National Park Service
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Natural Resource Stewardship and Science

Tonto National Monument

Geologic Resources Inventory Report

Natural Resource Report NPS/NRSS/GRD/NRR—2020/2212

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ON THE COVER
The cliff dwellings at Tonto National Monument sit among hills composed of Early and Middle Proterozoic (2.5-billion- to 1.0-billion-year-old) rocks. Talus and colluvium composed of these rocks mantle the slopes and valley floors within the monument. People of the culture known by archeologists as "Salado" built the Lower Cliff Dwelling, which looks out onto Theodore Roosevelt Lake. The cave in which the cliff dwelling is housed developed in dolomite of the Mescal Limestone. Photograph by Katie KellerLynn (Colorado State University).
THIS PAGE
Rocks of the colorful Dripping Spring Quartzite crop out along the trail to the Lower Cliff Dwelling. Photograph by Katie KellerLynn (Colorado State University).

Tonto National Monument

Geologic Resources Inventory Report

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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 in 2019. Appendix A provides lists of participants. Chapters of this report discuss the monument's geologic setting and significance, drawing connections between geologic and cultural resources; highlight distinctive geologic features and processes of interest for the monument, including geologic events leading to the monument's present-day landscape; discuss geologic issues facing resource managers; and provide information about the previously completed GRI map data. Two posters illustrate these data.

Tonto National Monument (referred to as the "monument" throughout this report) is in Gila County, Arizona. The nearest "census designated place" is Roosevelt, Arizona. The monument is within a transition zone between the Basin and Range and Colorado Plateau physiographic provinces. Arizona's transition zone has characteristics of both the Basin and Range and Colorado Plateau, though the monument's setting favors the Basin and Range.

On 19 December 1907, the monument became one of the nation's first national monuments designated under the Antiquities Act of 1906. Originally under stewardship of the USDA Forest Service, management of the monument transferred to the National Park Service in 1937. On 15 October 1966, 21 April 1989, and 9 September 2010, the National Register of Historic Places listed the Tonto National Monument Archeological District, Lower Ruins and Upper Ruins, and Tonto National Monument Visitor Center, respectively.

The geology of the monument played an essential role in the lives of the ancestral people who inhabited the area from around 1150 CE to 1450 CE. In the 1930s, archeologists working in the valley of the Salt River ("Rio Salado") applied the name "Salado" to this culture of people and associated artifacts. Geologic resources provided the raw materials from which people of the Salado culture shaped tools for everyday living and built structures. In addition, geologic processes created caves in which the Salado people found shelter and built dwellings. Moreover, groundwater springs served as a source of water, and major surface-water streams were vital to prehistoric farming.

The most distinguishing features at the monument are the Upper and Lower Cliff Dwellings (also referred to as the "Ruins"). Geologic processes created the caves—referred to as "shelter caves" or "alcoves"—that contain the cliff dwellings. Significantly, this inventory resulted in an important correction to the previously interpreted geologic location of the cliff dwellings. Raup (1959) had interpreted that both the Upper and Lower Cliff Dwellings occurred in the Dripping Spring Quartzite; park literature perpetuated that interpretation. Geologic mapping completed by the Arizona Geological Survey and compiled in the GRI GIS data for the monument, however, revealed that the Upper Cliff Dwelling occurs in the Dripping Spring Quartzite (geologic map unit **Ydsu**) whereas the Lower Cliff Dwelling occurs in the Mescal Limestone (**Ymd**). The "Geologic Features and Processes" chapter discusses these and other features of significance for the monument's geologic story.

Another significant change from past geologic interpretations is the application (more accurately, the non-application) of the term "Gila Conglomerate" to the monument's geology. Geologic mapping completed by the Arizona Geological Survey and compiled in the GRI GIS data for the monument does not include Gila Conglomerate because the unit is a "grab bag" of lithology (physical description such as color, mineral composition, and grain size), texture, and age. Two of the conglomerates in the monument—(1) older conglomerate (**Toc**) and (2) conglomerate, Apache Group clasts (**QTsa**)—take the place of the Gila Conglomerate. The "Conglomerates" section of the "Geologic Features and Processes" chapter of this report provides further explanation.

The monument's geologic setting is part of a remarkable geologic history, spanning back to the Early Proterozoic Era (2.5 billion to 1.6 billion years ago). Most of the monument's bedrock consists of the Middle Proterozoic (1.6-billion- to 1.0-billion-year-old) rocks of the Apache Group, which includes the Pioneer Formation, Dripping Spring Quartzite, and Mescal Limestone. These rock units make up the mountainous southwestern part of the monument. By contrast, the northeastern part of the monument is covered by Miocene and Pliocene (23-million- to 2.6-million-year-old) basin fill, Pleistocene (2.6-million- to 11,700-year-old) alluvial fans, and Holocene (less than 11,700-year-old) floodplain deposits. The contrast between the bedrock geology of the southwestern part of the monument and surficial geology in the northeastern part of the monument is conspicuously displayed on "Surficial Geologic Map of Tonto National Monument." Table 1 in the "Geologic Features and Processes" chapter shows the monument's geologic features and associated map units in a context of geologic time. This table is ordered stratigraphically, that is, from oldest (at the bottom) to youngest (at the top). Table 1 includes the entire geologic time scale, though not all geologic time periods are represented by rocks or unconsolidated deposits in the monument.

This report is supported by geologic and surficial geologic GIS data for the monument (see the "Geologic Map Data" chapter). As discussed in the "GRI Products" section, compilation of these data is one of three tasks undertaken as part of the GRI process. Significantly, writing of this GRI report followed compilation of these data, both in time and interpretation of the monument's geology. Two posters display these data: "Geologic Map of Tonto National Monument" and "Surficial Geologic Map of Tonto National Monument." The geologic map poster displays the "geologic" (i.e., both bedrock and surficial geologic units) data for the monument; the corresponding GRI GIS data set is tont_geology.mxd. Source maps for these data are Spencer and Richard (1999) and Spencer et al. (1999). Spencer and Richard (1999), which is Arizona Geological Survey Open-File Report OFR-99-06 (scale 1:24,000), mapped the monument's geology and the surrounding area of Theodore Roosevelt Dam. Spencer et al. (1999), which is Arizona Geological Survey Open-File Report OFR-99-12 (scale 1:24,000), mapped the geology of the Windy Hill quadrangle. An index map in the "Geologic Map Data" chapter illustrates the extents and coverages of these source maps. The surficial geologic map poster for the monument displays "surficial geologic" (unconsolidated deposits) data; the corresponding GRI GIS data set is tsur_geology.mxd. Anderson et al. (1987), which is US Bureau of Reclamation Seismotectonic Report 87-5 (scale 1:48,000), is the source map for the surficial geologic data. An index map in the "Geologic Map Data" chapter illustrates the extent and coverage of this source map.

Because the source maps include "Tertiary" ("**T**") map units and because of the significance of Tertiary basin fill (**Tbf**) to the monument's geologic story, an explanation of the usage of "Tertiary" is warranted. The "Tertiary Period" is no longer a formal chronostratigraphic unit as defined by the International Commission on Stratigraphy (ICS), but the term is commonly used and had widespread use in geologic mapping. The current trend is to use "Paleogene Period" (made up of the Paleocene, Eocene, and Oligocene Epochs) and "Neogene Period" (made up of the Miocene and Pliocene Epochs). As applied to the "deposits formerly known as Tertiary" in the Tonto Basin, Neogene is the most appropriate (Phil Pearthree, Arizona Geological Survey, director and state geologist, written communication, 1 June 2020). The Neogene Period took place 23 million to 2.6 million years ago.

The "Geologic Resource Management Issues" chapter discusses management issues related to the monument's geologic resources (features and processes). These issues are fire and slope movements; flash floods; aircraft-induced vibration; rockfall hazard; seismicity; active faults and earthquakes; cave resource management; paleontological resource inventory, monitoring, and protection; and climate change. The 2006 geologic scoping summary (National Park Service 2006), a geologic resources foundation summary (National Park Service 2015), the monument's foundation document (National Park Service 2017a), and notes from the 2019 GRI conference call identified these issues. Following a brief description, a table for each of these issues highlights park significance and associated map units or geologic features; identifies threats; lists planning, data, and research needs; and suggests resources for management. The issues are ordered with respect to management priority. "Additional Resources" provides online sources of information related to the geologic resource management issues discussed in this report.

"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 the NPS Geologic Resources Division for instructions to access GEOREF.

Appendix A of this report provides two lists: one of participants who attended the scoping meeting for the monument in 2006 and one of participants who joined in the follow-up conference call in 2019. These lists serve as a legacy document and reflect participants' names, affiliations, and positions at the time of scoping or the conference call.

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, state geological surveys, local museums, and/or universities developed the source maps and 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 field work 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), NPS *Management Policies 2006*, and the Natural Resources Inventory and Monitoring Guideline (NPS-75). The "Additional Resources" 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 2019 conference call** (see Appendix A) for their assistance in this inventory. In addition, thanks very much to all those who reviewed this report (see "Review" below); their interest and time is greatly appreciated. Thanks very much to the **Arizona Geological Survey** and **US Bureau of Reclamation** for their maps of the area. This report and the GRI GIS data could not have been completed without them. Thanks to **Mike Conway** (Arizona Geological Survey) for being the "liaison" between the GRI process and the Arizona Geological Survey. Thanks to **Lima Soto** (NPS Geologic Resources Division), **George Veni** and **Joel Despain** (National Cave and Karst Research Institute), **Chad Harrold** (Tonto National Forest), **Ray Keeler**, and **Phil Pearthree** (Arizona Geological Survey) for their input about the monument's caves. Thanks to **Randy Stanley** (NPS Natural Sounds & Night Skies Division) for his time and input about aircraft-induced vibration. Thanks to **Trista Thornberry-Ehrlich** (Colorado State University) and **Rebecca Port** (NPS Geologic Resources Division) for creating many of the graphics in this report. Thanks to **monument staff** for posting photographs at flickr (https://www.flickr.com/photos/tontonps/); this report features many of these photographs, which help illustrate geologic features, processes, and resource management issues.

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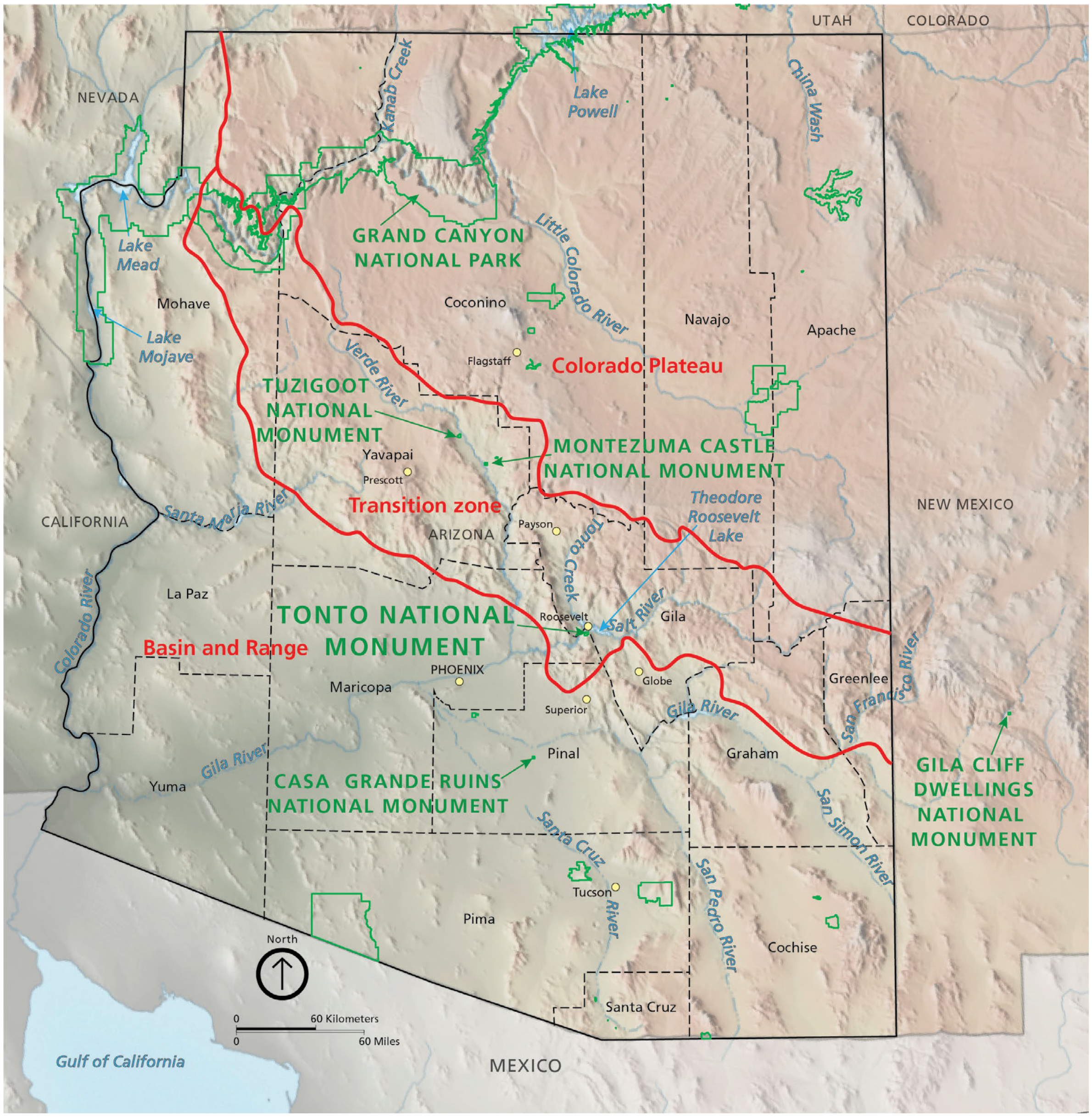


Figure 1. Location map.
Tonto National Monument is in the transition zone between two physiographic provinces: Colorado Plateau to the north and Basin and Range to the south. The monument is one of many NPS areas in Arizona (and New Mexico) that celebrate fascinating cultural periods and ancient North American civilizations. The figure shows many of these areas in green, though only those mentioned in this report are labeled. The monument is in Gila County, near the boundary with Maricopa County, and south of Theodore Roosevelt Lake, the largest reservoir contained entirely within the state. The Salt River runs through the area and provides a rare, year-round source of water. Graphic by Trista Thornberry-Ehrlich (Colorado State University). Base map by Tom Patterson (National Park Service).

Geologic Setting and Significance

This chapter describes the regional geologic setting for the monument and summarizes connections among geologic resources and other monument resources and stories.

Park Establishment

Tonto National Monument (referred to as the "monument" throughout this report) is in Gila County, Arizona (fig. 1). The monument is on the southwestern edge of the Tonto Basin, which archeologists have long considered the heartland of the Salado culture (Simon 1996; see "Cultural Background"). The monument is about 90 km (60 mi) northeast of Phoenix (population 1,445,632), which is in Maricopa County, the fastest growing county in the state (see GRI report about Casa Grande Ruins National Monument by KellerLynn 2018a). In contrast to Phoenix, nearby Roosevelt (population 28) is the nearest "census designated place" to the monument. With a population of 7,532, Globe is the closest city to the monument; Payson, also nearby, has 15,301 inhabitants (US Census Bureau 2019; numbers are from the 2010 census).

The monument was one of the first national monuments designated under the Antiquities Act of 1906. On 19 December 1907, President Theodore Roosevelt signed Presidential Proclamation 787, which established the monument, protecting "two prehistoric ruins of ancient cliff dwellings" and one section of land upon which these ruins were located. On 1 April 1937, the monument's original boundary changed when adjacent lands in Tonto National Forest became part of the National Park System "for the proper care, management, and protection of the said historic ruins and ancient cliff dwellings." Today, the monument encompasses 453 ha (1,120 ac), all of which are owned by the federal government. The monument is surrounded by Tonto National Forest. At 1.2 million ha (2.9 million ac), Tonto National Forest is the largest national forest in Arizona and the eighth largest in the United States (Worldatlas.com 2020).

Originally, the USDA Forest Service administered the monument, but stewardship transferred to the National Park Service on 10 August 1933. On 15 October 1966, 21 April 1989, and 9 September 2010, the National Register of Historic Places listed the Tonto National Monument Archeological District (reference number 66000081; see https://www.nps.gov/subjects/nationalregister/database-research.htm, accessed 23 May 2019), Lower Ruins (reference number 89000265) and Upper Ruins (reference number 89000266), and Tonto National Monument Visitor Center (reference number 10000734), respectively. The monument contains nearly 100 archeological sites spanning 10,000 years of human history; these include rock shelters ("shelter caves," "caves," or "alcoves" in geologic terminology), cliff dwellings, field houses, pueblos, lithic scatter, Yavapai and Apache camps, and historic ranching features (Duane Hubbard, Tonto National Monument, superintendent, written communication, 12 June 2020).

Physiographic Setting

The monument is within a transition zone between two major physiographic provinces: Basin and Range and Colorado Plateau (fig. 1). The transition zone has characteristics of both the Basin and Range and the Colorado Plateau, though the monument's setting favors the Basin and Range.

Basin and Range

The Basin and Range is a sprawling area that stretches from southeastern Oregon to northern Mexico. It involves eight states (Arizona, California, Idaho, New Mexico, Nevada, Oregon, Utah, and Texas) and occupies the southwestern half of Arizona. As the name implies, the province has ranges—more than 400, if all the small mountain ranges are included (Kiver and Harris 1999)—with basins between them. In general, the basins and ranges are oriented north to south, though along the margin of the Colorado Plateau, the orientation is more northwest to southeast.

The Basin and Range landscape started forming around 20 million–15 million years ago when the crust of this part of North America began pulling apart. As a result, the province is characterized by thin (28–35 km [17–22 mi] thick; Chulick and Mooney 2002), highly extended crust, as well as a plethora of normal faults (fig. 2). Normal faults separate basins, which dropped down along these faults, and ranges, which rose up. Faults shown in the surficial GRI GIS data (tsur_geology.mxd) bound the Tonto Basin and characterize Basin and Range extension, which is ongoing.

The monument's bedrock and surficial geologic deposits typify the Basin and Range. The southwestern part of the monument has "range-style" rocks whereas the northeastern part of the monument has "basin-style" deposits. That is, the Mazatzal Mountains—a "range"—are composed of crystalline bedrock alongside basin-fill sediments that accumulated in the Tonto Basin—a "basin." This basin–range configuration of rocks and deposits within the monument is particularly distinctive on the "Surficial Geologic Map of Tonto National Monument" poster.

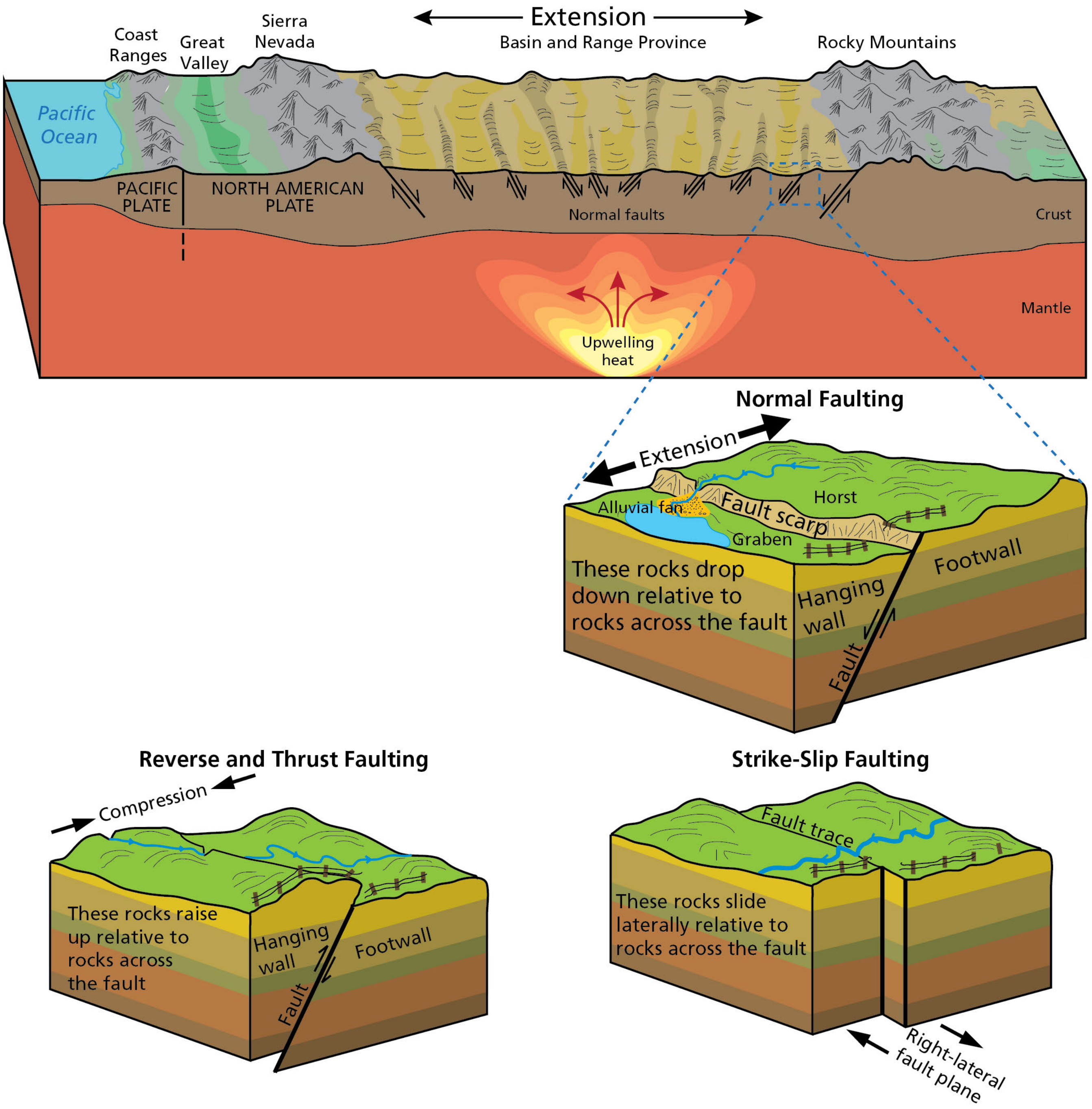


Figure 2. Graphic of Basin and Range extension, normal faults, and other fault types. **As Earth's crust cracks, movement takes place along a fault plane. Footwalls are below the fault plane, and hanging walls are above. Geologic forces in the Basin and Range physiographic province subjected it to extension (pulling apart of Earth's crust). The crust thinned and cracked as it pulled apart, creating normal faults. Mountain ranges were lifted up whereas basins dropped down along these faults, producing the distinctive alternating pattern of parallel ranges (referred to as "horsts") and basins (referred to as "grabens"). Besides normal faults, the two other principal fault types are reverse and strike-slip. In a reverse fault, crustal compression (squeezing together) moves the hanging wall up relative to the footwall. Reverse faults are characteristic of the Colorado Plateau physiographic province. 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 in this figure. When movement is to the left, it is a left-lateral strike-slip fault. Graphic by Trista Thornberry-Ehrlich (Colorado State University), incorporating a figure by Idaho Geologic Survey (2011, p. 2).**

Colorado Plateau

The Colorado Plateau occupies parts of four states, centered roughly on the Four Corners area of Arizona, Utah, Colorado, and New Mexico. Most of the plateau (about 90%) is drained southward by the Colorado River, for which the province was named, and its primary tributaries—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 "water trap" of the Basin and Range province. A small part of the eastern plateau drains into the Rio Grande.

The plateau displays flat-lying to mildly deformed, multihued, sedimentary rocks in cliffs, broad mesas, steep-sided canyons, and badland topography (Baars 1983). Paleozoic to Mesozoic (541-million- to 66-million-year-old) strata associated with the Colorado Plateau are not found within the monument. Nearby, however, the summit of Windy Hill is composed of the Mississippian Redwall Limestone (fig. 3). The hill's base (at the waterline of Theodore Roosevelt Lake), as well as outcrops on both the north and south sides of the lake, are composed of the Devonian Martin Formation (see "Geologic Map of Tonto National Monument" poster).

At least two key features define the Colorado Plateau. First, the continental crust that underlies the plateau is thick, much thicker than the crust of the adjacent Basin and Range. Controversy exists concerning the thickness of the plateau's crust, but Parsons et al. (1996) found that it ranged between about 30 and 48 km (19 and 30 mi), with the thickest area being the Kaibab uplift on the north rim of the Grand Canyon (see GRI report by Graham in preparation). Second, the plateau stands high above sea level. Elevations range from 610 m (2,000 ft) in the western Grand Canyon to 3,700 m (12,000 ft) in the high plateaus of Utah; the average elevation is 1,900 m (6,200 ft) (Price 2010).

An abrupt escarpment (topographic break) known as the Mogollon Rim bounds much of the southwestern side of the Colorado Plateau. The Mogollon Rim spans 320 km (200 mi) and has many picturesque portions; for example, it looms above the Verde Valley (northwest of the monument) as a sheer precipice ranging in height from 300 to 600 m (1,000 to 2,000 ft) (see GRI reports about Montezuma Castle and Tuzigoot National Monuments by KellerLynn 2019a, 2019b). Inward of the rim, the surface of the Colorado 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).

Transition Zone

Some investigators (e.g., Peirce 1985) have advocated that Arizona should be divided into three physiographic provinces—Basin and Range, Colorado Plateau, and "Transition Zone." Compilations and interpretations of the physiographic framework of the United States by the US Geological Survey (Vigil et al. 2000) and the National Park Service (National Park Service 2017b), however, do not include the "Transition Zone." Nevertheless, with respect to this geologic resources inventory and other National Park Service areas in Arizona (e.g., Tuzigoot National Monument; see GRI report by KellerLynn 2019b), discussion of a transition zone helps illustrate significant geologic features. For example, the transition zone has the most extensive display of Arizona's oldest rocks (see "Proterozoic Rocks"), which give the region its bold character. At 2,403 m (7,884 ft) above sea level, Mazatzal Peak represents the maximum elevation of the Proterozoic rocks in the transition zone (Peirce 1985). These ancient rocks house the caves and associated cliff dwellings at the monument (see "Caves and Cliff Dwellings").

Local Geologic Setting

Located in some of the most rugged terrain in Arizona, slopes in the monument range from 2% to 90%, and elevations range from 431 to 1,219 m (1,414 to 3,999 ft) above sea level (National Park Service 2019a). The monument lies on the southeastern flank of the Mazatzal Mountains, facing the even more precipitous Sierra Ancha to the northeast (fig. 3). Two Bar Ridge is the segment of the Mazatzal Mountains on which the monument is situated.

