National Park Service
U.S. Department of the Interior

Natural Resource Stewardship and Science

Organ Pipe Cactus National Monument

Geologic Resources Inventory Report

Natural Resource Report NPS/NRSS/GRD/NRR—2022/2399

ON THE COVER
Volcanic rocks of the Ajo Range peer through the long branches of an ocotillo (*Fouquieria splendens*) along Ajo Mountain Drive on the eastern side of the monument. This one-way loop road winds through a portion of the Ajo volcanic field, which was active between 22 million and 14 million years ago. Photograph by Katie KellerLynn (Colorado State University), taken 2006.

THIS PAGE
Although their habitat extends far south into Mexico, the heart of the US population of organ pipe cactus (*Stenocereus thurberi*) is found in the monument. The species arrived in the Sonoran Desert about 3,500 years ago. Then when global climate warmed about 11,700 years ago (i.e., at the end of the Pleistocene Epoch), the monument's namesake cactus slowly began migrating northward. Today, the monument is one of the only places in the United States with large stands (Organ Pipe Cactus National Monument 2015). NPS photograph, date unknown.

Organ Pipe Cactus National Monument

Geologic Resources Inventory Report

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June 2022

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

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

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Please cite this publication as:

KellerLynn, K. 2022. Organ Pipe Cactus National Monument: Geologic resources inventory report. Natural Resource Report NPS/NRSS/GRD/NRR—2022/2399. National Park Service, Fort Collins, Colorado. https://doi.org/10.36967/2293664.

NPS 157/181564, June 2022

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Executive Summary

Comprehensive park management to fulfill the mission of the National Park Service (NPS) requires an accurate inventory of the geologic features of a park unit, but park managers may not have the necessary information, geologic expertise, or means to complete such an undertaking; therefore, the Geologic Resources Inventory (GRI) provides information and resources to help park managers make decisions for visitor safety, planning and protection of infrastructure, and preservation of natural and cultural resources. Information in the GRI report may also be useful for interpretation.

Organ Pipe Cactus National Monument (referred to as the "monument" throughout this report) is in Pima County, Arizona, near the geographical center of the Sonoran Desert. The northern boundary of the monument begins approximately 20 km (12 mi) south of the town of Ajo, Arizona. The southern boundary of the monument traces the international border between the United States and Mexico. The monument encompasses a total area of 133,830 ha (330,689 ac or 516 mi^2) and is the best place in the United States to see organ pipe cactus (*Stenocereus thurberi*) for which the monument was named.

The monument is a place of expansive wilderness. Congress designated about 95% or approximately 126,500 ha (312,600 ac) of the monument as the Organ Pipe Cactus Wilderness with another 502 ha (1,240 ac) as potential wilderness as defined in the Wilderness Act of 1964, Public Law 88-577 (16 U.S.C 1131-1136).

The monument also is a place of multicultural connections and resources. The official interaction of the "tri-nations"—Tohono O'odham Nation, Mexico, and the United States—and the ancestral convergence in what is now the monument attests to human resilience and an evolving relationship with a dynamic landscape. This connection is an interpretive theme at the monument (National Park Service 2016).

In addition, the monument is a geologic place. Some of the oldest rocks in Arizona are preserved just north of the monument; these rocks record 1.7 billion years of geologic time. The monument's bedrock and other geologic features record about 200 million years of Earth's history, including building of the North American continent, rising of the Rocky Mountains, stretching of the Basin and Range, eruption of the Ajo volcanic field, and filling of valleys, referred to as "basins," with sediment.

This GRI report consists of the following chapters:

Introduction to the Geologic Resources Inventory—This chapter provides background information about the GRI, highlights the GRI process and products, and recognizes GRI collaborators. This chapter highlights the GRI GIS data, which are the principal deliverable of the GRI, as well as the geologic map (Skinner et al. 2008) that served as the source map used by the GRI team in compiling the GRI GIS data. The chapter also calls attention to the poster that illustrates the GRI GIS data.

Geologic Heritage—This chapter provides background information about the monument's setting and draws connections between geologic resources and other park resources and stories. It highlights significant geologic features, landforms, and landscapes preserved for their heritage values, including aesthetic, artistic, cultural, ecologic, economic, educational, recreational, and scientific. Geologic heritage evokes the idea that the geology of a place is an integral part of its history and cultural identity.

Geologic History, Features, and Processes—This chapter includes a geologic time scale and text that illustrate and describe the chronology of geologic events leading to the monument's present-day landscape. The chapter highlights the significant geologic features and processes of the monument and puts them in a context of geologic time, listing from oldest to youngest. In general, information provided in this chapter follows the geologic source map for the monument (Skinner et al. 2008). The geologic time scale and text make connections to the source map by including map unit symbols.

Geologic Resource Management Issues—This chapter discusses management issues related to the monument's geologic resources (features and processes). Scoping and conference-call participants, as well as reviewers of this report, deemed the following geologic issues worthy of inclusion: flash flooding, erosion, groundwater assessment, threats to Quitobaquito, climate change impacts to geologic resources, abandoned mineral lands, mining, mineral and energy development, slope movements, active faults and earthquakes, and giant desiccation cracks vs. earth fissures. These issues are discussed in order of management priority, starting with issues of greatest concern for human safety followed by important resource concerns then extremely rare events (Rijk Moräwe, Organ Pipe Cactus National Monument, chief of Natural and Cultural Resources Management, written communication, 17 May 2021). In addition, a discussion of geologic interpretation is included in this chapter; a need for geologic interpretation at the monument was identified during the review of this report.

Guidance for Resource Management—This chapter follows and is a follow up to the "Geologic Resource Management Issues" chapter. It provides resource managers with a variety of ways to find and receive management assistance with geologic resources.

Literature Cited—This chapter is a bibliography of references cited in this GRI report. Many of the cited 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 (GRD) 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 use. Monument staff may contact the GRI team or GRD staff for instructions to access GEOREF.

Introduction to the Geologic Resources Inventory

The Geologic Resources Inventory (GRI), which is administered by the Geologic Resources Division (GRD) of the NPS Natural Resource Stewardship and Science Directorate, 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 funded by the NPS Inventory and Monitoring Division.

GRI Products

The GRI team—which is primarily a collaboration between GRD staff and research associates at Colorado State University, Department of Geosciences and University of Alaska Museum of the North—completed the following tasks as part of the GRI process for Organ Pipe Cactus National Monument (referred to as the "monument" throughout this report): (1) conduct a scoping meeting and provide a scoping summary, (2) provide geologic map data in a geographic information system (GIS) format, (3) create a poster to display the GRI GIS data, and (4) provide a GRI report (this document). GRI products are available on the Geologic Resources Inventory—Products website and through the NPS Integrated Resource Management Applications (IRMA) portal (see "Guidance for Resource Management"). Ground-disturbing activities should neither be permitted nor denied based upon the information provided in GRI products.

Scoping Meeting

On 25–26 January 2006, the GRI team facilitated a scoping meeting at the monument, which brought together monument staff and geologic experts, who reviewed and assessed available geologic maps; developed a geologic mapping plan; and discussed geologic features, processes, and resource management issues to be included in the final GRI report. A scoping summary (National Park Service 2006) summarized the findings of this meeting.

GRI GIS Data

Following the scoping meeting, the GRI team compiled the GRI GIS data for the monument. These data are the principal deliverable of the GRI. The GRI team did not conduct original geologic mapping but compiled existing geologic information (i.e., paper maps and/or digital data) into the GRI GIS data (fig. 1). Scoping participants and the GRI team identified the best available source map 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. In addition, an ancillary map information document (orpi_geology.pdf) provides elements of the source map including map unit descriptions, two correlation charts of map units, a narrative rock-unit overview and regional geologic history written by the map authors, and references.

The source map for the compiled GRI GIS data is *Geological Reconnaissance at Organ Pipe Cactus National Monument, Arizona* (Skinner et al. 2008). The map consists of unpublished digital data by Northern Arizona University and the US Geological Survey. The GRI GIS data contain the full extent of the map by Skinner et al. (2008).

The GRI team standardizes map deliverables by using a data model. The GRI GIS data for the monument was compiled using data model version 2.3 (see "Access to GRI Products"). This data model dictates GIS data structure, including layer architecture, feature attribution, and relationships within ESRI ArcGIS software. Based on the source map scale (1:24,000) and US National Map Accuracy Standards, geologic features represented in the GRI GIS data are expected to be horizontally within 12 m (40 ft) of their true locations.

GRI Poster

A poster—*Geologic Map of Organ Pipe Cactus National Monument*—shows part of the GRI GIS data draped over a shaded relief image of the monument and surrounding area. This poster is the primary figure referenced throughout the GRI report. It is available at the GRI products website (see "Access to GRI Products"). The poster is not a substitute for the GIS data but is supplied as a tool for office and field use and for users without access to ArcGIS. Not all GIS feature classes are included on the poster. Geographic information, selected park features, and a digital elevation base layer (National Elevation Dataset of The National Map; see "Additional References, Resources, and Websites") have been added to the poster; these features are not part of the GRI GIS data and were added to enhance the poster.

GRI Report

On 23 November 2020, the GRI team hosted a follow-up conference call for monument staff and others interested in the geologic resources of the monument (see "Acknowledgements"). The call provided an opportunity to get back in touch with monument staff;

Figure 1. Index map of the GRI GIS data.
The index map displays the extent (dark-gray outline) of the GRI GIS data for Organ Pipe Cactus National Monument and vicinity. The GRI GIS data include the full extent of mapping by Skinner et al. (2008). The boundary of the monument is outlined in green. The border between the United States and Mexico is shown. The towns of Ajo, Lukeville, and Pisinemo, Arizona, are shown. Map by Stephanie O'Meara (Colorado State University).

introduce "new" staff (since the 2006 scoping meeting) to the GRI process; and update the list of geologic features, processes, and resource management issues for inclusion in the final GRI report.

This report is a culmination of the GRI process. It synthesizes discussions from the scoping meeting in 2006, the follow-up conference call in 2020, reviewers' comments in 2021 and 2022, and additional geologic research. The selection of geologic features discussed in the report was guided by the previously completed GRI GIS data and discussions during the scoping meeting and conference call. Notably, writing reflects the geologic interpretation provided by the authors of the source map (Skinner et al. 2008).

Surficial Geologic Mapping

Following the scoping meeting in 2006, the NPS and Arizona Geological Survey (AZGS) entered into a cooperative agreement for additional geologic mapping in the Valley of the Ajo and Sonoyta Valley (fig. 2). Whereas Skinner et al. (2008) focused on bedrock, AZGS mapping projects by Pearthree et al. (2012), Youberg and Pearthree (2012), and Young and Pearthree (2012) focused on surficial deposits. Consequently, the map by Skinner et al. (2008) groups all surficial deposits into two map units: terrace gravels (**QTg**) and alluvium and colluvium (**QTal**) that represent geologic activity during the past 66 million years. By contrast, surficial geologic maps by the AZGS divide surficial materials into as many as 16 units, including active channel deposits, areas of arroyo development, terrace deposits, sheetflood deposits, debris flow deposits, and alluvial fans. These deposits range in age from "active" to as old as 5.3 million years ago (Pliocene Epoch). More detailed mapping allows for a greater understanding of the evolution of the present-day landscape.

The AZGS surficial maps (Pearthree et al. 2012; Youberg and Pearthree 2012; Young and Pearthree 2012) are not part of the GRI GIS data but are available through the AZGS Document Repository (see "Additional References, Resources, and Websites"). Information from these surficial maps was used in writing this report.

The next generation of NPS inventories, which are expected to begin in 2023, may support surficial mapping projects in parks. Incorporating surficial mapping by the AZGS into the GRI GIS data for the monument may be possible as part of the new inventory program (see "Guidance for Resource Management").

