological Monitoring* chapter about earthquakes and seismic activity (Braile 2009) describes the following methods and vital signs: (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 movement along faults as well as ground shaking and other earthquake hazards (e.g., liquefaction) at the monument.

Conference call participants noted that monument managers could contact the Arizona Geological Survey (AZGS) with questions about earthquakes; Jeri Young is a particular contact (jeri.young@azgs.az.gov). The AZGS website (http://azgs.arizona.edu/center-natural-hazards/earthquakes) and AZGS "Natural Hazards in Arizona" map viewer (https://azgs.arizona.edu/center-natural-hazards) provide more information.

Table 11. Quaternary faults and earthquakes

Faults and Earthquakes	Explanation
Description	DeWitt et al. (2008) mapped the Bridgeport, Airport, and Verde faults west of the monument and faults in the Paleozoic and Tertiary rocks east of the monument (see poster, in pocket) but no faults within the monument. Tertiary and Quaternary deposits mostly conceal the fault segments west of the monument. All of the faults are normal faults. The closest active fault (i.e., having moved during the Quaternary Period, the past 2.6 million years) is an 8-km- (5-mi-) long section of the Verde fault zone, which Menges and Pearthree (1989) referred to as the "Camp Verde fault zone." It runs along the base of the Black Hills on the western side of the Verde Valley (fig. 18). Movement on this fault occurred less than 130,000 years ago. The slip rate along this portion of the fault is less than 0.2 mm (0.008 in) per year (Bausch and Brumbaugh 1997).
Core components of park significance	• Earthquakes produced by movement along faults may affect groundwater flow into Montezuma Well, which is a fundamental resource and value. • Past earthquakes are part of oral histories of native tribes, thus providing cultural connectivity, which is a fundamental resource and value.
Associated map units or geologic features	• Normal faults (polylines in GRI GIS data) • Nearby faults cut the following map units: alluvium (**Qal**); fanglomerate (**QTf**); Verde Formation, gravel (**Tvg**); Hickey Formation, alkali basalt (**Thab**); Toroweap Formation (**Ptc**); Schnebly Hill Formation (**Psh**); and Hermit Formation (**Ph**)
Threats	• As noted during GRI scoping in 2006, monument staff has observed changes in water flow into and out of Montezuma Well that seemed to correspond to an earthquake, probably along the Oak Creek fault. However, no studies have confirmed a link between earthquakes and changes to groundwater flow (GRI conference call, 5 December 2017). • 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 (Bausch and Brumbaugh 1997). • If the maximum credible earthquake on the Verde fault zone (magnitude 7.25) were to take place, the effects to Yavapai County will be extensive, including 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 and smaller stream valleys that are underlain by relatively unconsolidated sediment and shallow groundwater will be susceptible to liquefaction–induced ground failure.
Potential research, planning, and data needs	• Study the connection between movement along faults (earthquakes) and groundwater flow at Montezuma Well.

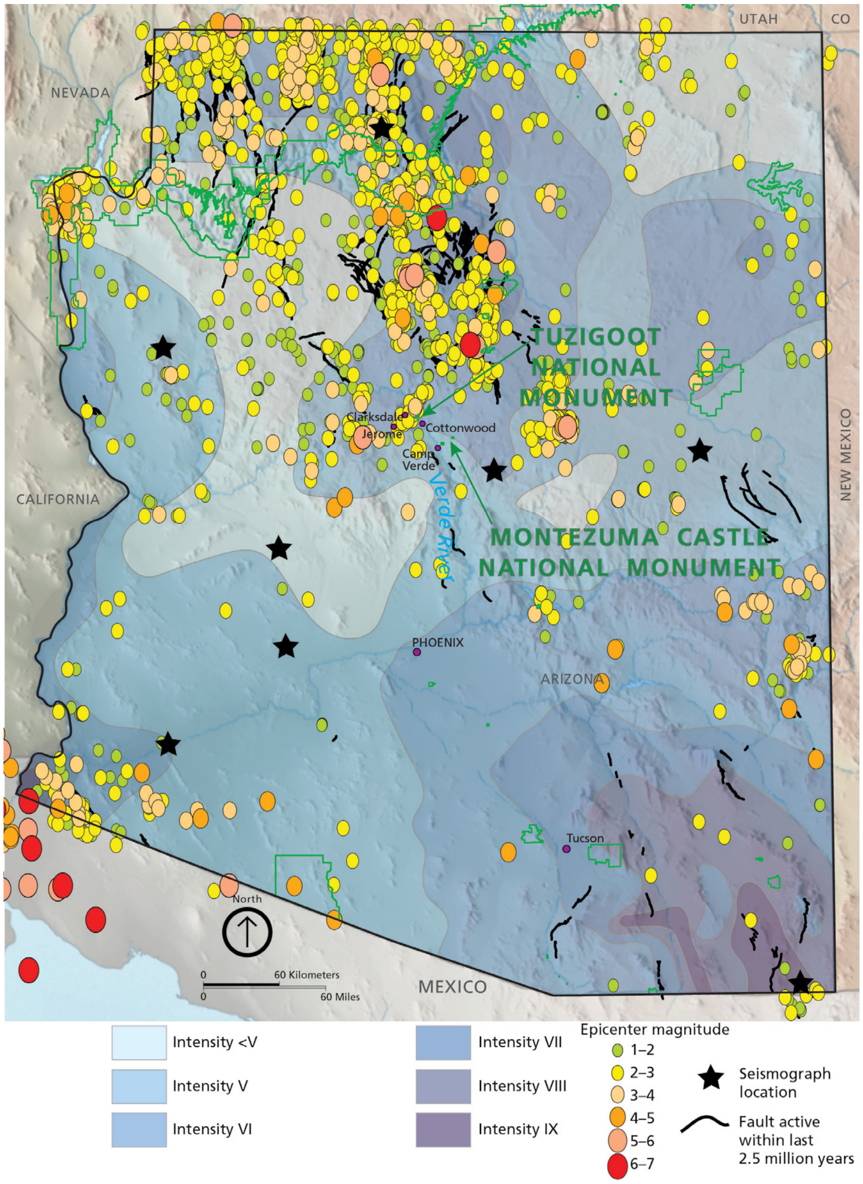

Figure 17. Map of active faults, earthquakes, and seismograph stations in Arizona.
Each year seismograph stations (black stars) record hundreds of felt and unfelt earthquakes in Arizona. These earthquakes generally occur within a swath from the north–northwestern part of the state to the southeastern part of the state. The Yuma area (southwestern corner of the state) also has earthquakes. Most earthquake activity is located within about 16 km (10 mi) of known faults (black lines). In addition to seismograph stations (black stars) and active faults (black lines), this map delineates Modified Mercalli Scale 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 past events show that the state has been subject to intensities of up to IX. During an intensity IX event, damage is considerable, even in specially designed structures; shaking throws well-designed frame structures out of plumb; damage is great in substantial buildings with partial collapse; and buildings shift off foundations. Green outlines on the map 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 http://azgs.arizona.edu/center-natural-hazards/earthquakes, http://data.azgs.az.gov/hazard-viewer/, and http://www.azgs.az.gov/eq_monitor.shtml (accessed 20 April 2018); and Arizona Earthquake Information Center graphic available at https://www.cefns.nau.edu/Orgs/aeic/ground_shaking.html (accessed 19 April 2018). Base map by Tom Patterson (National Park Service).