Steep, angular mountains, including the Mazatzal Mountains and Sierra Ancha, are typical of the Basin and Range physiographic province with northwest–southeast aligned ranges separated by basins, in this case, Tonto Basin. The mountains surrounding the Tonto Basin are composed of granitic, volcanic, metamorphic, and sedimentary rocks that accumulated during the Proterozoic Eon, more than a billion years ago (see "Proterozoic Rocks").

The monument is on the southwestern edge of the Tonto Basin, which is an arcuate, northwest-oriented, structural (formed by faulting) basin into which basin-filling sediments accumulated (see "Basin Fill"). The basin is about 60 km (40 mi) long and 10–15 km (6–9 mi) wide.

Two streams—Tonto Creek and the Salt River—drain the Tonto Basin. Tonto Creek is an intermittent stream originating in the area of the Mogollon Rim and flowing into the northern Tonto Basin. Morphologically, Tonto Creek is a gravelly, braided stream.

Figure 3. Photograph of the view from the Lower Cliff Dwelling.
Visitors to the Lower Cliff Dwelling can look north across Theodore Roosevelt Lake to the Sierra Ancha, which consists of a series of high plateaus, mesas, and ridges that extend from Theodore Roosevelt Lake on the south to the Mogollon Rim on the north. In the foreground of this photograph, basin fill and alluvial fan deposits compose the near (southern) side of the lake. Mississippian bedrock, Neogene basin fill, and Pleistocene pediment deposits make up the landforms on the far (northern) side of the lake. In addition, Windy Hill (the island in the foreground of the photograph) consists of Mississippian bedrock. NPS photograph by C. Sadler (Tonto National Monument) available at https://www.flickr.com/photos/tontonps/ (accessed 12 June 2019).

The Salt River is a perennial stream originating in the White Mountains (about 110 km [70 mi] east of the monument) and flowing into the eastern half of the basin. Morphologically, the Salt River is a meandering stream that transports a large bed load of coarse sand and gravel (Waters 1998). The monument contains three ephemeral riparian systems—Cave Canyon, Deadman Canyon, and Cholla Canyon—which are tributaries to the Salt River. All the tributaries of the Salt River and Tonto Creek, including those in the monument, are ephemeral, contributing runoff only after heavy rainfall. The only perennial surface water in the monument is Cholla Spring #1 (Martin 2001), which is also referred to as "Cave Canyon Spring" or "Cave Spring" (Baril et al. 2019).

In a narrow gorge once known as "The Crossing" (fig. 4), Theodore Roosevelt Dam (geologic map unit **Qd**; see "Geologic Map of Tonto National Monument" poster) is just downstream from the confluence of the Salt River and Tonto Creek. President Theodore Roosevelt dedicated the dam named in his honor on 18 March 1911 (fig. 4). The resultant reservoir, Theodore Roosevelt Lake, fills a large portion of the Tonto Basin, extending approximately 17 km (11 mi) upstream along the original Salt River course and approximately 15 km (9 mi) along the original Tonto Creek course (Lockridge et al. 2012). At full pond, Theodore Roosevelt Lake covers 8,700 ha (21,500 ac) and has 206 km (128 mi) of shoreline. It is the largest water body contained within the state. The larger Lakes Powell, Mead, and Mojave cross Arizona's borders with other states (for geologic information about Lake Powell, see the GRI report about Glen Canyon National Recreation Area by Graham 2016; for Lakes Mead and Mojave, see the geologic scoping summary about Lake Mead National Recreation Area by Connors and Covington 2004). The monument is about 870 m (2,900 ft) upslope and south of the southern shore of Theodore Roosevelt Lake.

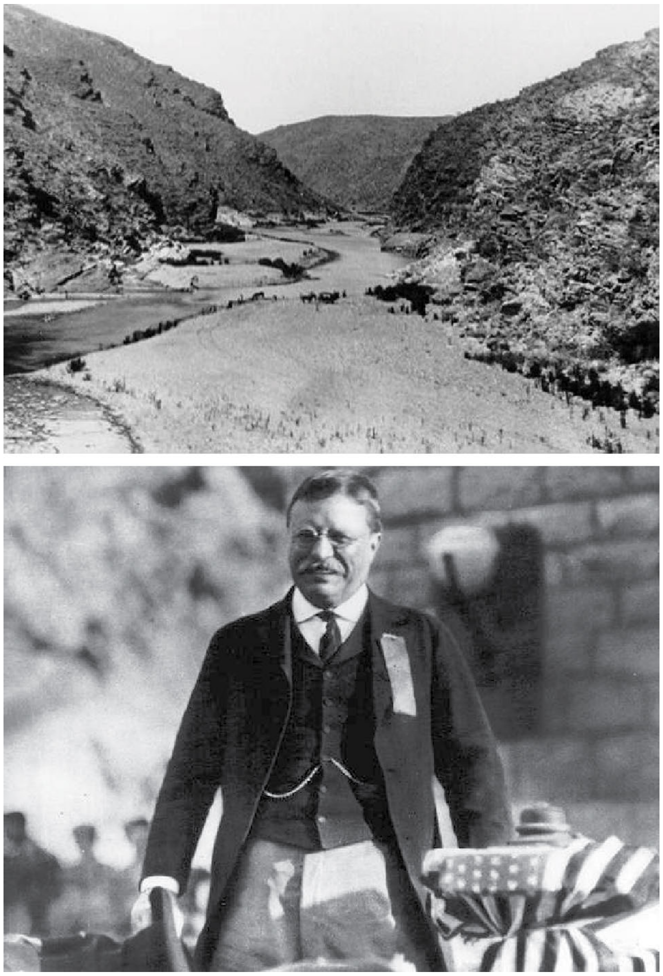


Figure 4. Historic photographs associated with Theodore Roosevelt Dam.
The upper photograph, taken in 1898, shows the area where the US Bureau of Reclamation would build Theodore Roosevelt Dam. The location, originally called "The Crossing," was the place in the Salt River where early Arizona farmers and ranchers would ford the river. In the photograph, a wagon, horse, and people prepare to cross. The site is in a narrow gorge a short distance below the confluence of the Salt River and Tonto Creek. The lower photograph shows President Theodore Roosevelt on 18 March 1911 during the dedication of the dam. Upwards of 1,000 people attended the event (US Bureau of Reclamation 2015). US Bureau of Reclamation photographs available at https://www.usbr.gov/lc/phoenix/projects/rooseveltdam/rdhistory.html (accessed 21 March 2019).

Cultural Background

Ancestral people arrived in the Tonto Basin more than 10,000 years ago (National Park Service 2019b). Initially they subsisted as hunters and gatherers but eventually adopted agriculture and a more sedentary (non-migratory) lifestyle (National Park Service 2019b).

A widespread irrigation system along the Salt, Gila, Santa Cruz, and San Pedro Rivers allowed for extensive food production. Irrigation agriculture along the middle Gila River may have taken place as much as 2,000 years ago (Haury 1976; see GRI report about Casa Grande Ruins National Monument by KellerLynn 2018a). Along the upper Salt River and Tonto Creek, irrigation of food crops began about 1,200 years ago (National Park Service 2019b) or about 750 CE.

A group of ancestral people, called the "Salado" by archeologists for the Salt River ("Rio Salado"), flourished in the Tonto Basin for about 300 years (1150 CE to 1450 CE) (National Park Service 2019b). People associated with the Salado culture lived in the basin and inhabited the cliff dwellings in what is now the monument. Making calculations based on streamflow estimates and available irrigable land, Waters (1998) found that the population supportable by intensive irrigation in the Tonto Basin at the time of the Salado would have been between 1,850 and 6,300 people, with a more refined estimate of 2,750 people.

The Salado culture was probably the result of interactions and exchanges among at least three major prehistoric Southwestern cultures (Threlkeld 1988): the ancestral Puebloans, the Mogollon, and the Ancestral Desert Sonoran People. The construction of new rooms and compounds and the presence of nonlocal artifacts confirms immigration into the Tonto Basin (Elson and Gregory 1995). The ancestral Puebloans migrated south from the Four Corners area between 1250 CE and 1450 CE (Lyons 2003). The Mogollon (see GRI report about Gila Cliff Dwellings National Monument by KellerLynn 2014) were from the mountains of southeastern Arizona and southwestern New Mexico. The Ancestral Desert Sonoran People (people of the Hohokam culture; see GRI report about Casa Grande Ruins National Monument by KellerLynn 2018a) are associated with the river valleys of southern and central Arizona. In the mid-1400s, the Salado migrated away from the Tonto Basin, an event that may have coincided with the arrival of the Apache. The Tonto Apache grew squash, corn, and beans, and they may have utilized fire to generate favorable conditions for hunting and gathering (National Park Service 2019b).

Following the discovery of gold in 1863, the local Apache and US military began to clash. Subsequently, military forces built several forts in the area, including Fort McDowell and Camp Reno. By 1875, European-American activities and control had extirpated the Tonto Apache from the Tonto Basin, with many removed to the San Carlos Reservation. Decreasing violence in the Tonto Basin favored an influx of prospectors. The 1880 gold rush in nearby Payson drew additional European-American settlement by merchants, farmers, and ranchers. The construction of Theodore Roosevelt Dam from 1903 to 1911 brought more people to the area (National Park Service 2019b).

Geologic Features and Processes

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

The monument's geologic setting is part of a remarkable geologic history, spanning back to the Proterozoic Eon (2.5 billion to 541.0 million years ago). Table 1 is a geologic time scale adapted to show the geologic map units within the monument and the geologic events associated with these map units. The geologic time scale highlights the events that led to the monument's present-day landscape.

During the 2006 scoping meeting (see National Park Service 2006) and 2019 conference call, participants (see Appendix A) identified many geologic features and processes of significance for the monument. In addition, research in conjunction with preparation of this report revealed some additional features and processes. These features and processes are discussed more-or-less in order of geologic age (oldest to youngest): Proterozoic Rocks

- Unconformities
- Conglomerates
- Basin Fill
- Pleistocene Deposits
- Caves and Cliff Dwellings
- Holocene Deposits
- Springs and Groundwater Resources
- Geothermal Resources
- Lithic Resources

Table 1. Geologic time scale for Tonto National Monument.

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 and map unit symbols are in parentheses. Rocks in the GRI GIS data for the monument include Early Proterozoic (X), Middle Proterozoic (Y), Tertiary (T), and Quaternary (Q). The Quaternary and Tertiary periods are part of the Cenozoic Era. The Triassic, Jurassic, and Cretaceous periods are part of the Mesozoic Era. The periods from Cambrian through Permian are part of the Paleozoic Era. Boundary ages ("Years Ago") are from the International Commission on Stratigraphy (2020).

Geologic Time Unit	Years Ago	Geologic Map Unit (Symbol)	Surficial Geologic Map Unit (Symbol)	Geologic Event
Quaternary Period (Q): Holocene Epoch (H)	11,700–today	Disturbed ground (**Qd**)	n/a	Humans become a notable geologic agent on the landscape. **Qd** is created by human activities <10,000 years ago (and probably historic).
Quaternary Period (Q): Holocene Epoch (H)	11,700–today	Young alluvium (**Qya**)	Floodplain deposits (**Qa**)	Sedimentation—both within channels and on floodplains (referred to as "overbank" sedimentation)—takes place along the Salt River and its tributaries.
Quaternary Period (Q): Pleistocene (PE) and Holocene (H) Epochs	2.6 million–today	Talus and colluvium (**Qtc**)	n/a	Gravity-driven processes deposit talus and colluvium, which mantle slopes and fill tributary valleys. Talus and colluvium cover many fault segments in the mountainous part of the monument.
Quaternary Period (Q): Pleistocene (PE) and Holocene (H) Epochs	2.6 million–today	Surficial deposits (**Qs**) Consists of undivided alluvium (**Qoal**), talus (**Qtc**), colluvium (**Qtc**), and local channel deposits (**Qya**)	Floodplain deposits (**Qa**) Alluvial fan deposits (**Qf**)	Continuation of sedimentation and gravity-driven processes

Table 1, continued. Geologic time scale for Tonto National Monument

Geologic Time Unit	Years Ago	Geologic Map Unit (Symbol)	Surficial Geologic Map Unit (Symbol)	Geologic Event
Quaternary Period (Q): Pleistocene (PE) and Holocene (H) Epochs	2.6 million–today	Associated with **Ydsu** (for the Upper Cliff Dwelling cave) and **Ymb** (for the Lower Cliff Dwelling cave)	n/a	Cave formation likely started between 3 million and 400,000 years ago. Enlargement of caves via spalling of rocks continues to the present day (primarily under wet conditions).
Quaternary Period (Q): Middle and early Pleistocene (PE) Epochs	2.6 million–~130,000 ***Note:*** See "Pleistocene Deposits" for explanation of age.	Older alluvium (**Qoal**)	Terrace deposits (**Qt**)	Once integration of the Salt River and its tributaries occur, the rivers gain the power to cut into basin fill (see **Tbf**) and transport it away
Tertiary (T): Neogene Period (N): Pliocene Epoch (PL)	5.3 million–2.6 million	n/a	Pediment deposit (**Qp1**) *Note*: No pediment deposits within the monument.	Basin-fill sedimentation ceases about 3 million years ago, that is, before the Salt River became integrated into the regional drainage system (Richard 1999a), which took place about 400,000 years ago (Anderson et al. 1987).
Tertiary (T): Neogene Period (N): Pliocene Epoch (PL)	5.3 million–2.6 million	n/a	Faults cut through basin fill (**Tbf**) and alluvial fan deposits (**Qf6** and **Qf8**) in the monument	Most of the faulting associated with Basin and Range extension ceased by 6 million to 3 million years ago (Shafiqullah et al. 1980) though some favorably oriented faults with respect to the current stress regime were reactivated during the Quaternary Period (Menges and Pearthree 1983).
Miocene Epoch (MI) to Quaternary Period (Q) [late Pleistocene Epoch (?)]	23.0 million–today	Conglomerate, Apache Group clasts (**QTsa**) Sandstone, pebbly sandstone and siltstone (**Tss**) Older conglomerate (**Toc**)	Basin fill (**Tbf**)	Regionally speaking, Basin and Range extension and tectonism, including widespread block faulting, began about 15 million years ago in central Arizona (Anderson et al. 1987). In the Tonto Basin, Basin and Range tectonism and extension started by about 18.6 million years ago (Nations 1990). Sediments accumulated in the basin as it subsided. Major faulting appears to have ceased, for the most part, by the time the uppermost basin fill was deposited (Nations 1987).
Tertiary (T): Paleogene Period (PG): Oligocene Epoch (OL)	33.9 million–23.0 million	n/a	n/a	See "Unconformities."
Tertiary (T): Paleogene Period (PG): Eocene Epoch(E)	56.0 million–33.9 million	n/a	n/a	See "Unconformities."
Tertiary (T): Paleogene Period (PG): Paleocene Epoch(EP)	66.0 million–56.0 million	n/a	n/a	Starting about 60 million years ago, the Colorado Plateau was uplifted. Uplift continues to the present day.

Table 1, continued. Geologic time scale for Tonto National Monument

Geologic Time Unit	Years Ago	Geologic Map Unit (Symbol)	Surficial Geologic Map Unit (Symbol)	Geologic Event
Cretaceous Period(K)	145.0 million–66.0 million	Faults (polylines in GRI GIS data)	n/a	The Laramide Orogeny (mountain-building event) in Arizona began about 80 million to 75 million years ago and ended about 55 million years ago (Dickinson 1989). Some of the faults in the monument may be related to this, in particular the formation of a monocline (a one-limbed fold in strata that are otherwise flat-lying; see cross section B–B[1] of Spencer and Richard 1999); alternatively, the monocline (and associated faulting) may be related to emplacement of diabase (Yd).
Jurassic Period (J)	201.3 million–145.0 million	n/a	n/a	See "Unconformities."
Triassic Period (TR)	251.9 million–201.3 million	n/a	n/a	See "Unconformities."
Permian Period (P)	298.9 million–251.9 million	n/a	n/a	See "Unconformities."
Carboniferous: Pennsylvanian Period (PN)	323.2 million–298.9 million	n/a	n/a	See "Unconformities."
Carboniferous: Mississippian Period (M)	358.9 million–323.2 million	n/a	n/a	See "Unconformities."
Devonian Period (D)	419.2 million–358.9 million	n/a	n/a	See "Unconformities."
Silurian Period (S)	443.8 million–419.2 million	n/a	n/a	See "Unconformities."
Ordovician Period (O)	485.4 million–443.8 million	n/a	n/a	See "Unconformities."
Cambrian Period (C)	541.0 million–485.4 million	n/a	n/a	See "Unconformities."
Unconformity	n/a	Surface between **Ymd** and **Toc** in the monument	n/a	After a long period of inactivity (more than 500 million years) in the region, Paleozoic strata were deposited on the Apache Group, which consisted of erosional surfaces of low relief (Richard 1999a). No Paleozoic or Mesozoic rocks are preserved within the monument, so an even longer "gap" in geologic time than the regional surface (unconformity) is recorded there.
Proterozoic Eon: Neoproterozoic (Z)	1.0 billion–541 million	n/a	n/a	See "Unconformities."

Table 1, continued. Geologic time scale for Tonto National Monument

Geologic Time Unit	Years Ago	Geologic Map Unit (Symbol)	Surficial Geologic Map Unit (Symbol)	Geologic Event
Proterozoic Eon: Mesoproterozoic (Y)	1.6 billion–1.0 billion	Diabase (**Yd**) Faults associated with **Yd**	Bedrock (**br**)	About 1.1 billion years ago (Wrucke 1989), diabase intruded the preexisting Proterozoic granitoid (e.g., **Xg3**) and Apache Group. High-angle faulting probably accompanied intrusion of sills (igneous intrusions that parallel the bedding of preexisting sedimentary rock), as indicated by abrupt changes in sill thickness and stratigraphic position across high-angle faults (Richard 1999a).
Proterozoic Eon: Mesoproterozoic (Y)	1.6 billion–1.0 billion	Apache Group: Mescal Limestone, basalt (**Ymb**)	Bedrock (**br**)	Production of magma along a Proterozoic fault
Proterozoic Eon: Mesoproterozoic (Y)	1.6 billion–1.0 billion	Apache Group: Mescal Limestone, dolomite (**Ymd**)	Bedrock (**br**)	See description for Pioneer Formation, undivided (**Yp**). Microbial mats grew in shallow water.
Proterozoic Eon: Mesoproterozoic (Y)	1.6 billion–1.0 billion	Apache Group: Dripping Spring Quartzite, upper unit (**Ydsu**)	Bedrock (**br**)	See **Yp**.
Proterozoic Eon: Mesoproterozoic (Y)	1.6 billion–1.0 billion	Apache Group: Dripping Spring Quartzite, middle unit (**Ydsm**)	Bedrock (**br**)	See **Yp**.
Proterozoic Eon: Mesoproterozoic (Y)	1.6 billion–1.0 billion	Apache Group: Dripping Spring Quartzite, lower unit (**Ydsl**)	Bedrock (**br**)	See **Yp**.
Proterozoic Eon: Mesoproterozoic (Y)	1.6 billion–1.0 billion	Apache Group: Dripping Spring Quartzite, Barnes Conglomerate (**Ydslb**)	Bedrock (**br**)	See **Yp**.
Proterozoic Eon: Mesoproterozoic (Y)	1.6 billion–1.0 billion	Apache Group: Dripping Spring Quartzite, undivided (**Yds**)	Bedrock (**br**)	See **Yp**.

Table 1, continued. Geologic time scale for Tonto National Monument

Geologic Time Unit	Years Ago	Geologic Map Unit (Symbol)	Surficial Geologic Map Unit (Symbol)	Geologic Event
Proterozoic Eon: Mesoproterozoic (Y)	1.6 billion–1.0 billion	Apache Group: Pioneer Formation, undivided (**Yp**)	Bedrock (**br**)	Sedimentary rocks (sandstone, siltstone, quartzite, and dolomite) were deposited on a deeply eroded surface of Early Proterozoic crystalline rocks as a shallow sea encroached upon the landscape. The Apache Group, which makes up most of the monument's bedrock, consists of these sedimentary rocks.
Unconformity	1.4 billion–1.2 billion years ago	Marked by a surface between **Xg3** and **Xp** at the monument	n/a	Erosion wore down the land surface to "an almost featureless plain" (Raup 1959, p. 11).
Proterozoic Eon: Paleoproterozoic (X) *Note*: Referred to as the "Early Proterozoic Era" and "Precambrian" by source map authors.	2.5 billion–1.6 billion	Granitic rocks of Cottonwood Creek, granodiorite (**Xg3**)	Bedrock (**br**)	Much of Earth's nascent crust developed.
Archean Eon	~4.0 billion–2.5 billion	n/a	n/a	Oldest rocks preserved on Earth (~4.0 billion years old)
Hadean Eon	4.6 billion–4.0 billion	n/a	n/a	Origin of Earth (~4.6 billion years ago)

Proterozoic Rocks

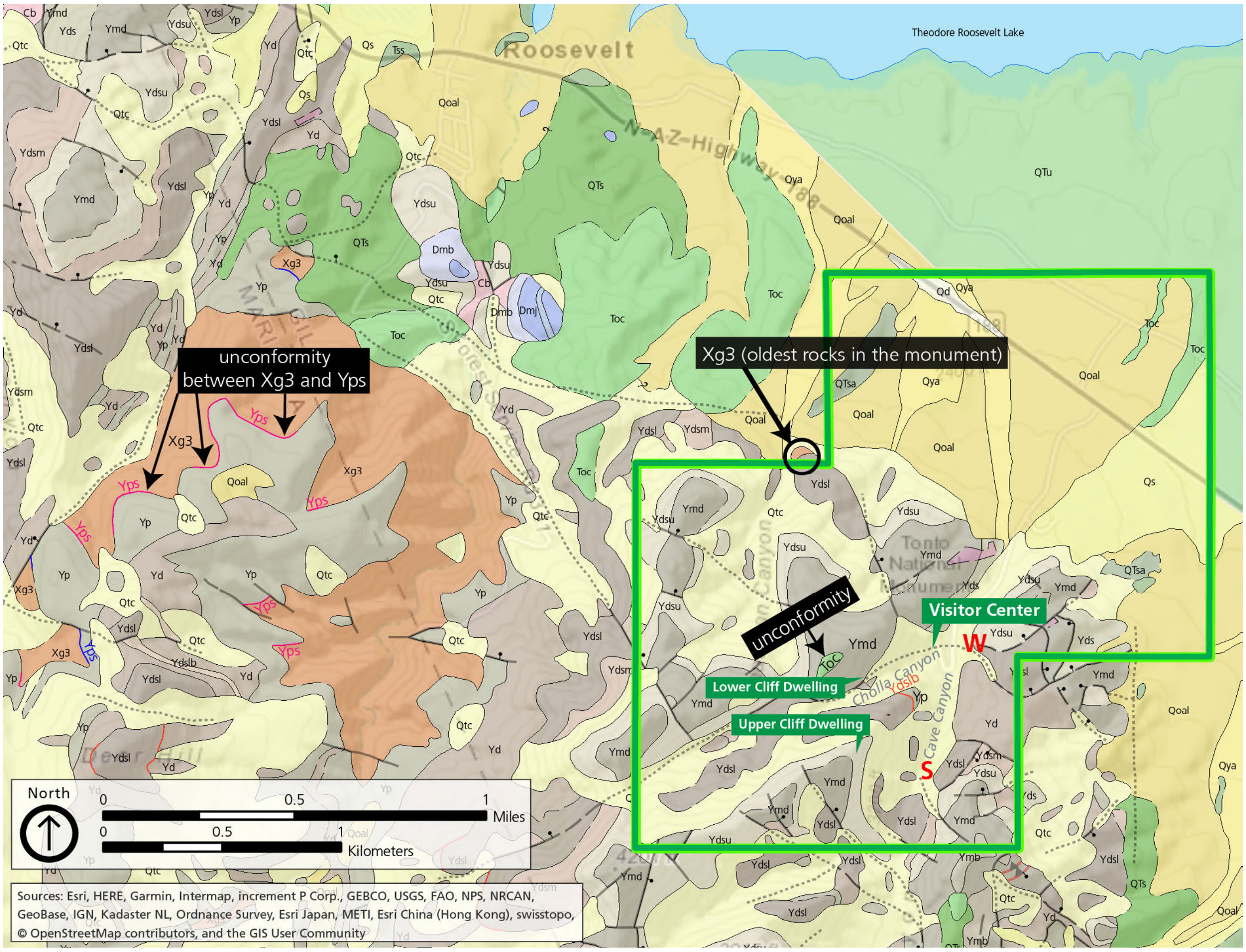
Geologic map units within the monument: **Xg3**, **Yp**, **Yds**, **Ydslb**, **Ydsl**, **Ydsm**, **Ydsu**, **Ymd**, **Ymb**, and **Yd**
Surficial geologic map unit within the monument: **br**

Rocks now divided into the Proterozoic Eon were traditionally part of Precambrian time, that is, rocks that predated the Cambrian Period, which began 541.0 million years ago (see table 1). The surficial geologic source map for the monument (Anderson et al. 1987) combined all bedrock into a single map unit (**br**) and identified this unit as either "Precambrian and Paleozoic" or "pre-Tertiary" (see "Basin Fill") in age. The geologic GRI GIS data for the monument (tont_geology.mxd) denote rocks of the Proterozoic Eon with the symbol **X** for the Early Proterozoic Era (also known as the "Paleoproterozoic" Era; 2.5 billion to 1.6 billion years ago) and **Y** for the Middle Proterozoic Era (also known as the "Mesoproterozoic" Era; 1.6 billion to 1.0 billion years ago).

The oldest rocks in the monument are the Early Proterozoic granitic rocks of Cottonwood Creek (**Xg3**; see table 1). These rocks occur where Deadman Canyon intersects the monument's northwestern boundary (fig. 5). A more exact numeric age for these rocks is unknown. Spencer and Richard (1999) described the granitic rocks of Cottonwood Creek as pale orangey tan, medium- to coarse-grained, equigranular (having crystals of the same or nearly the same size) biotite granite. Granite is the most common igneous rock in Earth's continental crust and perhaps the best known of all igneous rocks. At the monument, these granitic rocks contain 15%–20% mafic (dark-colored, magnesium- or iron-rich) minerals, mostly biotite. Biotite is a dark, shiny, silicate (silicon + oxygen) mineral characterized by perfect cleavage, readily splitting into thin sheets.

Most of the bedrock in the monument consists of the Middle Proterozoic Apache Group. In geologic terminology, a "group" is composed of "formations," which is the fundamental rock-stratigraphic unit, that is, mappable, lithologically distinct (with respect to rock type and other characteristics such as color, mineral composition, and grain size) from adjoining strata, and has definable upper and lower contacts. A formation can be divided into "members" or combined with other formations into a "group."