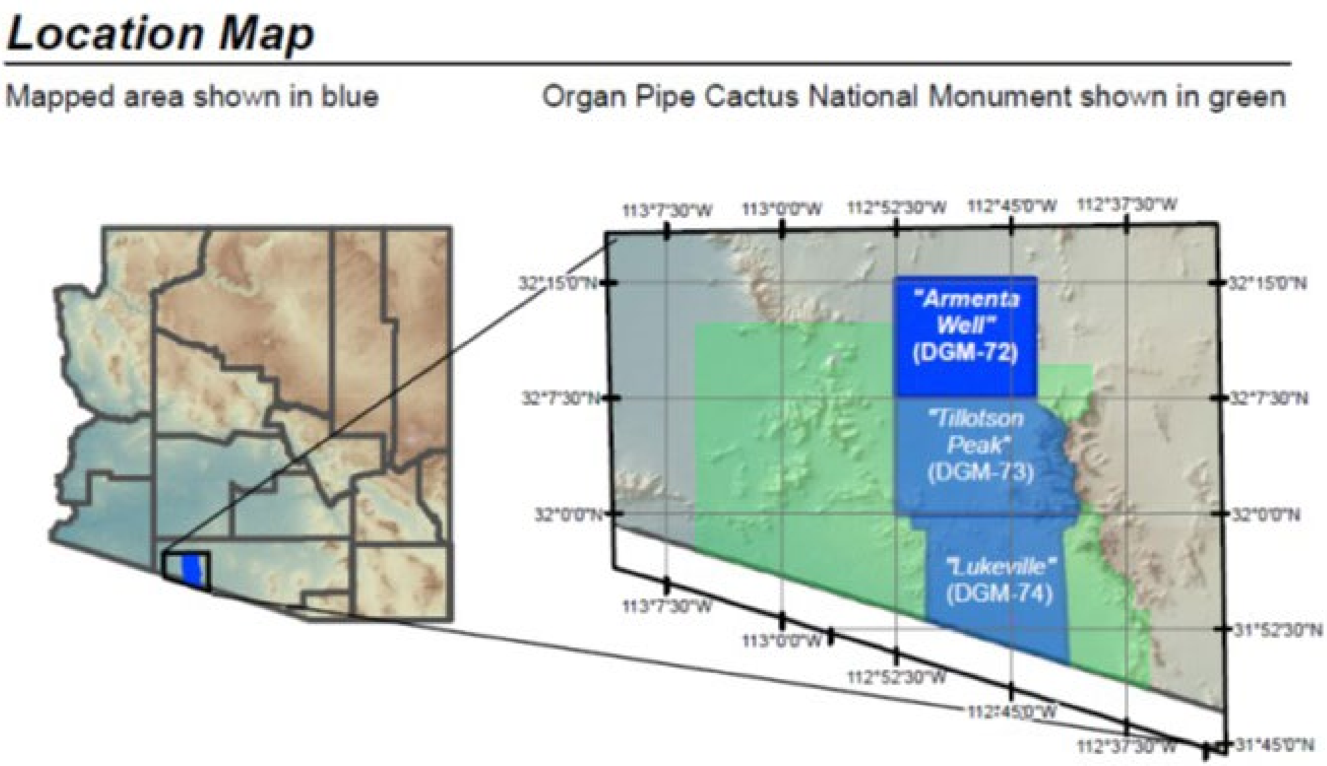

Figure 2. Index map of surficial mapping in the monument.
In 2012, the AZGS produced three geologic maps as part of its Digital Geologic Map (DGM) series. These maps, which cover the Valley of the Ajo and part of the Sonoyta Valley, provide surficial geologic mapping of greater detail than Skinner et al. (2008), which focused on bedrock. From north to south, "Armenta Well" (DMG-72) was mapped by Young and Pearthree (2012); "Tillotson Peak" (DMG-73) was mapped by Pearthree et al. (2012); "Lukeville" (DMG-74) was mapped by Youberg and Pearthree (2012). Map from Young and Pearthree (2012).

Acknowledgements

The GRI team thanks the participants of the 2006 scoping meeting and 2020 follow-up conference call for their assistance with this inventory. The following lists of participants reflect the names and affiliations of these participants at the time of the meeting and call.

Because the GRI team does not conduct original geologic mapping, we are particularly thankful for Northern Arizona University and the US Geological Survey for the source map. This report and accompanying GIS data could not have been completed without it. In addition, the AZGS provided surficial mapping in the eastern part of the monument, which also was used in preparation of this report.

Thanks to Trista Thornberry-Ehrlich (Colorado State University) for producing many of the figures in this report.

Thanks to Phil Pearthree (AZGS) for his guidance about the informal subdivisions of the Miocene Epoch, which was useful for understanding the timing of eruptions in the Ajo volcanic field, as well as his patience in answering many follow-up questions that were a consequence of the GRI review process of this report. Thanks to Joe Cook (AZGS) for his input and preliminary analysis of the potential for giant desiccations cracks at the monument. Thanks to Rijk Moräwe (NPS Organ Pipe Cactus National Monument) and Kara Raymond (NPS Southern Arizona Office) for their additional review of groundwater-related topics, which were added to the report following initial external review.

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Geologic Heritage

This chapter highlights the significant geologic features, landforms, landscapes, and stories of the monument preserved for their heritage values. It also draws connections between geologic resources and other park resources and stories.

Park Setting

The monument preserves more than 133,000 ha (330,000 ac) of the Sonoran Desert and is one of several protected areas that helps preserve the Sonoran Desert ecosystem along the international border with Mexico. The other protected areas are Cabeza Prieta National Wildlife Reserve (north and west of the monument), which is managed by the US Fish and Wildlife Service; Sonoran Desert National Monument (north of the monument), which is managed by the Bureau of Land Management; and Reserva de la Biosfera El Pinacate y Gran Desierto de Altar ("Reserva de la Biosfera," south of the monument), which is managed by the Mexican federal government, specifically the Secretariat of the Environment and Natural Resources, in collaboration with the state governments of Sonora and the Tohono O'odham Nation.

Collectively, these areas compose the largest multiagency, internationally protected area in the Sonoran Desert region of North America (National Park Service 2016). The United Nations Educational, Scientific and Cultural Organization (UNESCO) recognizes many biosphere reserves in the region. Designated in 1976, the monument was one of the first UNESCO biosphere reserves. Mexico has 40 UNESCO biosphere reserves, though Reserva de la Biosfera is not one of them. Reserva de la Biosfera was designated as a world heritage site by UNESCO in 2013, however.

The monument was named for the organ pipe cactus (*Stenocereus thurberi*), which is a large, columnar cactus (see inside front cover) and representative species of the Sonoran Desert. Many other types of cacti grow in the monument, including the endangered acuña cactus (*Echinomastus erectocentrus* var. *acunensis*), which is highly specific in its habitat—"only loose, chipped granite on hilltops will do" (Houk 2000, p. 30).

The monument is in a remote part of Pima County in southwestern Arizona (fig. 3). The monument's northern boundary is about 20 km (12 mi) south of Ajo, Arizona. The monument's visitor center—Kris Eggle Visitor Center—is about 28 km (17 mi) south of the north entrance. Part of the monument's northern boundary and the entire western boundary are shared with Cabeza Prieta National Wildlife Reserve. The monument's southern boundary runs along the international border between the United States and Mexico. Lukeville, Arizona, which is at the southern boundary, is a border crossing point to Sonoyta, Sonora, Mexico, and a main gateway to the resort town of Puerto Peñasco on the Sea of Cortez. Located about 3 km (2 mi) south of the international border where the Rio Sonoyta breaches the Sonoyta Mountains, Sonoyta is the principal town in the region.

The eastern boundary of the monument is shared with the Tohono O'odham Nation, which is a federally recognized tribe that includes approximately 28,000 members. Historically, the O'odham inhabited an enormous area of land, extending south to Sonora, Mexico, north to central Arizona (just north of Phoenix), west to the Gulf of California, and east to the San Pedro River. This land base was known as the Papagueria and was home to the O'odham for thousands of years. From the early 18th century to the present, O'odham land has been occupied by foreign governments (Tohono O'odham Nation 2016). Today, the Tohono O'odham Nation is the second largest reservation in Arizona in both population and geographical size. The Navajo Nation, situated in northeastern Arizona, is the largest. Four noncontiguous areas of land make up the Tohono O'odham Nation, which encompasses more than 1.1 million ha (2.8 million ac or 4,460 mi^2). The Tohono O'odham Nation is composed of 11 districts: Pisinemo, Hickiwan, Gu Vo, Chukut Kuk, San Lucy, San Xavier, Baboquivari, Sif Oidak, Schuk Toak, Sells, and Gu Achi (Tohono O'odham Nation 2016). Members of the Tohono O'odham Nation also live in Mexico.

Of interest for the GRI, a geologist, Edwin D. McKee (1906–1984), was the first to propose establishment of NPS areas for the protection of the columnar cacti in the US Southwest (Bennett and Kunzmann 1989). In 1931, "Eddie" McKee, who was the chief park naturalist of Grand Canyon National Park at that time (1929–1940), wrote a proposal and memorandum to Grand Canyon Superintendent M. R. Tillotson, who then forwarded the memorandum to NPS Director Horace M. Albright who, in turn, requested that Yellowstone Superintendent Roger Toll evaluate McKee's suggestion. An outcome of McKee's proposal was establishment of the monument by presidential proclamation on 13 April 1937. Following McKee's NPS career in Grand Canyon National Park, he became assistant director for research at the Museum of Northern Arizona then a professor