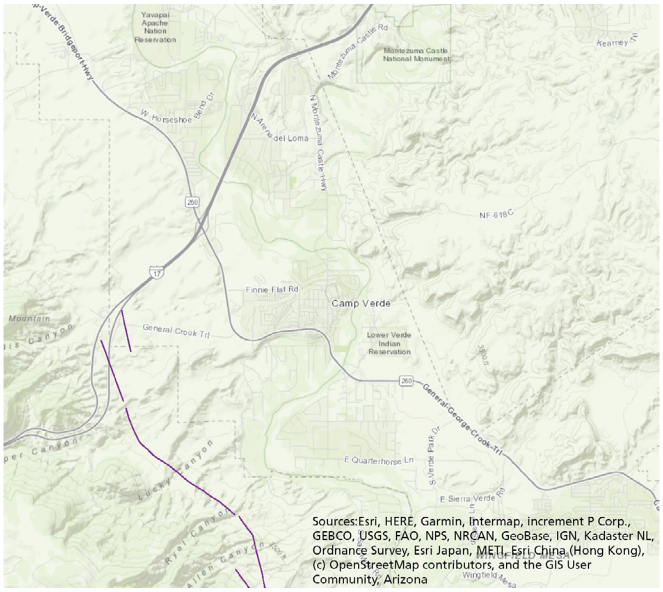

Figure 18. Map of Quaternary faults near the monument.
Faults with movement taking place during the Quaternary Period (the last 2.6 million years) are considered active. The Camp Verde fault, which is part of the Verde fault zone (purple lines), is the closest active fault to the monument. Movement took place on the Camp Verde fault less than 130,000 years ago. The fault zone has a slip rate of less than 0.2 mm (0.008 in) per year. Graphic generated from AZGS "Natural Hazards in Arizona" map viewer at https://azgs.arizona.edu/center-natural-hazards (accessed 16 April 2019).

Slope Movements

For background information and determining potential sites to monitor for slope hazards in the Castle and Well Units, monument managers are encouraged to review Wachter (1978), in particular, "Rock Deterioration Report B," which included annotated color photos.

In 2009, natural resources staff at Montezuma Castle and Tuzigoot National Monuments identified water-related uplands soil erosion as an immediate concern. In response, the National Park Service conducted an erosion assessment of uplands areas as part of the Natural Resource Condition Assessment program (see Nauman 2010). The assessment completed erosion indices and field surveys. Data collected during the assessment included GPS locations of active rill, gully, and sheet erosion, with ocular estimates of depth, width, and length to help estimate soil loss at these locations. Based on these data, investigators identified a feature referred to as the "northeast fan" in the Castle Unit (fig. 17) where intense accelerated erosion may require management attention. DeWitt et al. (2008) mapped this location as Quaternary terrace gravel (**Qt**), which is bounded by a meander bend of Beaver Creek (see poster, in pocket). Nauman (2010) recommended restoring vegetation cover and slowing overland runoff with small structures in key areas on the fan. Nauman (2010) also documented the context and severity of other areas exhibiting notable erosion; these other areas do not require immediate management action but warrant continued observation. The NPS Geologic Resources Division can provide further recommendations and assist with mitigation efforts.

The *Geological Monitoring* chapter about slope movements (Wieczorek and Snyder 2009) describes five vital signs for understanding and monitoring slope movements: (1) types of landslide, (2) landslide causes and triggers, (3) geologic materials in landslides, (4) measurement of landslide movement, and (5) assessment of landslide hazards and risks. In addition, a landslide handbook (Highland and Bobrowsky 2008) 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 Slope Movement Monitoring (http://go.nps.gov/geomonitoring) websites provide detailed information regarding slope movements, monitoring, and mitigation options.

If funding allows, resource managers could consider obtaining quantitative information via photogrammetry (the science of making measurements from photographs) that could be used in monitoring slope movements in both the Castle and Well Units. The NPS 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, though a camera attached to a low-altitude unmanned vehicle is an option. The result is a 3D model. The NPS Geologic Resources Division's Photogrammetry website (http://go.nps.gov/grd_photogrammetry) provides more information and examples of applications of photogrammetry for resource management.

Table 12. Slope movements

Slope Movements	Explanation
Description	Spalling in caves (see "Cave and Karst Resource Management") and rockfall (as large as boulders) from cliff faces are the main types of slope movements in the monument. Slope movements can cause long-term maintenance problems, disruption along roads, damage to park infrastructure and facilities, damage to cultural resources, and significant safety concerns. Managing slope movements involves balancing public access, maintenance, funding, and risk (National Park Service 2014).
Core components of park significance	Cliff dwellings, which spalling or rockfall may impact, have park significance and are a fundamental resource and value.
Associated map units or geologic features	• Verde Formation, limestone (**Tvls**) • Verde Formation, travertine (**Tvt**) • Terrace gravel (**Qt**) as mapped by DeWitt et al. (2008) for the "northeast fan" (a site with accelerated erosion identified by Nauman 2010, discussed below).
Threats	• Rockfall from cliff faces is common and impacts the trails visitors take to view the castle and alcoves. A slab above Castle A appears ready to fall (GRI conference call, 5 December 2017). • Rockfall deposits and other sediment could clog the outlet of Montezuma Well, resulting in changes to the outlet location and disruption of drainage into the irrigation canal. • An erosion assessment (Nauman 2010) identified the parking lot on the east side of the visitor center (fig. 19) as an area with hillside erosion that creates drainage issues, flooding, and unpredictable rockfall. • Visitor use of small remote-controlled drones to examine interior rooms and areas along the cliff face has the potential for impact damage along with illegal trespassing and resource damage due to the retrieval of lost drones. The use of drones causes visitor safety and resource concerns from retrieval activities due to falling rock and damage caused during off-trail trampling.
Potential research, planning, and data needs	• A geologic hazard analysis of steep cliffs in high-visitation areas would help determine locations for safe viewing of cliff dwellings and other sites of public interest. The NPS Unstable Slopes Management Program (contact GRD) provides a mechanism for documenting and rating hazardous slopes and cliffs. • Conducting a geologic hazard analysis of the overhang areas along the perimeter of Montezuma Well would help resource management and planning for visitor safety. • Long-term, repeat photographic documentation and monitoring of identified geohazards would be useful for planning. GRD staff can provide assistance with acquisition and analysis of 3D photogrammetric images.