The entire section of the Apache Group occurs in the monument. From oldest to youngest, the group consists of the Pioneer Formation (**Yp**), Dripping Spring Quartzite (**Ydslb**, **Ydsl**, **Ydsm**, and **Ydsu**), and Mescal



Sources: Esri, HERE, Garmin, Intermap, increment P Corp., GEBCO, USGS, FAO, NPS, NRCAN, GeoBase, IGN, Kadaster NL, Ordnance Survey, Esri Japan, METI, Esri China (Hong Kong), swisstopo, © OpenStreetMap contributors, and the GIS User Community

Figure 5. Annotated screen capture of the GRI GIS data.
The black circle marks the location of the oldest rocks in the monument—the Early Proterozoic granitic rocks of Cottonwood Creek (Xg3). In addition, a local unconformity (in the monument's rock record) between Xg3 and the Middle Proterozoic Dripping Spring Quartzite, lower unit (Ydsl) occurs at that location. The unconformity in the monument's rock record is representative of a widespread, regional unconformity between Xg3 and the Middle Proterozoic Pioneer Formation, Scanlan Conglomerate (Yps), which represents a "gap" in the regional geologic record of at least 100 million years and possibly longer. The label and arrows west of the monument mark an occurrence of the regional unconformity between Xg3 and Yps (delineated as a pink line). A second (younger) unconformity in the monument's rock record is between the Middle Proterozoic Mescal Limestone, dolomite (Ymd) and Tertiary (Miocene) older conglomerate (Toc). This unconformity occurs on the hilltop above the Lower Cliff Dwelling. It represents a gap in the rock record of about 1.18 billion years. The Barnes Conglomerate (Ydslb) was mapped at one location in the monument (northeast of the Upper Cliff Dwelling). The red "W" on the figure marks the location of the monument's well and the approximate location of one of two springs in the monument; water no longer flows to the surface at this spring, which was referred to as "Cholla #2." The other spring in the monument (marked by a red "S" on the figure) is farther up Cave Canyon. Martin (2001) referred to this spring as "Cholla #1"; Baril et al (2019) referred to this spring as "Cave Canyon Spring" or "Cave Spring." Graphic compiled by Rebecca Port (NPS Geologic Resources Division) using GRI GIS data and base map sources: Esri, HERE, Grmin, Intermap, increment P Corp., GEBCO, USGS, FAO, NPS, NRCAN, GeoBase, IGN, Kadaster NL, Ordnance Survey, Esri Japan, METI, Esri China (Hong Kong), swisstopo, © OpenStreetMap contributors, and the GIS User Community.

Limestone (**Ymd** and **Ymb**) (see table 1). Mulder et al. (2018) provided the following numeric ages for rocks in the Apache Group: 1.34 billion years old for the Pioneer Formation (referred to as the Pioneer "Shale"), a maximum age of 1.256 billion ± 3 million years old for the Dripping Springs Quartzite (referred to as the Dripping Springs "Formation"), and a minimum age of 1.080 billion years old for the Mescal Limestone.

Pioneer Formation

Geologic map units within the monument: **Yp**
Surficial geologic map unit within the monument: **br**

The Pioneer Formation comprises the oldest rocks of the Apache Group. Outcrops of this formation in the monument consist of dark maroon siltstone (clastic sedimentary rock composed of silt-sized grains; see table 1). Exposures occur in lower Cholla Canyon, south of the visitor center (see "Geologic Map of Tonto National Monument" poster). The formation includes the Scanlan Conglomerate (**Yps**) at its base. This basal portion of the Pioneer Formation was not mapped within the monument, but many other conglomerates were (see "Conglomerates"). The closest occurrence of Scanlan Conglomerate is about 1.4 km (0.8 mi) west of the monument (fig. 5). The Scanlan Conglomerate overlies a significant unconformity ("gap" in the rock record; see "Unconformities").

Dripping Spring Quartzite

Geologic map units within the monument: **Yds**, **Ydslb**, **Ydsl**, **Ydsm**, and **Ydsu**
Surficial geologic map unit within the monument: **br**

The middle portion of the Apache Group is composed of the Dripping Spring Quartzite, which authors of the source maps (Spencer and Richard 1999 and Spencer et al. 1999) divided into three units: lower (**Ydsl**), middle (**Ydsm**), and upper (**Ydsu**). Where these authors could not differentiate individual units, they mapped an undivided unit (**Yds**). Significant for the monument, the Upper Cliff Dwelling is in a cave that developed in the Dripping Spring Quartzite, upper unit (**Ydsu**; see "Caves and Cliff Dwellings"). The Barnes Conglomerate (**Ydslb**) is part of the lower unit (see "Conglomerates").

Quartzite is metamorphosed quartz sandstone (composed of predominantly sand-sized grains, 1/16–2 mm [0.0025–0.08 in] in diameter). More specifically, it is a medium-grained, nonfoliated (no preferred arrangement of crystals) metamorphic rock composed mostly of quartz (silicon dioxide, SiO_2; the only silicate [silicon + oxygen] mineral consisting entirely of silicon and oxygen). Although the term "quartzite" is part of the formation's official name, only the lower unit (**Ydsl**) truly consists of quartzite. The middle and upper units consist of sedimentary rocks, namely siltstone (composed of silt-sized grains, ranging from 0.004 [1/256] to 0.06 [1/16] mm [0.00015 and 0.0025 in] in diameter, thus smaller than sand), shale (composed of clay-sized particles, less than 0.004 [1/256] mm [0.00015 in] in diameter, and characterized by fissility), and silty sandstone in the middle unit, and sandstone and shale in the upper unit (see table 1). Use of "Quartzite" is a convention that builds on prior use of a formation's name, though some investigators, following Drewes (1975), used Dripping Spring "Formation" rather than Dripping Spring "Quartzite." The US Geologic Names Lexicon (Geolex) accepts both terms (see https://ngmdb.usgs.gov/Geolex/Units/DrippingSpring_7984.html; accessed 17 April 2019).

The Dripping Spring Quartzite has interested researchers, past and present. In the 1950s and 1960s, investigators (e.g., Granger and Raup 1964) extensively studied the Dripping Spring Quartzite in the region for its uranium potential. The unit also provides the opportunity for study of ancient life on Earth. Investigators (e.g., Granger and Raup 1964; Wrucke 1989) noted an unusually high organic carbon content in the upper unit (**Ydsu**). Raup (1959) reported that the carbon contents of certain units of the Dripping Springs Quartzite indicate the presence of primitive life forms. At Theodore Roosevelt Dam, Horodyski et al. (1989) described acritarchs from dark shales. Acritarchs are a major, long-ranging and successful group of small, capsule-like, organically preserved fossils; they include mostly single-celled microfossils ranging from a few micrometers (one-millionth of a meter) to one millimeter in size; each is composed of a sack of organic tissue, referred to as a "vesicle."

Mescal Limestone

Geologic map units within the monument: **Ymd** and **Ymb**
Surficial geologic map unit within the monument: **br**

Like the Dripping Spring Quartzite, the name of the Mescal Limestone follows convention. That is, although the name "Limestone" reflects the most prevalent rock type in all the mapped Mescal Limestone of the region, within the monument, the formation consists primarily of dolomite (**Ymd**) and some basalt (**Ymb**). Both limestone and dolomite are carbonate sedimentary rocks, but dolomite contains more than 50% of the mineral dolomite (calcium-magnesium carbonate) whereas limestone contains less than 5% dolomite and more than 95% calcite (i.e., calcium carbonate). Notably, the name "dolomite" applies to both the rock and the mineral that composes the rock.

Sometimes geologists refer to the rock as "dolostone" to distinguish it from the mineral. Dolomite closely resembles limestone, and a continuous gradation in composition separates them. Names such as "limy dolomite" or "dolomitic limestone," sometimes used in map unit descriptions, exemplify the gradation between limestone and dolomite. Most dolomite is more brittle than limestone and breaks apart more easily. Dolomite also is less susceptible to chemical erosion than limestone. In caves, dolomite typically forms resistant ledges, rough, fractured walls, or porous zones (see "Caves and Cliff Dwellings").

The Mescal Limestone, dolomite (**Ymd**) contains 1.2-billion-year-old microbial colonies, called "stromatolites" (fig. 6). Stromatolites are trace fossils (evidence of an organism's activity such as nests, burrows, tracks, or coprolites [fossil dung]), rather than body fossils (any remains of the actual organism such as bones, teeth, shells, or leaves). During the formation of stromatolites, layer upon layer of single-celled microbes formed mats that passively trapped sediment and, in turn, blocked access to sunlight and nutrients, forcing the microorganisms to grow over the sediment. This continuous, upward-building process led to the development of roughly concentric layers of sediment preserved as fossils. Raup (1959) documented blocks of Mescal Limestone with stromatolite structures in Cholla Canyon. Scoping participants noted that at least one of these blocks was used in the construction of trails in the monument (fig. 6).

Basalt (**Ymb**) overlies—possibly conformably (without interruption; see "Unconformities")—the stromatolite unit. This basalt represents ancient lava flows that were erupted onto the stromatolite unit. Three mapped areas of Mescal Limestone, basalt (**Ymb**) occur within the monument. In addition, this unit occurs at the southern boundary of the monument and in a linear swath southward (see "Geologic Map of Tonto National Monument" poster).

Diabase

Geologic map unit within the monument: **Yd**
Surficial geologic map unit within the monument: **br**

Middle Proterozoic diabase (**Yd**) is younger than the Mescal Limestone (see table 1). In contrast to the Mescal Limestone, basalt (**Yb**), diabase intruded the rocks of the Apache Group below the surface. The diabase formed dikes and sills that, in the case of dikes, cut across the bedding of preexisting rock or, in the case of sills, along the bedding. Diabase occurs south of the visitor center, as well as on the north side of Cholla Canyon and in Deadman Canyon (see "Geologic Map of Tonto National Monument" poster).

Figure 6. Photographs of stromatolites.
The Mescal Limestone at the monument contains ancient microbial mats known as stromatolites. The mats form is shallow water, trapping, binding, and cementing sediments into layered mounds, columns, or sheet-like sedimentary rocks. Stromatolites are trace fossils; nothing remains of the actual organism. Rather, the fossils preserve evidence of microbial activity. As shown in these photos, at least one specimen was used during trail construction at the monument. Upper photograph by Katie KellerLynn (Colorado State University). Lower photograph by Melanie Ransmeier (NPS Geologic Resources Division).

Unconformities

Layers of rock are "conformable" where they have been deposited essentially without interruption. Although certain outcrops or landscapes may exhibit conformable beds representing significant spans of geologic time, no place on Earth contains a full set of conformable strata. "Unconformities" are breaks in strata. Each unconformity represents a period when deposition ceased or where erosion removed previously formed

Figure 7. Photograph of the Great Unconformity.
Of all the unconformities (gaps) in geologic strata throughout the world, the Great Unconformity is probably the most well-known. Above and below the unconformity, the rocks represent vastly different origins and times in Earth's history. Lisa Graves (left) and Bob Biek (right) have their hands on the Great Unconformity at Blacktail Canyon (between River Mile 120 to 121), which is a popular stop on the Colorado River within the Grand Canyon where the unconformity is well displayed. The unconformity surface itself represents a gap of 1.25 billion years in the rock record. Photograph courtesy of Bob Biek (Utah Geological Survey).

rocks. Because unconformities may be widespread across a region, they can be useful for correlating rocks over long distances.

Perhaps the world's most famous unconformity, referred to as the "Great Unconformity," occurs in Arizona. Recognition of the Great Unconformity helps put the monument's unconformities in a context that connects the monument's geology to other areas in the state and other units of the National Park System. The Great Unconformity is commonly recognized by its appearance (and excellent exposure) at the bottom of the Grand Canyon (fig. 7). In 1869, John Wesley Powell—the one-armed soldier, explorer, ethnologist, and geologist who led the first trip down the Colorado River by boat, including the first trip through the Grand Canyon—was the first person to record this exceptional unconformity. Below the surface of the unconformity lies a package of rocks known as the Grand Canyon Supergroup (sedimentary marine and terrestrial rocks); these rocks were deposited during the Middle and Late Proterozoic Era (1.6 billion to 541 million years ago). Above the surface of the unconformity lies the Tapeats Sandstone, which was deposited during a completely different era of geologic time—the Paleozoic Era (541.0 million to 251.9 million years ago)—as well as in a completely different world, following a global extinction event.

The rock record at the monument includes two significant unconformities (see table 1). The first unconformity is between the rocks of the Early Proterozoic (**X**) and Middle Proterozoic (**Y**) Eras, namely the granitic rocks of Cottonwood Creek (**Xg3**)—the oldest rocks in the monument—and the Pioneer Formation (**Yp**). This unconformity represents a gap in the geologic record of at least 100 million years and possibly longer. In the region, this unconformity underlies the Scanlan Conglomerate (**Yps**) (i.e., basal unit of the Pioneer Formation). This unconformity is recognized in the hills west of the monument (see fig. 5). The lateral persistence of the basal Pioneer Formation (**Yps**) indicates that the older, Early Proterozoic (**X**) and Middle Proterozoic (**Y**) basement rocks in the region were beveled remarkably flat during a period of erosion that took place sometime between about 1.4 billion and 1.2 billion years ago (Shride 1967). A thin (several-meter-thick) veneer of fluvial gravels of the Scanlan Conglomerate (**Yps**) covers this ancient erosion surface (Shride 1967; Trujillo 1984), marking a change from an erosional environment to a depositional environment. Various workers (e.g., Burns 1987; Trujillo 1984; Weiss 1986) suggested that this change was related to eustatic (global) sea level rise or tectonic activity, but the cause is uncertain (Skotnicki 2002). A similar unconformity within the monument marks this same erosional event, though more time and more rock are missing at the location within the monument. The unconformity's surface within the monument is between the Early Proterozoic granitic rocks of Cottonwood Creek (**Xg3**) and the Middle Proterozoic Dripping Spring Quartzite, lower unit (**Ydsl**) (see fig. 5).

The second unconformity in the monument's rock record is located on the ridge crest above the Lower Cliff Dwelling. The unconformity is between the Middle Proterozoic Mescal Limestone, dolomite (**Ymd**) and the Miocene older conglomerate (**Toc**). Mulder et al. (2018) provided a minimum age of 1.080 billion years old for the Mescal Limestone. The older conglomerate is Miocene (23.0 million to 5.3 million years old). Thus, at this location, the surface between these two rock formations represents a gap in the geologic record of about 1.057 billion years.

Conglomerates

Geologic map units within the monument: **Ydslb**, **Toc**, **QTsa**, and **Qoal**
Surficial geologic map unit within the monument: **br** and **Qt**

Conglomerates are coarse-grained, poorly sorted, sedimentary rocks consisting of cemented fragments of preexisting rocks larger than 2 mm (0.08 in) in diameter. Spencer and Richard (1999) mapped four different conglomerates in the monument: (1) Barnes Conglomerate (**Ydslb**; Middle Proterozoic); (2) older conglomerate (**Toc**; Miocene); (3) conglomerate, Apache Group clasts (**QTsa**; Miocene to Pleistocene); and (4) older alluvium (**Qoal**; middle and early Pleistocene). The Barnes Conglomerate (**Ydslb**) (fig. 8) occurs at the base of the Dripping Spring Quartzite, lower unit (**Ydsl**); it appears as a linear geologic unit (**Ydslb**) in the GRI GIS data (see fig. 5). Older conglomerate (**Toc**) makes up a distinctive outcrop above the Lower Cliff Dwelling (see "Unconformities") and occurs in the northeast corner of the monument. Conglomerate, Apache Group clasts (**QTsa**) occurs in the northeastern part of the monument. Older alluvium (**Qoal**), which has hardened into a cobble and boulder conglomerate, forms terraces 3–10 m (10–30 ft) above active channels and floodplains. In addition, Spencer and Richard (1999) mapped the Scanlan Conglomerate (**Yps**) near the monument. Anderson et al. (1987) mapped conglomerate as part of Pleistocene terraces (see "Terrace Deposits").

Figure 8. Photograph of the Barnes Conglomerate. In 2006, this chunk of Barnes Conglomerate (Ydslb) was along the trail to the Lower Cliff Dwelling. The clasts in the rock are approximately 10 cm (4 in) or less across. It is a pebble to cobble conglomerate. Photograph by Katie KellerLynn (Colorado State University).

Gila Conglomerate

Unlike Raup (1959), upon which many of the monument's interpretive materials are based, Spencer and Richard (1999) neither mapped nor described the well-known and widespread Gila Conglomerate as occurring in the monument. Originally described in 1875 by G. K. Gilbert to encompass the clastic deposits in the upper Gila River drainage (Gilbert 1875), subsequent investigators applied the name "Gila Conglomerate" to other drainages. Deposits of at least eight major basins, covering an area of 1.7 million km^2 (660,000 mi^2) in southeastern Arizona and southwestern New Mexico, have been described as "Gila Conglomerate" (Leopoldt 1981). To compound matters, some investigators have referred to the Gila Conglomerate as the "Gila Formation" and divided it into members while others have raised the unit to group status, subdividing it into formations. Additionally, while mapping groundwater aquifers and flow systems between the United States and Mexico, investigators divided the Gila Conglomerate into upper, middle, and lower hydrostratigraphic units (Hawley et al. 2000; Kennedy et al. 2000).

Two of the conglomerates in the monument—(1) older conglomerate (**Toc**) and (2) conglomerate, Apache Group clasts (**QTsa**)—were deposited at the same time as the Gila Conglomerate elsewhere, and like the Gila Conglomerate are basin-filling units (see "Basin Fill"). However, mapping these units as "Gila Conglomerate" is not the practice of the Arizona Geological Survey (AZGS) because Gila Conglomerate is "kind of a grab bag of lithology, texture, and age" (Phil Pearthree, Arizona Geological Survey, state geologist, email communication, 3 April 2019). Similarly, Leopoldt (1981, p. 12) described the Gila Conglomerate as a "formational waste basket" for Neogene (i.e., Miocene and Pliocene) terrestrial basin-fill deposits. Heinal (1962) recommended that the use of the term "Gila Conglomerate" be discontinued in future mapping because (1) it includes a large portion of deposits other than conglomerates, (2) it suggests that deposits in separate basins are identical, (3) its use masks sequences of alluvial deposition within individual basins, and (4) it oversimplifies a complex Cenozoic history.

In contrast to AZGS geologists, mapping by the US Geological Survey in Arizona and New Mexico commonly applies the term "Gila Conglomerate" to Miocene and Pliocene (and in some cases, Pleistocene) basin-fill units. For example, a source map for the GRI GIS data compiled for Gila Cliff Dwellings National Monument in New Mexico (Ratté et al. 2014) used "Gila Conglomerate" (see the GRI report about Gila Cliff Dwellings National Monument by KellerLynn 2014). Its use in that setting seems more appropriate, however, because that monument is in the upper Gila River drainage where the unit was originally described. Ratté et al. (1994) provided the most recent description of Gila Conglomerate recorded in Geolex (https://ngmdb.usgs.gov/Geolex/UnitRefs/GilaRefs_8273.html; accessed 30 June 2020).

Basin Fill

Geologic map units within the monument: **Toc**, **Tss**, and **QTsa**
Surficial geologic map unit within the monument: **Tbf**

According to a definition provided by Scarborough (1981, p. 5), basin fill is "that sedimentary material deposited in southern Arizona basins in response to that episode of block faulting which is thought to be of primary importance in producing the modern basin and range physiography." Anderson et al. (1987) provided a date for basin filling of between 19 million and 5–3 million years ago. This range comes from K-Ar (potassium–argon) dates on dacite (a type of volcanic rock) for the base of the fill and correlation with similar basin-fill deposits elsewhere in central and southern Arizona for the top of the fill. Moreover, fossil evidence (e.g., remains [a tooth] of an extinct horse *Pliohippus*; Lance et al. 1962) indicates that basin fill in the Tonto Basin is no younger than late Miocene or early Pliocene; that is, about 5.3 million years old.

The Tonto Basin contains a relatively thick sequence of Tertiary sediments, greater than 300 m (1,000 ft) thick (Anderson et al. 1987). In this case, "Tertiary" is now interpreted as "Neogene" (Miocene and Pliocene Epochs) (Phil Pearthree, Arizona Geological Survey, director and state geologist, written communication, 25 May 2020). Nations (1990) informally named the basin fill in the Tonto Basin the "Tonto Basin formation." The informal formation is contemporaneous with the development of the Tonto Basin by normal faulting. The formation/fill consists of sediments eroded from the surrounding elevated areas and deposited in the basin by streams, within lakes, and as debris flows (Nations 1988). Initially as the basin subsided, a gray to reddish-brown conglomerate facies accumulated throughout the basin. Each facies has a characteristic set of properties—such as color, mineral constituents, grain size, and sedimentary structures—owing to deposition in a particular environment. The maximum observed thickness of the conglomerate facies is about 150 m (500 ft) (Nations 1987). Later, presumably as tectonic activity waned, the conglomerate facies accumulated only along the margins of the basin. Subsequently, a reddish-brown mudstone facies—including minor evaporites ("salts" deposited from aqueous solution as a result of extensive or total evaporation) and carbonates (e.g., limestone, calcite, and dolomite, which consist primarily of carbonate [$CaCO_3$] minerals)—accumulated on distal mudflats and in lacustrine environments.

The boundary between the two facies is gradational; that is, the conglomerate grades upward and laterally into mudstone. The gradation between the two units is observable on the north side of Rock Island (see "Surficial Geologic Map of Tonto National Monument" poster) as a vertical transition from dacite boulder conglomerate upward through sandstone, siltstone, into mudstone (Nations 1987).

With respect to the GRI GIS data for the monument, Spencer and Richard (1999) mapped three basin-fill units in the monument. From oldest to youngest, these are (1) older conglomerate (**Toc**); (2) sandstone, pebbly sandstone, and siltstone (**Tss**); and (3) conglomerate, Apache Group clasts (**QTsa**). The first and third units were discussed in the "Conglomerates" section. The second unit—sandstone, pebbly sandstone, and siltstone (**Tss**)—consists of distal fluvial to lacustrine deposits such as relict stream channels and bars or debris flows associated with the older conglomerate (**Toc**). As mapped by Anderson et al. (1987), one basin-fill unit—basin fill (**Tbf**)—occurs in the monument. Like the three basin-filling units of Spencer and Richard (1999), basin fill (**Tbf**) occurs in the northeast part of the monument (see "Surficial Geologic Map of Tonto National Monument" poster). Reflecting work by Nations (1987, 1988, 1990), the texture of the basin fill (**Tbf**) as mapped by Anderson et al. (1987) varies from a gravel-rich conglomerate facies, 135 m (440 ft) thick, to a mudstone facies, 280 m (920 ft) thick.

Basin fill contains fossils, including snails, ostracodes, a camelid, an equid (*Pliohippus* sp.), and a variety of plant types known from stems, leaves, fruitlets, pollen, and other remains. The basin fill within the monument has yielded no fossils to date, but fossils have been found in basin fill near Punkin (or Pumpkin) Center, a few kilometers northwest of Theodore Roosevelt Lake, or about 30 km (19 miles) northwest of the monument (Gray 1960; Lance et al. 1962; Lindsay and Tessman 1974; Lindsay and Mead 2005).

Pleistocene Deposits

Geologic map units within the monument: **Qs**, **Qoal**, and **Qtc**
Surficial geologic features: pediment, terrace, and alluvial fan deposits (listed and discussed below)

Note: In Arizona, the Pleistocene Epoch is commonly divided into three unofficial stages: early (2.6 million–770,000 years ago), middle (770,000–130,000 years ago), and late (130,000–12,000 years ago). These are not formal divisions of geologic time and differ from the ICS chronostratigraphic chart (International Commission on Stratigraphy 2020; see table 1). The widespread Bishop Tuff, which erupted 767,000 years ago, provides a marker for the boundary between the early and middle Pleistocene Epoch. The age of the most recent interglacial interval prior to the Holocene Epoch (approximately 130,000 years ago) marks the boundary between the middle and late Pleistocene Epoch. The end of the Younger Dryas (the last really cold interval as global climate, a transition from glacial to interglacial conditions) marks the end of the Pleistocene Epoch about 12,000 years ago (Phil Pearthree, Arizona Geological Survey, and state geologist, written communication, 1 July 2020).

The post–basin-filling portion of the monument's geologic history started with incision of the Salt River and its tributaries into basin fill. Incision was followed by transport of this material out of the basin. Basin filling ended about 5 million–3 million years ago (Anderson et al. 1987). The highest pediment surface (**Qp1**; see "Pediment Deposits") in the Tonto Basin provides a minimum age of at least 400,000 years ago for the inception of drainage out of the basin because such surfaces, which formed by erosion, could not have formed under internal drainage conditions (Anderson et al. 1987).

Pediment, terrace, and alluvial fan deposits record the development of the Salt River drainage. As mapped by Anderson et al. (1987), only alluvial fan deposits occur within the monument, but pediment and terrace deposits occur nearby. Anderson et al. (1987) suggested that pediments dominate the early record of the through-going drainage in the basin because once the basin was breached and through-going drainage commenced, side streams could erode broad surfaces and deposit their gravel. However, as incision of the basin and entrenchment of the streams increased, streams lost their ability to erode broad surfaces. Therefore, terrace formation has dominated the more recent geologic record.

Pediment Deposits

Surficial geologic map unit: **Qp**

Anderson et al. (1987) mapped 10 pediment deposits in the Tonto Basin (see "Surficial Geologic Map of Tonto National Monument" poster). Pediment surfaces are about 20 to 183 m (70 to 600 ft) above the Salt River, Tonto Creek, and their larger tributaries (e.g., Pinto, Campaign, and Slate Creeks). The oldest pediment deposits (**Qp1**) project to a height of at least 168 to 183 m (550 to 600 ft) above the Salt River.

Anderson et al. (1987) used the term "pediment" to mean "erosion surface" at the top of basin fill (see "Basin Fill"). Other investigators, including those at the Arizona Geological Survey, restrict the use of "pediment" to bedrock erosion surfaces and apply the term "piedmont" instead, which literally means "foot of the mountain." In geomorphology, the term piedmont is applied to the space between topographic mountain fronts and whatever is in the valley axis such as a through-flowing river, playa, or lake. The term "piedmont" is thought to be a better descriptor and less ambiguous than "pediment" (Phil Pearthree, Arizona Geological Survey, director and state geologist, written communication, 1 June 2020).

No pediment deposits occur within the monument, but they are significant for the Quaternary history and warrant inclusion in the GRI. The closest, **Qp2**, is southwest of the monument. Moreover, deposits of **Qp5** are found north (across Theodore Roosevelt Lake) and northwest (on the same side of the lake as the monument) of the monument (see "Surficial Geologic Map of Tonto National Monument" poster). Both **Qp2** and **Qp5** developed during the middle Pleistocene Epoch. According to Anderson et al. (1987), pediment deposits 1–4 formed at least 400,000 years ago; pediment deposits 5–8 formed at least 200,000 years ago. Lower numbers (e.g., **Qp2**) represent older deposits than higher numbers (e.g., **Qp5**). Numbered pediment deposits grade or project into similarly numbered terrace deposits and are inferred to correlate with them (see "Terrace Deposits").