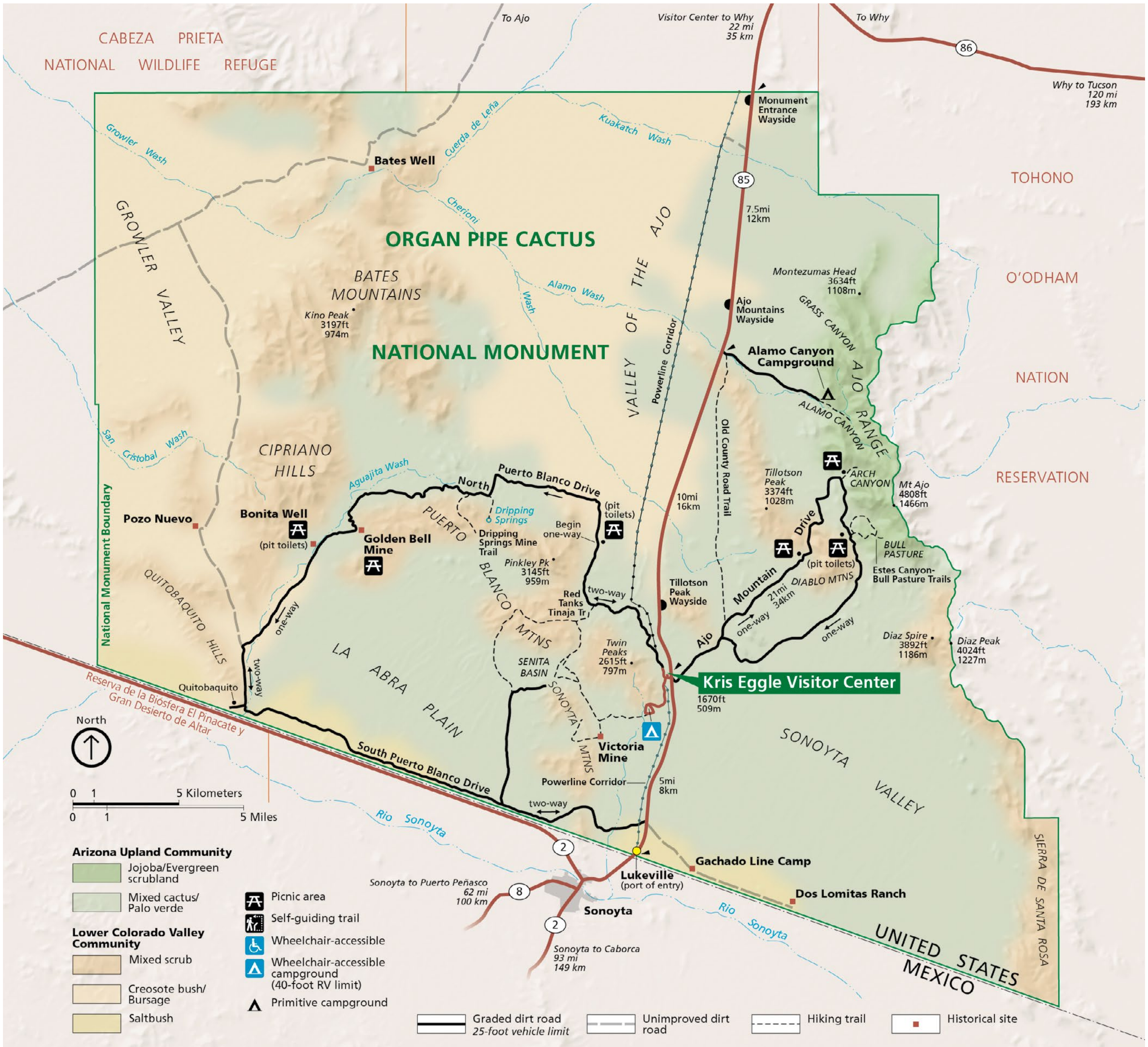

Figure 3. Location map of the monument.
The monument is in southwestern Arizona. The southern boundary coincides with the international border between the United States and Mexico. Various colors on the map indicate vegetation communities, not geology. Highway 85 between Why and Lukeville traverses the monument north to south. Two scenic drives—Puerto Blanco and Ajo Mountain—highlight areas west and east of the highway, respectively. Another road provides access to the Alamo Campground. North of the international border, the Tohono O'odham Nation (on the east) and Cabesa Prieta National Wildlife Refuge (on the northwest) surround the monument. NPS Harpers Ferry Center map, available at https://www.nps.gov/carto.

in the Department of Geology at the University of Arizona, Tucson, as well as a research geologist with the US Geological Survey in Denver. McKee's geological work spanned the globe, but his devotion to Arizona's geology, primarily the Grand Canyon but including the dunes at White Sands National Monument (McKee 1966, see also GRI report by KellerLynn 2012), became "a prism through which to view the world" (Spamer 1999, p. 18).

Geologic Setting

The primary figure for this GRI report is a poster, *Geologic Map of Organ Pipe Cactus National Monument*. This poster is based on the source map by Skinner et al. (2008) (see “Introduction to the Geologic Resources Inventory”). The geologic map displayed by the poster shows distinctive multicolored northwest–southeast-oriented mountain ranges that appear like islands in a yellow-colored sea. Yellow areas represent sediment and landforms deposited during the past 5 million years, ranging in age from Pliocene to modern. These deposits fill in basins and cover valley floors. Other colors on the poster represent bedrock in mountain ranges. The oldest named bedrock in the monument—the Bolsa and Abrigo Formations (map unit **Cs**)—was deposited about 500 million years ago in marine waters during the Cambrian Period. The youngest bedrock in the monument—the Batamote Andesite complex (“**Tb**” map units)—erupted from a volcano between 16 million and 14 million years ago (Miocene Epoch).

The monument is noted for its ruggedness (National Park Service 2016). Six mountain ranges—Bates Mountains, Cipriano Hills, Quitobaquito Hills, Puerto Blanco Mountains, Diablo Mountains, and Ajo Range—and parts of four others—Growler Mountains, Sonoyta Mountains, Sierra de Santa Rosa, and Gunsight Hills—are in the monument. Intermontane valleys include Growler, Sonoyta, La Abra Plain, and Valley of the Ajo. Elevation differences between mountaintops and valley floors exceed 1,000 m (3,500 ft). For instance, the highest peak in the monument, Mount Ajo, stands 1,469 m (4,819 ft) above sea level, whereas the valley floor below it is about 413 m (1,355 ft) above sea level—a difference of 1,056 m (3,464 ft).

The valleys in the monument contain four major wash systems including, from north to south, Cuerda de Leña, Kuakatch, Alamo, and Cherioni. These washes drain the central and eastern areas of the monument and are greatly influenced by bajadas (broad, gently inclined surface at the base of a mountain front; see “Bajada”).

The monument is in the Sonoran Desert, which is one of four major deserts in North America. The other three are the Mojave, Chihuahuan, and Great Basin (fig. 4). The Sonoran Desert covers approximately 260,000 km^2 (100,387 mi^2) of the southwestern United States and northwestern Mexico, including the southern half of Arizona, southeastern California, and most of the states of Sonora and Baja California, Mexico (Sonoran Desert Network 2019b). Bounded on the north by the Mogollon Rim (topographic and geologic feature that cuts across the northern half of Arizona and forms the southern edge of the Colorado Plateau; see GRI report about Tuzigoot National Monument by KellerLynn 2019b), the Sonoran Desert grades into the Chihuahuan Desert to the east, the Mohave Desert to the west, and the tropical forests and montane forests of central Mexico to the south.

Annual precipitation in the Sonoran Desert averages from 76 to 500 mm (3 to 20 in), depending on location (Sonoran Desert Network 2019b). In the monument, geologic features influence precipitation as reflected in a strong gradient from east to west with declining values (fig. 5).

Perhaps no feature defines the Sonoran Desert better than its bimodal precipitation regime. Interspersed between the Mohave and Chihuahuan Deserts, the Sonoran Desert receives the frequent low-intensity winter (December/January) rains of the former as well as the violent summer (July/August) monsoon thunderstorms of the latter (Sonoran Desert Network 2019b). The term “monsoon” describes large-scale wind shifts that transport moist tropical air to dry desert locations. These storms frequently result in local flash flooding of ephemeral drainages (see “Flash Flooding”).

Rainy seasons support an array of warm- and cool-season flora and fauna and are the primary cause of the diversity of lifeforms in the Sonoran Desert. The Sonoran Desert is home to a remarkable number of species: more than 20 amphibian, 30 native fish, 60 mammal, 100 reptile, and 350 bird species. In addition, more than 2,000 species of plants have been identified in the Sonoran Desert. Even more striking, perhaps, than species diversity is the tremendous variability in Sonoran Desert lifeforms, from columnar cacti to conifers, Gila monsters to pygmy owls, cyanobacterial soil crusts to native ferns (Sonoran Desert Network 2019b).

The Sonoran Desert also has distinctive landforms, including alluvial fans, ephemeral washes, and desert pavement (see “Bajada,” “Flash Flooding,” and “Desert Pavement”). Sonoran Desert landforms are quite different from the fields of sand dunes that are common in many of the world’s deserts. The Algodones Dunes are the only large body of sand in the Sonoran Desert; they are situated in southeastern California, near the border with Arizona and Baja California, Mexico.

The name “Algodones Dunes” refers to the entire geologic feature. The administrative designations for the portions managed by the Bureau of Land Management are Imperial Sand Dunes Recreation Area (sometimes called Glamis Dunes) and North Algodones Dunes Wilderness. In 1966, Imperial Sand Hills, which is in the North Algodones Dunes Wilderness, was designated a National Natural Landmark by the NPS (National Park Service 2020a).

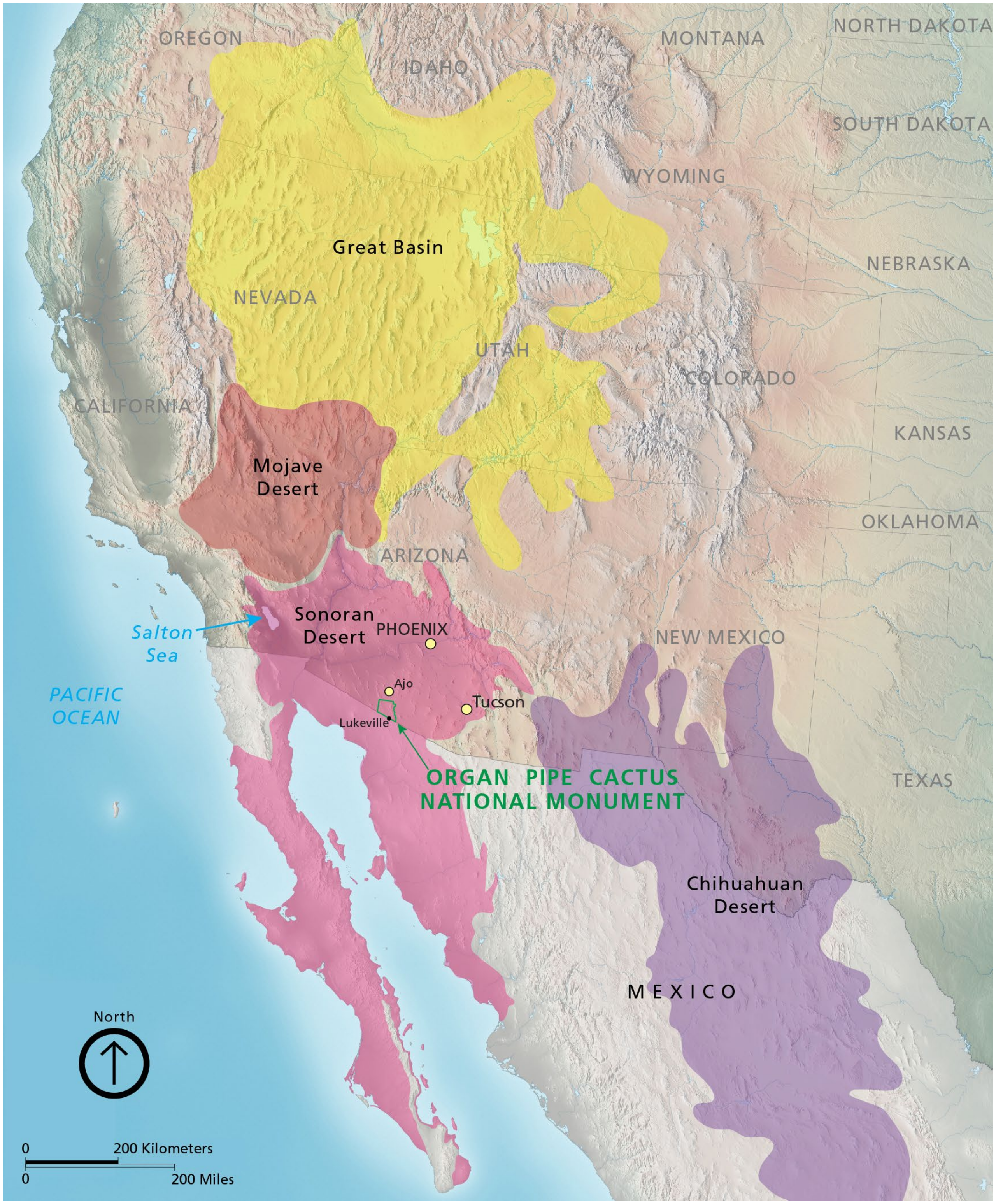

Figure 4. Map of major North American deserts.
The Sonoran Desert is one of four major deserts in North America. The continent's deserts are largely between the Rocky Mountains and Sierra Madre Oriental on the east and the Sierra Nevada, Transverse, and Peninsular Ranges on the west. About two-thirds of the Sonoran Desert lies in the namesake state of Sonora, Mexico. In the United States, the Sonoran Desert covers southeastern California and southwestern Arizona. Map by Trista Thornberry-Ehrlich (Colorado State University) using NPS base map by Tom Patterson and desert extents from Houk (2000, p. 1 and 7).