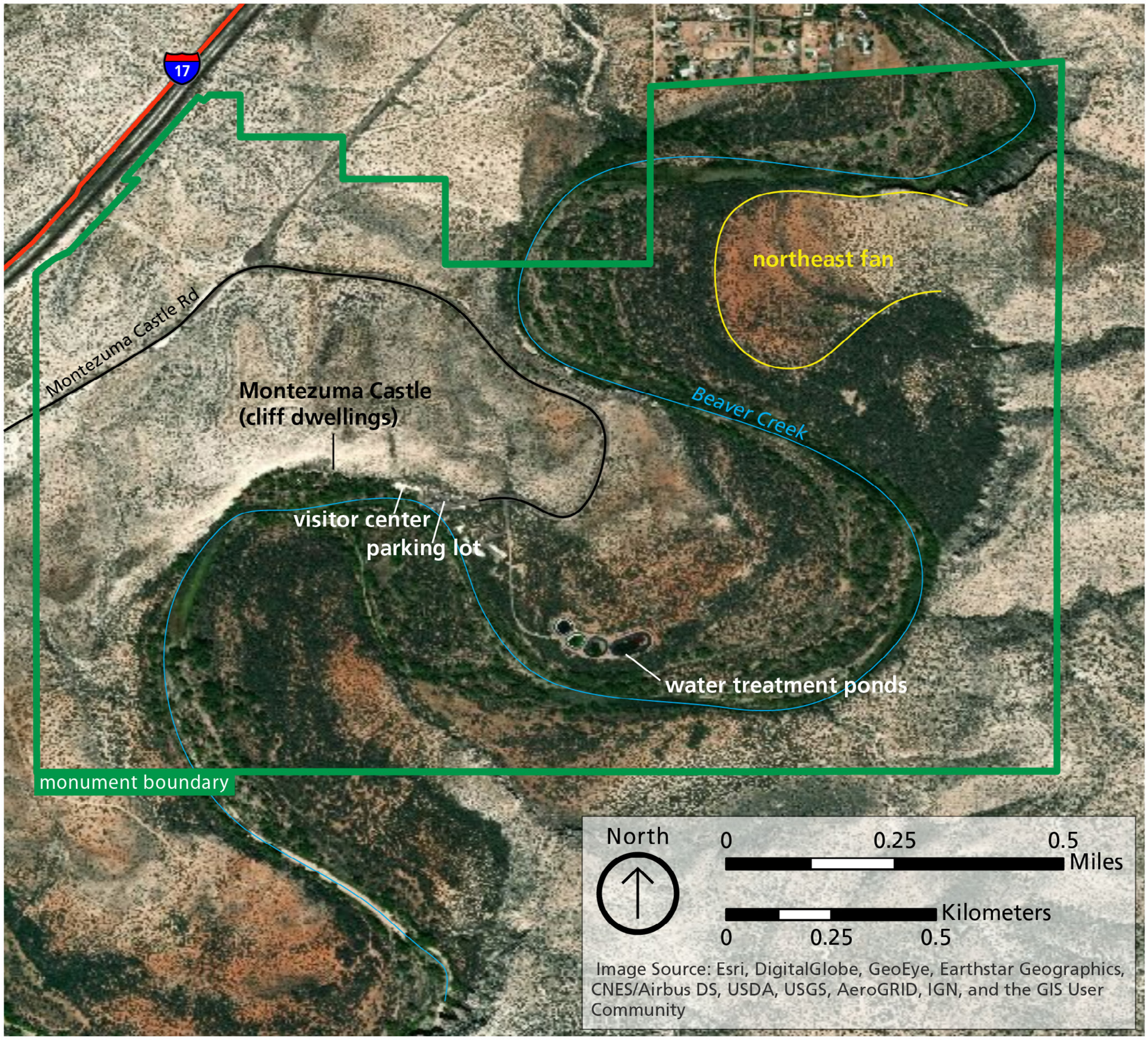

Figure 19. Satellite imagery of the Castle Unit.
The parking lot (east of the visitor center) is a depositional area for rock debris shed from the adjacent hill to the north. The "northeast fan" is another area of accelerated erosion identified by Nauman (2010) (see "Slope Movements"). Beaver Creek flows to the south. Graphic by Rebecca Port (NPS Geologic Resources Division) using information from Nauman (2010).

Geologic Map Data

A geologic map in GIS format is the principal deliverable of the GRI program. The GRI team produced GIS geologic data for the monument using the source map listed in this chapter. These data include components described in this chapter. A poster (in pocket) displays the data 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. On the geologic map for the monument, shades of green represent the Verde Formation, blues represent Paleozoic rocks, and yellow represents Quaternary deposits. In addition to color, each map unit has a corresponding symbol that stands for rocks and deposits. Usually, the map unit symbol consists of an uppercase letter indicating the age (e.g., **Q** for Quaternary or **T** for Tertiary) and lowercase letters indicating the rock formation's name or the type of deposit (e.g., lowercase **v** for Verde Formation; table 1). 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. Geologic maps also may show anthropogenic features such as mines or quarries, as well as observation or collection localities. The American Geosciences Institute's website, http://www.americangeosciences.org/environment/publications/mapping, provides more information about geologic maps and their uses.

Geologic maps are generally one of two types: bedrock or surficial. Bedrock geologic maps encompass older, typically more consolidated sedimentary, metamorphic, or igneous rocks. Bedrock map units are differentiated based on age and/or rock type and commonly have a formation name. A formation is a fundamental rock-stratigraphic unit that is mappable, lithologically distinct 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 a unit. Surficial geologic maps typically encompass 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.

The GRI GIS data for the monument contains both bedrock and surficial map units, though the focus of the source map (DeWitt et al. 2008) was bedrock. Surficial map units of DeWitt et al. (2008) were simplified from House and Pearthree (1993) and House (1994).

Source Map

The GRI team does not conduct original geologic mapping. In compiling a GRI GIS project for a park unit, the team digitizes existing paper maps or converts digital data to the GRI GIS data model. GRI GIS data include essential elements of a source map 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 a GRI ancillary map information document (i.e., moca_tuzi_geology.pdf).

The source map for the GRI GIS data of the monument is *Geologic Map of Prescott National Forest and the Headwaters of the Verde River, Yavapai and Coconino Counties, Arizona* by DeWitt et al. (2008). This map is USGS Scientific Investigations Map SIM-2996 (fig. 20). Mapping was compiled at a scale of 1:100,000.

In the late 1980s and early 1990s (see Blakey and Knepp 1989; Blakey 1990), the nomenclature of the Paleozoic rocks, particularly Pennsylvanian and Permian rocks, in the Montezuma Castle area underwent a major revision in an effort to provide a regional correlation between the Grand Canyon and Mogollon Rim. A patchwork of exposed outcrops where various units of the Paleozoic sequence are partly or entirely absent and a diversified depositional setting (i.e., three separate basins with several intervening shelves and arches) coupled with eustatic (worldwide sea level) changes made correlation between these areas a decades' long endeavor (Blakey 1990). The revision, which was compiled by Ron Blakey (Northern Arizona University), who was a scoping participant (see Appendix A), is in wide use today. For the most part, DeWitt et al. (2008) followed this revised nomenclature, which was a primary reason for using this map as opposed to other options (i.e., Weir et al. 1989) in compiling the GRI GIS data for the monument.

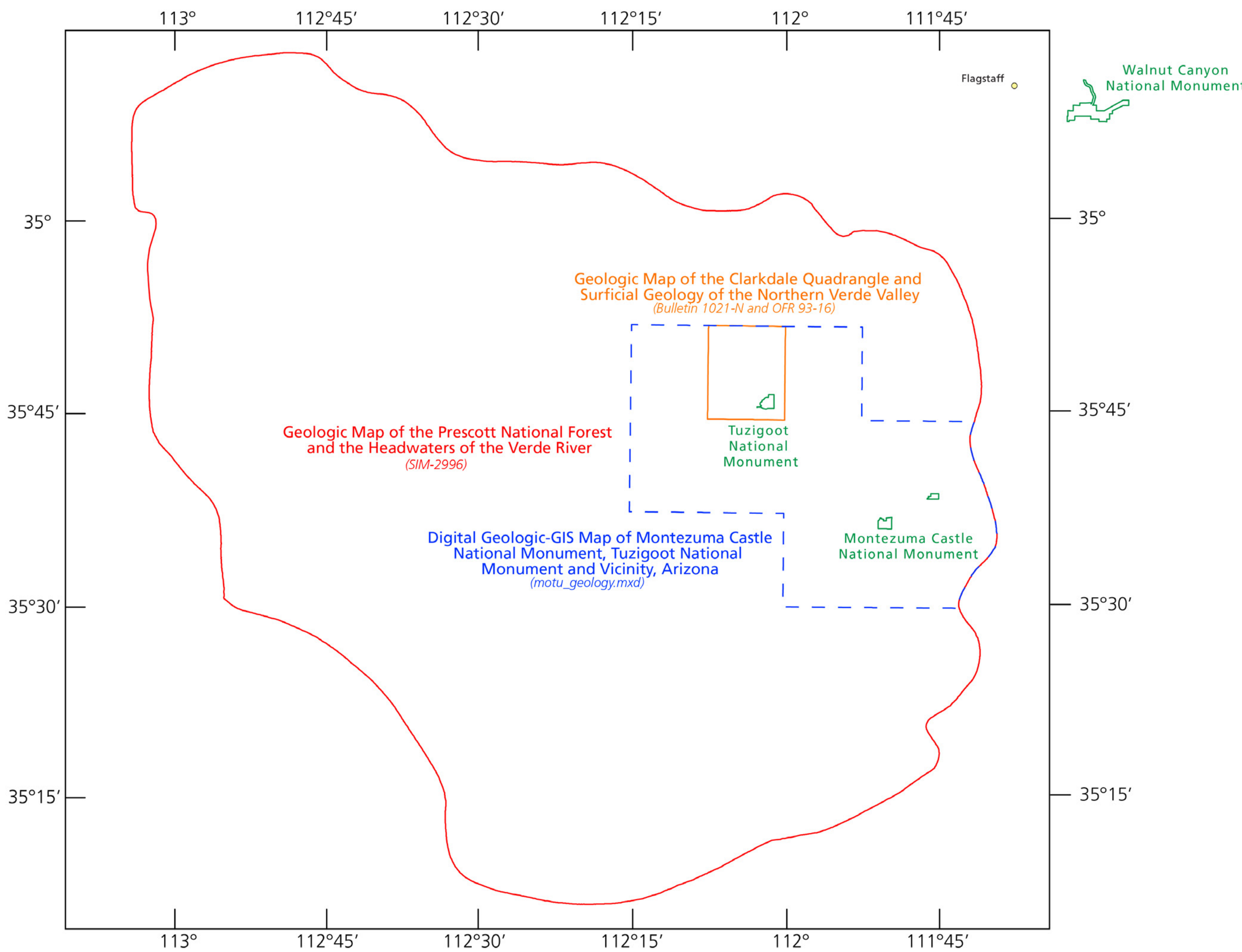

Figure 20. Index map for the monument's GRI GIS data.
The figure displays the extent of GRI GIS data produced for Montezuma Castle and Tuzigoot National Monuments as well as the extent of the source maps used to produce these data. The dashed blue line on the figure shows the extent of the GRI GIS data 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), which 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 the Castle and Well Units of Montezuma Castle National Monument as well as the boundary of Tuzigoot National Monument. GRI graphic by James Winter (Colorado State University).