As mapped by Anderson et al. (1987), the most extensive pediment deposits occur unconformably above the mudstone facies of the basin fill. The deposits consist of sandy boulder and cobble gravel, 3–10 m (10–30 ft) thick. The lithology of the material reflects the source rocks of a drainage; as such, it may be "mixed" or nearly 100% granite or quartzite. Fine-grained deposits, possibly loess (windblown silt), cover higher pediments (**Qp6** and higher) with 2–25 cm (0.8–10 in) of material. Lower pediments locally include areas of modern alluvium (**Qa**) (see "Holocene Deposits").

Terrace Deposits

Geologic map units: **Qoal**
Surficial geologic map units: **Qt**

Terraces are characteristic landforms formed by rivers. They are remnants of former floodplains that rest topographically above modern floodplains to create relatively flat, bench-like landforms. The terrace tread (flat or gently sloping surface) records a period of lateral erosion or the culmination of a period of aggradation by a fluvial system. Incision into the terrace tread characterizes abandonment of that surface.

Spencer and Richard (1999) mapped older alluvium (**Qoal**), which forms Pleistocene terraces 3–10 m (10–30 ft) above active channels and floodplains (see "Geologic Map of Tonto National Monument" poster). As mapped by Anderson et al. (1987), Pleistocene deposits form terraces from 3 m (10 ft) to about 153 m (502 m) above Tonto Creek, Salt River, and their larger tributaries. Anderson et al. (1987) mapped terrace deposits **Qt2** to **Qt12**, older to younger, based chiefly on height above the modern drainage and degree of soil development. Multiple terraces indicate that incision of a valley was not steady (Connell et al. 2005). Because Anderson et al. (1987) did not recognize a terrace deposit correlative with pediment deposit **Qp1**, no **Qt1** deposits are shown on that map.

Anderson et al. (1987) mapped no terrace deposits within the monument, but remnants of terraces **Qt2** and **Qt3** occur north of the monument (see "Surficial Geologic Map of Tonto National Monument" poster). These are some of the oldest terrace deposits in the Tonto Basin. They developed as the Salt River cut into basin fill during the early Pleistocene Epoch (about 2.6 million–767,000 years ago); Anderson et al. (1987) estimated that terraces **Qt2** and **Qt3** formed at least 400,000 years ago.

Alluvial Fan Deposits

Surficial geologic map units within the monument: **Qf**

Anderson et al. (1987) mapped four levels of alluvial fans (**Qf4**, **Qf5**, **Qf6**, and **Qf8**) within the monument. Alluvial fans are gently sloping masses of alluvium (stream-deposited sediment). Viewed from above, alluvial fans have the shape of an open, handheld fan, with the "handle" of the fan at the tributary valley's mouth and the "body" of the fan spreading outward and thinning onto the main valley floor. Fan morphology distinguishes alluvial fan deposits from other types of deposits. Alluvial fan surfaces commonly have steeper gradients than pediment surfaces, though the alluvial fan deposits **Qf3** and **Qf4** mapped near the monument may be steeper portions of more extensive pediment surfaces (Anderson et al. 1987).

With respect to general geologic processes, alluvial fans are located where stream gradient decreases abruptly, and the flow of water slows down markedly. As a result, a major change in carrying capacity takes place, and streams dump entrained sediment at a mountain front. The alluvial fan deposits in the monument consist chiefly of subrounded (showing the effects of considerable abrasion) to subangular (showing the effects of slight abrasion) pebbles and larger clasts (as large as boulders) that interfinger with discontinuous sand-rich beds or lenses.

Running water during the middle Pleistocene Epoch (767,000–130,000 years ago) deposited alluvial fans in the Tonto Basin. Anderson et al. (1987) estimated that **Qf4** formed at least 400,000 years ago while the other three alluvial fans in the monument (**Qf5**, **Qf6**, and **Qf8**) formed at least 200,000 years ago.

Caves and Cliff Dwellings

About 1150 CE, when people associated with the Salado culture came to the Tonto Basin seeking a protected place to live, they found natural caves set in the cliffs of Cave Canyon and Cholla Canyon (fig. 9). The monument's caves, referred to as "shelter caves" or "alcoves," were sufficiently large to house a small community (see "Cultural Background"). The term "shelter cave" is commonly used in archeological and paleontological studies and carries the implication that

Figure 9. Photograph of caves containing the Upper and Lower Cliff Dwellings. Archeologist Roger Dorr points to the Upper Cliff Dwelling (left side of photograph) and Lower Cliff Dwelling (right side of photograph). With a difference in elevation of about 70 m (230 ft), the Upper Cliff Dwelling sits at 1,033 m (3,390 ft) above sea level whereas the Lower Cliff Dwelling is at 963 m (3,159 ft) above sea level. NPS photograph by C. Sadler (Tonto National Monument) available at https://www.flickr.com/photos/tontonps/ (accessed 12 June 2019).

humans or animals used a particular cave for shelter. The term "alcove" is generally used to describe caves that are wider than they are deep. Moreover, with respect to geomorphology, by definition, alcoves occur in a precipitous rock face (Neuendorf et al. 2005). Thus, both "shelter cave" and "alcove" are suitable terms for describing the caves at the monument.

This geologic resources inventory provides a significant correction to the geologic location of the cliff dwellings (fig. 10). Raup (1959) reported that both the Upper Cliff Dwelling and Lower Cliff Dwelling were in the Dripping Spring Quartzite. Raup's interpretation was subsequently used in park literature (e.g., Wade 2010). Geologic mapping completed by the Arizona Geological Survey (Spencer and Richard 1999) and compiled in the GRI GIS data for the monument (see "Geologic Map Data" chapter), however, revealed that the Lower Cliff Dwelling actually occurs in the Mescal Limestone (**Ymd**). This revelation can be seen in the GRI GIS data (tont_geology.mxd), the GRI GIS data viewable in Google Earth (tont_geology.kml), "Geologic Map of Tonto National Monument" poster, and figure 10 of this report.

Cave Formation

In 1959, US Geological Survey (USGS) geologist Robert B. Raup Jr. wrote an unpublished, geologic report in which he stated that the caves at the monument probably started to form at least 50,000 years ago and maybe as long as 400,000 years ago. Unfortunately, Raup (1959) did not provide any details about how or why he

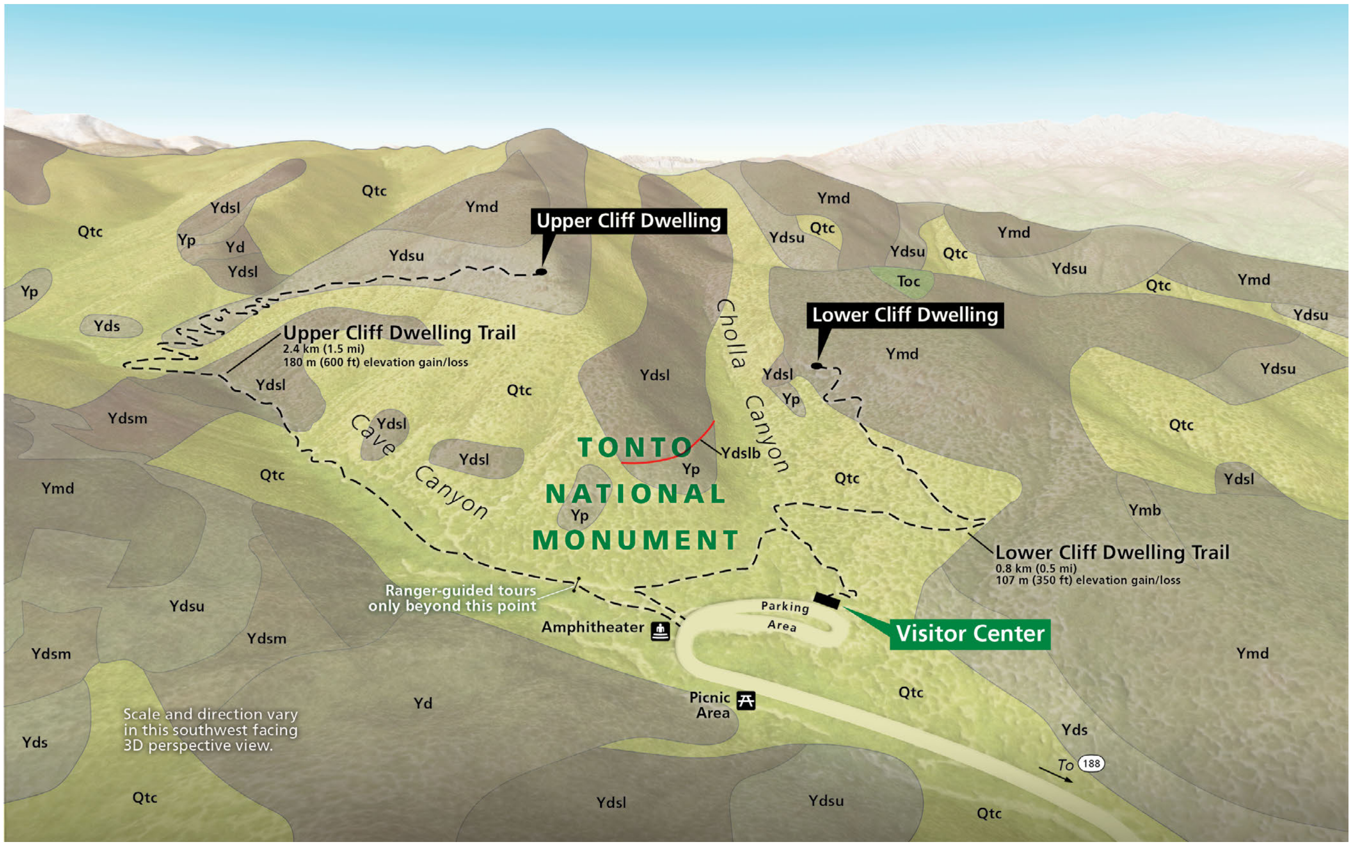


Figure 10. Graphic showing the monument's geology draped over shaded relief. A long-standing interpretation of the monument's geology by Raup (1959) reported that both the Upper Cliff Dwelling and the Lower Cliff Dwelling occur in the Dripping Spring Quartzite. Geologic mapping completed by the Arizona Geological Survey (Spencer and Richard 1999) and compiled in the GRI GIS data (see "Geologic Map Data" chapter), however, revealed that the cave containing the Lower Cliff Dwelling actually occurs in the Mescal Limestone, dolomite (Ymd). The cave containing the Upper Cliff Dwelling occurs in Dripping Spring Quartzite, upper unit (Ydsu). Other map units shown on the graphic include the following (listed alphabetically): Qtc = talus and colluvium. Toc = older conglomerate. Yds = Dripping Spring Quartzite, undivided. Ydsl = Dripping Spring Quartzite, lower unit. Ydslb = Dripping Spring Quartzite, Barnes Conglomerate. Yp = Pioneer Formation, undivided. Graphic by Trista Thornberry-Ehrlich (Colorado State University) using NPS graphic from Harper's Ferry Center and GRI GIS data (tont_geology.mxd).

made this estimate, and literature review and personal communications in the process of preparing this GRI report yielded no additional studies conducted on the monument's caves. Nevertheless, based on the probable process of cave formation (discussed below), initiation of cave formation in what is now the monument would have coincided with the development of the Salt River–Tonto Creek drainage system, which began incising basin fill less than 3 million years ago (see "Basin Fill"). As another point of reference, inception of drainage out of the Tonto Basin began at least 400,000 years ago, based on the age of the highest pediment surface (**Qp1**), which could not have formed under internal drainage conditions (see "Pediment Deposits"). Thus, cave formation likely started between 3 million and 400,000 years ago.

With respect to the geologic process, work by Ratté (2000, 2001) in Gila Cliff Dwellings National Monument provides a model for cave formation at Tonto National Monument. According to Ratté (2000, 2001), as "Cliff Dweller creek" cut down through bedrock (Gila Conglomerate), incising Cliff Dweller Canyon, it likely encountered a relatively soft layer of rock and cut laterally through it, thus initiating cave formation (see GRI report about Gila Cliff Dwellings National Monument by KellerLynn 2014). In contrast, Raup (1959) stated that spalling (flakes of rock—from less than a centimeter to several meters thick—successively fall from the bare surface of a large rock mass) was the primary mode of cave formation at Tonto National Monument. According to George Veni (National Cave and Karst Research Institute, executive director, email communication, 25 April 2019), however, spalling is not generally how these [types of caves] form, though it is part of the process. Shelter caves form when streams were at higher elevations and eroded into valleys walls (George Veni, National Cave and Karst Research Institute, executive director, email communication, 25 April 2019). The monument's caves were probably at stream level at the bottom of a former valley at the time of their genesis. As a result of stream incision in the past 3 million to 400,000 years ago, the caves are now high above the valley floor; they also were high above the valley floor when humans inhabited them 870 years ago.

Under favorable conditions, cave formation continues to the present day. If caves are below valleys, along fractures, or along other structural features that channel groundwater, then general seepage results in "sapping" which weakens the rock, resulting in spalling, grain-by-grain erosion, and increased susceptibility to wind erosion. In nearby Tonto National Forest, for example, a few caves have formed in volcanic tuff by aeolian processes (wind erosion), though the majority of the caves on the Tonto National Forest have formed from the dissolution of limestone (Chad Harrold, Tonto National Forest, geologist/cave & karst program manager, email communication, 9 May 2019).

Cliff Dwellings

Table 2 highlights physical and geologic characteristics of the caves that house the Upper and Lower Cliff Dwellings.

The prehistoric builders of the Upper and Lower Cliff Dwellings used stone and adobe (a mixture of clay and silt; fig. 11) to build walls (Vance 2013a, 2013b). Ample building stone (fallen from the cave ceiling and walls) littered the floors of the caves and found use in construction (Threlkeld 1988; Wade 2010). In addition, the builders used wood elements—such as sycamore, cottonwood, birch, pinyon, juniper, Douglas fir, ponderosa pine, willow, and chokecherry—for door lintels and roofs. Also, saguaro cactus ribs, bark, yucca, and reeds found use as roofing material. While these latter supplies could have been acquired locally, the higher-elevation tree species (ponderosa pine, Douglas fir, birch, and possibly juniper) would have required substantial travel, transport, or exchange (Vance 2013b).

Builders constructed the cliff dwellings using locally sourced bedrock, but not all at once. Instead, building started with only one or two rooms; additional rooms were added over a period of perhaps 30 years. The Lower Cliff Dwelling consisted of 16 rooms on the ground floor—three having a second story. Adjacent to the primary structure was a 12-room annex. The Upper Cliff Dwelling consisted of 32 rooms on the ground floor, eight of which had second stories (National Park Service 2017a). New rooms were built on bedrock, artificially leveled floors, and accumulated trash (Vance 2013a, 2013b).

Figure 11. Photograph of adobe-covered walls in the Upper Cliff Dwelling.
Construction began about 1300 CE and continued until between about 1400 CE and 1450 CE. The size of the cave, with 24-m- (80-ft-) high ceilings, allowed for living quarters with second and third story rooms. NPS photograph by C. Sadler (Tonto National Monument) available at https://www.flickr.com/photos/tontonps/ (accessed 12 June 2019).

Contours of the cave walls influenced the shapes of the rooms. In constructing the Upper Cliff Dwelling, for example, the prehistoric builders made use of the natural topography of the alcove, leaving it open (i.e., building no wall) at the rear of the cave, allowing access to a site of dripping water. Ancient peoples collected these waters in cisterns at the rear of the cave. The cistern in the Upper Cliff Dwelling could hold an estimated 380 L (100 gal) (National Park Service 2020). Additionally, the prehistoric builders augmented natural ledges (of which there are five) in the Dripping Spring Quartzite (**Ydsu**) to create foundations and walls for the rooms of the Upper Cliff Dwelling (Vance 2013b).

Table 2. Comparison of the caves housing the Upper and Lower Cliff Dwellings.

Dimensions of the Upper Cliff Dwelling are from National Park Service (2020) for height and Jake DeGayner (NPS Southern Arizona Office, geographer, email communication, 4 May 2020) for width, depth, and floor area. Dimensions of the Lower Cliff Dwelling cave are from Holmlund (2011).

Characteristics	Upper Cliff Dwelling	Lower Cliff Dwelling
Dimensions	Width: 57 m (187 ft) Depth: 25 m (82 ft) Height (measurement location unknown): 24 m (80 ft) Floor area: 793 m^2 (8,536 ft^2)	Width: 27.8 m (91.2 ft) Depth: 12.7 m (41.7 ft) Height at mouth of cave: 10–12 m (30–40 ft) Floor area: 217.2 m^2 (2,337.9 ft^2)
Bedrock	Dripping Spring Quartzite, upper unit (**Ydsu**) ● Sandstone with interbedded shale ● Slope-forming, commonly forms cliffs ● Intensely fractured; forms loose blocks (Wachter 1978)	Mescal Limestone, dolomite (**Ymd**) ● Dolomite with blobs, stringers, and laminations of protruding silica ● Contains nonresistant beds and breccia zones, possibly related to dissolution of evaporite minerals ● No large, continuous vertical or sub-vertical fractures; appears more stable than rock of the Upper Cliff Dwelling (Cloues 2002)
Cave features	Calcium-carbonate infillings or coatings, "cementing" (Cloues 2002)	Calcium-carbonate speleothems (Holmlund 2011)
	Spring at the rear of the cave (Vance 2013a)	Water seeps from an area at the back of the cave (Holmlund 2011)
	Solutional activity in the geologic past not continuing at the present time (Cloues 2002)	Solutional activity in the geologic past not continuing at the present time (Cloues 2002)
	Ongoing spalling	Ongoing spalling

Holocene Deposits

Geologic map unit within the monument: **Qtc** and **Qya**
Surficial geologic map unit within the monument: **Qa**

In the southwestern part of the monument, gravity-deposited talus and colluvium (**Qtc**), rather than stream-deposited alluvium, dominate the Holocene record. The accumulation of talus and colluvium likely began in the Pleistocene Epoch (2.6 million–11,700 years ago). These deposits cover the floors of Cave and Cholla Canyons (see "Geologic Map of Tonto National Monument" poster).

Stream activity characterizes the Holocene record of the Tonto Basin, including the northeastern part of the monument. The source map authors mapped one unit each: Anderson et al. (1987) mapped floodplain deposits (**Qa**) (see "Surficial Geologic Map of Tonto National Monument" poster). Spencer and Richard (1999) mapped young alluvium (**Qya**) (see "Geologic Map of Tonto National Monument" poster). Both these map units delineate where the Salt River, Tonto Creek, and their tributaries have flowed in the past 12,000 years or so (Phil Pearthree, Arizona Geological Survey, director and state geologist, written communication, 28 May 2020). Spencer and Richard (1999) noted that most **Qya** surfaces are modern, but vegetated bars may be several hundred years old.

For the purposes of geoarchaeology, in this case the study of the prehistoric Salado people in the Tonto Basin, Waters (1998) provided greater detail of the Holocene geomorphic record than either Anderson et al. (1987) or Spencer and Richard (1999). Geoarchaeology is a multidisciplinary approach that uses the techniques and methods of the earth sciences to examine topics that inform archeological knowledge and thought and vice versa. Waters (1998) defined and mapped three Holocene terraces (Terrace 3 to Terrace 1, oldest [highest] to youngest [lowest]) in the Tonto Basin and made correlations among the terraces based on relative elevation above the streambed, relative soil profile development, radiocarbon ages, and diagnostic artifacts.

According to the landscape reconstruction by Waters (1998), when people of the Salado culture occupied the Tonto Basin, the "constant elements" of the landscape would have been Pleistocene surfaces (i.e., pediment, terrace, and alluvial fan deposits) as well as Holocene Terrace 3 (fig. 12). Waters (1998) defined "constant elements" as features that have not changed since humans have been in the Tonto Basin (i.e., all pre–12,000-year-old landforms). These landscape elements

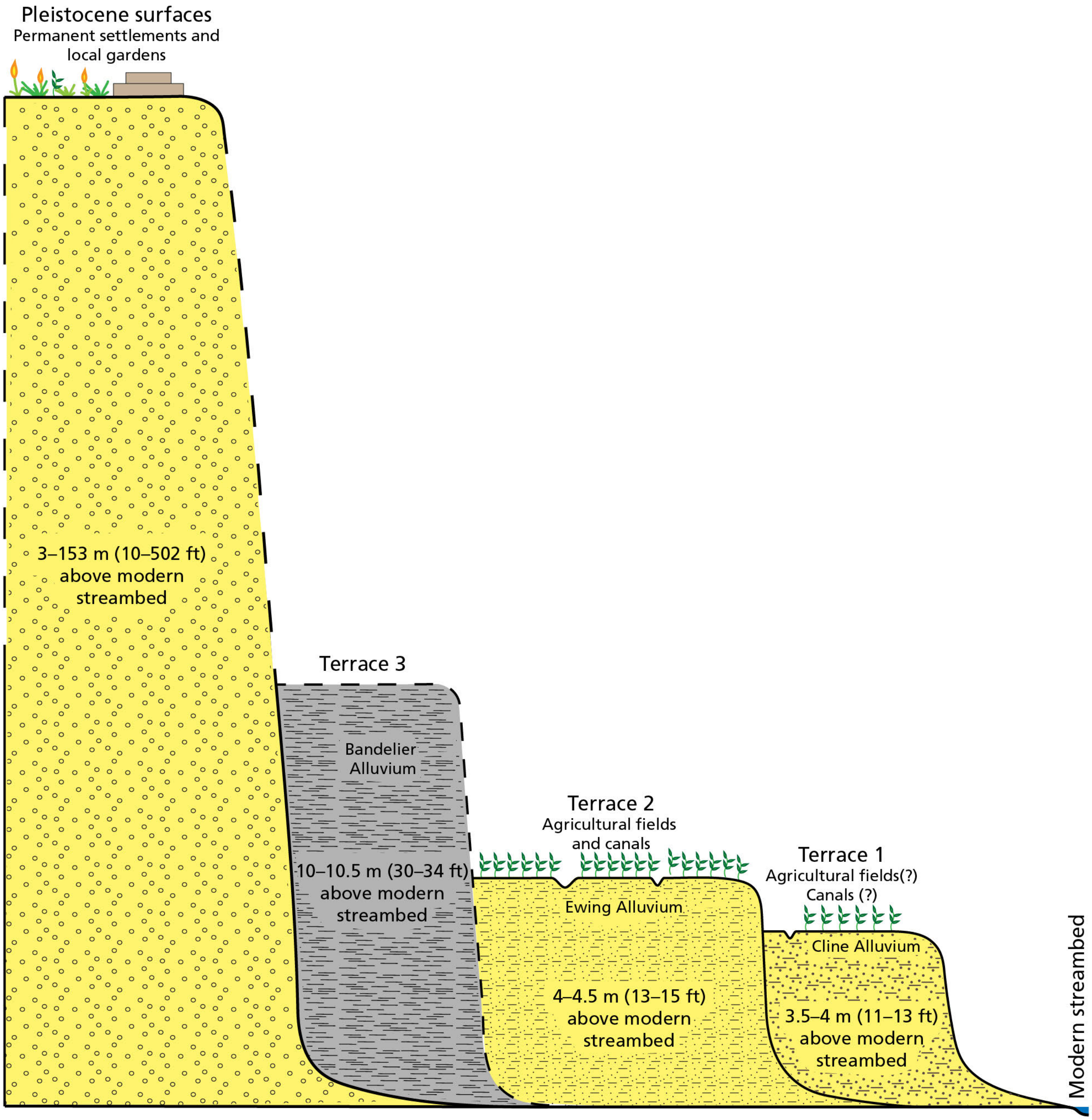


Figure 12. Generalized cross section of terraces in the Tonto Basin.
At the time of the Salado occupation of the Tonto Basin (1150 to 1450 CE), Pleistocene landforms (e.g., pediments, terraces, and alluvial fans) and Holocene Terrace 3 were the stable elements on the landscape (Waters 1998). Height above the streambed protected these surfaces and associated settlements from flooding. The surface of Holocene Terrace 2 was the most likely location for irrigation agriculture; investigators have discovered prehistoric canals there. At that time, Terrace 2 would have been only 2 m (7 ft) above the active streambed. Bringing water to this surface would have been fairly easy given the level of Salado irrigation technology. Although Terrace 3 was suitable cropland, it was too high above the prehistoric streambed for the Salado to have brought water to it. In addition, very few remnants of this surface were available for use at that time (as illustrated by the gray shading on the figure). The Pleistocene surfaces were too high for irrigation agriculture, and the soils were poor, so only local gardening took place there. Graphic by Trista Thornberry-Ehrlich (Colorado State University) after Waters (1998, figure 16).

would have been stable surfaces undergoing no deposition except for minor accumulations of alluvial (water-deposited) and colluvial (gravity-deposited) sediments (Waters 1998), and possibly loess (Anderson et al. 1987). Due to their stability and height above the floodplain, all major settlements in the Tonto Basin were located on Pleistocene surfaces and Holocene Terrace 3 (not to be confused with terrace deposits **Qt3** of Anderson et al. 1987, which is Pleistocene in age).

Springs and Groundwater Resources

Numerous small faults cut the bedrock throughout the mountains in the southwestern part of the monument and adjacent areas. These faults are interconnected and create a network of conduits for groundwater to flow from recharge areas (e.g., mountainous summit areas) to discharge areas (e.g., springs). Because groundwater flow is through this network of interconnected faults, however, reliably predicting the source area for water discharging at any particular spring or well is impossible. Nevertheless, most spring water is probably of local origin (i.e., within a few miles) rather than from a regional flow system, which might accumulate water from several tens of miles (Martin 2001).

The monument's well is associated with faults. A sketch geologic map prepared by Raup (1959) showed the [future] well's location to be at the intersection of two faults, making the site more favorable for test drilling. The monument's well was drilled in 1963 (discussed below).

As indicated by the geologic log of the monument's well, the geologic strata underlying the monument contain three water-bearing beds. The first is at the base of stream alluvium, 9–11 m (30–35 ft) below ground surface. The second is at the base of conglomerate, 20–21 m (65–70 ft) below ground surface. The third is in brecciated (fractured into angular clasts) quartzite, 21–24 m (70–80 ft) below ground surface. The driller's log indicates that the main water-bearing zones in the well are from the first and second water-bearing beds. The relative contribution of water from the two main water-bearing zones is unknown (Martin 2001).