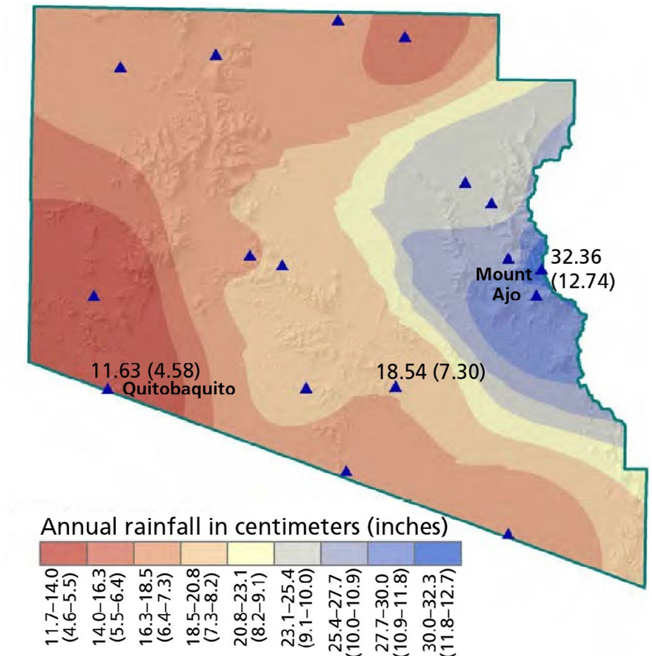

Figure 5. Map of annual rainfall at the monument. The map shows the interpolation of 2010 annual rainfall from 17 rain gauges (marked by triangles on the figure). The gradient—spanning between red for low and blue for high—reflects the more mountainous eastern part of the monument to the lower desert areas on the west. Annual totals ranged from a high of 32.36 cm (12.74 in) at Mount Ajo to a low of 11.63 cm (4.58 in) at Quitobaquito. Notably, half of the annual rainfall at Quitobaquito occurred in January. Monument headquarters received 18.54 cm (7.30 in). NPS map from Organ Pipe Cactus National Monument (2011, p. 7) modified by Trista Thornberry-Ehrlich (Colorado State University).

The primary source of the sand to the dunes is the Colorado River, which has been supplying sand, silt, clay, and gravel to the delta/northern Gulf of California for the past 4.5 million years (Muhs et al. 2003). Northwesterly winds blow sand to the east where it settles into elegant high dunes along the lower end of the Colorado River.

Geologic Connections to Cultural Resources

The continuum of human history is a fundamental resource and value at the monument (National Park Service 2016). The monument's diverse cultural resources document thousands of years of human presence and adaptation to the arid environment. Prehistoric sites within the monument contain important artifacts useful for understanding past occupation and lifeways, including year-round villages, seasonal open campsites, roasting pits, sleeping circles, trade routes and trails, rock shelters, and rock art sites. Evidence for year-round villages on monument lands is increasing and is challenging the previous notion that aboriginal peoples practiced only a "dual-residence system" of floodwater farming in the desert lowlands during the summer and moving to the mountains during the winter (National Park Service 2013). Sites may be as old as 15,000 years before common era (BCE). Many sites are associated with the Hohokam cultural period, which dates from about 150 to 1450 common era (CE).

The monument provides a sense of place that is imbued with myriad meanings, including traditional homeland. The following tribes or groups are traditionally associated with the monument: Ak-Chin Indian Community of the Maricopa (Ak Chin) Indian Reservation, Arizona; Cocopah Tribe of Arizona; Fort Mojave Indian Tribe of Arizona, California, and Nevada; Gila River Indian Community of the Gila River Indian Reservation, Arizona; Hia C'ed O'odham; Hopi Tribe of Arizona; Pascua Yaqui Tribe of Arizona; Quechan Tribe of the Fort Yuma Indian Reservation, California and Arizona; Salt River Pima-Maricopa Indian Community of the Salt River Reservation, Arizona; Tohono O'odham Nation of Arizona; Yavapai-Prescott Indian Tribe, Arizona; and Zuni Tribe of the Zuni Reservation, New Mexico (National Park Service 2016). In addition, descendants of Mexican farmers and European-American explorers and pioneers also recognize many of the monument's cultural sites, objects, landscapes, and natural resources as important touchstones that contribute to group identity and heritage (National Park Service 2016).

Listings in the National Register of Historic Places show connections among US history, cultural identity, and underlying geology. Seven sites within the monument are listed: (1) Montezuma Head (listed as I'itoi Mo'o [Montezuma's Head] and 'Oks Daha [Old Woman Sitting]), (2) Dos Lomitas Ranch, (3) Bull Pasture, (4) Gachado Well and Line Camp, (5) Victoria Mine, (6) Growler Mine Area, and (7) Milton Mine. Two additional sites—Quitobaquito, and Bates Well and Ranch—have been nominated but not listed. Many of these and other sites are discussed in this GRI report, illustrating the connection that people have with the monument's geologic features, landforms, and landscape.

Water Supply

Early civilizations in the region learned how to use and manage the meager surface and near-surface water supply. Research is ongoing at several sites in the monument where a year-round water supply attracted people. Archeologists have identified many desert water-control devices such as wells, represos (small dams with basins behind them to store flood water for drinking), and irrigation canals. While not on the scale of the extensive Hohokam canal works in the Tucson and Phoenix basins (see GRI report about Casa Grande Ruins National Monument by KellerLynn 2018), the water control devices in the monument are representative of the Ak-Chin floodwater farming that went on at nearly every wash in the monument during the monsoons (Rankin 1995; Altschul and Rankin 2008).

Early European-American miners, ranchers, and settlers dug wells to tap into groundwater supplies. These widely scattered wells acquired the names of those who dug them, for example, Dobbs, Bates, Blankenship, Hocker, Dowling, Walls, and Menager (Keith 1971; Rijk Moräwe, Organ Pipe Cactus National Monument, chief of Natural and Cultural Resources Management, written communication, 7 April 2021).

In 1917, the importance of sources of water in the Sonoran Desert led to the initiation of a hydrological reconnaissance by the US Geological Survey; Congress appropriated $10,000 to fund the effort. Water-Supply Paper 499 (Bryan 1925), which is an outcome of the investigation that started in 1917, is a classic study of water conditions in the region, including many areas now in the monument such as Quitobaquito Hills, Growler Mountains, La Abra Valley (now, Plain), Valley of the Ajo, and Sonoita (now, Sonoyta) Valley. Bryan's report included information about climate, flora, fauna, geology, physiography, surface water (e.g., tinajas), and groundwater (e.g., springs). Notably, the paper served as a guide to desert watering places and provided road logs and detailed descriptions of certain routes, including to and from Ajo. It also provided "guidance for road difficulties and suggestions for surmounting them" (Bryan 1925, p. 261–265), including crossing an arroyo in an automobile (see "Flash Flooding").

Quitobaquito

Located at the southern base of the Quitobaquito Hills (see poster), Quitobaquito—including Quitobaquito Springs, pond, and environs—is a fundamental resource and value of the monument (National Park Service 2016). It is home to a diverse range of plants and animals, including many rare and endangered species such as the Quitobaquito pupfish (*Cyprinodon eremus*), Sonoyta mud turtle (*Kinosternon sonoriense longifemorale*), and Quitobaquito freshwater snail (*Tryonia quitobaquitae*) (National Park Service 2016). Quitobaquito is also home of the desert caper plant (*Atamisquea emarginata*), which supports the caper butterfly (*Ascia howarthi*). When present, this rare butterfly is only found coexisting with the desert caper plant (National Park Service 2018).

Human habitation of Quitobaquito ended in 1957 when the site came under NPS management (for background, see Bennett and Kunzmann 1989; Nabhan 2003; Nick 2021b). However, ongoing human use continues by traditionally associated tribes and groups as well as NPS visitors (National Park Service 2016).

Quitobaquito has a long history as a multicultural crossroads and oasis, filling the basic need for water in a desert environment. Prehistoric Paleo-Indian, Archaic, Hohokam, Tohono O'odham, Hia C'ed O'odham, Spanish, French, Anglo, Mexican, and American people all left their mark on Quitobaquito. "The area has been shot up, dug up, plowed, channeled, bulldozed, built upon, knocked flat, and otherwise 'improved'" (Bennett and Kunzmann 1989, p. 1). It has been a hunting ground; resting place for both the living and the dead; homesite; village; settlement; store for mining supplies, food, and clothing; mill for corn; ranch for raising goats or cattle; farm for producing watermelons, figs, or pomegranates; camp for the Arizona National Guard; and border station of the US Bureau of Animal Industry (i.e., to prevent cattle trespass from Mexico and stem the spread of hoof and mouth disease into the United States).

In Arizona, access to Quitobaquito is through the monument via South Puerto Blanco Drive (see fig. 3). Presently, built structures at the site include a gravel parking lot, a walking trail, and interpretive signs that provide information and guidance. In addition, the NPS has plans to install a vault toilet (Rijk Moräwe, Organ Pipe Cactus National Monument, chief of Natural and Cultural Resources Management, email communication, 27 October 2021).

In 1917, "Quitobaquito" became the site's official name on US maps (US Board on Geographic Names 1984). Variants of the name have included "Quitobaquita" and "Quitovaquita." The O'odham people know Quitobaquito Springs as "A'al Vaipia."

The meaning of the name, "Quitobaquito," is speculative (see Greene 1977a, p. 74–75). Suggestions include "get away little cow" (National Park Service 2018), "wet place where a little house is" (Houk 2000, p. 45), and "a place of little water" (Rijk Moräwe, Organ Pipe Cactus National Monument, chief of Natural and Cultural Resources Management, written communication, 17 May 2021).

Quitobaquito covers roughly 16 ha (40 ac) of flat to slightly rolling terrain near the southern boundary of the monument. The source map (Skinner et al. 2008) of the GRI GIS data shows alluvium and colluvium (**QTal**)—unconsolidated to weakly consolidated, caliche-cemented, poorly stratified, flat-lying to very shallow-dipping gravel, sand, and minor silt—as covering the area. This material is generally referred to as "basin fill" and can be quite thick, though basin fill at Quitobaquito is relatively thin compared to other areas in the monument: 10 m (30 ft) thick at Quitobaquito (Macey et al. 2021) compared to 1,500 m (4,800 ft) thick elsewhere (see "Basin Fill").

The primary feature at Quitobaquito is Quitobaquito pond (fig. 6), which covers approximately 0.3 ha (0.8 ac) and is about 1 m (3 ft) deep. Encroachment of vegetation into the pond interior, however, makes the open water area only about 0.2 ha (0.6 ac) (Kara Raymond, NPS Southern Arizona Office, hydrologist, written communication, 2 November 2021). Quitobaquito has been the site of an artificial pond since circa 1860 (Greene 1977a).

Two perennial springs feed the pond. Together, these springs compose Quitobaquito Springs (official name in the Geographic Names Information System [GNIS]; US Geological Survey and US Board on Geographic Names 1980). The main spring head (fig. 7), which Sonoran Desert Network staff refers to as "Quitobaquito Spring Southwest," is northwest of the pond. The second spring, referred to as "Quitobaquito Spring Northeast," lies just north of the main spring. Waters from the two springs flow about 100 m (300 ft) through a system of pipes, flume, and cement-lined channel to the pond.