In addition to the source map and accompanying pamphlet by DeWitt et al. (2008), the maps and reports of a USGS bulletin (Lehner 1958) and Arizona Geological Survey (AZGS) open-file report (House and Pearthree 1993) were primary sources used in preparation of this report. Notably, Lehner (1958) and House and Pearthree (1993) are source maps for the GRI GIS data for Tuzigoot National Monument (see GRI report by KellerLynn 2019). Another AZGS open-file report (House 1994) contains a surficial map that covers the Castle Unit of the monument. That map (and the accompanying report) provided useful information about the geomorphic evolution of the Verde River and its tributaries, though it is not part of the GRI GIS data. In addition, mapping by Cook et al. (2010a), which supersedes mapping by House (1994), provided useful information for this report.

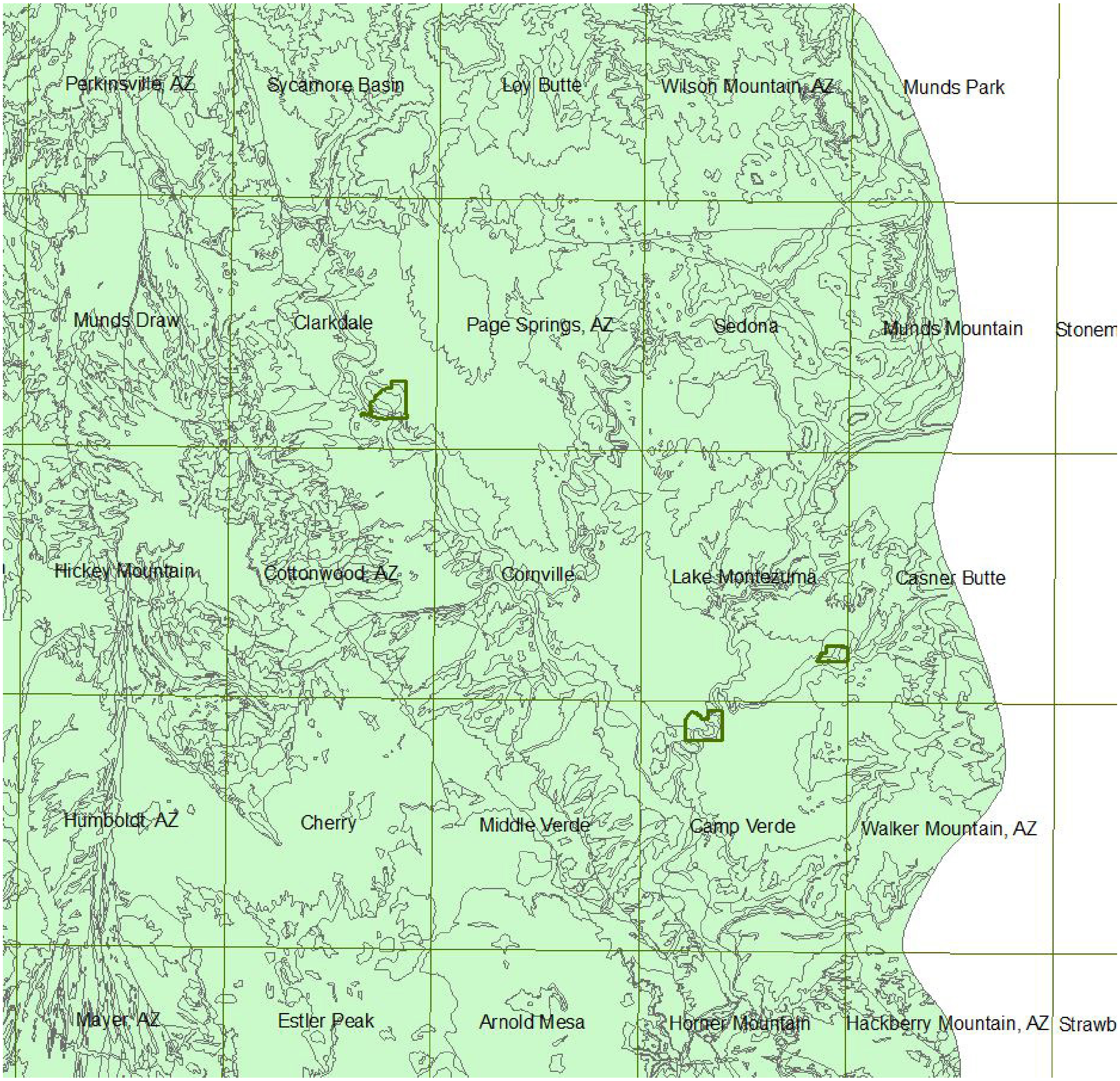

Figure 21. Graphic of quadrangles in the Verde Valley.
Geologic mapping of a portion of the area shown on the graphic is included in the GRI GIS data for Montezuma Castle and Tuzigoot National Monuments (motu_geology.mxd). The GRI GIS data incorporate nine 7.5-minute quadrangles—Munds Draw, Clarkdale, 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 Montezuma Castle National Monument (Well Unit in the Lake Montezuma quadrangle; Castle Unit in the Camp Verde quadrangle) and Tuzigoot National Monument (in the Clarkdale quadrangle). Graphic by Stephanie O'Meara (Colorado State University).

GRI GIS Data

The GRI GIS data for the monument 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). The Castle Unit is in the Camp Verde quadrangle. The Well Unit is in the Lake Montezuma quadrangle.

These data also cover Tuzigoot National Monument, which is in the Clarkdale quadrangle, as well as much of the Verde Valley between the two monuments. The poster (in pocket) illustrates the full extent of the data, though its focus is on the area of the Castle and Well Units (see "GRI Map Poster").

The GRI team standardizes map deliverables using a data model. The team compiled the GRI GIS data for the monument using data model version 2.3, which is available at http://go.nps.gov/gridatamodel. The data model dictates GIS data structure, including layer architecture, feature attribution, and relationships within ESRI ArcGIS software.

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

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

- A readme 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 (table 3);
- 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 document (motu_geology.mxd) that displays the GRI GIS data;
- A version of the data viewable in a Google Earth/KMZ file; and
- A version of the data viewable via auto-generated ArcGIS online map service ("web service"); see https://irma.nps.gov/DataStore/Reference/Profile/2251483.

GRI Map Poster

The poster—"Geologic Map of Montezuma Castle National Monument"—included in the pocket of this report shows a snapshot of the full extent of the GRI GIS data for the monument (motu_geology.mxd), but the main focus is the monument area. The poster displays the GRI GIS data draped over a shaded relief image. Not all GIS feature classes are included on the poster (see table 13). The poster includes selected park features and other geographic information. Added geographic information and digital elevation data are not included in the GRI GIS data but are available online from a variety of sources. Monument mangers may contact the GRI team for assistance locating these data sources.