The surface water in Theodore Roosevelt Lake does not have an effect on local groundwater conditions at the monument, most obviously because the monument is topographically far above the lake surface and local aquifers would not be directly connected to the lake (Phil Pearthree, Arizona Geological Survey, director and state geologist, written communication, 28 May 2020). In addition, the low permeability of the basin-fill sediments (Martin 2001) and the lack of faults in the "basin-fill portion" (northeastern part) of the monument (Spencer and Richard 1999; see "Geologic Map of Tonto National Monument" poster) restrains infiltration of lake water.

Two springs are associated with the cliff dwellings at the monument (see fig. 5). Both springs probably provided water for the people who occupied the Upper and Lower Cliff Dwellings (Duane Hubbard, Tonto National Monument, superintendent, written communication, 12 June 2020). Referred to as Cholla Spring #1 by Martin (2001) and "Cave Canyon Spring" or "Cave Spring" by Baril et al. (2019), one of the springs is located at the base of the hill below the Upper Cliff Dwelling. This spring allows for diverse riparian vegetation, which in turn provides habitat for nesting birds and other wildlife. It also provides breeding pools for amphibians and drinking water for mammals (Albrecht et al. 2007). A second spring, Cholla Spring #2, was located immediately downstream of the confluence of Cave and Cholla Canyons. Cholla Spring #2 ceased to flow during a regional drought in the early 1960s.

Water emerging from Cholla Spring #1 flows down Cave Canyon for a short distance before infiltrating into the alluvium. The length of the streambed containing flowing water is a function of the infiltration rate of the sediments in the streambed and the discharge rate of the spring (Martin 2001). In addition, evapotranspiration is a significant factor in the length of the wetted channel. Evapotranspiration has both a seasonal and a diurnal impact, causing the terminus of flowing water to retreat upstream as temperature increases throughout the day (Kara L. Raymond, NPS Southern Arizona Office, hydrologist, written communication, 5 May 2020).

In 2016–2019, before the Woodbury Fire, flowing water in the Cave Canyon channel covered between 70 m (230 ft) and 95 m (312 ft) of the streambed (Kara L. Raymond, NPS Southern Arizona Office, hydrologist, written communication, 5 May 2020). Albrecht et al. (2005) measured lengths of 51 m (167 ft) to 70 m (230 ft) over a two-year period (2001–2003). In 2003, deposition of alluvium in the channel caused surface water to nearly cease completely (Albrecht et al. 2005). A scouring event in 2004, allowed surface water to flow again (Kara L. Raymond, NPS Southern Arizona Office, hydrologist, written communication, 5 May 2020). For at least 10 years before the 2019 Woodbury Fire, the channel was entrenched 0.9–1.2 m (3–4 ft), and surface flow was continuous. After the 2019 Woodbury Fire and subsequent flooding, the channel was almost entirely filled with alluvium, and flow is now intermittent (Kara L. Raymond, NPS Southern Arizona Office, hydrologist, written communication, 5 May 2020).

In about 1942, the National Park Service developed Cholla Spring #1/Cave Canyon Spring/Cave Spring by constructing collection boxes and pipelines and used the water for domestic purposes at the monument and for supplying water to a couple of stock-watering troughs. In 1975, grazing (and associated use of this water) ended at the monument. During a site visit in 1980, much of the collection and distribution system was still in place, presumably to provide watering places for wildlife. A flash flood in August 1999, however, destroyed most of the pipes and tanks associated with this collection and distribution system (Martin 2001).

In 1963, the National Park Service drilled a well at the site of Cholla Spring #2. This well became the source of domestic water for the monument. The spring has not flowed since drilling. Pumping of groundwater at the well location probably prevents the spring from reemerging, even if wetter hydrologic conditions might otherwise allow it. In addition, backfilling and leveling associated with construction of the road and well site might prevent the spring from ever reoccurring in this area, even if groundwater pumping ceased. Furthermore, local downcutting of the stream near the well may have effectively lowered the base level for groundwater discharge, which could also prevent the spring from reemerging in this area (Martin 2001).

Geothermal Resources

Various investigators (Witcher et al. 1982; Stone and Witcher 1983; Love et al. 2014) have reported on geothermal resources near the monument. Such resources would be associated with springs. Witcher et al. (1982) provided a map of geothermal resources of Arizona; that map shows Roosevelt Hot Springs located at Theodore Roosevelt Dam. Moreover, Stone and Witcher (1983) mentioned Roosevelt Hot Springs. Love et al. (2014), however, did not sample Roosevelt Hot Springs because they could not find it.

Water from wells in Tonto National Forest—at Roosevelt Marina and Tonto Basin Ranger Station—have high concentrations of sodium, chloride, and trace elements, which are indicative of thermal groundwater from a deep source. The temperature of water from the marina's well is about 49°C (120°F). The water from the ranger station's well was reported as being "hot." In contrast, the temperature of water from the monument's well is about 16°C (60°F). Such water commonly comes from shallow limestone or calcic sandstone aquifers that readily intercept surface precipitation. The well at the monument produces calcium carbonate water with high hardness. The marked differences in water chemistry between the monument's well and the wells in Tonto National Forest indicate that the waters come from different geologic environments (Martin 2001).

Lithic Resources

Slaughter et al. (1992) identified and summarized source areas of lithic raw materials (e.g., basalt, rhyolite, granite, chert, dacite, obsidian [fig. 13], argillite, chalcedony, and quartzite) in Arizona. Source areas in the transition zone include the Mogollon Rim, Tonto Basin, Hardscrabble Mesa, the Verde Valley, the Prescott area, Picketpost Mountain, Cow Creek, Burro Creek, and Peridot Mesa (fig. 14).

Figure 13. Photographs of lithic resources. In the upper photograph, a bird sits on a metate made of Early Proterozoic granitic rock, which is a specimen of the oldest rock unit in the monument. In the lower photograph, obsidian comprises the spearhead, arrowheads, and scraper. Obsidian is volcanic glass most commonly found in lava flows or domes of rhyolitic composition. High-quality obsidian is usually jet black and free of bubbles, crystals, and imperfections (Goff 2009). Obsidian does not naturally occur within the monument, but source areas include Picketpost Mountain, Cow Creek, and Burro Creek (see fig. 14). NPS photographs available at https://www.flickr.com/photos/tontonps/ (accessed 12 June 2019). Upper photograph by an unknown photographer. Lower photograph by M. Steward (Tonto National Monument).

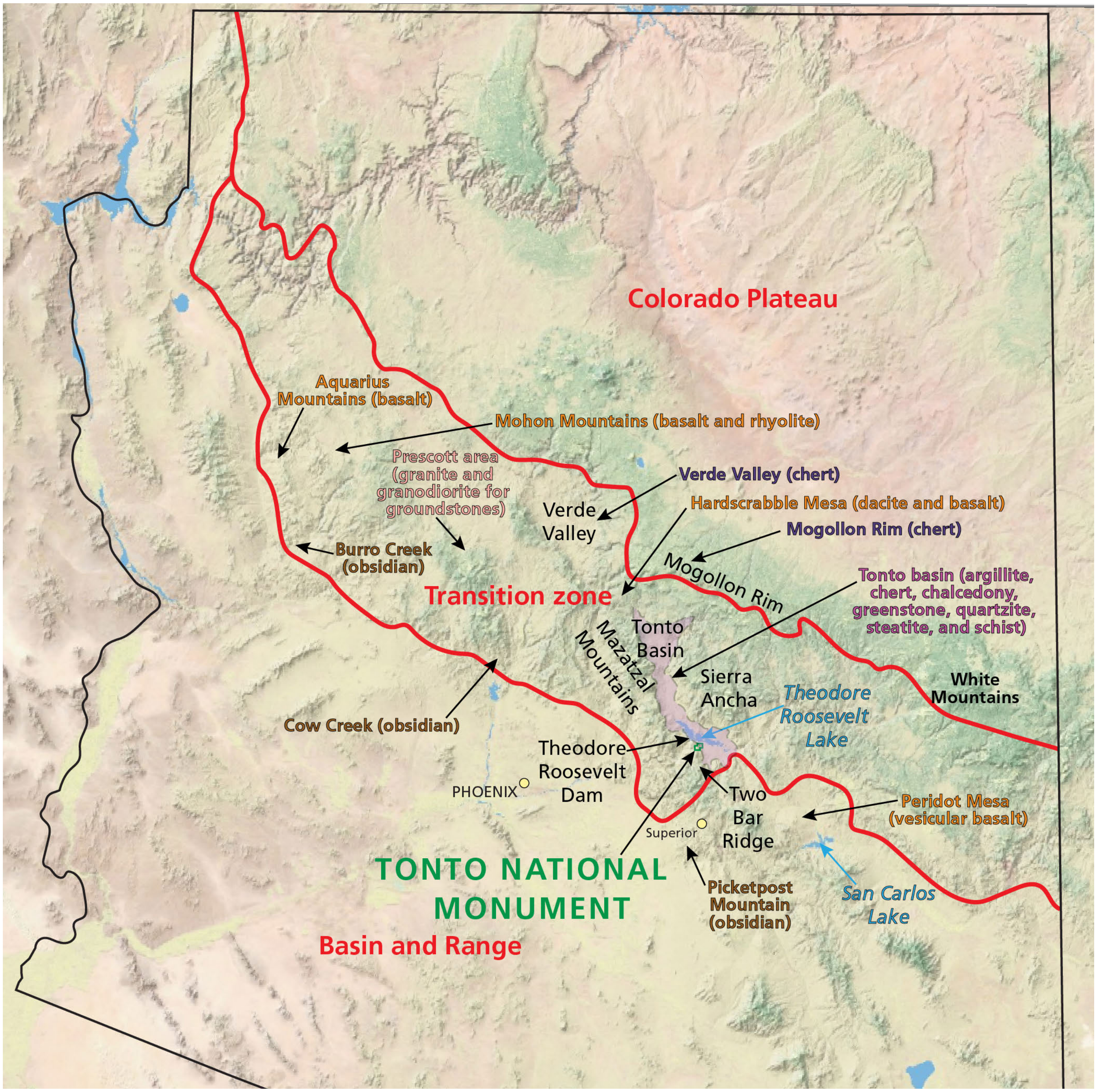


Figure 14. Map of lithic resources in Arizona's transition zone.
Tonto National Monument is in a transition zone between the Colorado Plateau and Basin and Range physiographic provinces. The Mogollon Rim defines the northern boundary of the transition zone. Source areas of lithic raw materials identified by Slaughter et al. (1992) include the Mogollon Rim where outcrops of the Paleozoic Redwall Limestone and Supai Formation yield chert. Exposures of the Redwall Limestone (Mr) also occur in the Tonto Basin, yielding chert there as well. Other source areas in the vicinity of the monument include Hardscrabble Mesa for dacite. Another source area, the Verde Valley, is known for chert, which the Verde Formation yields (see GRI report about Tuzigoot National Monument by KellerLynn 2019b). Exposures in the Prescott area yield granitic ground stone. Source areas for obsidian (volcanic glass) include Picketpost Mountain, Cow Creek, and Burro Creek. Peridot Mesa (north of San Carlos Lake) is a source area for vesicular (containing small, nearly spherical holes formed by gas bubbles) basalt. Graphic by Trista Thornberry-Ehrlich (Colorado State University) using information from Slaughter et al. (1992), Trapp and Reynolds (1995), and Vance (2014). Base map by Tom Patterson (National Park Service).

Prehistoric people manufactured two main types of tools—flaked stone and ground stone—from these raw materials. Simply stated, sharp tools such as knives, arrowheads, and scraping utensils are types of flaked stone, whereas blunt tools such as ax heads, hoe heads, anvils (e.g., used in paddle-and-anvil pottery making), manos (hand tool for grinding), and metates (trough slab for grinding) are types of ground stone (see fig. 13). The spearhead (flaked stone) on display in the visitor center is made of “Strawberry dacite” from Hardscrabble Mesa. Pleistocene surfaces (i.e., pediments, alluvial fans, and terraces) and Holocene floodplain deposits supplied pebbles, cobbles, and boulders of mixed lithology for use as ground stone (table 3).

Chert is a particularly notable lithic resource. It is an extremely hard sedimentary rock with conchoidal (smoothly curved, referring to a conch shell) fracturing, consisting mostly of interlocking crystals of quartz. Chert is an excellent flint-knapping material and was the source of stone knives, arrowheads, drills, and other sharp implements. Both the Mescal Limestone (**Ymd** and **Ym**) and Dripping Spring Quartzite, lower unit (**Ydsl**) yield chert (table 3). The Dripping Spring Quartzite, lower unit (**Ydsl**) also yields jasper (red chert). The Martin Formation, Beckers Butte Member (**Dmb**) yields black chert (Spencer and Richard 1999); Spencer et al. (1999) mapped the Beckers Butte Member (**Dmb**) north and west of the monument (see “Geologic Map of Tonto National Monument” poster). Moreover, the Redwall Limestone (**Mr**) exposed on Windy Hill (north of the monument) is known for chert (Mike Conway, Arizona Geological Survey, geologist, personal communication during GRI conference call, 3 April 2019) as is the Mescal Limestone, argillite (**Yma**).

At the monument, lithic assemblages range by culture (Duane C. Hubbard, Tonto National Monument, superintendent, written communication, 12 June 2020). For example, sites that date primarily to the Middle Archaic period (5,500–3,500 years ago) contain a wide range of lithic material from nonlocal sources. The most common artifacts found at these sites are by far flaked stone, with materials consisting of a range of chert, jasper, chalcedony, quartzite, metamorphosed sediment, petrified wood, obsidian, dacite, and basalt. Of all the raw materials used to make stone tools at these sites, however, archaeologists were able to determine the source for only two. The first is Windy Hill, located approximately 3 km (2 mi) from the site and the source of an opaque, white to gray chert with oolitic inclusions (concentrically layered spheres that form in warm, supersaturated, shallow, highly agitated, marine intertidal environments), microfossils, and occasional red or brown dendritic (branching) inclusions. The Windy Hill chert is local to the monument but at least some of the dacite and basalt artifacts found at the Middle Archaic site appear to have originated on Hardscrabble Mesa (see fig. 14), near Strawberry, Arizona, some 90 km (60 mi) away (Huckell et al. 2010).

The Salado-period inhabitants had a different assemblage of lithics as highlighted during the 1995 excavations at the Upper Cliff Dwelling (Fox 1996). Investigators identified nine raw-material types—basalt, rhyolite, quartz, quartzite, chert, chalcedony, silicified limestone, limestone, and unidentified igneous/metamorphic rock—from local sources (Duane C. Hubbard, Tonto National Monument, superintendent, written communication, 12 June 2020).

Another type of artifact found at the monument is ceramics. The ceramics from the Tonto Basin, including the distinctive Salado polychrome (distinguished by white, black, and red paint), were made from clays weathered from granite (e.g., **Xg3** and **Xga3**), diabase (**Yd**), a combination of granite and diabase, or volcanic rocks (e.g., **Ymb**). Moreover, the three major groups of temper (added to clay to prevent shrinkage and cracking) of Tonto Basin were composed of granite, granite/diabase, and diabase (Simon 1996).

Table 3. Lithic resources in the rocks and deposits at the monument.

Geologic Map Unit (Symbol)	Lithic Resources
Young alluvium (**Qya**)	Pebbles of mixed lithology potentially used for making tools
Floodplain deposits (**Qa**)	Boulders and cobbles of mixed lithology used as building stone and for making tools
Talus and colluvium (**Qtc**)	Boulders composed of local cap-rock or cliff-face lithology. Locally includes deposits with boulders >1 m (3 ft) in diameter. Potentially used as building stone or for making tools.
Older alluvium (**Qoal**)	Chert
Surficial deposits (**Qs**)	Boulders and cobbles of mixed lithology potentially used as building stone or for making tools
Alluvial fan deposits (**Qf**)	Cobbles and pebbles of mixed lithology used as building stone or for making tools
Conglomerate, Apache Group clasts (**QTsa**)	Chert
Older conglomerate (**Toc**)	Chert
Redwall Limestone (**Mr**)	Chert
Martin Formation, Beckers Butte Member (**Dmb**)	Chert
Diabase (**Yd**)	Slabs used for grinding tools. Weathered clays used in Salado polychrome pottery. Source of temper.
Mescal Limestone, argillite (**Yma**)	Chert
Mescal Limestone, basalt (**Ymb**)	Salado artifacts at the monument suggest a preference for vesicular (characterized by abundant vesicles [holes] formed as a result of the expansion of gases during the fluid stage of the lava) basalt rather than denser, fine-grained basalt (Raup 1959). Locally, in the Windy Hill quadrangle, the Mescal Limestone, basalt (**Ymb**) contains vesicular basalt (Spencer et al. 1999). Weathered clays used in Salado polychrome pottery. Source of temper.
Mescal Limestone, dolomite (**Ymd**)	Chert fragments and nodules; chert fragments are common in float (isolated, displaced fragments of a rock, especially on a hillside below an outcropping ledge or vein). Potentially used for making tools. Spalled dolomite in alcoves used as building stone.
Dripping Spring Quartzite, upper unit (**Ydsu**)	Vitreous (having the luster and appearance of glass) quartzite marker bed, 0.5 m (20 in) thick, forms prominent float; potentially used for making tools. Spalled quartzite in alcoves used as building stone.
Dripping Spring Quartzite, middle unit (**Ydsm**)	Vitreous quartzite bed. Scattered quartzite beds form subtle to prominent ledges. Potentially used for making tools.
Dripping Spring Quartzite, lower unit (**Ydsl**)	Chert used for making tools. Quartzite cobbles and pebbles used as building stone.
Dripping Spring Quartzite, Barnes Conglomerate (**Ydslb**)	Chert
Dripping Spring Quartzite, undivided (**Yds**)	Weathered clays used in Salado polychrome pottery; see also **Ydsu**, **Ydsm**, and **Ydsl**.
Pioneer Formation, undivided (**Yp**)	Siltstone of the Pioneer Formation (**Yp**), which tends to break into thin plates, was useful as blanks for weapons and tools (Raup 1959).
Granitic rocks of Cottonwood Creek, aplite and aplitic granite (**Xga3**)	Float (displaced fragments of a rock) below an outcropping ledge or vein of this unit contains resistant aplitic (light-colored, fine-grained, intrusive igneous rock emplaced at relatively shallow depths beneath Earth’s surface) material for use in making tools.
Granitic rocks of Cottonwood Creek, granodiorite (**Xg3**)	Yields ground stone. Weathered clays used in Salado polychrome pottery. Source of temper.

Geologic Resource Management Issues

Some geologic features, processes, or human activities may require management for human safety, protection of infrastructure, and preservation of natural and cultural resources. The NPS Geologic Resources Division provides technical and policy assistance for these issues.

During the 2006 scoping meeting, for which a scoping summary (National Park Service 2006) was prepared, and the 2019 conference call, participants (listed in Appendix A) identified the following geologic resource management issues, which are ordered with respect to management priority:

- Fire and Slope Movements
- Flash Floods
- Aircraft-Induced Vibration
- Rockfall Hazard
- Seismicity
- Active Faults and Earthquakes
- Cave Resource Management
- Paleontological Resource Inventory, Monitoring, and Protection
- Climate Change

Following a brief description, each issue is highlighted in a series of bulleted lists, which makes a connection to park significance by identifying fundamental resources and values from the monument's foundation document (National Park Service 2017a). In addition, the lists connect the issue to the monument's geology by listing the associated geologic map units or geologic features. For each issue, the lists include planning, data, or research needs, as well as provides resources for management. "Additional Resources" provides other references, resources, and websites of use in addressing these geologic resource management issues.

Monitoring springs is another topic that warrants mention in this GRI report. Shallow groundwater associated with two springs is monitored by the Sonoran Desert Network and Southern Arizona Office. Before 2018, monitoring was conducted by Colleen Filippone (NPS Intermountain Region, hydrologist, Tucson, Arizona). The monument's water supply for administrative purposes is related to this issue; the longevity of the monument's well is a concern for resource managers (National Park Service 2006). A pressure transducer is located about 9 m (30 ft) downstream from where Cave Canyon Spring discharges. A second pressure transducer is in Cinda's Seep, within the Hidden Ridge riparian woodland in the northwestern part of the monument. Cinda's Seep may be an expression of a perched aquifer, and it tends to discharge water to the surface during sufficiently wet periods only (Kara L. Raymond, NPS Southern Arizona Office, hydrologist, written communication, 5 May 2020). Questions about monitoring of these springs should be directed to staff at either the Sonoran Desert Network or Southern Arizona Office.

Although not identified as a priority during the 2019 conference call, 2006 scoping participants and the scoping summary discussed aeolian (windblown) features and processes. At the time of scoping, Colleen Filippone (NPS Intermountain Region, hydrologist) was monitoring wind erosion at the monument. Monitoring revealed some wind activity in the northeastern flat area of the monument. Wind erosion probably caused pockets of soil erosion there (National Park Service 2006). At present, aeolian features or processes are not being monitoring at the monument (Duane Hubbard, Tonto National Monument, superintendent, written communication, 12 June 2020). Salek Shafiqullah (National Park Service [DOI Regions 6–8], regional hydrologist) has access to Colleen Filippone's files, which would provide past monitoring data (Kara L. Raymond, NPS Southern Arizona Office, hydrologist, written communication, 5 May 2020). If monitoring is deemed necessary in the future, monument managers may find the chapter in *Geological Monitoring* (Young and Norby 2009) about aeolian features and processes (Lancaster et al. 2009) useful.

The NPS Geologic Resources Division can assist with the issues described 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 with issues regarding cave resource management and paleontological resource inventory, monitoring, and protection. Staff from the active process and hazards emphasis area can assist with fire and slope movements, flash floods, aircraft-induced vibration, rockfall hazard, seismicity, and active faults and earthquakes. 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 described in this chapter. Monument staff can formally request assistance via https://irma.nps.gov/Star/.

Resource managers may find *Geological Monitoring* (Young and Norby 2009) useful for addressing geologic resource management issues. The manual provides guidance for monitoring vital signs (measurable parameters of the overall condition of natural resources). Each chapter of *Geological Monitoring* covers a different geologic resource and includes detailed recommendations for resource managers, suggested methods of monitoring, and case studies. Chapters of the manual are available at http://go.nps.gov/geomonitoring and highlighted, as appropriate, in the following tables.

In addition, the Arizona Geological Survey (AZGS)'s "Natural Hazards in Arizona" map viewer—http://data.azgs.az.gov/hazard-viewer/, updated at https://uagis.maps.arcgis.com/apps/webappviewer/index.html?id=98729f76e4644f1093d1c2cd6dabb584—is a handy tool for resource management. The original and updated map viewers show active faults, earthquake epicenters, flood potential, landslides, and fire risk, as well as earth fissures, though earth fissures are not a geologic resource management issue at the monument. "Additional Resources" lists other web-based information about natural hazards.

The NPS Scientists in Parks (SIP) internship program (formerly Geoscientists-in-the-Park and Mosaics in Science programs) provides an easy to use mechanism by which NPS parks, networks, regions, and programs can hire non-federal interns to undertake projects that address natural resource management issues. Participants may assist with site evaluations, resource inventorying and monitoring, impact mitigation, geologic mapping, GIS analysis, research, synthesis of scientific literature and reporting, developing informative media, and educating monument staff and visitors. Monument managers are encouraged to contact scientists_in_parks@nps.gov and refer to the program's websites at https://doimspp.sharepoint.com/sites/nps-scientistsinparks (internal NPS only site) for information about the placement of a geoscience intern in the monument.

Fire and Slope Movements

Concerns expressed during the GRI conference call on 3 April 2019 about wildfire and post-wildfire debris flows in the upper watershed were realized during the Woodbury Fire, which ignited in June 2019 in a remote area of Tonto National Forest (near the Woodbury Trailhead in the Superstition Wilderness). The entire watershed upstream of the monument (49,728 ha [122,877 ac]) and 88% (400 ha [989 ac]) of the monument were burned by the fire (Shafiqullah and Thornburg 2019). In addition, participants at the 2006 scoping meeting suggested that prescribed burning to control mesquite on surrounding national forest lands may have contributed to erosion and sedimentation downstream in the monument. Also, GRI conference call participants suggested that grazing may have accelerated erosion and caused changes in vegetation, which may influence the fire regime.

Park Significance

- Although fires and slope movements are not a fundamental resource and value, slopes and canyon bottoms (across which fire, water, and debris move) are associated with the Upper Sonoran Desert setting, which is a fundamental resource and value.

Associated Map Units or Geologic Features

- The GRI GIS data show landslide deposits (**QTls**, though not debris flows) in the upper watersheds south of the monument (fig. 15). These landslides were deposited during the Pleistocene Epoch (2.6 million–11,700 years ago) (Arizona Geological Survey 2018) but may be susceptible to future activity.
- Scoping participants identified small landslides on the opposite side of the valley from the Upper Cliff Dwelling (northeast side of Cave Canyon) (see National Park Service 2006). These landslides were not mapped at a scale of 1:24,000 (i.e., they do not occur in the GRI GIS data), and they are not debris flows.

Threats

- Debris flows are destructive and occur with little warning. They can transport large materials (in size and amount) over relatively gentle slopes and develop momentum and impact forces that can cause considerable destruction. Mitigation of debris-flow hazards can be more difficult than mitigation of flood hazards (Cannon 2001).
- Flooding and debris flows pose a high risk to the monument's groundwater well, pump house, and slopes along the entrance road (Shafiqullah and Thornburg 2019).
- Hazard trees and saguaros, loss of trail, and rockfall, as well as flooding and debris flows, pose a very high risk to the Upper and Lower Cliff Dwelling trails (Shafiqullah and Thornburg 2019). Shafiqullah et al. (2019) recommended closure of the Upper Cliff Dwelling trail, placement of hazards signs when the trail reopens, and potentially a complete reroute of the trail out of the creek. To address this recommendation, the National Park Service rerouted the trail out of the creek, except in locations where the trail crosses the creek. The work was completed in early 2020 (Kara L. Raymond, NPS Southern Arizona Office, hydrologist, written communication, 4 May 2020).