Discharge through the outlet of the pond is rare. When water does discharge from the pond, it occupies vestiges of channels from past farming activity and then seeps into the soil or becomes lost through evaporation and transpiration (Rijk Moräwe, Organ Pipe Cactus National Monument, chief of Natural and Cultural Resources Management, written communication, 17 May 2021). At present, the pond only discharges water during or after a storm event; for example, water discharged through the pond's outlet and other places around the pond's perimeter during a 500-year storm event on 30 July 2021. The lack of water flowing through the outlet is likely due to decreasing discharge rates, increased evapotranspiration, and periodic leaks in the pond (Kara Raymond, NPS Southern Arizona Office, hydrologist, written communication, 27 April and 2 November 2021).

The NPS has been monitoring pond levels since 1991. In 2011, the Sonoran Desert Network inventoried the spring complex and has consistently monitored it since 2016 (Kara Raymond, NPS Southern Arizona Office, hydrologist, written communication, 27 April 2021). In addition, the US Geological Survey records discharge and precipitation at gage number 09535900, referred to as "Quitobaquito Spring." The record is long with the first field measurement occurring in July 1919. Recording of daily statistics began in October 1981 (US Geological Survey 2020).

Geomorphologist Kirk Bryan (1888–1950) provided the first geologic description of Quitobaquito during his survey of the area in 1917. The description was later published by the US Geological Survey in Water-Supply Paper 499 (Bryan 1925). Bryan, who is now honored by the Geological Society of America with the namesake and prestigious Kirk Bryan Award, is known best for his work in arid regions. He was a pioneer in explaining the development of landforms in arid lands.

Figure 6. Panoramic photograph of Quitobaquito.
Quitobaquito is an oasis in the middle of the Sonoran Desert. Warm springs, about 25°C (77°F), feed a shallow pond. Flow varies seasonally and annually but averages about 100 L (30 gal) per minute (Bezy et al. 2000). NPS photograph, taken 2008.

Figure 7. Photograph of Quitobaquito Spring Southwest.
The spring emerges from the orifice (referred to as "Orifice A" by Raymond et al. 2019) and appears as a muddy seep on the slope of a low hill. The water forms a channel that extends for 16 m (53 ft). Beyond that, water flows through a spring box into an artificial, concrete-lined channel for the remainder of the 100 m (330 ft) to Quitobaquito pond. The water flows quickly and clearly in channelized segments, becoming slow and algae choked in occasional pools. NPS photograph from Raymond et al. (2019, figure 4-5), taken March 2018.

Investigations since Bryan's time show that a combination of the following geologic features is likely responsible for the existence of Quitobaquito (fig. 8). However, a comprehensive groundwater flow model has yet to be fully described and understood. A primary unknown is the source of the groundwater issuing from the spring complex (see "Groundwater Assessment").

- Basin-fill deposits (unconsolidated to weakly consolidated gravel, sand, and silt) serve as the primary aquifer that supplies water to the springs at Quitobaquito. This material is deep in the basin center and thins along the mountain fronts (see "Basin Fill"). The geologic source map (Skinner et al. 2008) shows these deposits as alluvium and colluvium (**QTal**). Surficial mapping efforts divide these deposits into alluvial fan, terrace, debris flow, sheetflood, or active channel deposits, as well as areas of active arroyo development (Pearthree et al. 2012; Youberg and Pearthree 2012; Young and Pearthree 2012).
- Highly fractured bedrock consisting of 80-million-year-old (Late Cretaceous) Aguajita Spring granite (**Kga**) underlies the basin fill and is exposed in the Quitobaquito Hills and adjacent outcrops. As described in the groundwater model by Carruth (1996), fractured granite underlying La Abra Plain transmits southwesterly flowing groundwater to a line of springs—including Quitobaquito Springs and Aguajita Spring—at the southern end of Quitobaquito Hills (see fig. 8).
- A northwestward-oriented, high-angle fault—which was originally mapped by Haxel et al. (1984) and is included in the GRI GIS data—controls the location of the springs. The fault cuts across Aguajita Spring granite (**Kga**) on the southwest side of Quitobaquito Hills (see poster). Bezy et al. (2000) proposed that rocks within the fault zone were crushed to a powder, and the reduction in grain size sped up the chemical reaction with circulating groundwater, causing the rock powder to be altered to clay minerals. The resulting fine-grained, clay-rich rock, called "fault gouge," forms an impervious barrier that forces groundwater to rise to the surface as springs (see fig. 8).

Tinajas

Geomorphologist Kirk Bryan was one of the first scientists to study tinajas (natural potholes) in the US Southwest. He referred to these features as "rock tanks," though noted the name "tinaja," meaning bowl or jar in Spanish. The NPS uses the term "tinaja" for these features.

Bryan saw tinajas as "an interesting geologic problem" and noted that regional physiography controlled their distribution. Scoping participants proposed that tinajas may form along mathematically predictable spacing, though a formal study looking at distribution in the monument has not been conducted (National Park Service 2006). Such a study would be an interesting project for a Scientists in Parks (SIP) participant (see "Guidance for Resource Management").

Another interesting observation by Bryan (1923, p. 301) is that "an effective seal composed of the slime from decayed organic matter and dust" commonly covers the bottom of tinajas. More recent investigations have analyzed Bryan's so-called "slime," referring to it as "biofilm" (Chan et al. 2001, 2005, 2006). Composed of prokaryotes (single-celled organisms without a distinct nucleus) and eukaryotes (single- or multi-celled organisms with distinct nucleus or nuclei), the biofilm is likely an important component of tinaja development; it may be responsible for dissolving the cement between

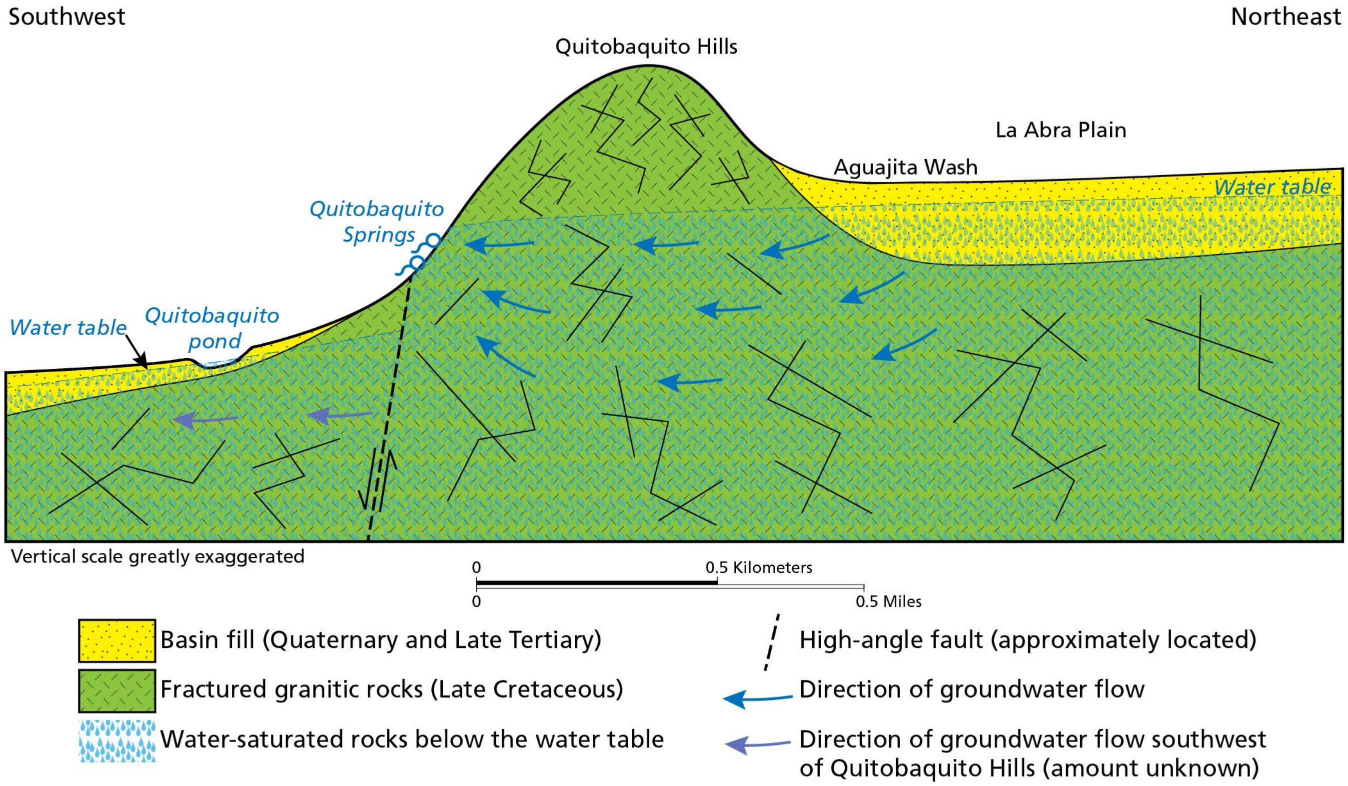

Figure 8. Hydrogeologic model for Quitobaquito.
A model by Carruth (1996) illustrates the flow of groundwater from northeast to southwest underneath La Abra Plain and the formation of Quitobaquito Springs by a fault zone on the southwestern side of Quitobaquito Hills. Basin fill, which covers fractured granitic bedrock and interfingers with stream-channel deposits in Aguajita Wash, serves as the primary aquifer. Exposed bedrock, for example in the Puerto Blanco Mountains (not shown), provides a surface for mountain-front recharge, though local annual recharge may be small relative to the total amount of groundwater in storage. Figure by Trista Thornberry-Ehrlich (Colorado State University) after Carruth (1996, figure 4) and Zamora et al. (2020, figure 5).

rock grains, allowing the tinaja to enlarge, as well as for sealing the tinaja, enabling it to retain water longer than the surrounding rock. Thus, studies of tinajas have revealed interesting links between biology (life) and geology (rocks and water).

Although a formal study has not been conducted on the relationship between tinajas and host-rock type at the monument, scoping participants thought that most tinajas occurred in the rhyolite of Montezuma's Head ("**Tm**" map units), though the Childs Latite ("**Tc**" units) also may host tinajas (National Park Service 2006). Tinajas in the monument tend to form at drainage bottoms (Kara Raymond, NPS Southern Arizona Office, hydrologist, written communication, 27 April 2021).

Although Bryan recognized the importance of tinajas in arid regions—where small water supplies made possible "a journey which otherwise could not be undertaken" (Bryan 1920, p. 188)—recognition of the importance of tinajas long predates him. During an overland journey in 1699 to the mouth of the Colorado River, for example, Father Eusebio Kino relied almost entirely on water obtained from tinajas, which were made known to him by the Hia C'ed O'odham people. In 1744, Spanish Lt. Juan Bautista de Anza led an expedition from Nogales, Arizona, to San Francisco Bay, where he established the first non-Native settlement in that area (see GRI report about John Muir National Historic Site by KellerLynn 2021a). Juan Bautista de Anza retraced Kino's route to the mouth of the Colorado River, watering his horses at the Tinajas Altas (Bolton 1936), which is within the Cabeza Prieta National Wildlife Refuge west of the monument.

The route followed by Kino and de Anza, which led to and from the Colorado River, became known as the Camino del Diablo ("Devil's Highway"). Traces of the Camino del Diablo occur in the monument (National Park Service 2016). Virtually all the water available along this route was provided by tinajas (Brown and Johnson 1983). Where tinajas were lacking, Hohokam and O'odham would place large ollas (ceramic jars) within the landscape as artificial tinajas (Rijk Moräwe, Organ Pipe Cactus National Monument, chief of Natural and Cultural Resources Management, written communication, 7 April 2021).