Table 13. GRI GIS data layers for motu_geology.mxd (source map: DeWitt et al. 2008, scale 1:100,000).

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

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. Please contact the GRI team with any questions.

Minor inaccuracies may exist with respect to the locations of geologic features relative to other geologic or geographic features in the GRI GIS data or on the poster. Based on the source map (DeWitt et al. 2008, scale 1:100,000) and US National Map Accuracy Standards, geologic features represented in the GRI GIS data and on the poster are expected to be horizontally within 51 m (167 ft) of their true locations.

Future Mapping Projects

During the 2017 conference call, AZGS geologists 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 Wet Beaver Creek), respectively. Sheet C of Cook et al. (2010b, "Verde River map") covers Tuzigoot National Monument. Sheet D of Cook et al. (2010a, "tributaries map") covers both the Castle and Wells Units in Montezuma Castle National Monument. Sheet C of Cook et al. (2010a) shows the headwater area of Wet Beaver Creek downstream to about Lawrence Crossing. Notably, Cook et al. (2010a, "tributaries map") has GIS data, which would facilitate incorporation into the GRI GIS data model.

Of possible interest to monument managers: Both Cook et al. (2010b, "Verde River map") and Cook et al. (2010a, "tributaries map") contain a geoarcheological evaluation, including information about 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 general description of the archeological materials and features found at a site. These data and associated reports are currently available at the Arizona Geological Survey's document repository, http://repository.azgs.az.gov/.

If monument managers are interested in acquiring this updated information 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," may support such expanded map coverages. The estimated starting date for inventories 2.0 is 2020. Notably, culturally sensitive information would not be included in the publically available GRI GIS data.

Literature Cited

This report cites the following references. Contact the NPS Geologic Resources Division for assistance in obtaining these references or for access to GEOREF (the premier online geologic citation database).

Anderson, C. A., P. M. Blacet, L. T. Silver, and T. W. Stern. 1971. Revision of Precambrian stratigraphy in the Prescott-Jerome area, Yavapai County, Arizona. Bulletin 1324-C. US Geological Survey, Reston, Virginia. https://pubs.er.usgs.gov/publication/b1324C.

Arizona Earthquake Information Center. 2010. Arizona seismic monitoring. Online information. Northern Arizona University, Arizona Earthquake Information Center, Flagstaff, Arizona. https://www.cefns.nau.edu/Orgs/aeic/seismic_monitoring.html (accessed 8 November 2017).

Arizona Geological Survey. 2018. Energy resources of Arizona. Online information. Arizona Geological Survey, Tucson, Arizona. http://azgs.arizona.edu/energy-resources-arizona (accessed 2 October 2018).

Baars, D. L. 1983. The Colorado Plateau. University of New Mexico Press, Albuquerque, New Mexico.

Bausch, D. B., and D. S. Brumbaugh. 1997. Earthquake hazard evaluation, Yavapai County, Arizona (28 June 1997). Northern Arizona University, Arizona Earthquake Information Center, Flagstaff, Arizona. https://www.cefns.nau.edu/Orgs/aeic/reports/yavapai.html.

Blake, W. P. 1906. Origin of depression known as Montezuma's Well, Arizona. Science 24(618):568.

Blakey, R. C. 1990. Stratigraphy and geologic history of Pennsylvanian and Permian rocks, Mogollon Rim region, central Arizona and vicinity. Geological Society of America Bulletin 102(9):1189–1217.

Blakey, R. C., and R. Knepp. 1989. Pennsylvanian and Permian geology of Arizona. Pages 313–347 *in* J. P. Jenney and S. J. Reynolds, editors. Geologic evolution of Arizona. Digest 17. Arizona Geological Society, Tucson, Arizona.

Blasch, K. W., J. P. Hoffmann, L. F. Graser, J. R. Bryson, and A. L. Flin. 2005. Hydrogeology of the upper and middle Verde River watersheds, central Arizona. Scientific Investigations Report 2005-5198. US Geological Survey, Reston, Virginia. https://pubs.usgs.gov/sir/2005/5198/.

Blinn, D. W., R. H. Hevly, and O. K. Owen. 1994. Continuous Holocene record of diatom stratigraphy, paleohydrology, and anthropogenic activity in a spring-mound in southwestern United States. Quaternary Research 42:197–205.

Brady, L. F., and P. Seff. 1959. Elephant Hill. Plateau 31(4):80–82.

Braile, L.W. 2009. Seismic monitoring. Pages 229–244 *in* R. Young, R. and L. Norby, editors. Geological monitoring. Geological Society of America, Boulder, Colorado. http://go.nps.gov/geomonitoring.

Breshears, D. D., N. S. Cobb, P. M. Rich, K. P. Price, C. D. Allen, R. G. Balice, W. H. Romme, J. H. Kastens, M. L. Floyd, J. Belnap, J. J. Anderson, O. B. Myers, and C. W. Meyer. 2005. Regional vegetation die-off in response to global-change-type drought. Proceedings of the National Academy of Sciences of the USA 102:15,144–15,148.

Cole, G. A. 1982. The uniqueness and value of the Montezuma well-ditch system as a research resource. Manuscript submitted to National Park Service, Montezuma Castle National Monument, Camp Verde, Arizona.

Cole, G. A., and W. T. Barry. 1973. Montezuma Well, Arizona, as a habitat. Journal of the Arizona Academy of Science 8:7–13.

Cole, G. A., and G. L. Batchelder. 1969. Dynamics of an Arizona travertine-forming stream. Journal of the Arizona Academy of Science 5:271–283.

Colten, H. S., and F. C. Baxter. 1932. Days in the Painted Desert and the San Francisco Mountains. Second edition. Museum of Northern Arizona, Flagstaff, Arizona.

Cook, J. P., P. A. Pearthree, J. A. Onken, and E. R. Bigio. 2010a. Mapping of Holocene river alluvium along Oak Creek, Wet Beaver Creek, West Clear Creek, Fossil Creek, and the East Verde River, Central Arizona (scale 1:24,000). Digital Map - River Map 03 (DM-RM-03). Arizona Geological Survey, Tucson, Arizona. http://repository.azgs.az.gov/uri_gin/azgs/dlio/780. [*Note*: Sheet D covers Montezuma Castle National Monument.]

Cook, J. P., P. A. Pearthree, J. A. Onken, A.Youberg, and E. R. Bigio. 2010b. Mapping of Holocene river alluvium along the Verde River, central Arizona (scale 1:24,000). Digital Map - River Alluvium 02 (DM-RM-02). Arizona Geological Survey, Tucson, Arizona. http://repository.azgs.az.gov/uri_gin/azgs/dlio/999. [*Note*: Sheet C covers Tuzigoot National Monument.]

Crossey, L. J., K. E. Karlstrom, A. E. Springer, D. Newell1, D. R. Hilton, T. Fischer. 2009. Degassing of mantle-derived CO_2 and He from springs in the southern Colorado Plateau region—neotectonic connections and implications for groundwater systems. GSA Bulletin 121(7/8):1034–1053.

Davey, C. A., K. T. Redmond, and D. B. Simeral. 2007. Weather and climate inventory, National Park Service, Sonoran Desert Network. Natural Resource Technical Report. NPS/SODN/NRTR—2007/044. National Park Service, Fort Collins, Colorado. https://irma.nps.gov/DataStore/Reference/Profile/649250.

Davis, O. K., and D. S. Shafer. 1992. A Holocene climatic record for the Sonoran Desert from pollen analysis of Montezuma Well, Arizona, USA. Palaeogeography, Palaeoclimatology, Palaeoecology 92:107–119.

DeWitt, E., V. E. Langenheim, E. Force, R. K. Vance, P. A. Lindberg, and R. L. Driscoll. 2008. Geologic map of Prescott National Forest and the headwaters of the Verde River, Yavapai and Coconino Counties, Arizona (scale 1:100,000). Scientific Investigations Map SIM-2996. US Geological Survey, Reston, Virginia. https://pubs.er.usgs.gov/publication/sim2996.