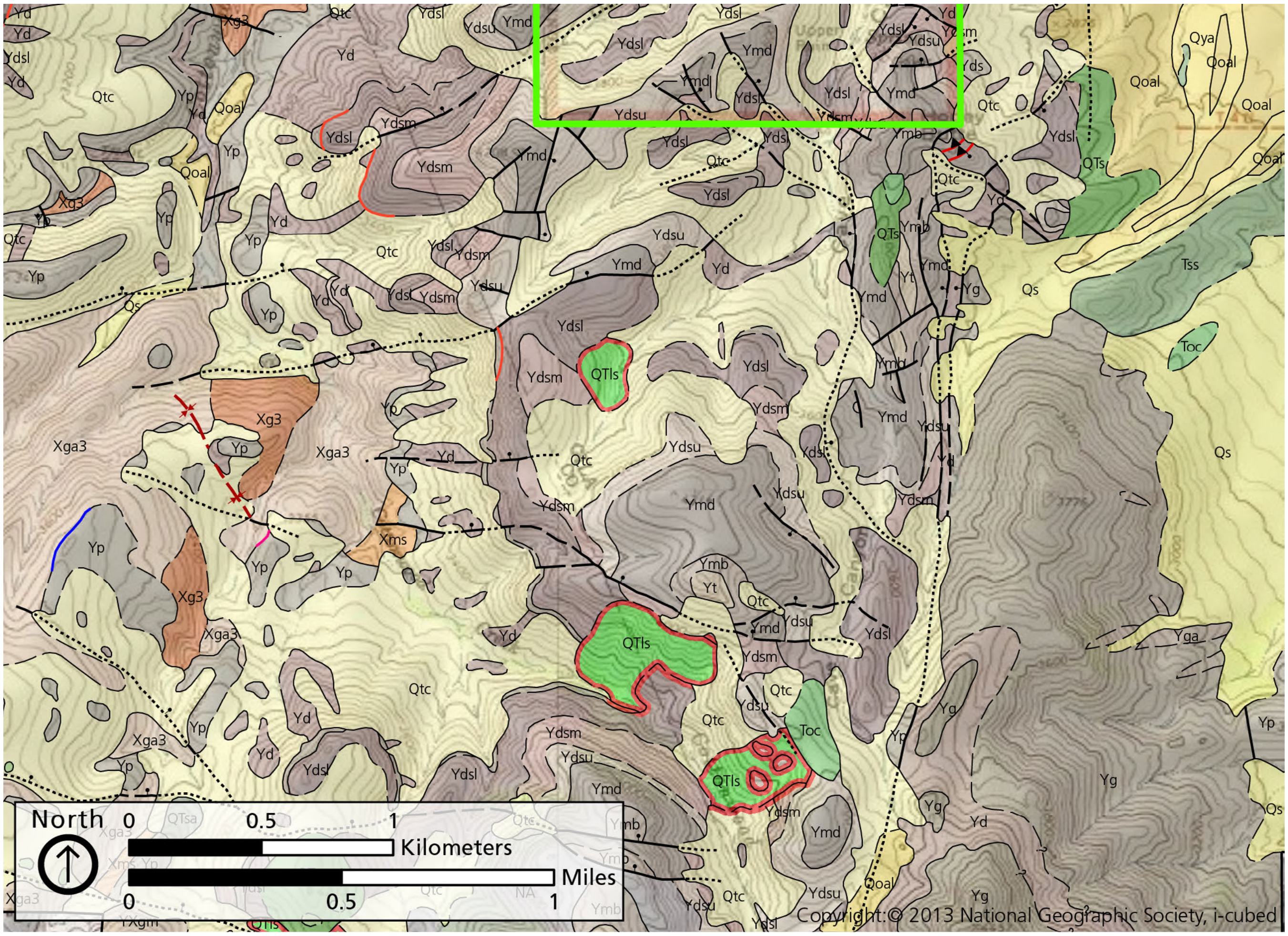


Figure 15. Screen capture of GRI GIS data showing landslide deposits.
Landslide deposits (green geologic map unit QTls, outlined in red) occur south of the monument in the upper drainages of Cottonwood Canyon and an unnamed canyon west of Cave Canyon. Note the green outline at the top of the figure, which marks the southern boundary of the monument. The landslide deposits consist of poorly consolidated to unconsolidated, very poorly sorted mud to large boulders, characterized by a hummocky surface littered with boulders. Mapping of landslide deposits by Spencer and Richard (1999). A topographic base map (USA Topo Maps, © 2013 National Geographic Society, i-cubed) underlies the data.

- Sediment erosion, as well as flooding and debris flows, pose an intermediate risk to cultural sites and a very high risk to the culvert crossing of the main entrance road (Shafiqullah and Thornburg 2019).
- The east side of the main entrance road cuts across the toe of a hill with steep slopes (fig. 16). The shoulder is narrow at this location. The entire slope was burned during the Woodbury Fire. In July 2019, investigators observed dry ravel of slope material on the road. Shafiqullah et al. (2019) recommended the placement of Jersey barriers at this location to contain rockfall debris, shield motor vehicles, and protect the roadway and buried utilities, as well as possible seeding/mulching to stabilize the slope.
- Many cultural sites located away from the cliff areas burned during the Woodbury Fire. Ash washing off these sites could lead to erosion such as rill formation. Shafiqullah et al. (2019) suggested covering surfaces with “barriers,” including spreading straw or matting and/or native seeding, to help dissipate rain drop energy and local rill formation. Shafiqullah et al. (2019) also recommended rapid site condition assessments by archaeologists followed by localized erosion potential assessments.

Figure 16. Photograph of burned slope.
Located between the picnic area and the culvert crossing, the main entrance road into the monument passes the toe of a hill with steep slopes. The slope was burned during the Woodbury Fire in June 2019 and is prone to slope movement, such as rockfall. Notably, the shoulder is narrow, so debris (e.g., dry ravel following the Woodbury Fire) commonly ends up on the road. BAER investigators recommended placing Jersey barriers at this location. NPS photograph from Shafiqullah et al. (2019, p. 4).

- Rotational grazing takes place on the Tonto National Forest. According to the rotation schedule, parts of the Cave Canyon watershed are grazed six months out of every 18 months, though the Woodbury Fire may have affected this schedule. This type of management partially mitigates the impacts of grazing, but historic grazing management, both inside and outside the monument boundary, is likely still having impacts on the watershed, in terms of vegetation change and soil compaction (Kara L. Raymond, NPS Southern Arizona Office, hydrologist, written communication, 4 May 2020).

Planning, Data, and Research Needs

- Monument managers need a better understanding of the impacts of grazing and prescribed burns on monument resources. As suggested in the monument's foundation document (National Park Service 2017a), collecting GIS fire data from land surrounding the monument will help with this need.
- Shafiqullah et al. (2019) recommended assessment of erosion potential and resource impacts to inform burn area recovery plans following initial emergency stabilization efforts. As of 18 February 2020, conditions were as follows: With respect to slope hazards, no evidence of mass wasting or dry ravel before the monsoon season. After the monsoon season, still no mass wasting. Conditions appear stable. With respect to flooding, elevated flow potential was perceived before the monsoon season. After the monsoon season, although significant precipitation did occur, slope related flow or damage was not observed. With respect to vegetation, post–monsoon vegetation growth was robust and the hill slopes appear to be recovering (Salek Shafiqullah, National Park Service [DOI Regions 6–8], regional hydrologist, email communication to Rebecca Port, National Park Service, Geologic Resources Division, GRI report coordinator, 18 February 2020).

- The monument's foundation document (National Park Service 2017a) noted wildfire as potentially causing damage to the cliff dwellings, but no study has specifically addressed this (Baril et al. 2019).
- Monument managers are very interested in a study of the efficacy of biological soil crust–restoration methods for stabilizing the ground following fire, flooding, and other disturbances (Kara L. Raymond, NPS Southern Arizona Office, hydrologist, written communication, 4 May 2020).
- A research question is whether the retaining walls along the trail to the Lower Cliff Dwelling are exacerbating slope movements.

Resources For Management

- Monument managers are encouraged to contact the NPS Geologic Resources Division with questions and concerns about resource management and park planning with respect to slope movements.
- The chapter about monitoring slope movements by Wieczorek and Snyder (2009) in *Geological Monitoring* (Young and Norby 2009) is applicable for this resource management issue.
- Managers at Bandelier National Monument may be able to provide guidance. Fires have had a tremendous effect on the landscape at Bandelier; it is the driving component in an interconnected system of streamflow, sediment transport, stream channel morphology, and slope movements (see GRI report about Bandelier National Monument by KellerLynn 2015a).
- Work by the Arizona Geological Survey (Youberg 2008, 2012, 2015; Youberg et al. 2011; Loverich et al. 2017) may be applicable.
- Work by the US Geological Survey on forecasting debris flows before fires (e.g., Staley et al. 2018) may be useful.
- The US Forest Service burned area emergency response (BAER) team produced a burned severity map for the area impacted by the Woodbury Fire (see Tonto National Forest 2019) and conducted pre- and post-fire hydrological modeling. The map and model for Cave Canyon will aid in addressing down-gradient, post-wildfire issues within the monument (Shafiqullah et al. 2019). The estimate of the likelihood of post-fire debris flows in the monument is as much as 20% (US Geological Survey 2020).

Flash Floods

The monument contains three steep-gradient, ephemeral riparian systems: Cave Canyon, Deadman Canyon, and Cholla Canyon. Heavy precipitation events have the potential to cause flash floods in these drainages. Flash floods in Cave Canyon are a concern for visitor safety and an issue for resource management because the wash is not a stable stream channel and slopes can fail during flooding events. As predicted by Shafiqullah et al. (2019), elevated flood flows with associated debris followed the Woodbury Fire, which started in June 2019. In September 2019, a 200-year storm event deposited 10.3 cm (4.05 in) of rain in 12 hours. The storm was associated with Hurricane Lorena. The flood moved boulders protecting the main water tank, damaged bank-stabilizing gabions along the Upper Cliff Dwelling trail, and caused substantial erosion in the creek channel (Kara L. Raymond, NPS Southern Arizona Office, hydrologist, written communication, 4 May 2020). In addition, the flood destroyed half of the Upper Cliff Dwelling trail, costing nearly $90,000 to repair in 2019 and 2020 (Duane Hubbard, Tonto National Monument, superintendent, written communication, 12 June 2020).

Park Significance

- Although flash floods are not a fundamental resource and value, slopes and canyon bottoms are associated with the Upper Sonoran Desert setting, which is a fundamental resource and value. Slopes and canyon bottoms are areas of concern during flash floods.

Associated Map Units or Geologic Features

- Active channel and floodplain deposits (**Qs**, **Qya**, and **Qa**)
- Floods on Tonto Creek and the Salt River typically occur from December to April but are most common in March when both winter rainfall and melting snow combine (Waters 1998).

Threats

- Flash floods are a concern for infrastructure, primarily in Cave Canyon (National Park Service 2006). Flooding could impact the monument's well and associated storage tanks and water-distribution system. Water is pumped from the well to a 50,000-gallon underground storage tank next to the well house. Water from this storage tank supplies the restrooms in the picnic area, facilities at the maintenance shop, and four residences in the employee housing area. A booster pump pumps water from the 50,000-gallon tank to a 25,000-gallon tank above the visitor center. Water from the 25,000-gallon tank supplies the visitor center and administrative offices (Martin 2001).
- Soil crusts stabilize banks along the Cave Canyon drainage; flash floods could damage these features (National Park Service 2006).
- Heavy precipitation events could cause erosion and damage to sites next to drainages. As an example of

heavy precipitation, in 2016, approximately 23 cm (9 in) of rain fell in a single event, creating significant drainage issues (National Park Service 2017a).

- The Woodbury Fire elevated the risk of flash flooding for Cave Canyon creek

Planning, Data, and Research Needs

- Study the relationship, influences, and consequences of wildfire (see "Fire and Slope Movements") on flash floods.
- Shafiqullah et al. (2019) recommended developing a flash flood evacuation plan and monitoring weather radar for storm-cells in the watershed. Current weather and emergency notifications can be found at the following websites: https://www.weather.gov/psr/ and https://www.spc.noaa.gov/ products/wwa/.
- Develop a visitor and staff safety plan for a flash flood event at the monument.
- Identify the most-likely slopes to fail during a flash flood event and determine necessary mitigation measure.
- The Procedural Manual 77-2: Floodplain Management states that day use facilities, such as foot trails, in areas subject to flash flooding "must contain signs informing visitors of flood risk and suggested actions in the event of flooding" (National Park Service 2002, p. 11). This is most applicable to the Upper Cliff Dwelling trail, which crosses Cave Canyon Creek several times. Currently visitors are only allowed on that trail when accompanied by NPS staff, so signage may not be needed, but it would be prudent to put a sign on the gate at the trailhead, identifying the area as a flash flood area (Kara L. Raymond, NPS Southern Arizona Office, hydrologist, written communication, 4 May 2020). Tonto National Forest issued a "special note" with its incident report of the Woodbury Fire; the wording may be useful for signage: "Everyone near and downstream from the burned areas should remain alert and stay updated on weather conditions that may result in heavy rains over the burn scars. Flash floods may occur quickly during heavy rain events" (see "Fire and Slope Movements").

Resources for Management

- Monument managers are encouraged to contact the NPS Geologic Resources Division with questions and concerns about resource management and park planning with respect to flash floods.
- The chapter about fluvial geomorphology (i.e., monitoring stream systems in response to a changing environment) by Lord et al. (2009) in *Geological Monitoring* (Young and Norby 2009) is applicable for this resource management issue.
- In 2006 (i.e., at the time of scoping), the Intermountain Region (i.e., Colleen Filippone, hydrologist) was monitoring stream channel morphology at the monument. Ongoing, active monitoring is no longer taking place, but the Sonoran Desert Network did some test channel-morphology surveys in 2005–2008. The NPS Southern Arizona Office has also done recent project-related channel morphology work (Kara L. Raymond, NPS Southern Arizona Office, hydrologist, written communication, 4 May 2020).

Aircraft-Induced Vibration

A specific concern related to seismicity (see "Seismicity") is that vibration caused by military overflights or hovering helicopters could damage the cliff dwellings. A vibration investigation of these impacts at the monument (King and King 1998b) recommended that no aircraft should pass within 60 m (200 ft) of the cliff dwellings. However, the National Park Service has no authority over the monument's airspace, which is solely the domain of the Federal Aviation Administration (FAA) up to an altitude of 15,000 m (50,000 ft). For aircraft other than helicopters, FAA regulations (14 CFR 19.119) require minimum altitudes of 150 m (500 ft) above the surface. FAA Advisory Circular 91-36D (Federal Aviation Administration 2004) encourages pilots who are operating noise-producing aircraft to avoid noise-sensitive areas or make every effort to fly not less than 610 m (2,000 ft) above ground level (AGL), defined as the highest terrain within 2,000 feet AGL laterally of the route of flight or the uppermost rim of a canyon or valley. This advisory, however, is voluntary and has not been enforced (Baril et al. 2019).

Park Significance

- The cliff dwellings are a fundamental resource and value, as well a fragile, one-of-a-kind archeological structures (King and King 1998b). Aircraft-induced vibration may damage these structures.

Associated Map Units or Geologic Features

- The Mescal Limestone, dolomite (**Ymd**), houses and composes the Lower Cliff Dwelling; King and King (1998b) described this bedrock as "slightly friable" and sensitive to 3 to 14 Hz ranges in vibration.
- The Dripping Spring Quartzite, upper unit (**Ydsu**), houses and composes the Upper Cliff Dwelling; King and King (1998b) described this bedrock as "slightly friable" and sensitive to 3 to 14 Hz ranges in vibration.
- Cliff dwellings are composed of bedrock (**Ymd** and **Ydsu**) and adobe.

Threats

- Helicopter flyovers and low-flying aircraft can increase noise levels and noise induced-vibration, potentially leading to cliff face degradation, damage to ruins, and impacts to visitor experience (National Park Service 2017a).
- Unauthorized helicopters frequently hover above the cliff dwellings, sometimes as low as 30 m (100 ft) off the ground (National Park Service, unpublished document, 2005, cited in Baril et al. 2019, p. 58). Whether and how these unauthorized flights have affected the cliff dwellings is unknown.
- The National Park Service has no legislative authority to prohibit overflights, but monument managers discourage helicopter hovering near the cliff dwellings (National Park Service 2006). In cases where monument staff members have been able to identify tail numbers, they send letters to owners of the aircraft requesting consideration of cultural resources and visitor experience (Baril et al. 2019).

Planning, Data, and Research Needs

- Besides direct impacts caused by unmanned aerial vehicles (UAVs or drones), identifying which types of aircraft and the circumstances under which these aircraft can damage the cliff dwellings is needed.
- Quantifying the acoustic environment of the monument may help with understanding and mitigating the impacts of overflights. An acoustical inventory and monitoring are beyond the scope of the GRI program, and monument managers are directed to the NPS Natural Sounds & Night Skies Division for assistance (see https://www.nps.gov/orgs/1050/index.htm).

Resources For Management

- A vibration investigation for the monument (King and King 1998b) provided a discussion, summary, and recommendations for management.
- The NPS and FAA work together to implement the National Parks Air Tour Management Act, which requires the FAA, in cooperation with NPS, to develop an air tour management plan for each park or tribal land where air tour operations occur or are proposed. Information in this act, as well as committee notes, may be useful for developing a plan for the monument.
- The NPS annually reports on commercial air tour operations over units of the National Park Service (e.g., see Lignell 2019). The NPS reported no commercial air tours over the monument from 2013 to 2018; however, monument staff observes dozens of overflights each year, presumably by private citizens or government aircraft. The NPS Overflights Program, which is now part of the Natural Sounds & Night Skies Division, works with the FAA (see https://www.nps.gov/subjects/sound/overflights.htm).

Rockfall Hazard

Rockfall is ongoing at the monument. Slope movements, such as rockfall, 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. According to Rutenbeck (1985, p. 4), “The caves and ruins [at the monument] are safer than they appear, but are not completely without hazards.” For example, instant failures or movements are possible during seismic events (see “Seismicity”) or periods of high rainfall.

Park Significance

- Although rockfall is not a fundamental resource and value, slopes are associated with the Upper Sonoran Desert setting, which is a fundamental resource and value.
- Steep slopes are commonly the site of archeological resources, including structures that served a defensive purpose against intruders. Thus, slopes are associated with Tonto National Monument Archeological District, which is fundamental resource and value.

Associated Map Units or Geologic Features

- Talus and colluvium (**Qtc**) are evidence of ongoing rockfall.
- Sources of rockfall material include the Pioneer Formation (**Yd**), Dripping Spring Quartzite (**Yds**, **Ydsl**, **Ydsm**, and **Ydsu**), and Mescal Limestone (**Ymd**).

Threats

- Rockfall, especially after storms, is a hazard for both resources and visitors (National Park Service 2017a).
- Rockfall occurs within the alcoves and along the trails to both the Lower and Upper Cliff Dwellings.
- The area below the overhanging cave roof at the Lower Cliff Dwelling is an area of particular concern.
- "Site 44" in the southeastern part of the monument has rockfall (GRI conference call, 3 April 2019).
- Rockfall can damage infrastructure. In early May 2020, for example, rockfall impacted the monument’s water tank; the main boulder in the rockfall did not hit the tank, but smaller rocks did. This was not related to a storm event (Kara L. Raymond, NPS Southern Arizona Office, hydrologist, written communication, 5 May 2020).

Planning, Data, and Research Needs

- Past trip reports and studies (see "Resources for management" below) suggested regular monitoring and mitigation of rockfall hazard within the caves.
- 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 (fig. 17).
- Recommendations from past investigations may help with planning and visitor safety. For example, Rutenbeck (1980) made the following recommendations: (1) defining and minimizing the risk such as monitoring movement, (2) wearing hard hats in the dwellings, (3) diverting water, (4) removing loose rock fragments, and (5) minimizing the time people spend in the most hazardous areas. Cloues (2002) suggested informing visitors via appropriate signage or brochure language, for example, "The cliffs and alcoves are formed by the natural process of erosion, rock spalling, and present a risk of falling rock. Stay alert!"

Figure 17. Photograph of trail to the Upper Cliff Dwelling.
Rockfall is a hazard along the trail to the Upper Cliff Dwelling (shown in this photograph) as well as along the trail and under the overhanging cave roof at the Lower Cliff Dwelling. Boulders below the trail to the Upper Cliff Dwelling (circled in red) attest to past events (i.e., failures from the cliff face above the trail). Earthquakes or periods of high rainfall may induce rockfall. NPS photograph by M. Mora (Tonto National Monument) available at https://www.flickr.com/photos/tontonps/ (accessed 12 June 2019).

Resources For Management

- In 1978, heavy rainfall and water damage to the Upper Cliff Dwelling caused concern about the potential for rockfall within the cave. Since that time, various reports and memorandums, namely by Rutenbeck (1978, 1980, 1985, 1993), have addressed rockfall hazard at the monument. Todd Rutenbeck was a structural engineer with the NPS Western Archeological Center in Tucson, Arizona, and later with the US Bureau of Reclamation.
- Wachter (1978) provided a geologic analysis of the types of "rock motion hazards" at the Lower and Upper Ruins and associated trails.

- Cloues (2002) addressed a technical assistance request to analyze and interpret rock movements at the monument.
- Highland and Bobrowsky (2008), which is a guide to understanding landslides and other slope movements, is applicable for resource management at the monument; the handbook was produced by the US Geological Survey.
- The chapter about monitoring slope movements by Wieczorek and Snyder (2009) in *Geological Monitoring* (Young and Norby 2009) is applicable.
- Resource managers could consider obtaining quantitative information to assess the frequency and magnitude of rockfall (and other slope movements) in high visitation areas. A low-cost option suggested by Cloues (2002) is raking the sandy floors of rooms of cliff dwellings that are not entered and monitor for newly fallen rock to obtain some hard data on the frequency of small rockfalls.
- Monument mangers are encouraged to submit a technical assistance request to the Geologic Processes and Hazards (Coasts, Rivers, and Hillslopes) program area administered by the NPS Geologic Resources Division (GRD).
- Photomonitoring is a possibility for monitoring the frequency of rockfall. The GRD Photogrammetry website (http://go.nps.gov/grd_photogrammetry) provides examples of how photographic techniques support structural analysis of rockfall areas. Photogrammetry may be an alternative to lidar rescanning of cliff dwellings (last done 2007–2009) to analyze structural or surface degradation, as listed in the monument foundation document (National Park Service 2017a, p. 21). GRD staff can assist with photogrammetry projects.
- American Southwest Virtual Museum has 3D models of the Upper and Lower Cliff Dwellings and specific features (e.g., cistern in the Upper Cliff Dwellings) at http://swvirtualmuseum.nau.edu/wp/index.php/national-parks/tonto-nm/3d-cliff-dwelling-models-tonto-national-monument/.

Seismicity

Seismicity—the phenomenon of earth movements—includes all vibrations, both induced by natural processes and by human activities (see "Threats" below). The primary concern regarding seismicity at the monument is that vibration could damage archeological structures (see "Aircraft-Induced Vibration"). Seismicity also may induce rockfall (see "Rockfall Hazard").

Park Significance

- The cliff dwellings are a fundamental resource and value. Seismicity has the potential to damage these structures.

Associated Map Units or Geologic Features

- Seismic events could produce talus and colluvium (**Qtc**).
- Seismic events could cause shaking within bedrock and rock failures on cliff faces composed of Pioneer Formation (**Yd**), Dripping Spring Quartzite (**Yds**, **Ydsl**, **Ydsm**, and **Ydsu**), and Mescal Limestone (**Ymd**).

Threats

- Earthquakes (movement along a fault) (see "Active Faults and Earthquakes") causes seismicity.
- Slope failures such as rockfalls, landslides, and debris flows (see "Rockfall Hazard" and "Fire and Slope Movements") cause seismicity.
- Anthropogenic activities such as blasting, drilling, road building, and vehicular traffic cause seismicity.
- Low-flying aircraft and hovering helicopters cause seismicity (see "Aircraft-Induced Vibration").

Planning, Data, and Research Needs

- Conduct a study of seismic risk of the caves and cliff dwellings.
- Conduct a vibration impact study of the cliff dwellings.

Resources For Management

- The US Geological Survey and independent contractors have studied seismic risk of archeological structures in the National Park System. Particularly notable is work by K. W. King, who conducted vibration studies in more than 20 parks over a 20-year period (1985–2005), including a vibration investigation in the monument (King and King 1998b). The NPS Natural Sounds & Night Skies Division retains copies of these reports.
- The following completed GRI reports have discussions about seismicity and cited work by King and others: Casa Grande Ruins National Monument (KellerLynn 2018a; King and King 1998a), Chaco Culture National Historical Park (KellerLynn 2015b; King et al. 1985, 1991; King and King 2001), El Morro National Monument (KellerLynn 2012; King and King 2003); and Salinas Pueblo Missions National Monument (KellerLynn 2018b; referred to investigations at Chaco Culture National Historical Park).
- Stanley (2014) is an annotated bibliography of vibroacoustic studies in the National Park System.

Monument mangers may contact either the GRI team or the NPS Natural Sounds & Night Skies Coordinator, Regions 6-8, for a copy of this bibliography.

- The monument has 25 years of data from a series of gauges that measured cracks in archeological structures.
- The monument's natural resource condition assessment (Baril et al. 2019) noted work by Fisher (2009), which investigated cracking in the south wall of room 4 in the Lower Cliff Dwelling. Besides visually monitoring, no management activity was required when the crack was evaluated by Preston Fisher (NPS Vanishing Treasures Program, structural engineer) on 26 January 2008, but an increase in 10 cm (4.0 in) would warrant future management action.
- Researchers at the University of Utah, Department of Geology & Geophysics (see http://geohazards.earth.utah.edu/team.html), are studying and monitoring arches, which are dynamic natural features that bend, sag, sway, and shake in response to a variety of environmental forces (see http://geohazards.earth.utah.edu/arch.html). Findings by Jeffrey Moore (assistant professor) and his colleagues, including PhD candidate Riley Finnegan, whose thesis topic is anthropogenic induced resonance of rock arches, may be applicable to the cliff dwellings for understanding its ambient vibrations and deformation. Monument managers are encouraged to contact the NPS Geologic Resources Division (https://www.nps.gov/orgs/1088/contactus.htm) for assistance in finding researchers who have expertise to conduct a vibration impact study. Monument staff can formally request assistance via https://irma.nps.gov/Star/.
- The NPS Geologic Resources Division (GRD) has equipment and software to conduct close-range photogrammetry to create 3D models (e.g., of the cliff dwellings). The GRD Photogrammetry website (http://go.nps.gov/grd_photogrammetry) provides more information and examples of a variety of photogrammetry applications for resource management, including modeling vibrations (see https://www.nps.gov/articles/active-process-monitoring-example-landscape-arch.htm). Monument managers may contact the GRD (https://www.nps.gov/orgs/1088/contactus.htm) or formally request assistance via https://irma.nps.gov/Star/.
- American Southwest Virtual Museum has 3D models of the Upper and Lower Cliff Dwellings and specific features (e.g., cistern in the Upper Cliff Dwellings) at http://swvirtualmuseum.nau.edu/wp/index.php/national-parks/tonto-nm/3d-cliff-dwelling-models-tonto-national-monument/. These may be useful for monitoring changes to the walls and facades of the cliff dwellings.