The creation of paved highways through the region decreased the importance of tinajas to desert travelers, but the importance of tinajas continues. Scoping participants went so far as to identify tinajas as the most significant source of surface water in the monument (National Park Service 2006). Moreover, a study by Brown et al. (1983, p. 88) stated "from the standpoint of relative abundance and widespread distribution, tinajas are the most important surface water resource at [Organ Pipe Cactus National Monument]." Today, tinajas are important as water sources for recreational backcountry users. Selected tinajas in the monument also show evidence that these features are used along illegal border-crossing routes between Mexico and the United States (Cunningham 1982). In the backcountry, humans compete with wildlife for one of the desert's most important but limited resources.

Because of the way reporting has taken place (i.e., "site" vs. "individual tinaja") and because water retention in tinajas is ephemeral, the actual number of tinajas in the monument is unclear. For example, a study by Brown et al. (1983) noted 60 individual tinajas at 48 sites in the monument while Brown and Johnson (1983) reported 49 known intermittent and perennial tinajas. Of these 49 tinajas, 34 were in the Ajo Range, 10 were in the Bates Mountains, and five were in the Puerto Blanco Mountains. An ecological monitoring report (Pate and Filippone 2006) estimated that the monument had 68 major tinajas.

Some tinajas at the monument are so large that they support their own riparian vegetation (National Park Service 2006). The largest tinaja documented by Brown and Johnson (1983)—Estes Canyon No. 1—covers an area of 83 m^2 (890 ft^2). At 2.7 m (8.9 ft) deep, the tinaja referred to as "Spring Arroyo No. 2" by Brown and Johnson (1983) is the deepest.

Large tinajas have been known to trap animals that enter them for water or vegetation. For example, Snake Pit tinaja in Alamo Canyon was so named because of the large numbers of snakes that were trapped at the bottom of this steep-sided tinaja (Brown et al. 1983). Notably, Hensley (1950) described a new subspecies of Sonoran whipsnake (*Masticophis bilineatus lineolatus*) from specimens taken from this tinaja (Brown et al. 1983).

Most tinajas are passive water sources and require recharge by direct precipitation. Tinajas of insufficient depth to maintain water from one rainy season to the next become dry. Factors that affect the presence or longevity of water in a tinaja include the amount of protection or shade, the size of the adjacent bedrock catchment area, the amount of sediment infilling, and the permeability of the bedrock (Brown and Johnson 1983; Pate and Filippone 2006). In general, factors affecting the longevity of water storage act in unison and are difficult to separate, but clearly, water in protected tinajas remains longer because of reduced evaporation by sun and desiccation by winds (Brown and Johnson 1983).

Brown and Johnson (1983) discussed the permanence of water in tinajas and classified them as "ephemeral," "intermittent," and "perennial." That study's measurements provide general guidelines for tinaja classification, though the actual longevity of water retention may vary somewhat from these guidelines. In the Ajo Range, water loss during the dry season (15 April to 15 July) ranged from 0.8 cm (0.3 in) per day to 2.0 cm (0.8 in) per day, averaging 1.5 cm (0.6 in) per day (Sellers and Hill 1974; Henry and Sowls 1980). Based on those data and a drought lasting six months, water in a tinaja must be at least 2.7 m (8.9 ft) deep for it to be considered perennial (180 days at 1.5 cm [0.6 in] per day average water loss). An ephemeral tinaja is no more than 0.6 m (2 ft) deep (30 days at the maximum water loss of 2.0 cm [0.8 in] per day), this being the minimum depth necessary to sustain water for at least a one-month period during the dry season. Intermittent tinajas are of intermediate depth between ephemeral and perennial.

In the monument, monitoring of tinajas, as well as springs and seeps, by the Sonoran Desert Network focuses on four sentinel sites: East Arroyo tinaja (fig. 9), Snake Pit tinaja, Dripping Springs, and Quitobaquito Springs (McIntyre et al. 2018; Raymond et al. 2019). The two tinajas are in the Ajo Range. The two springs are in the Quitobaquito Hills. Bull Pasture is the site of a third major spring systems in the monument.

Bull Pasture

In the Ajo Range on the eastern side of the monument, Bull Pasture (see poster) represents another human–geologic connection. A combination of topography and geology—creating a hidden valley with a spring, tinajas, and grass suitable for grazing—drew and focused human activity to the site.

Bull Pasture covers about 60 ha (150 ac) and averages 950 m (3,100 ft) in elevation. It overlooks Estes Canyon and is surrounded by ridges. Topographic differences between valley floor and ridgetop result in a large grassy, enclosed "pasture," which is underlain by alluvium and colluvium (**QTal**). Adjacent cliffs consist of the rhyolite

Figure 9. Photographs of tinajas.
Left: Located in the Ajo Range, East Arroyo tinaja is a large rock basin formed in the rhyolite of Montezuma's Head (Tmr). The primary orifice pool (shown here) is a round, 10 × 10 m (33 × 33 ft), bedrock tank. Two "bathtub rings" are visible above the pool, indicating historically higher water levels. The pool was approximately 70–100 cm (30–40 in) deep when measured in March 2018. NPS photograph from Raymond et al. (2019, figure 4-3). Right: Located in Bull Pasture, this tinaja is surrounded by the rhyolite of Montezuma's Head (Tma and Tmv). A spring that feeds this tinaja emerges along a normal fault. The Sonoran Desert Network does not monitor this tinaja. NPS photograph from Organ Pipe Cactus National Monument (2011, p. 10), date unknown.

of Montezuma's Head (**Tmr** and **Tma**). A spring—Bull Pasture Spring—emerges at the northern part of the pasture, and several tinajas provide water (see fig. 9).

The Mexican names for Bull Pasture are "Tinajas de los Torres," meaning "watering tanks of the bulls," or "Los Portreritos," meaning "little pastures." These names highlight Bull Pasture as a culturally significant locale associated with the evolving cattle industry of southern Arizona during the early part of the 20th century. Use of the area for livestock grazing and corralling ended in the late 1920s.

The site also played an interesting part in the border disturbances of the early 20th century when groups representing various disfavored factions of Mexican politics crossed the border and hid in Bull Pasture to escape their revolutionary adversaries. It served as a rendezvous location for armed Mexican refugees during the turmoil of the Mexican Revolution. In 1915, one group of Villistas (followers of Francisco "Pancho" Villa, who was a Mexican revolutionary general and one of the most prominent figures of the Mexican Revolution) was arrested in the basin by US immigration authorities. As the threat of such visitations increased, the US government dispatched army troops to the scene (Greene 1977b).

Now, Bull Pasture is a popular hiking destination. The 5 km (3 mi) roundtrip is considered difficult because of steep grade and exposed cliffs but rewards hikers with spectacular views of Mexico and the monument. The hike can be done as a loop with the Estes Canyon trail (National Park Service 2020c).

Historic Mines

Mining is an important component of US heritage (Burghardt et al. 2014). Long before the arrival of Europeans, Native peoples mined flint (see GRI report about Alibates Flint Quarries National Monument by KellerLynn 2015b), obsidian (see GRI report about Bandelier National Monument by KellerLynn 2015a), and copper (see GRI report about Tuzigoot National Monument by KellerLynn 2019b) for tools and weapons; turquoise and other stones for jewelry; and clay (see GRI report about Casa Grande Ruins National Monument by KellerLynn 2018) for pots, pipes, and building materials. During the 16th century, the lure of gold and the prospect of great wealth drove Spanish explorers into North and South America. Later, gold rushes and "Manifest Destiny" were responsible for people of European descent settling much of the western United States. The industrial age of the 19th and 20th centuries introduced large-scale extraction of mineral resources such as coal, copper, iron, oil, and gas, leaving significant adverse environmental impacts on the land (Burghardt et al. 2014; see "Abandoned Mineral Lands").

In 1854, in Ajo, the Arizona Mining and Trading Company launched the modern era of hard-rock mining. A burgeoning mining industry stimulated early growth in the Arizona Territory. By 1864, prospectors made up nearly 25% of the male, non-Native population. By the 1870s, a plethora of hard-rock mines were yielding prodigious volumes of copper, lead, zinc, silver, and gold ore. In 1912, the newly christened state of Arizona supported 445 active mines, 72 concentrating facilities, and 11 smelters with a gross value of nearly $67 million (equivalent to $1.4 billion in 2006 dollars) (Arizona Geological Survey 2020c).

The following three mines within the monument are listed in the National Register of Historic Places. These mines highlight the monument's mining legacy.

- Victoria Mine—Of all the mining properties within the monument, the Victoria Mine is one of the most historic and singularly successful (Greene 1977f). The mine produced silver, lead, and gold. At about 120 m (400 ft) deep, it is an example of an early deep-shaft mine (National Park Service 2013). Originally called "La Americana" by Cipriano Ortega, an outlaw-turned-entrepreneur who acquired the mine in about 1880, the mine was renamed by Mikul G. Levy, who purchased the mine in 1899. Levy used the name "Victoria" after Victoria Leon, the wife of Jose Leon, who minded Levy's store at Quitobaquito (Greene 1977f). The Victoria Mine (fig. 10), as well as the Lost Cabin and Martinez Mines, are situated on the eastern flank of the Sonoyta Mountains (see poster). These mines exploited the granite of Senita Basin (**TKgs**), which was emplaced as a pluton (igneous intrusion) during the Laramide Orogeny (mountain-building event; see "Laramide Orogeny"). The Victoria, Lost Cabin, and Martinez Mines are located along the margins of this granitic pluton.

Figure 10. Photograph of the store at Victoria Mine. Victoria Mine represents the oldest known example of mining activity within the monument and constitutes one of its major historical properties. The surviving structures at Victoria Mine include a dilapidated rectangular stone building, probably built around 1900, which served as a store. The building measures roughly 6 m × 5 m (21 ft ×16 ft). Its walls are 80 cm (30 in) thick and made of light-colored (pink and white) granite (probably granite of Senita Basin, TKgs) with mud and gravel chinking. The roof of the structure, now gone, was sheet iron. NPS photograph, date unknown.

- Growler Mine Area—West of Growler Pass and Bates Well at the southern end of the Growler Mountains, the Growler Mine Area represents one of the earliest and most intensely worked copper areas in the "border country" south of Ajo. The mine area consisted of many working mines, including Growler Mine, Alice, Golden Eagle, Copper Hill shaft (82 m [268 ft] deep), Yellow Hammer (76 m [250 ft] deep and the richest claim), and the Morning Star. Growler Mine was one of the first mines opened in the region and became a reliable producer of high-grade copper ore (Greene 1977b). Sometime in the late 1880s, Growler Mine was named by Frederick Wall for his friend John Growler. Wall was a well-known prospector who frequented the area as early as 1874; however, little is known about John Growler for whom the mine—as well as the pass and mountains—is named (Greene 1977c). Occupation of the mine area quickly followed the discovery of rich copper deposits, and by the 1890s a small

community, called “Growler Camp,” was established near the mine. Mining began on a small scale and blossomed early in the 20th century. Productivity peaked in 1916. In 1956 and 1957, the patented claims were turned over to the NPS (Greene 1977c). The Growler Mine exploited Cretaceous volcanic rocks, undivided (**Kvu**). These rocks area associated with Laramide-related volcanism (Skinner et al. 2008).
- Milton Mine—Located on the southernmost fringe of the Puerto Blanco Mountains (see poster), the Milton Mine exemplifies a low-budget form of surface mining that was common in the border country early in the 20th century (Greene 1977d). Throughout its existence, the Milton Mine produced gold and copper ore in very small quantities. The mine was named after its discoverer, Jefferson Davis Milton, who found it while serving as an immigration agent in the border region. Milton filed a claim for the mine in 1911. Rocks of La Abra, greenschist and metaconglomerate (**Jag**), serve as host rocks for mineralization at the Milton Mine. These rocks are associated with arc magmatism and plutonism that took place during the Jurassic Period (see “North American Cordillera”).