Donchin, J. H. 1983. Stratigraphy and sedimentary environments of the Miocene–Pliocene Verde Formation in southeastern Verde Valley, Yavapai County, Arizona. Thesis. Northern Arizona University, Flagstaff, Arizona.

Garfin, G., A. Jardine, R. Merideth, M. Black, and S. LeRoy, editors. 2013. Assessment of climate change in the southwest United States: a report prepared for the National Climate Assessment. A report by the Southwest Climate Alliance. Island Press, Washington, DC.

Goldstone, L. A., and D. H. White. 1980. Geothermal development plan: northern Arizona Counties. Open-File Report OFR-80-10. Arizona Geological Survey, Tucson, Arizona. http://repository.azgs.az.gov/uri_gin/azgs/dlio/541.

Gonzalez, P. 2014. Climate Change summary, Montezuma Castle National Monument, Arizona. National Park Service Climate Change Response Program, Washington, DC. https://irma.nps.gov/DataStore/Reference/Profile/2217724.

Gwilliam, E., K. Raymond, and L. Palacios. 2017. Status of climate and water resources at Montezuma Castle and Tuzigoot National Monuments: water year 2016. Natural Resource Report. NPS/SODN/NRR—2017/1551. National Park Service. Fort Collins, Colorado. https://irma.nps.gov/DataStore/Reference/Profile/2246090.

Hahman, W. R. Sr., C. Stone, and J. C. Witcher. 1978. Preliminary map: geothermal energy resources of Arizona (scale 1:1,100,000). Map 15-1 (Geothermal Map No. 1). Arizona Bureau of Geology and Mineral Technology, Tucson, Arizona. http://repository.azgs.az.gov/uri_gin/azgs/dlio/1493.

Hancock, P. L., R. M. L. Chalmers, E. Altunel, and Z. Cakir. 1999. Travitonics: using travertine in active fault studies. Journal of Structural Geology 21(8):903–916.

Heasler, H. P., C. Jaworowski, and D. Foley. 2009. Geothermal systems and monitoring hydrothermal features. Pages 105–140 *in* R. Young and L. Norby, editors. Geological monitoring. Geological Society of America, Boulder, Colorado. http://go.nps.gov/geomonitoring.

Henderson, J. 1933. Caverns, ice caves, sinkholes, and natural bridges: part II. University of Colorado Studies 20(3 and 4):130.

Hevly, R. H. 1974. Recent paleoenvironments and geological history at Montezuma Well. Journal of the Arizona Academy of Science 9(2):66–75.

Hevly, R. H., J. D. Nations, and B. Zabo. 1992. History and environment of Pleistocene tufa deposition at Montezuma Well and Red Tank Draw, Verde Valley, Arizona. Abstract 125. Page 28 *in* Program and abstracts, proceedings of the Southwestern and Rocky Mountain Division, American Association for the Advancement of Science, Sixty-Eighth Annual Meeting, "Beauty in Science," 17–21 May 1992, Tucson, Arizona.

Highland, L. M. and P. Bobrowsky. 2008. The landslide handbook—A guide to understanding landslides. Circular 1325. US Geological Survey, Reston, Virginia. http://pubs.usgs.gov/circ/1325/.

House, P. K. 1994. Surficial geology of the southern Verde Valley, Yavapai County, Arizona, Middle Verde, Camp Verde, and Horner Mountain quadrangles (scale 1:24,000). Open-File Report OFR-94-23. Arizona Geological Survey, Tucson, Arizona. http://repository.azgs.az.gov/uri_gin/azgs/dlio/267.

House, P. K., and P. A. Pearthree. 1993. Surficial geology of the northern Verde Valley, Yavapai County, Arizona (scale 1:24,000). Open-File Report OFR-93-16. Arizona Geological Survey, Tucson, Arizona. http://repository.azgs.az.gov/uri_gin/azgs/dlio/287.

Hunt, A. P., V. L. Santucci, and S. G. Lucas. 2005. Vertebrate trace fossils from Arizona with special reference to tracks preserved in National Park Service units and notes on the Phanerozoic distribution of fossil footprints. Pages 159–167 *in* A. B. Heckert and S. G. Lucas, editors. Bulletin 29. Vertebrate Paleontology in Arizona. New Mexico Museum of Natural History and Science, Albuquerque, New Mexico.

Idaho Geological Survey. 2011. Putting down roots in earthquake country: your handbook for earthquakes in Idaho, version 3/19/11. Idaho Geological Survey, Boise, Idaho. http://www.idahogeology.org/uploads/Hazards/Putting_Down_Roots_3_19_11.pdf.

International Commission on Stratigraphy. 2018. International chronostratigraphic chart (v2018/08). International Union of Geological Sciences, International Commission on Stratigraphy (ICS), Durham, England (address of current ICS Executive Committee chair). Drafted by K. M. Cohen, D. A. T. Harper, P. L. Gibbard, and J.-X. Fan (August 2018). http://www.stratigraphy.org/index.php/ics-chart-timescale

Jenkins, O. P. 1923. Verde River lake beds near Clarkdale, Arizona. American Journal of Science, 5th Series, 5(25):65–81.

Johnson, R. H., and E. DeWitt. 2009. The unique geology and geochemistry of Montezuma Well, a natural spring at Montezuma Castle National Monument, central Arizona. Geological Society of America Abstracts with Programs 41(7):244. https://gsa.confex.com/gsa/2009AM/finalprogram/abstract_161469.htm.

Johnson, R. H., E. DeWitt, and L. R. Arnold. 2012a. Part 1: using hydrogeology to identify the source of groundwater to Montezuma Well, a natural spring in central Arizona, USA. Environmental Earth Sciences 67:1821–1835. doi: 10.1007/s12665-012-1801-1.

Johnson, R. H., E. DeWitt, and L. R. Arnold. 2012b. Part 2: using geochemistry to identify the source of groundwater to Montezuma Well, a natural spring in central Arizona, USA. Environmental Earth Sciences 67:1837–1853. doi: 10.1007/s12665-012-1844-3.

Johnson, R. H., E. DeWitt, L. Wirt, L. R. Arnold, and J. D. Horton. 2011. Water and rock geochemistry, geologic cross sections, geochemical modeling, and groundwater flow modeling for identifying the source of groundwater to Montezuma Well, a natural spring in central Arizona. Open-File Report 2011–1063. In cooperation with the National Park Service, US Geological Survey, Reston, Virginia. https://pubs.er.usgs.gov/publication/ofr20111063.

KellerLynn, K. 2010. Petrified Forest National Park: geologic resources inventory report. Natural Resource Report NPS/NRSS/GRD/NRR—2010/218. National Park Service, Fort Collins, Colorado. http://go.nps.gov/gripubs.

KellerLynn, K. 2012. El Morro National Monument: geologic resources inventory report. Natural Resource Report NPS/NRSS/GRD/NRR—2012/588. National Park Service, Fort Collins, Colorado. http://go.nps.gov/gripubs.

KellerLynn, K. 2014. Gila Cliff Dwellings National Monument: geologic resources inventory report. Natural Resource Report NPS/NRSS/GRD/NRR—2014/849. National Park Service, Fort Collins, Colorado. http://go.nps.gov/gripubs.

KellerLynn, K. 2015. Bandelier National Monument: geologic resources inventory report. Natural Resource Report NPS/NRSS/GRD/NRR—2015/1036. National Park Service, Fort Collins, Colorado. http://go.nps.gov/gripubs.

KellerLynn, K. 2016. Aztec Ruins National Monument: geologic resources inventory report. Natural Resource Report NPS/NRSS/GRD/NRR—2016/1245. National Park Service, Fort Collins, Colorado. http://go.nps.gov/gripubs.

KellerLynn, K. 2018. Casa Grande Ruins National Monument: geologic resources inventory report. Natural Resource Report NPS/NRSS/GRD/NRR—2018/1785. National Park Service, Fort Collins, Colorado. http://go.nps.gov/gripubs.

KellerLynn, K. 2019. Tuzigoot National Monument: geologic resources inventory report. Natural Resource Report NPS/NRSS/GRD/NRR—2018/2017. National Park Service, Fort Collins, Colorado. http://go.nps.gov/gripubs.