Active Faults and Earthquakes

According to Arizona Geological Survey (2018), neither the fault in the monument mapped by Anderson et al. (1987) nor those mapped by Spencer and Richard (1999) is active (i.e., having moved during the Quaternary Period, the last 2.6 million years). The closest active fault to the monument is the Sugarloaf fault zone, which moved less than 130,000 years ago (fig. 18). Localized small-scale seismicity is the likely means by which this portion of Arizona's transition zone releases stress associated with continental crustal deformation. Twenty-six earthquakes recorded near Theodore Roosevelt Lake ranged from magnitude 0.1 to 3.1 between 11 December 1979 and 26 September 2010 (Lockridge et al. 2012).

Park Significance

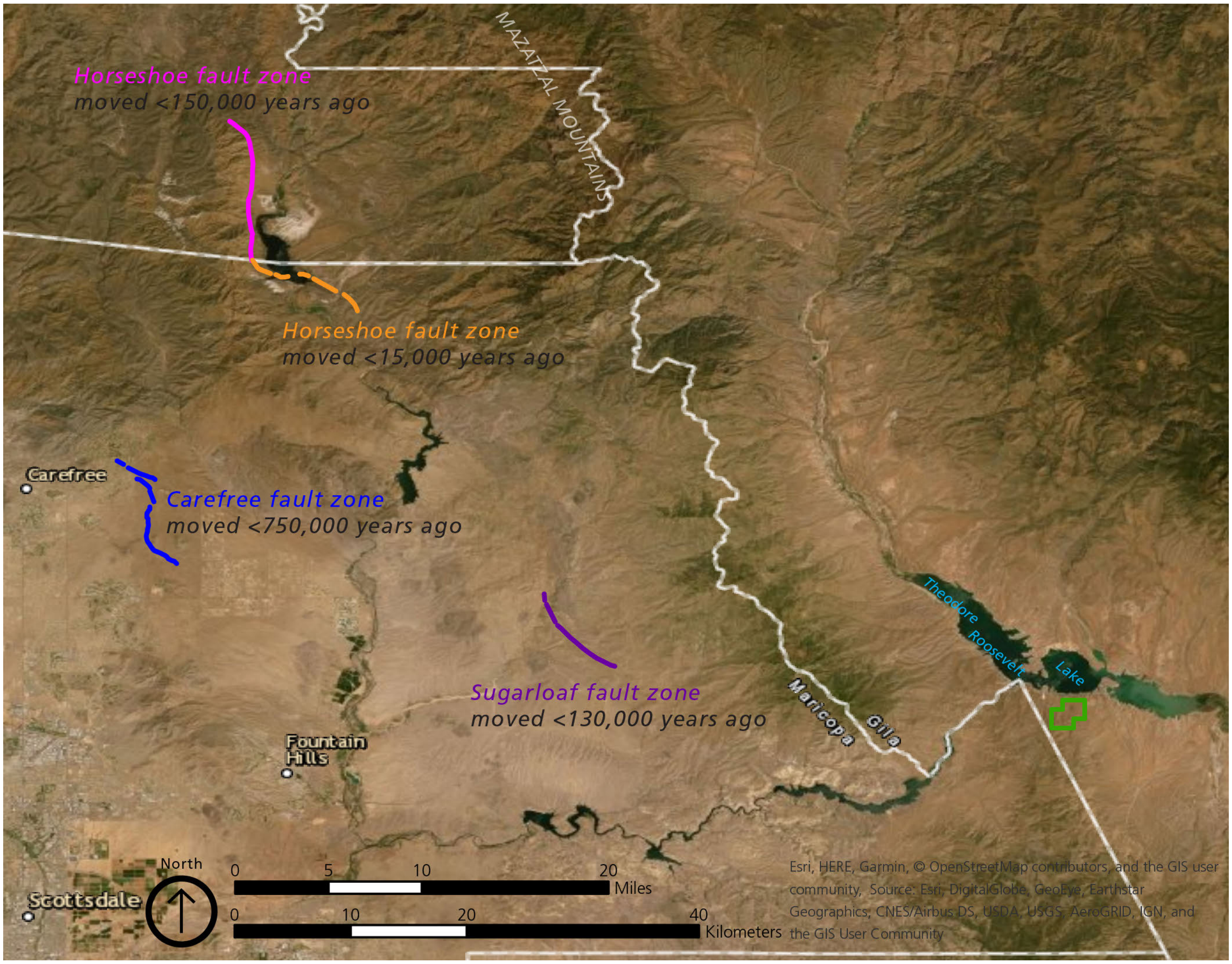
- Earthquakes produced by movement along faults may affect the cliff dwellings, which is a fundamental resource and value.

Associated Map Units or Geologic Features

- Spencer and Richard (1999) mapped more than 20 segments of high-angle faults in the mountainous portion of the monument. These faults cut Middle Proterozoic bedrock. Talus and colluvium conceal many of these faults.
- Anderson et al. (1987) mapped a fault that crosses the monument, cutting basin fill and alluvial fan deposits. This fault, which Lockridge et al. (2012) referred to as the "Two Bar North fault," appears to bound the Tonto Basin. Approximately 600 m (2,000 ft) of vertical movement has occurred along the Two Bar North fault in the vicinity of the monument, bringing Tertiary (Neogene [Miocene and Pliocene]) basin fill adjacent to Middle Proterozoic bedrock (Martin 2001).
- Faults (polylines in the GRI GIS data) represents areas of past movement and may be susceptible to future movement.

Threats

- Earthquakes evoke a minimal threat because the monument is in an area of low seismic hazard potential (National Park Service 2006). Moreover, low levels of historic seismicity, few Quaternary ("active") faults, and the predominance of landscapes indicative of tectonic stability are evidence of a low seismic threat (Anderson et al. 1987).



Esri, HERE, Garmin, © OpenStreetMap contributors, and the GIS user community, Source: Esri, DigitalGlobe, GeoEye, Earthstar Geographics, CNES/Airbus DS, USDA, USGS, AeroGRID, IGN, and the GIS User Community

Figure 18. Annotated imagery of Quaternary faults near Tonto National Monument.
The closest active fault to the monument (outlined in green) is the Sugarloaf fault zone to the west, which moved less than 130,000 years ago. The youngest fault is the southern segment of the Horseshoe fault zone (orange line, northwest of the monument); this fault moved less than 15,000 years ago. The northern segment of the Horseshoe fault zone (pink line) moved less than 130,000 years ago. The Carefree fault zone is between (and farther west) of the previously mentioned faults; movement along that fault zone took place less than 750,000 years ago. Graphic by Rebecca Port (NPS Geologic Resources Division) using data compiled from AZGS hazard map viewer (https://uagis.maps.arcgis.com/apps/webappviewer/index.html?id=98729f76e4644f1093d1c2cd6dabb584; accessed 30 May 2019).

- Lockridge et al. (2012) observed no clear temporal correlations between water levels in Theodore Roosevelt Lake and seismic activity.
- The Arizona Geological Survey assessed the evidence for Quaternary faulting in the transition zone, including the monument area, in the mid-1980s and found no evidence of Quaternary activity (Pearthree and Scarborough 1985).

Planning, Data, and Research Needs

- A research question is whether the maximum credible earthquake on the Sugarloaf fault zone (magnitude 6.75; Anderson et al. 1987) could produce shaking that would damage the cliff dwellings.
- Raup (1959, p. 8) observed that some of the faults in the monument must have had as much as 60 m (200 ft) of movement along them as indicated, for example, by the difference in elevation of similar rocks at the Upper and Lower Cliff Dwellings. Now that the Upper and Lower Cliff Dwellings are known to be in different rock units, this analysis deserves reconsideration.

Resources For Management

- Earthquake monitoring in the state of Arizona occurs at seismograph stations throughout the state (fig. 19). Most of these stations are maintained by two seismograph networks: Northern Arizona Seismograph Network (NASN) and 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 do research on earthquakes occurring in the state (Arizona Earthquake Information Center 2010).
- The chapter about earthquakes and seismic activity by Braile (2009) in *Geological Monitoring* (Young and Norby 2009) described 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 and ground shaking at the monument.

Cave Resource Management

The Federal Cave Resources Protection Act of 1988 requires the identification of “significant caves” in NPS areas; the regulations stipulate that all caves on NPS properties are “significant.” In addition, the act requires that caves be considered in any land management planning 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 Freedom of Information Act (FOIA) request. 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.

Park Significance

- Caves (referred to as “alcoves” and “shelter caves”) house the Upper and Lower Cliff Dwellings, which are a fundamental resource and value.

Associated Map Units or Geologic Features

- A cave in the Mescal Limestone, dolomite (**Ymd**), houses the Lower Cliff Dwelling.
- A cave in the Dripping Spring Quartzite, upper unit (**Ydsu**), houses the Upper Cliff Dwelling.
- Talus caves in talus deposits (**Qtc**) probably host archeological resources.

Threats

- Falling rocks (flakes from spalling in alcoves and larger pieces from cliff faces) are a safety hazard for visitors and staff and may damage cliff dwellings. Rockfall events are frequently associated with wet periods.
- Significant precipitation events can result in groundwater entering the caves through bedrock fractures. This water has the potential to damage the cliff dwellings.
- The Upper and Lower Cliff Dwellings serve as bat habitat, which does not seem to be adversely affecting the cliff dwellings; however, birds and rodents appear to be accelerating erosion (Rutenbeck 1993).
- Beehives occur in the caves near the cliff dwellings. The hives are a concern for visitor safely, not archeological preservation.
- Vandalism, including unintentional damage by visitors, and some animal activities cause degradation of archeological resources in caves.

Planning, Data, and Research Needs

- The monument needs a cave management plan. Such plans are park specific and include a comprehensive evaluation of current and potential visitor use and activities, as well as a plan to study known and discover new caves.
- A thorough inventory of the cave resources at the monument, including alcoves and talus caves, is the first step in a cave management plan.
- Future study of the timing and rates of downcutting by streams in Arizona’s transition zone could help refine the timing of cave formation at the monument. Such studies have taken place in the Colorado Plateau, namely in conjunction with the lower Colorado River and the evolution of the Grand Canyon and its caves (e.g., Damen et al. 1978; Fenton et al. 2001; Hill et al. 2004).
- The discovery and analysis of packrat (*Neotoma* spp.) middens or other cave fossil could put a minimum date on cave formation. Packrat middens can go back to at least the limits of radiocarbon dating. If a cave contained the remains of an animal that went extinct in the Pliocene or early to middle Pleistocene Epochs, for example, the cave must be at least that old (Justin Tweet, NPS Geologic Resources Division, paleontologist, written communication, 1 May 2020) (see “Paleontological Resource Inventory, Monitoring, and Protection”).

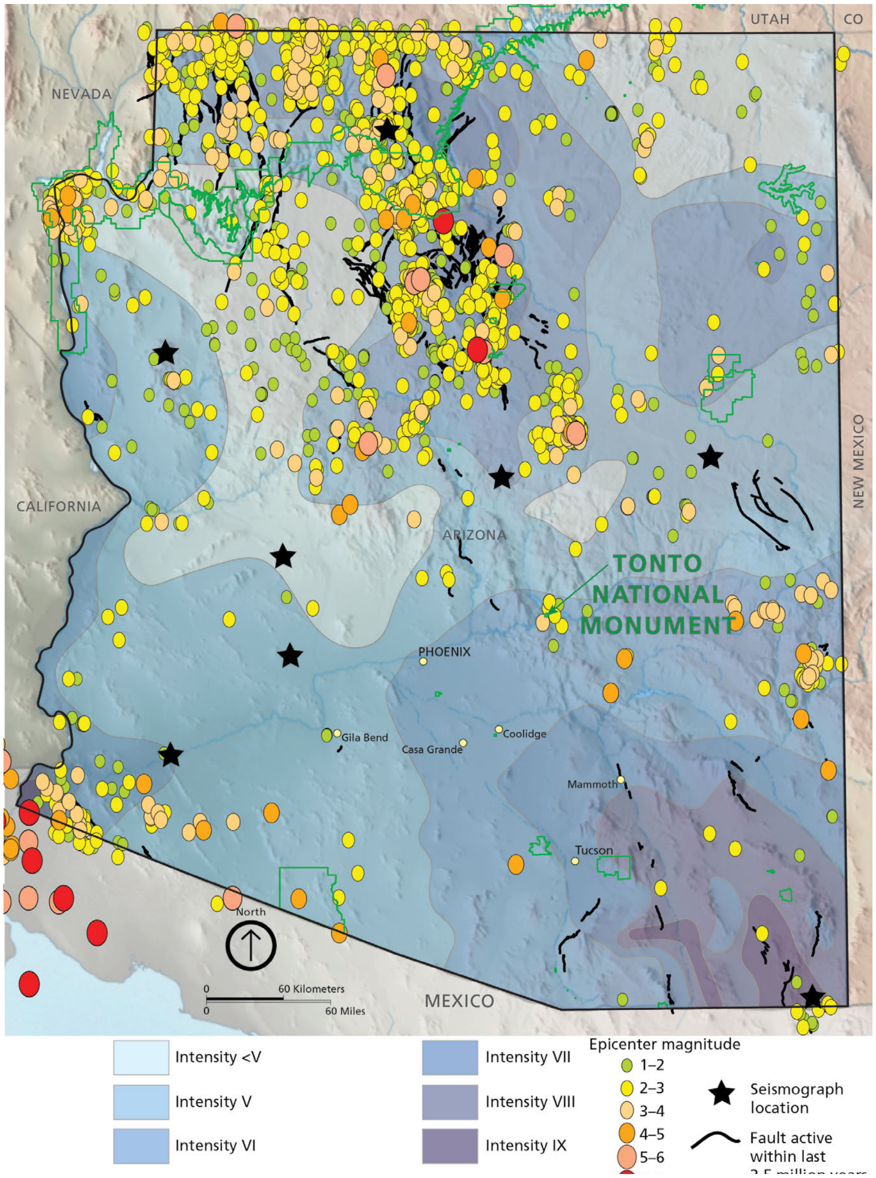


Figure 19. Map of active faults, earthquakes, and seismograph stations in Arizona.
Each year seismograph stations (black stars) record hundreds of felt and unfelt earthquakes in Arizona. The map is an illustration of seismic activity from 1887 to 2015. Earthquakes generally occur within a swath from the north–northwestern part of the state to the southeastern part of the state. Within this zone, which includes Tonto National Monument (note green arrow), several magnitude 5 to 6 earthquakes have occurred since 1900. The Yuma area (southwestern corner of the state) also has earthquakes. In addition to seismograph stations (black stars) and active faults (black lines), the figure delineates Modified Mercalli Scale intensities (zones of blue and purple colors representing intensities of less than V to IX) from 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 (i.e., 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. Graphic by Trista Thornberry-Ehrlich (Colorado State University) using AZGS graphics and data available at http://azgs.arizona.edu/center-natural-hazards/earthquakes and Arizona Earthquake Information Center graphic available at https://www.cefns.nau.edu/Orgs/aeic/ground_shaking.html (accessed 30 June 2020). Base map by Tom Patterson (National Park Service).

- A research question is whether the retaining walls constructed since 1950 are altering natural drainage and causing damage to archeological structures within the caves. During scoping in 2006, participants thought that an upcoming study using ground penetrating radar might help to answer this question. However, the final report (Holmlund 2011) did not address this issue.

Resources For Management

- The "Caves and Cliff Dwellings" section of this GRI report provides information useful for management.
- Many resources are available for cave management, including NPS policies and directives (see Appendix B), inventory and monitoring reports, and the work at other parks to create cave management plans and management documents. Monument managers are encouraged to contact the NPS Geologic Resources Division and/or the National Cave and Karst Institute (NCKRI) for assistance, including the development of a cave management plan. The NPS Cave and Karst Program coordinator, who is located at NCKRI in Carlsbad, New Mexico, provides technical assistance.
- The chapter about geological monitoring of caves and associated landscapes by Toomey (2009) in Geological Monitoring (Young and Norby 2009) is applicable for cave resource management.
- Holmlund (2011, figure 1) provided a detailed topographic and planimetric map of the Lower Cliff Dwelling cave, which showed the location of calcium-carbonate speleothems. That map may be useful as a base for an inventory of cave resources in that cave.

Paleontological Resource Inventory, Monitoring, and Protection

Paleontological resources (fossils) are any evidence of life preserved in a geologic context (Santucci et al. 2009). They may be body fossils (any remains of the actual organism such as bones, teeth, shells, or leaves) or trace fossils (evidence of an organism's activity such as nests, burrows, tracks, or coprolites [fossil dung]). All fossils are nonrenewable. Fossils in NPS areas occur in rocks or unconsolidated deposits, museum collections, and cultural contexts such as building stones or archeological resources. Fossils are rare at the monument because the bedrock is so old; that is, these rocks were deposited before plants and animals had evolved to the extent of having hard parts that could be preserved as fossils (Raup 1959). However, some of the Middle Proterozoic rocks, caves within these rocks, and Tertiary (Neogene [Miocene and Pliocene]) basin fill within the monument have yielded or have the potential to yield fossils.

Park Significance

- The monument's museum collection is a fundamental resources and value. The collection contains well-preserved artifacts associated with the Salado cliff dwellings and other archeological sites in the monument. Fossils are commonly part of museum collections; examples include bone used for making awls, needles, gaming pieces, or beads; and shells used for making jewelry (bracelets and pendants) (fig. 20) or scraping utensils.

Figure 20. Photograph of shell beads. Beads composed of shell illustrate how archeological artifacts may also be paleontological resources. The beads shown in the photograph were created in 2016 during "Heritage Days" at the monument. NPS photograph by M. Mora (Tonto National Monument) available at https://www.flickr.com/photos/tontonps/ (accessed 12 June 2019).

Associated Map Units or Geologic Features

- Mescal Limestone, dolomite (**Ymd**) contains structural features ("stromatolites") attributed to the growth of microbial colonies during deposition (Spencer and Richard 1999).

- Dripping Spring Quartzite, upper unit (**Ydsu**) potentially contains acritarchs (single-celled microfossil).
- Basin fill (**Toc**, **Tss**, and **QTsa** of Spencer and Richard 1999, and **Tbf** of Anderson et al. 1987) contains vertebrate, invertebrate, and plant fossils.
- Caves may contain packrat (*Neotoma* spp.) middens, which resemble piles or mounds of plant material with a dark glossy coating of crystallized packrat urine. Fossil middens can provide important paleoecological information.
- The Western Archeological Conservation Center (WACC) maintains four specimens from the monument that have both paleontological and cultural significance: (1) TONT 2567 is a scraper with an impression of a ribbed bivalve or brachiopod (latter more likely) and an impression of a cylindrical segmented fossil, potentially a crinoid or a small straight-shelled nautiloid with exaggerated chambers; (2 and 3) TONT 4681 and TONT 5509 are matching halves of cylindrical fossils with radiating internal structure, possibly straight-shelled cephalopods (perhaps natural casts of nautiloids because mollusks, unlike crinoids and other echinoderms, recrystallize easily); less likely is the possibility of something else with a cylindrical structure that has been entirely replaced by calcite such as a burrow or piece of plant stem; and (4) TONT 6930 is a possible piece of petrified wood (Justin Tweet, NPS Geologic Resources Division, paleontologist, written communication, 1 May 2020).
- Vance (2014) reported petrified wood as a common artifact found at the Hidden Ridge Archaic site within the monument.

Threats

- Threats to in situ paleontological resources include erosion, geohazards, theft, and vandalism.

Planning, Data, and Research Needs

- A paleontological field inventory would more fully document in situ occurrences of fossils at the monument.
- A formal site documentation and condition assessment for known fossil localities may be warranted, followed by monitoring of significant sites at least once a year.
- A research question is whether the monument's museum collection contains any fossils, such as bones and shells, used by people of the Salado culture.
- The Mescal Limestone contains microfossils (filaments and spherules possibly from cyanobacteria [blue-green algae]) that would be of interest to researchers of ancient life on Earth and the colonization of land. Such microfossils are not yet known from the rocks in the monument, but future study could reveal them (Tweet et al. 2008).

Resources For Management

- Raup (1959) reported the Precambrian stromatolites from the Mescal Limestone.
- McConnell (1974, 1975) and Bertrand-Sarfati and Awramik (1992) documented the stromatolites of the Mescal Limestone algal member (elsewhere, outside of the monument).
- Skotnicki (2001)—a PhD thesis from Arizona State University—discussed Proterozoic microbial life preserved in the Mescal Limestone.
- Santucci et al. (2001) discussed paleontological resources associated with NPS caves.
- Kenworthy and Santucci (2006) provided an overview of NPS paleontological resources in cultural resource contexts.
- Tweet et al. (2008) completed a paleontological resource inventory, monitoring, and protection report for the Sonoran Desert Network of parks, including Tonto National Monument.
- If a packrat midden is discovered in one of the monument's caves, the NPS Geologic Resources Division can facilitate communication between the monument managers and researchers of packrat middens in the Southwest.
- The chapter about monitoring in situ paleontological resources by Santucci et al. (2009) in *Geological Monitoring* (Young and Norby 2009) described five methods and vital signs for monitoring: (1) erosion (geologic factors), (2) erosion (climatic factors), (3) catastrophic geohazards, (4) hydrology/bathymetry, and (5) human access/public use.

Climate Change

Climate change has the potential to disrupt monument resources, including geologic resources, as well as park operations, including visitor services, and visitation patterns (Fisichelli and Zeisler 2015). Although climate change planning is beyond the scope of the GRI program, climate change is included in this GRI report because of its relevance to geologic features and processes. Monument managers are directed to the NPS Climate Change Response Program to address issues related to climate change (https://www.nps.gov/orgs/ccrp/index.htm).

Park Significance

- According to the monument's foundation document (National Park Service 2017a), climate change and its associated influences (e.g., temperature change along with major precipitation events and seasonal unpredictability) are threats to the Tonto National Monument Archeological District and the cliff dwellings, which are fundamental resources and values.

Threats

Note: The following threats were compiled from NPS documents specific to the monument. Other potential climate-related threats to geologic features and processes include accelerated weathering; increased wind erosion (sand blasting) of cliff dwellings; increased deposition of windblown silt; lower visibility and safety risks related to dust storms; lower groundwater levels and less discharge to Cholla Spring #2 and the monument's well, as well as to Cholla Spring #1 (aka Cave Canyon Spring or Cave Spring, the only perennial surface water in the monument); impacts to infrastructure in Cave Canyon as a result of more intense or frequent flooding; and increased erosion rates due to increased storm frequency/intensity. Furthermore, fire frequencies could increase up to 25% by 2100 (Moritz et al. 2012). Greater frequency of slope movements could result from more wildland fire.

- The climate change resource brief for the monument (Monahan and Fisichelli 2014) found five (of seven) temperature variables as "extreme warm" (i.e., exceeding 95% of the historical range of conditions).
- A climate change summary for the monument (Gonzalez 2015) found that average annual temperature at the monument had increased at a statistically significant rate in the period 1950–2010. The highest warming was in spring (March–May).
- Increased temperature causes microcracking of archeological structures from thermal stress (Morgan et al. 2016).
- Increased temperature causes faster deterioration of newly exposed artifacts and sites (Morgan et al. 2016), as well as increased vulnerability of paleontological resources through exposure.
- Increased temperature causes increased crystallization of efflorescent salts due to increased evaporation rates, leading to increased rates of structural cracking (Morgan et al. 2016).
- Climate change will manifest itself not only as changes in average conditions but also as changes in particular climatic events (e.g., more intense storms, floods, or drought) (Monahan and Fisichelli 2014).
- Higher temperatures due to climate change have coincided with low precipitation in the southwestern United States, intensifying droughts in the region (Gonzalez et al. 2018).

Planning, Data, and Research Needs

- The monument's foundation document (National Park Service 2017a) identified collecting and analyzing climate change data as a need (see "Resources for management" below).
- A climate change vulnerability assessment, scenario planning, and adaptation strategy could be completed in cooperation with the NPS Climate Change Response Program (see https://www.nps.gov/orgs/ccrp/index.htm). Climate change planning would help monument managers develop plausible science-based scenarios that would inform strategies and adaptive management activities that would allow mitigation or adjustment to climate realities.
- A research question is what impact climate change could have on the long-term viability of the monument's well.
- Another research question is whether climate change will disrupt spring flow at Cholla Spring #1 and how this will impact the associated riparian area.

Resources For Management

- Davey et al. (2007) completed a weather and climate inventory for the Sonoran Desert Network.
- *Climate Change Impacts on Cultural Resources* (Morgan et al. 2016) provided an "impacts table" that succinctly describes how different manifestations of climate change will affect different types of cultural resources. Many of the measurable trends are geologic processes (e.g., increased wind, flooding, and freeze-thaw cycles).
- Through spatial analyses of historical and projected temperature and precipitation, Gonzalez et al. (2018) revealed a previously unreported disproportionate magnitude of climate change in US national parks, including hotter and drier historical trends and a greater fraction of the area with projected temperature increases >2°C (4°F), than the rest of the United States. National parks in the southwestern United States are most exposed to precipitation decreases.
- Until 2019, the monument had no weather station within its boundary, but 28 weather or climate stations were within 40 km (25 mi) of the monument (Davey et al. 2007). In July 2019, a COOP station ("Roosevelt 1 WNW"), which was 3 km (2 mi) northwest of the monument and had a record dating back to 1905, was moved within the monument's boundary (next to the headquarters building).

Monument staff members now are responsible for collecting data (Kara L. Raymond, NPS Southern Arizona Office, hydrologist, written communication, 4 May 2020). The RAWS station "Roosevelt," which Davey et al. (2007) documented, was within 1 km (0.6 mi) of the monument; it had a very complete data record from 1992 to 2009 (Kara L. Raymond, NPS Southern Arizona Office, hydrologist, written communication, 4 May 2020).

- The Sonoran Desert Network monitors climate at the monument by compiling and analyzing climate information from existing long-term stations. Data are interpreted in climate monitoring reports and resources briefs; climate data are referenced in most reports for other vital signs. Gwilliam et al. (2019) reported on the status of climate and water resources at the monument for water year 2018.

Geologic Map Data

A geologic map in GIS format is the principal deliverable of the GRI program. GRI GIS data produced for the monument follows the source maps listed in this chapter and includes components described in this chapter. Two posters display 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 and ages present in an area. On the geologic map for the monument, pinks and browns represent the oldest rocks whereas yellows represent the youngest deposits. In addition to color, map units and associated symbols delineate rocks on geologic maps. Usually, the map unit symbol consists of an uppercase letter indicating age (e.g., **Q** for Quaternary, **T** for Tertiary, and **X** or **Y** for Proterozoic) and lowercase letters indicating the rock formation's name or the type of deposit (see 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 and sills. Some map units, such as landslide deposits, delineate locations of past geologic hazards, which may be susceptible to future activity. Geologic maps also may show anthropogenic features, such as mines or quarries, or observation or collection locations. The American Geosciences Institute's website (http://www.americangeosciences.org/environment/publications/mapping) provides more information about geologic maps and their uses.