Montezuma Head

Montezuma Head (official spelling of the US Board on Geographic Names; US Geological Survey 1981) is near the eastern boundary of the monument at the northern end of the Ajo Range. Spelled “Montezuma’s Head,” the feature was listed in the National Register of Historic Places in 1994. Skinner et al. (2008) also used the possessive form—Montezuma’s Head—for the map unit named after this feature.

Montezuma Head is a sacred mountain of the Tohono O’odham Nation and a home of I’itoi (“creator god”); Montezuma is another name for I’itoi (Underhill 1969; Galinier 1991). Montezuma Head (I’itoi Mo’o) is one of three “homes” of I’itoi; the other two are Baboquivari Peak in the Tohono O’odham Nation (east of the monument) and Carnegie Peak in the Pinacate region of Mexico (south of the monument). Montezuma Head is the primary feature on the official seal of the Gu Vo District of the Tohono O’odham Nation. District residents, especially from Kuakatch and Shuchuli, regularly visit the site to meditate, worship, and leave gifts of food and personal belongings for I’itoi. The site is also sacred to the Hia C’ed O’odham people, whose name for Montezuma is I’ithi (Rijk Moräwe, Organ Pipe Cactus National Monument, chief of Natural and Cultural Resources Management, written communication, 24 May 2021).

The rock formation of Montezuma Head is perceived as an old woman sitting (‘Oks Daha; Hoy 1976) with her head and shoulders facing southwest (fig. 11). A smaller rock formation situated just to the north is the woman’s basket (Hoy 1976).

With respect to a geologic interpretation, Montezuma Head is a monolith erupted onto the landscape about 17.5 million to 16 million years ago. It is composed of the rhyolite of Montezuma’s Head (see poster and “Ajo Volcanic Field”).

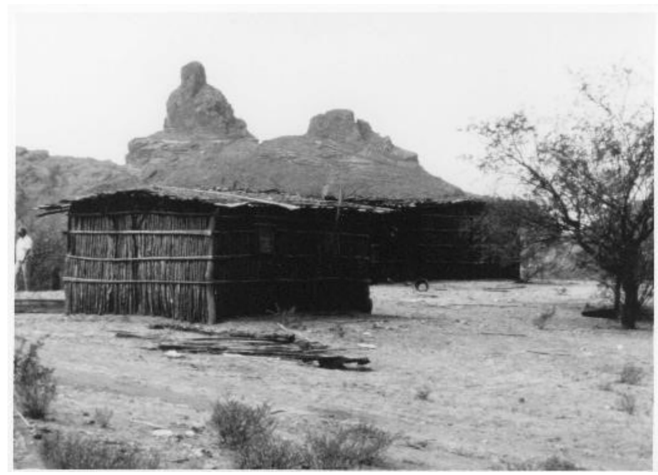

Figure 11. Photograph of Montezuma Head. As viewed from the Gu Vo District of the Tohono O’odham Nation (east of the monument), Montezuma Head appears as Old Woman Sitting (left) and Old Woman’s Basket (right). The old woman’s head and the uppermost part of the basket are composed of the rhyolite of Montezuma’s Head, rhyolite, rhyodacite, and minor dacite flows, flow breccias, and plugs (Tmr). The lower portions of these features are composed of the rhyolite of Montezuma’s Head, tuff and tuff breccia (Tmt). The features sit atop sedimentary and volcanic rocks, undivided (Tsvu). Photograph by B. Jones (NPS Western Archeological and Conservation Center, taken April 1972) from Greene (1977e).

Rock Varnish and Petroglyphs

Also called “desert varnish,” rock varnish (a natural veneer composed of clays, manganese and iron oxides, and organic compounds) covers many surfaces in the monument. Rock varnish appears to have developed best on rocks with moderately rough surfaces that are resistant to weathering. Sandstone, basalt, and many metamorphic rocks are commonly well varnished, whereas siltstones and shales disintegrate too rapidly to retain such a coating. Also, desert pavement—pebble- and cobble-covered ground surface abundant in arid lands (see "Desert Pavement")—commonly glistens because of its rock-varnish patina (Bezy et al. 2000).

About 70% of the total mass of a rock-varnish deposit is composed of clay minerals. Notably, this clay component comes from windblown dust and is not an alteration product of the surface of the underlying rock. Many researchers have proposed that microbial activity is significant for the formation of rock varnish, though others have invoked an inorganic origin such as silica (SiO_2) coatings composed of opal. Despite the extensive literature related to rock varnish, many uncertainties and controversies regarding its composition and formation remain (Dickerson 2011).

The oft-lustrous coating of rock varnish ranges in color from light brown to black, depending on how much has accumulated. Well-varnished surfaces have a luster that causes entire hillsides to glisten in the intense desert sunlight. This mineral coating gives the landscape its warm tones of brown and ebony, commonly masking brilliantly colored bedrock underneath (Bezy et al. 2000).

Although rock varnish forms on surfaces in arid regions throughout the world, varnish in the US Southwest provokes great interest because of its archeological importance (Bezy et al. 2000). By chipping away the varnish, prehistoric peoples created distinctive dark-on-light petroglyphs (rock art). Documented petroglyphs at the monument (see Rankin 1995; National Park Service 2021b) include geometric designs (e.g., concentric circles, spirals, and parallel lines), zoomorphic lifeforms (e.g., snakes), and anthropomorphs (human-like figures) (fig. 12). These images lend cultural significance to geologic features and connect the people who created them to the monument's geologic foundation.

The presence of petroglyphs links the monument to other units of the National Park System, including Saguaro National Park (see GRI report by Graham 2010), Great Basin National Monument (see GRI report by Graham 2014), Lava Beds National Monument (see GRI report by KellerLynn 2014b), Petrified Forest National Park (see GRI report by KellerLynn 2010), and Petroglyph National Monument (see GRI report by KellerLynn 2017).

According to the monument's archeological survey (Rankin 1995), the monument also hosts pictographs (painted rock art). Arches National Park (see Geologic Resource Evaluation [GRE, precursor to the GRI] report by Graham 2004), Canyonlands National Park (see GRE report by KellerLynn 2005), Dinosaur National Monument (see GRE report by Graham 2006b), and Gila Cliff Dwellings National Monument (see GRI report by KellerLynn 2014a) also contain notable pictographs.

Figure 12. Photographs of petroglyphs.
A patina of rock varnish paints the landscape in warm tones of brown and black. Further decoration is provided by petroglyphs, a form of rock art where prehistoric people pecked images into the “mineral skin” to reveal fresh rock below. NPS photographs, taken 2004 and 2007.

Geologic History, Features, and Processes

The geologic features and processes highlighted in this chapter represent geologic events that led to the monument's present-day landscape. Selection of these features and processes was based on input from scoping and conference-call participants, analysis of the GRI GIS data, and research of the scientific literature and NPS reports. These features and processes are discussed more-or-less in order of geologic age (oldest to youngest).

Geologic Time Scale

The following geologic time scale (table 1) puts the divisions of geologic time in stratigraphic order, with the oldest divisions at the bottom and the youngest at the top. Likewise, rocks and unconsolidated deposits are listed stratigraphically. Except for the oldest (Proterozoic) rocks, which are found north of the monument, only geologic units mapped within the monument are included in table 1. Proterozoic rocks are included because of their tie to a particular rock unit—orthogneiss and foliated granite (map unit **TRYXo**)—which is found in the monument.

Items in parentheses in the geologic time scale include GRI map abbreviations for geologic time units (see "Period" and "Epoch" columns in table 1). For example, "**K**" in a map unit symbol means that a map unit was deposited during the Cretaceous Period (~145.0 million to 66.0 million years ago). "**T**" in a map unit symbol stands for Tertiary, which is a widely used but obsolete term for the geologic period from 66.0 million to 2.6 million years ago (see "A Note About the Obsolete Tertiary Period"). Accompanying lowercase letters of a map unit symbol indicate the name of a map unit such as "**dc**" for Daniels Conglomerate (**Tdc**).

The names of map units used in this table and throughout the report reflect the formal nomenclature found in the US Geologic Names Lexicon ("Geolex"), which is a national compilation of names and descriptions of geologic units (see "Additional References, Resources, and Websites"). In geologic terminology, a formation is the fundamental rock-stratigraphic unit, meaning it is mappable (at a particular scale), lithologically distinct (with respect to rock type and other characteristics such as color, mineral composition, and grain size) from adjoining strata, and has a definable upper and lower contact (surface between two types or ages of rock). A formation can be divided into "members" or combined into a "group." Map unit names that are formally recognized as formations are capitalized, for example Daniels Conglomerate (**Tdc**) and Childs Latite ("**Tc**" units), whereas those that are not formally recognized are lowercase, for example Gunsight Hills granodiorite (**Kgg**) and rhyolite of Pinkley Peak ("**Tp**" units), though the associated geographic names are capitalized. Table 1 notes the formal names found in Geolex.

The table also has a column for "Age." The various ages listed in the table follow the International Commission on Stratigraphy (2021), except for informal ages of the early, middle, and late Miocene Epoch, which reflect guidance from the AZGS (see "A Note About the Miocene Epoch"). Although "Tertiary" is not a formally accepted term of the International Commission on Stratigraphy (2021), it is used in this report because the source map (Skinner et al. 2008) and accompanying GRI GIS data use it.

Additionally, the table has a column for "Geologic Events." By reading the "Geologic Events" column from bottom to top, a geologic history is provided. Detailed descriptions of geologic events and associated geologic features are provided in sections of this chapter. The "Location" column of the table lists examples of where a geologic event is represented in the monument.

Information in the geologic time scale, including timing of geologic events, is primarily from the geologic source map (Skinner et al. 2008) but also Keith (1971), Bezy et al. (2000), and Anderson (2015).

A Note About the Miocene Epoch

This GRI report follows guidance provided by the AZGS regarding the informal (early, middle, and late) ages of the Miocene Epoch: early Miocene (23 million to 16 million years ago), middle Miocene (16 million to 10 million years ago), and late Miocene (10 million to 5.3 million years ago). Notably, the breaks between these informal subdivisions probably depend on individual workers' opinions (Phil Pearthree, AZGS, director and state geologist, email communication, 31 August 2020). Events considered part of the late Miocene Epoch took place following the most severe crustal extension in western Arizona.

Table 1. Geologic time scale.