Kenworthy, J. P., and V. L. Santucci. 2006. A preliminary investigation of National Park Service paleontological resources in cultural context: Part 1, general overview. Pages 70–76 *in* S. G. Lucas, J. A. Spielmann, P. M. Hester, J. P. Kenworthy, and V. L. Santucci, editors. America's antiquities: 100 years of managing fossils on federal lands. Bulletin 34. New Mexico Museum of Natural History and Science, Albuquerque, New Mexico. https://www.nps.gov/subjects/fossils/research-volumes.htm.

Kiver, E. P., and D. V. Harris. 1999. Geology of US parklands. Fifth edition. John Wiley & Sons, Inc., New York.

Konieczki, A. D., and S. A. Leake. 1997. Hydrology and water chemistry of Montezuma Well in Montezuma Castle National Monument and surrounding area, Arizona. Water Resources Investigations Report 97-4156. Prepared in cooperation with the National Park Service by the US Geological Survey, Reston, Virginia. https://pubs.er.usgs.gov/publication/wri974156.

Ladd, E. 1964. Excavation of Swallet Cave. Project MOCA A2. National Park Service, Mission 66 Program, Washington, DC. https://irma.nps.gov/DataStore/Reference/Profile/663646.

Lange, A. 1957. Studies on the origin of Montezuma Well and cave, Arizona. Cave Studies (Publication of Cave Research Associates) 9:39–53.

Lenihan, D. 2011. Diving Montezuma Well: what's down there is still a mystery. Natural History 119(11):14–19.

Lehner, R. E. 1958. Geology of the Clarkdale quadrangle, Arizona. Bulletin 1021-N. US Geological Survey, Washington, DC. https://pubs.er.usgs.gov/publication/b1021N.

Lord, M. L., D. Germanoski, and N. E. Allmendinger. 2009. Fluvial geomorphology: Monitoring stream systems in response to a changing environment. Pages 69–103 *in* R. Young and L. Norby, editors. Geological monitoring. Geological Society of America, Boulder, Colorado. http://go.nps.gov/geomonitoring.

McGeorge, R., and C. Schur. 1994. Preliminary mapping of Elephant Hill, Verde Formation. Unpublished report. Southwest Paleontological Society, Mesa Southwest Museum, Mesa, Arizona.

McKee, E. D., H. Hastings, and H. S. Colton. 1947. Montezuma Well, result of preliminary soundings, July 18, 1947. Unpublished manuscript. Museum of Northern Arizona, Flagstaff, Arizona.

McKee, E. H., and D. P. Elston. 1980. Reversal chronology from a 7.9- to 11.5-M.Y.-old volcanic sequence in central Arizona: comparison with ocean flood polarity record. Journal of Geophysical Research 85:327–337.

Menges, C. M., and P. A. Pearthree. 1989. Late Cenozoic tectonism in Arizona and its impact on reginal landscape evolution. Pages 649–680 *in* J. P. Jenney and S. J. Reynolds, editors. Geologic evolution of Arizona. Digest 17. Arizona Geological Society, Tucson, Arizona.

Monahan, W. B., and N. A. Fisichelli. 2014. Recent climate change exposure of Montezuma Castle National Monument. National Park Service, Inventory and Monitoring Division and Climate Change Response Program, Fort Collins, Colorado. https://irma.nps.gov/DataStore/Reference/Profile/2212863.

Moritz, M. A., M.-A. Parisien, E. Batllori, M. A. Krawchuk, J. Van Dorn, D. J. Ganz, and K. Hayhoe. 2012. Climate change and disruptions to global fire activity. Ecosphere 3(6):1–22. doi:10.1890/ES11-00345.1.

National Park Service. 1981. Sewage treatment and disposal system, special study. Montezuma Castle National Monument, Camp Verde, Arizona.

National Park Service. 1992. Water resources management plan, Montezuma Castle and Tuzigoot National Monuments (September 1992). Montezuma Castle National Monument, Camp Verde, Arizona. https://irma.nps.gov/DataStore/Reference/Profile/135716.

National Park Service. 2006. Geologic resource evaluation scoping summary, Montezuma Castle National Monument, Arizona. US Department of the Interior, National Park Service, Geologic Resources Division, Lakewood, Colorado. http://go.nps.gov/gripubs.

National Park Service. 2014. Geologic resources foundation summary, Montezuma Castle National Monument (14 February 2014). National Park Service, Natural Resource Stewardship and Science, Geologic Resources Division, Lakewood, Colorado.

National Park Service. 2016. Foundation document: Montezuma Castle National Monument, Arizona (March 2016). Montezuma Castle National Monument, Camp Verde, Arizona.

Nations, J. D., R. H. Hevly, D. W. Blinn, and J. J. Landye. 1981. Paleontology, paleoecology, and depositional history of the Miocene–Pliocene Verde Formation, Yavapai County, Arizona. Arizona Geological Society Digest 13:133–149.

Nauman, T. 2010. Erosion assessment for Montezuma Castle and Tuzigoot National Monuments. Natural Resource Technical Report. NPS/SODN/NRTR—2010/281. National Park Service, Natural Resource Program Center, Fort Collins, Colorado. https://irma.nps.gov/DataStore/Reference/Profile/663876.

Owen-Joyce, S. J., and C. K. Bell. 1984. Hydrology of a stream-aquifer system in the Camp Verde area, Yavapai County, Arizona. Bulletin 3. Arizona Department of Water Resources, Phoenix, Arizona.

Protas, J. 2002. A past preserved in stone: a history of Montezuma Castle. Western National Parks Association, Tucson, Arizona. http://npshistory.com/publications/moca/protas/index.htm.

Rauzi, S. L. 2001. Arizona has oil & gas potential! Circular C-29. Arizona Geological Survey, Tucson, Arizona. http://repository.azgs.az.gov/uri_gin/azgs/dlio/1074.

Reidmiller, D.R., C.W. Avery, D.R. Easterling, K.E. Kunkel, K.L.M. Lewis, T.K. Maycock, and B.C. Stewart (eds.). 2018. Impacts, Risks, and Adaptation in the United States: Fourth National Climate Assessment, Volume II. U.S. Global Change Research Program, Washington, DC. doi: 10.7930/NCA4.2018.

Ross, P. P., and C. D. Farrar. 1980. Map showing potential geothermal-resource areas, as indicated by the chemical character of ground water, in Verde Valley, Yavapai County, Arizona. Water-Resources Investigations Open-File Report 80-13. US Geological Survey, Reston, Virginia. https://pubs.er.usgs.gov/publication/ofr8013.

Santucci, V. L. 2012. On-site evaluation of paleontological resources, Montezuma Castle National Monument, Arizona. Memorandum [trip report] to Dorothy FireCloud, superintendent, Montezuma Castle National Monument, from Vincent L. Santucci, senior geologist / Washington liaison, Geologic Resources Division (16 September 2012). Includes attachment A—Montezuma Castle National Monument: paleontological resources. National Park Service, Geologic Resources Division, Denver, Colorado.

Santucci, V. L., A. P. Hunt, and M. G. Lockley. 1998. Fossil vertebrate tracks in National Park Service areas. Dakoterra 5:107–114.

Santucci, V. L., J. P. Kenworthy, and R. Kerbo. 2001. An inventory of paleontological resources associated with National Park Service caves. Technical Report NPS/NRGRD/GRDTR-01/02. National Park Service, Geological Resources Division, Denver, Colorado.

Santucci, V. L., J. P. Kenworthy, and A. L. Mims. 2009. Monitoring in situ paleontological resources. Pages 189–204 *in* R. Young and L. Norby, editors. Geological monitoring. Geological Society of America, Boulder, Colorado. http://go.nps.gov/geomonitoring.

Schroeder, A. H. 1948. Montezuma Well. Plateau 20(3):37–40.

Shafer, J. P. 1971. Memorandum on Pliocene mammal tracks at Montezuma Castle, Arizona, to Keith A. Trexler, Grand Canyon National Park, Arizona, 27 May 1971. US Geological Survey, Flagstaff, Arizona.