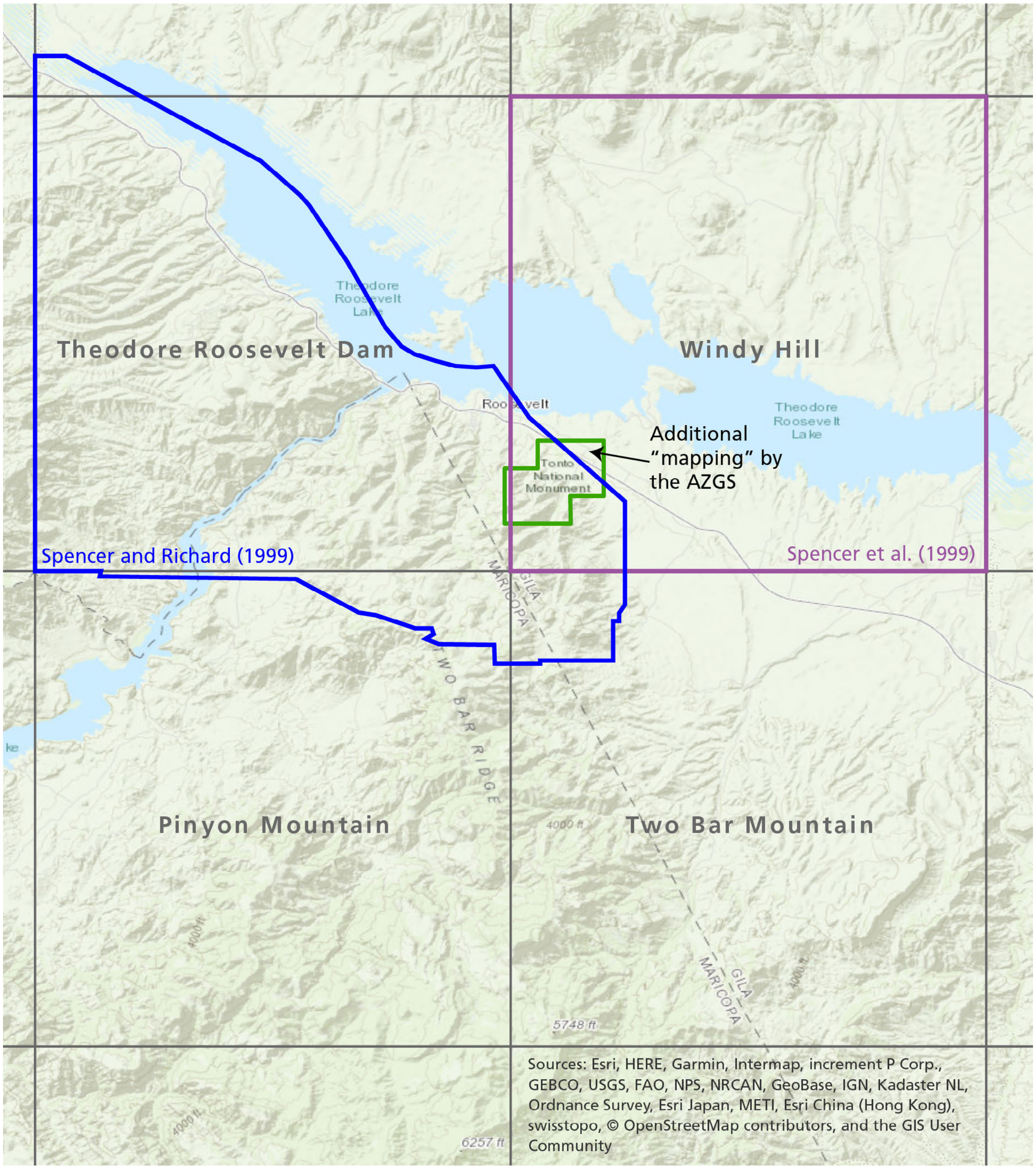
Geologic maps are generally one of two types: bedrock or surficial. Bedrock geologic maps encompass older, typically more consolidated sedimentary, metamorphic, or igneous rocks. Bedrock map units are generally differentiated based on age and rock type. Surficial geologic maps typically encompass deposits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

Source Maps

The GRI team does not conduct original geologic mapping. Scoping participants (see Appendix A) and the GRI team identify the best available geologic maps for a park unit. Determinations are made based on coverage (extent or area mapped), map scale, date of mapping, and compatibility of the mapping to the current geologic interpretation of an area. The GRI team then digitizes paper maps and/or converts exiting digital data to the GRI GIS data model. The GRI team may compile multiple source maps to cover a park boundary or provide a greater extent as needed for resource management.

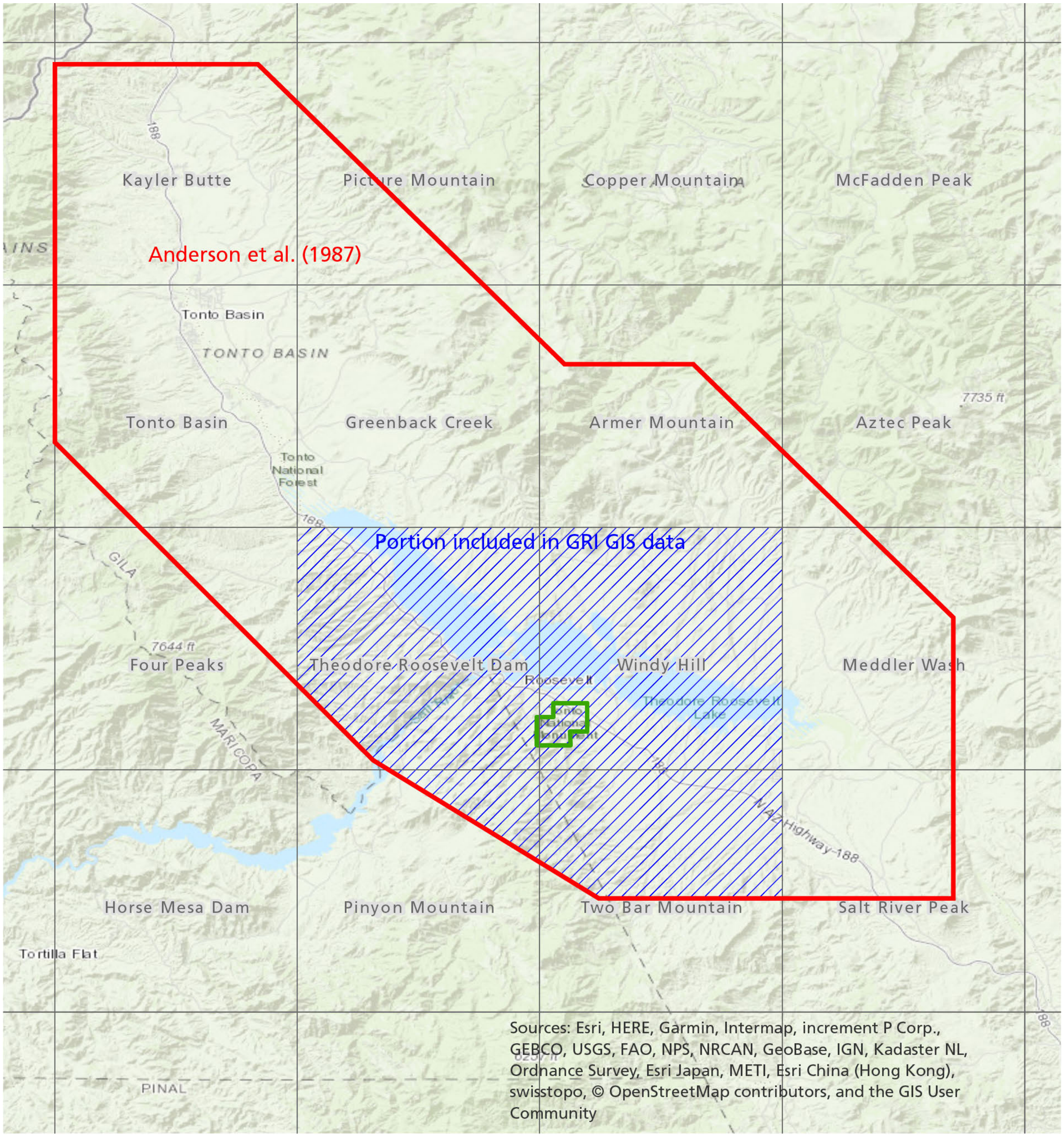
The GRI team used the following three source maps to produce the GRI GIS data for the monument. The first two are part of the "geologic" data set (tont_geology.mxd). The third composes the "surficial" data set (tsur_geology.mxd).

- Spencer and Richard (1999), Arizona Geological Survey Open-File Report OFR-99-06 (scale 1:24,000), provided geologic data that cover the southwestern portion of the monument, where Proterozoic rocks crop out in hills that are mantled by talus and colluvium. The caves and cliff dwellings are in this portion of the monument. Notably, original mapping by Spencer and Richard (1999) did not cover the triangular-shaped area of the northeastern corner of the monument (fig. 21). In order to extend geologic mapping to cover the entire monument, Stephen Spencer "filled in the blank" using original mapping and his knowledge of the area. This information was included in the GRI GIS data for the monument (Jim Chappell, Colorado State University, research associate/GIS specialist, telephone communication, 26 March 2019).
- Spencer et al. (1999), Arizona Geological Survey Open-File Report OFR-99-12 (scale 1:24,000), provided geologic data that cover the Windy Hill quadrangle (fig. 21).
- Anderson et al. (1987), US Bureau of Reclamation Seismotectonic Report 87-5 (scale 1:48,000), mapped geomorphic surfaces and surficial deposits in the Tonto Basin (fig. 22). The source map by Anderson et al. (1987) combined all bedrock into a single map unit (**br**) but provided detailed mapping of surficial units (e.g., basin fill, pediments, terraces, and alluvial fans), which record the landscape evolution of the Tonto Basin.



Sources: Esri, HERE, Garmin, Intermap, increment P Corp., GEBCO, USGS, FAO, NPS, NRCAN, GeoBase, IGN, Kadaster NL, Ordnance Survey, Esri Japan, METI, Esri China (Hong Kong), swisstopo, © OpenStreetMap contributors, and the GIS User Community

Figure 21. Index map for geologic GRI GIS data (tont_geology.mxd).
Scoping participants identified four 7.5-minute quadrangles of interest for the monument: (1) Theodore Roosevelt Dam, (2) Windy Hill, (3) Pinyon Mountain, and (4) Two Bar Mountain. These quadrangles are labeled and outlined in gray on the figure. The monument boundary is outlined in green. To compile the GRI GIS data associated with these quadrangles, the GRI team used two source maps: (1) Spencer and Richard (1999), which is a geologic map for the Theodore Roosevelt Dam area. The blue outline on the figure shows the extent of this source map. The entire map was included in the GRI GIS data. (2) Spencer et al. (1999), which is a geologic map of the Windy Hill 7.5-minute quadrangle. The violet outline on the figure shows the extent of this source map. The portion of this map that overlaps with mapping by Spencer and Richard (1999) was not included in the GRI GIS data. Assistance from the Arizona Geological Survey (AZGS) allowed the northeastern, triangular portion of the monument, which was not included in the original mapping project by Spencer and Richard (1999), to be added and included in the GRI GIS data. Graphic by Jim Chappell (Colorado State University) and Rebecca Port (NPS Geologic Resources Division).



Sources: Esri, HERE, Garmin, Intermap, increment P Corp., GEBCO, USGS, FAO, NPS, NRCAN, GeoBase, IGN, Kadaster NL, Ordnance Survey, Esri Japan, METI, Esri China (Hong Kong), swisstopo, © OpenStreetMap contributors, and the GIS User Community

Figure 22. Index map for surficial geologic GRI GIS data (tsur_geology.mxd).
The four 7.5-minute quadrangles of interest for the monument are (1) Theodore Roosevelt Dam, (2) Windy Hill, (3) Pinyon Mountain, and (4) Two Bar Mountain. To compile the surficial geologic GRI GIS data associated with these quadrangles, the GRI team used Anderson et al. (1987). The red outline on the figure shows the extent of that map, which covers a larger portion of the Tonto Basin than included in the GRI GIS data for the monument. Blue hatch lines on the figure represent the extent of Anderson et al. (1987) included in the GRI GIS data for the monument. The monument boundary is outlined in green. Graphic by Jim Chappell (Colorado State University) and Rebecca Port (NPS Geologic Resources Division).

GRI GIS Data

The GRI team standardizes map deliverables by using a data model. The GRI GIS data for the monument was compiled using data model version 2.1, which is available at http://go.nps.gov/gridatamodel. This data model dictates GIS data structure, including layer architecture, feature attribution, and relationships within ESRI ArcGIS software. The GRI Geologic Maps website (http://go.nps.gov/geomaps) provides more information about the program's map products.

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 GIS readme file (tont_gis_readme.pdf) that describes the GRI data formats, naming conventions, extraction instructions, use constraints, and contact information;
- Data in ESRI geodatabase GIS format;
- Layer files with feature symbology (see tables 4 and 5);
- Federal Geographic Data Committee (FGDC)–compliant metadata;
- An ancillary map information document (tont_geology.pdf) that contains information captured from source maps such as map unit descriptions, geologic unit correlation tables, legends, cross sections, and figures;
- ESRI map documents (tont_geology.mxd and tsur_geology.mxd) that display the GRI GIS data; and
- Versions of the data viewable in Google Earth (tont_geology.kml and tsur_geology.kml; see tables 4 and 5).

Table 4. GRI GIS data layers in tont_geology.mxd.

Data Layer	On Poster?	Google Earth Layer?
Geologic Cross Section Lines	No	No
Geologic Attitude Observation Localities	No	No
Geologic Point Features	Yes	No
Mine Point Features	No	No
Geologic Sample Localities	No	No
Map Symbology (i.e., fault down-side [bar and ball] indicator and syncline symbols)	No	No
Linear Dikes	Yes	Yes
Linear Geologic Units	Yes	Yes
Geologic Line Features	Yes	Yes
Folds	Yes	Yes
Faults	Yes	Yes
Deformation Area Boundaries	Yes	No
Deformation Areas	Yes	Yes
Geologic Contacts	Yes	Yes
Geologic Units (including unit labels)	Yes	Yes

Table 5. GRI GIS data layers in tsur_geology.mxd.

Data Layer	On Poster?	Google Earth Layer?
Geologic Observation Localities (i.e., type section locality)	Yes	Yes
Faults	Yes	Yes
Geologic Contacts	Yes	Yes
Geologic Units (including unit labels)	Yes	Yes

GRI Map Posters

Two posters accompany the hard copies of this report, which the GRI team gives to monument managers and reviewers of this report. "Geologic Map of Tonto National Monument" shows the bedrock geologic data (tont_geology.mxd). "Surficial Geologic Map of Tonto National Monument" shows the surficial geologic data (tsur_geology.mxd). These posters are available for download through the IRMA portal (https://irma.nps.gov/App/Portal/Home); enter "GRI" as the search text and select a park from the unit list. Both posters have GRI GIS data draped over a shaded relief image of the monument and surrounding area. Not all GIS feature classes (see tables 4 and 5) are included on the posters. Geographic information and selected park features have been added to the posters. Digital elevation data and added geographic information are not included in the GRI GIS data but are available online from a variety of sources. Monument managers may contact the GRI team for assistance locating these data.

Use Constraints

Graphic and written information provided in this report is not a substitute for site-specific investigations. Ground-disturbing activities should neither be permitted nor denied based on the information provided in this GRI report. Monument managers are encouraged to contact the GRI team with any questions.

Minor inaccuracies may exist regarding the locations of geologic features relative to other geologic or geographic features in the GRI GIS data and on the posters. Based on the scales of the source maps and US National Map Accuracy Standards, geologic features in the GRI GIS data and posters are expected to be horizontally within 12 m (40 ft) on the geologic map data (scale 1:24,000) or 24 m (80 ft) on the surficial geologic map data (scale 1:48,000) of their true locations.

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These references are cited in this report, including "Additional Resources." Contact the Geologic Resources Division for assistance in obtaining them.

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Additional Resources

These references, resources, and websites may be of use to resource managers. Refer to Appendix B for laws, regulations, and policies that apply to NPS geologic resources.

Arizona Mine Information

- Arizona Geological Survey (AZGS) "Mining in Arizona" website: https://azgs.arizona.edu/minerals/mining-arizona
- Arizona major mines map (compiled in 2015) shows three mines in Gila County—(1) Carlota (copper), (2) Pinto Valley (copper and molybdenum), and (3) Miami (copper): https://azgs.arizona.edu/minerals/mining-arizona
- AZGS mine data (files for approximately 21,000 mines, thousands of maps, and more than 6,000 historic photographs): http://minedata.azgs.arizona.edu/
- Directory of active mines in Arizona (Niemuth et al. 2007) shows three mines in Gila County—(1) Chapman Pit (sand and gravel), (2) Punkin Center Pit (sand and gravel), and (3) Tonto Pit (sand and gravel): http://repository.azgs.az.gov/uri_gin/azgs/dlio/1601
- Richard (1999) provided a map and commodities (e.g., sand and gravel, asbestos, and uranium) information for the Tonto Basin, Gila County: http://repository.azgs.az.gov/uri_gin/azgs/dlio/1044
- Conway and Wrucke (1986), published in Arizona Geological Society Digest XVI, discussed mines in the Sierra Ancha, including the Red Bluff Mine (uranium) and the American Ore Mine (asbestos): https://www.arizonageologicalsoc.org/InPrintPublications (table of contents only). Monument staff may contact the GRI team for a PDF of this publication.

Cave Management

- Karst Information Portal (open-access digital library): https://digital.lib.usf.edu/karst
- National Cave and Karst Research Institute (NCKRI) website: http://www.nckri.org/
- NPS Caves and Karst website: https://www.nps.gov/subjects/caves/index.htm
- NPS website regarding white-nose syndrome, which is a fatal disease caused by the fungus *Pseudogymnoascus destructans* that affects cave-dwelling bats: https://www.nps.gov/subjects/bats/white-nose-syndrome.htm

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 (AGI): http://www.americangeosciences.org/
- AGI information about geologic maps: http://www.americangeosciences.org/environment/publications/mapping
- 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/

Geothermal Resources in Arizona

- Arizona Geological Survey (AZGS) "Geothermal in Arizona" website: https://azgs.arizona.edu/energy/geothermal-arizona
- Witcher et al. (1982) provided a map of geothermal resources of Arizona. The map shows Roosevelt Hot Springs located at Theodore Roosevelt Dam: http://repository.azgs.az.gov/uri_gin/azgs/dlio/1718
- Richard (1999b) considered the potential for occurrence of geothermal resources in the monument area as low with moderate confidence: http://repository.azgs.az.gov/uri_gin/azgs/dlio/1042

Natural Hazards

- Arizona Geological Survey (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/
- Arizona Earthquake Information Center and Northern Arizona Seismograph Network (Northern

Arizona University): https://www.cefns.nau.edu/Orgs/aeic/index.html

- Arizona Broadband Seismic Network (operated by AZGS): https://www.fdsn.org/networks/detail/AE/
- AZGS information about earthquakes, including time-lapse video of historic earthquake epicenters of Arizona and information about the June 2014, M 5.3 earthquake in Duncan, Arizona: http://azgs.arizona.edu/center-natural-hazards/earthquakes
- AZGS information about volcanoes in Arizona; http://azgs.arizona.edu/center-natural-hazards/volcanism
- NPS Geologic Resources Division Geohazards website: http://go.nps.gov/geohazards
- NPS Geologic Resources Division Slope Movement Monitoring website: http://go.nps.gov/monitor_slopes
- Southern Arizona Seismic Observatory (University of Arizona): https://www.geo.arizona.edu/saso/
- US Geological Survey (USGS) Earthquake Hazards Program (information by region—Arizona): https://earthquake.usgs.gov/earthquakes/byregion/arizona.php
- USGS debris-flow forecasting (before fires): https://landslides.usgs.gov/research/featured/2018/before-fire-forecasts/
- USGS landslides website: http://landslides.usgs.gov/

Geologic Outreach, Interpretation, and Education

- Arizona Geological Survey (AZGS) Ask a Geologist (most commonly asked questions and online form for submitting questions): http://azgs.arizona.edu/ask-a-geologist
- AZGS “Arizona Geology” blog (more than 4,500 posts since 2007): http://blog.azgs.arizona.edu/
- AZGS Document Repository (more than 1,000 publications dating from 1915 to the present): http://repository.azgs.az.gov/
- AZGS Down-to-Earth Series (a collection of geologic booklets for the lay public): http://repository.azgs.az.gov/facets/results/og%3A1452
- AZGS Facebook (more than 18,979 followers as of 12 June 2019): https://www.facebook.com/AZ.Geological.Survey/
- AZGS Flickr (561 photographs as of 12 June 2019): https://www.flickr.com/photos/azgs/
- AZGS Twitter (17,029 Tweets and 6,948 followers as of 12 June 2019): https://twitter.com/AZGeology
- AZGS YouTube channel (created in 2009): https://www.youtube.com/user/azgsweb/playlists
- 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 Education website: http://go.nps.gov/geoeducation
- NPS Scientists in Parks (SIP) internship program: scientists_in_parks@nps.gov
- NPS geology interpretation training manuals (Blue Ridge Parkway, Gulf Islands National Seashore, Olympic National Park, Sunset Crater Volcano National Monument, Grand Canyon National Park, Redwood National and State Parks, Yosemite National Park, and Craters of the Moon National Monument and Preserve).
- *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 Resource Management Guidance and Documents

- 1998 National Parks Omnibus Management Act: http://www.gpo.gov/fdsys/pkg/PLAW-105publ391/pdf/PLAW-105publ391.pdf
- *America’s Geologic Heritage: An Invitation to Leadership* (2015) by the NPS Geologic Resources Division and American Geosciences Institute (AGI)
- Appendix B of this GRI report
- *Geological Monitoring* by Rob Young and Lisa Norby (2009); available 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-77—Natural resource management reference manual: 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 9 May 2006, or the follow-up report writing conference call, held on 3 April 2019. 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
Andy Hubbard	NPS Sonoran Desert Network	Network coordinator
Duane Hubbard	Tonto National Monument	Resource program manager
Katie KellerLynn	Colorado State University	Research associate/geologist
Larry Laing	NPS Southern Arizona Office	Ecologist
Lisa Norby	NPS Geologic Resources Division	Geologist
Melanie Ransmeier	NPS Geologic Resources Division	GIS specialist
Jon Spencer	Arizona Geological Survey	Geologist
Brad Traver	Tonto National Monument	Superintendent
Laurie Wirt	US Geological Survey	Geologist

2019 Conference Call Participants

Name	Affiliation	Position
Brett Cockrell	Tonto National Monument	Chief of resources
Tim Connors	NPS Geologic Resources Division	Geologist
Mike Conway	Arizona Geological Survey	Geologist
Duane Hubbard	Tonto National Monument	Superintendent
Katie KellerLynn	Colorado State University	Research associate/geologist
Jason Kenworthy	NPS Geologic Resources Division	Geologist, GRI coordinator
Stephanie Mack	Tonto National Monument	Archeological technician
Hal Pranger	NPS Geologic Resources Division	Supervisory geologist
Eric Schreiner	Tonto National Monument	Chief of interpretation
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 April 2020. 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.

Resource	Resource-specific Laws	Resource-specific Regulations	2006 Management Policies
Paleontological Resources	**Archaeological Resources Protection Act of 1979, 16 USC §§ 470aa – mm Section 3 (1) Archaeological Resource—**nonfossilized and fossilized paleontological specimens, or any portion or piece thereof, shall not be considered archaeological resources, under the regulations of this paragraph, unless found in an archaeological context. Therefore, fossils in an archaeological context are covered under this law. **Federal Cave Resources Protection Act of 1988, 16 USC §§ 4301 – 4309 Section 3 (5) Cave Resource—**the term "cave resource" includes any material or substance occurring naturally in caves on Federal lands, such as animal life, plant life, paleontological deposits, sediments, minerals, speleogens, and speleothems. Therefore, every reference to cave resource in the law applies to paleontological resources. **National Parks Omnibus Management Act of 1998, 54 USC § 100701** protects the confidentiality of the nature and specific location of paleontological resources and objects. **Paleontological Resources Preservation Act of 2009, 16 USC § 470aaa et seq.** provides for the management and protection of paleontological resources on federal lands.	**36 CFR § 2.1(a)(1)(iii)** prohibits destroying, injuring, defacing, removing, digging or disturbing paleontological specimens or parts thereof. **Prohibition in 36 CFR § 13.35** applies even in Alaska parks, where the surface collection of other geologic resources is permitted. **43 CFR Part 49** (in development) will contain the DOI regulations implementing the Paleontological Resources Preservation Act.	**Section 4.8.2** requires NPS to protect geologic features from adverse effects of human activity. **Section 4.8.2.1** emphasizes Inventory and Monitoring, encourages scientific research, directs parks to maintain confidentiality of paleontological information, and allows parks to buy fossils only in accordance with certain criteria.
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.

Resource	Resource-specific Laws	Resource-specific Regulations	2006 Management Policies
Geothermal	**Geothermal Steam Act of 1970, 30 USC. § 1001** *et seq*. as amended in 1988, states -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.		**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.
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.

Resource	Resource-specific Laws	Resource-specific Regulations	2006 Management Policies
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. **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.	
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.		

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

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.	**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.	**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 putting new developments in areas subject to natural shoreline processes unless certain factors are present.

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.	None Applicable.	**Section 4.1** requires NPS to investigate the possibility to restore natural ecosystem functioning that has been disrupted by past or ongoing human activities. This would include climate change, as put forth by Beavers et al. (in review). **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. **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.	**Section 4.1** requires NPS to manage natural resources to preserve fundamental physical and biological processes, as well as individual species, features, and plant and animal communities; maintain all components and processes of naturally evolving park ecosystems. **Section 4.1.5** directs the NPS to re-establish natural functions and processes in human-disturbed components of natural systems in parks, unless directed otherwise by Congress. **Section 4.4.2.4** directs the NPS to allow natural recovery of landscapes disturbed by natural phenomena, unless manipulation of the landscape is necessary to protect park development or human safety. **Section 4.6.4** directs the NPS to (1) manage for the preservation of floodplain values; [and] (2) minimize potentially hazardous conditions associated with flooding. **Section 4.6.6** directs the NPS to manage watersheds as complete hydrologic systems and minimize human-caused disturbance to the natural upland processes that deliver water, sediment, and woody debris to streams. **Section 4.8.1** directs the NPS to allow natural geologic processes to proceed unimpeded. Geologic processes… include…erosion and sedimentation… processes. **Section 4.8.2** directs the NPS to protect geologic features from the unacceptable impacts of human activity while allowing natural processes to continue.

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

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https://www.nps.gov/nature/index.htm