Shafer, D. S., and O. K. Davis. 1987. Paleoecologic and paleoclimatic analysis of late Quaternary sediments from Montezuma Well, Yavapai County, Arizona. Geological Society of America Abstracts with Programs 19(7):839.

Shafer, D. S., and O. K. Davis. 1988. Paleoecologic and paleoclimatic analysis of late Quaternary sediments from Montezuma Well, Yavapai County, south-central Arizona. American Quaternary Association Program and Abstracts 10:150.

Shafiqullah, M., P. E. Damon, D. J. Lynch, S. J. Reynolds, W. A. Rehrig, and R. H. Raymond. 1980. K-Ar geochronology and geologic history of southwestern Arizona and adjacent areas. Pages 201–260 *in* J. P. Jenney and C. Stone, editors. Studies in western Arizona. Digest 12. Arizona Geological Society, Tucson, Arizona.

Sonoran Desert Network. 2010. Climate change in the Sonoran Desert Network: current findings and how future monitoring will detect it. National Park Service, Sonoran Desert Network Inventory and Monitoring Program, Tucson, Arizona. https://irma.nps.gov/DataStore/Reference/Profile/2245995.

Sonoran Desert Network. 2018. Groundwater. Online information. National Park Service, Sonoran Desert Network Inventory and Monitoring Program, Tucson, Arizona. https://www.nps.gov/im/sodn/groundwater.htm (accessed 2 August 2018).

Sutton, M. 1953. Geology of the Verde Valley: an interpretive treatment. Unpublished report. National Park Service, Montezuma Castle National Monument, Camp Verde, Arizona.

Thompson, J. R. 1983. Camp Verde evaporites. The Mineralogical Record 14(2):83–90.

Toomey, R. S. III. 2009. Geological monitoring of caves and associated landscapes. Pages 27–46 *in* R. Young and L. Norby, editors. Geological monitoring. Geological Society of America, Boulder, Colorado. http://go.nps.gov/geomonitoring.

Tweet, J. S., V. L. Santucci, and J. P. Kenworthy. 2008. Paleontological resource inventory and monitoring, Sonoran Desert Network. Natural Resource Technical Report NPS/NRPC/NRTR-2008/130. National Park Service, Fort Collins, Colorado.

Twenter, F. R. 1962. New fossil localities in the Verde Formation, Verde Valley, Arizona. Pages 109–114 *in* R. H. Weber and H. W. Peirce, editors. Mogollon Rim region, east-central Arizona. Fall Field Conference Guidebook 13. New Mexico Geological Society, Socorro, New Mexico. https://nmgs.nmt.edu/publications/guidebooks/13/.

Twenter, F. R., and D. G. Metzger. 1963. Geology and ground water in Verde Valley–the Mogollon Rim region, Arizona. Bulletin 1177. US Geological Survey, Reston, Virginia. https://pubs.er.usgs.gov/publication/b1177.

Wachter, B.G. 1978. Rock motion hazard: geologic analysis of rock deterioration at selected National Park Service archeological sites. Western Archeological Center. Tucson, Arizona. https://irma.nps.gov/DataStore/Reference/Profile/108511.

Weir, G. W., G. E. Ulrich, and L. D. Nealey. 1989. Geologic map of the Sedona 30' x 60' quadrangle, Yavapai and Coconino Counties, Arizona (scale 1:100,000). Miscellaneous Investigations Series Map I-1896. US Geological Survey, Reston, Virginia. https://pubs.er.usgs.gov/publication/i1896.

Wieczorek, G. F. and J. B. Snyder. 2009. Monitoring slope movements. Pages 245–271 *in* R. Young and L. Norby, editors. Geological monitoring. Geological Society of America, Boulder, Colorado. http://go.nps.gov/geomonitoring.

Young, R. and L. Norby, editors. 2009. Geological monitoring. Geological Society of America, Boulder, Colorado. http://go.nps.gov/geomonitoring.

Additional Resources

These websites, online information, and books may be of use for geologic resources management and interpretation at Montezuma Castle National Monument.

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

- AZGS mine data (files for approximately 21,000 mines, thousands of maps, and more than 6,000 historic photographs): http://minedata.azgs.arizona.edu/

Arizona Natural Hazards

- 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 earth fissures and ground subsidence: https://azgs.arizona.edu/center-natural-hazards/earth-fissures-ground-subsidence
- AZGS information about volcanoes in Arizona; http://azgs.arizona.edu/center-natural-hazards/volcanism
- AZGS "Natural Hazards in Arizona" map viewer includes earth fissures, active faults, earthquake epicenters, flood potential, fire risk index, and landslides: http://data.azgs.az.gov/hazard-viewer/. An updated version is available at https://azgs.arizona.edu/center-natural-hazards.
- 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

Climate Change

- 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: http://www.globalchange.gov/home

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/

Groundwater Level

- Arizona Department of Water Resources (ADWR): http://www.azwater.gov/azdwr/
- ADWR groundwater site inventory data: http://gisweb.azwater.gov/waterresourcedata/
- *Groundwater Depletion in the United States (1900–2008)* by L. F. Konikow. Published in

2013 by the US Geological Survey as Scientific Investigations Report 2013-5079. http://pubs.usgs.gov/sir/2013/5079.

- "Indicators in the Groundwater Environment of Rapid Environmental Change" by W. M. Edmunds. Pages 121–136 *in* A. R. Berger and W. J. Iams, editors. *Geoindicators: Assessing Rapid Environmental Changes in Earth Systems*. Published in 1996 by A. A. Balkema, Rotterdam, The Netherlands.
- International Groundwater Resources Assessment Centre: https://www.un-igrac.org/
- International Union of Geological Sciences (IUGS), Geoindicators—groundwater level: http://www.lgt.lt/geoin/doc.php?did=cl_groundwaterlevel
- Sonoran Desert Network (information about groundwater): https://www.nps.gov/im/sodn/groundwater.htm
- USGS groundwater information pages: https://water.usgs.gov/ogw/

NPS Geologic 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 Geodiversity Atlas (park-specific geology information): https://www.nps.gov/articles/geodiversity-atlas-map.htm
- NPS Geoscientist-in-the-Parks (GIP) internship and guest scientist program: http://go.nps.gov/gip
- *Parks and Plates: The Geology of Our National Parks, Monuments, and Seashores* by Robert J. Lillie (Oregon State University). Published in 2005 by W. W. Norton and Company, New York.

NPS Geologic Resources

- NPS Geologic Resources Division (Lakewood, Colorado) *Energy and Minerals; Active Processes and Hazards; Geologic Heritage*: http://go.nps.gov/geology
- NPS Geologic Resources Inventory: http://go.nps.gov/gri

NPS Resource Management Guidance and Documents

- 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): http://gnis.usgs.gov/
- GeoPDFs (download PDFs of any topographic map in the United States): http://store.usgs.gov (click on "Map Locator")
- Publications warehouse (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	Montezuma Castle and Tuzigoot National Monuments	Archeological technician
Dennis Casper	Montezuma Castle and Tuzigoot National Monuments	Biologist
Kathy Davis	Montezuma Castle and Tuzigoot National Monuments	Superintendent
Travis Ellison	Montezuma Castle and Tuzigoot 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	Montezuma Castle and Tuzigoot 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	Montezuma Castle and Tuzigoot National Monuments	Superintendent
Brian Gootee	Arizona Geological Survey	Research geologist
Tina Greenawalt	Montezuma Castle and Tuzigoot National Monuments	Chief of Natural Resources
Matt Guebard	Montezuma Castle and Tuzigoot National Monuments	Chief of Cultural Resources
Evan Gwilliam	NPS Sonoran Desert Network	Ecologist
Lucas Hoedl	Montezuma Castle and Tuzigoot 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).

The Department of the Interior protects and manages the nation's natural resources and cultural heritage; provides scientific and other information about those resources; and honors its special responsibilities to American Indians, Alaska Natives, and affiliated Island Communities.

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