Period	Epoch	Age	Geologic Map Units	Geologic Events	Locations
Quaternary (Q) and Tertiary (T) (or Neogene [N]; see "A Note About the Obsolete Tertiary Period")	Holocene (H), Pleistocene (PE), and Pliocene (PL)	Less than 5.3 million years ago	alluvium and colluvium (**QTal**)	**QTal** is deposited during basin filling and modern landscape development. Basin filling correlates with extension (pulling apart of Earth's crust in the Basin and Range physiographic province), which ended about 5 million years ago in southwestern Arizona. Modern sedimentation includes formation of bajadas and development of washes.	• Valley of the Ajo • Sonoyta Valley • La Abra Plain • Growler Valley
Quaternary (Q) and Tertiary (T) (or Neogene [N])	Pleistocene (PE) and Pliocene (PL)	5.3 million to 11,700 years ago	terrace gravels (**QTg**)	Terrace gravels (**QTg**) record a period of landscape development between basin filling and modern landscape development. As interpreted by Skinner et al. (2008), terrace gravels are high remnants of earlier valley floors, but they are perhaps more accurately referred to as relict ("abandoned") alluvial fans (Phil Pearthree, AZGS, director and state geologist, written communication, 29 June 2021).	• Cipriano Hills, southeast margins • Puerto Blanco Mountains, west and northwest of Twin Peaks Campground
Tertiary (T) (or Neogene [N])	Late Miocene (MI)	10.0 million to 5.3 million years ago	normal faults *Note:* Most (95%) of mapped faults in the monument are normal faults (see poster).	In general, Basin and Range extension (younger than Oligo-Miocene extension) takes place following active volcanism in the Ajo volcanic field and ceases in southwestern Arizona about 5 million years ago.	Mountain ranges in the monument rise up as basins drop down along normal faults.
Tertiary (T) (or Neogene [N])	Middle Miocene (MI)	16 million to10 million years ago	Batamote Andesite complex (**Tbau**, **Tba**, **Tbai**, and **Tbab**) *Note:* Batamote Andesite is formally recognized in Geolex.	"**Tba**" units, which are associated with the Ajo volcanic field, erupt onto the landscape between 16 million and 14 million years ago (Skinner et al. 2008).	• Batamote Mountains shield volcano (northeast of monument) • Tillotson Peak • Low hills in the southern part of the Valley of the Ajo • Cipriano Hills ("Tb" units erupted onto rhyolite of Pinkley Peak)
Tertiary (T) (or Neogene [N])	Early Miocene (MI)	23 million to 16 million years ago	sedimentary and volcanic rocks, undivided (**Tsvu**)	Oligo-Miocene extension takes place about 36 million to 17 million years ago (Brown 1992). Volcanic rocks overlap and are interbedded with clastic sedimentary rocks derived from underlying bedrock (**Tsvu**), suggesting that volcanism and extension were synchronous. **Tsvu** contains dikes and flows composed of rhyolite of Montezuma's Head (**Tmd**, **Tmr**).	• Little Ajo Mountains • Ajo Range

Table 1, continued. Geologic time scale.

Period	Epoch	Age	Geologic Map Units	Geologic Events	Locations
Tertiary (T) (or Neogene [N])	Early Miocene (MI)	23 million to 16 million years ago	rhyolite of Montezuma's Head (**Tmu**, **Tma**, **Tmat**, **Tmr**, **Tmt**, **Tmb**, and **Tmd**)	"**Tm**" units are associated with the Ajo volcanic field and erupt onto the landscape between 17.5 million and 16 million years ago (Skinner et al. 2008).	Ajo Range
Tertiary (T) (or Neogene [N])	Early Miocene (MI)	23 million to 16 million years ago	basalt and basaltic andesite, undivided (**Tbu**)	**Tbu** is associated with development of the Ajo volcanic field.	• Batamote Mountains shield volcano • Bates Mountains
Tertiary (T) (or Neogene [N])	Early Miocene (MI)	23 million to 16 million years ago	dacite, undivided (**Tdu**)	**Tdu** is associated with development of the Ajo volcanic field.	• Batamote Mountains shield volcano • Bates Mountains • Diablo Mountains
Tertiary (T) (or Neogene [N])	Early Miocene (MI)	23 million to 16 million years ago	rhyolite flows, dikes, and felsic pyroclastic rocks, undivided (**Tru**)	**Tru** is associated with development of the Ajo volcanic field.	• Batamote Mountains shield volcano • Southern end of the Growler Mountains
Tertiary (T) (or Neogene [N])	Early Miocene (MI)	23 million to 16 million years ago	Growler Mountain rhyolite, welded tuff (**Ttu**)	**Ttu** is associated with development of the Ajo volcanic field.	Growler Mountains
Tertiary (T) (or Neogene [N])	Early Miocene (MI)	23 million to 16 million years ago	Daniels Conglomerate and associated lake deposits (**Tdc**) *Note*: Daniels Conglomerate is formally recognized in Geolex.	Volcanic rocks overlap and are interbedded with clastic sedimentary rocks derived from underlying bedrock (**Tdc**), suggesting that volcanism and Oligo-Miocene extension were synchronous. *Note*: Basal portion of the Daniels Conglomerate interfingers with Childs Latite (**Tcl**).	• Growler Mountains • Ajo Range
Tertiary (T) (or Neogene [N])	Early Miocene (MI)	23 million to 16 million years ago	Childs Latite and coeval plutonic rocks (**Tcm**, **Tcb**, **Tca**, **Tcl**, and **Tcu**) *Note*: Childs Latite is formally recognized in Geolex.	"**Tc**" units are associated with the Ajo volcanic field and erupt onto the landscape more than 18 million years ago (Skinner et al. 2008).	• Summit of Pinkley Peak • Ajo Range • Northeast side of Puerto Blanco Mountains • Bates Mountains
Tertiary (T) (or Neogene [N])	Early Miocene (MI)	23 million to 16 million years ago	rhyolite of Pinkley Peak (**Tpa**, **Tphd**, **Tpt**, **Tprd**, and **Tpr**)	"**Tp**" units are associated with the Ajo volcanic field and erupt onto the landscape between 22 million and 18 million years ago (Skinner et al. 2008).	• Cipriano Hills • Northeast side of Puerto Blanco Mountains • Gunsight Hills

Table 1, continued. Geologic time scale.

Period	Epoch	Age	Geologic Map Units	Geologic Events	Locations
Tertiary (T) (or Paleogene [PG] and Neogene [N])	Late Oligocene (OL) and early Miocene (MI)	28.4 million to 16 million years ago *Note*: 28.4 million is from the 2009 GSA timescale, which still shows "late Oligocene" (Chattian). 16 million is from guidance by the AZGS.	volcanic and volcaniclastic rocks, undivided (**Tvu**)	**Tvu** marks the beginning of volcanic activity in the Ajo volcanic field. **Tvu** is between about 25 million and 21 million years old (Skinner et al. 2008). *Note*: **Tvu** underlies Childs Latite (**Tcl**) and Daniels Conglomerate (**Tdc**).	Three outcrops at the southern boundary of the monument, near Dos Lomitas Ranch (east of Lukeville)
Tertiary (T) (or Paleogene [PG] and Neogene [N])	Eocene (E) to early Miocene (MI)	56.0 million to 16 million years ago	Tertiary dikes, undivided (**Td**) *Note*: This is a linear geologic unit (see poster).	Oligo-Miocene extension takes place about 36 million to 17 million years ago (Brown 1992). Dikes (**Td**), which are indicative of extension, intrude preexisting rocks, including **Kga**, **Tpr**, **Tmr**, and **Tcl**.	• Quitobaquito Hills • Puerto Blanco Mountains • Twin Peaks
Paleogene (PG)	Eocene (E)	56.0 million to 33.9 million years ago	No diagnostic rocks recorded in the region or monument	Deformation and sedimentation associated with the Laramide Orogeny end about 40 million years ago in southwestern Arizona (Skinner et al. 2008). The Eocene Epoch is a relatively quiescent period.	n/a
Tertiary (T) (or Paleogene [PG]; see "A Note About the Obsolete Tertiary Period") and Cretaceous (K)	Late Cretaceous (K), Paleocene (EP), Eocene (E), and Oligocene (O)	100.5 million to 23.0 million years ago	granite of Senita Basin (**TKgs**)	The Laramide Orogeny continues but ends by the early Tertiary (~60 million to 58 million years ago; Skinner et al. 2008). Maximum convergence rates occur between 70 million and 50 million years ago (Shafiqullah et al. 1980). **TKgs** is the youngest major suite of rocks associated with the widespread igneous intrusions of the Laramide Orogeny.	Senita Basin
Cretaceous (K)	Late Cretaceous (K)	100.5 million to 66.0 million years ago	Bandeja Well granodiorite (**Kgb**)	**Kgb** is associated with Laramide Orogeny plutonism.	Growler Mountains, including hills on either side of Growler Wash
Cretaceous (K)	Late Cretaceous (K)	100.5 million to 66.0 million years ago	Ajo pluton, granitic rocks and metavolcanic schist, undivided (**Kap**)	**Kap** is associated with Laramide Orogeny plutonism.	Sonoyta Mountains

Table 1, continued. Geologic time scale.

Period	Epoch	Age	Geologic Map Units	Geologic Events	Locations
Cretaceous (K)	Late Cretaceous (K)	100.5 million to 66.0 million years ago	Gunsight Hills granodiorite and related rocks (**Kgg**)	**Kgg** is associated with Laramide Orogeny plutonism about 67 million years ago (Skinner et al. 2008).	• Gunsight Hills • Two knobs north of Alamo Wash
Cretaceous (K)	Late Cretaceous (K)	100.5 million to 66.0 million years ago	Aguajita Spring granite (**Kga**) tectonic slide	"Compressive deformation" and faulting during the Laramide Orogeny puts **TRYXo** in contact with **Kga**. Reactivation of the Quitobaquito thrust takes place.	Quitobaquito Hills
Cretaceous (K)	Late Cretaceous (K)	100.5 million to 66.0 million years ago	Cretaceous volcanic rocks, undivided (**Kvu**)	The Laramide history of southwestern Arizona commences in the Late Cretaceous Period (~80 million to 70 million years ago; Skinner et al. 2008). **Kvu** is associated with Laramide-related volcanism.	Growler Mountains, including hills on either side of Growler Wash
Cretaceous (K) and Jurassic (J)	Late Jurassic (J) to Early Cretaceous (K)	163.5 million to 100.5 million years ago	conglomerate at Scarface Mountain (**KJc**)	Metamorphosed conglomerates and breccias (**KJc**, as well as **Jag**) represent sediments that erode from highland areas about 150 million to 140 million years ago (Bezy et al. 2000). Highland areas are uplifted during an earlier period of deformation as part of the magmatic arc.	Growler Mountains, including hills on either side of Growler Wash
Jurassic (J)	Late Jurassic (J)	163.5 million to 145.0 million years ago	rocks of La Abra (**Japs**, **Jap**, **Jaq**, **Jas**, and **Jgr**) tectonic slide	Jurassic plutonic rocks (**Jga**, **Jgr**, **Jgrr**, **Jgd**; see below) are variably metamorphosed, possibly due to deformation–related thrust faulting less than 160 million years ago (based on the age of **Jaq**; Skinner et al. 2008).	• Puerto Blanco Mountains • Agua Dulce Mountains (west of the monument) • Quitobaquito Hills
Jurassic (J)	Late and Middle Jurassic (J)	174.1 million to 145.0 million years ago	thrust fault	Thrust faulting between 170 million and 148 million years ago (Anderson 2015) is associated with the local Quitobaquito thrust, regional Mojave–Sonora megashear, and continental-scale Mexico–Alaska megashear (see fig. 14).	Quitobaquito thrust in Quitobaquito Hills
Jurassic (J)	Late and Middle Jurassic	174.1 million to 145.0 million years ago	rocks of La Abra (**Jag**, **Jgrr**, **Jgr**, and **Jga**) tectonic slide	Rocks of La Abra are volcanic and intrusive rocks associated with the formation of a magmatic arc (raised area of the subduction zone; see fig. 13) about 190 million to 175 million years ago.	• Puerto Blanco Mountains • Agua Dulce Mountains (west of the monument)
Jurassic (J)	Early to Middle Jurassic (J)	201.3 million to 163.5 million years ago	n/a	The supercontinent Pangea begins breaking apart about 200 million years ago.	n/a

Table 1, continued. Geologic time scale.

Period	Epoch	Age	Geologic Map Units	Geologic Events	Locations
Triassic (TR)	All TR epochs	251.9 million to 201.3 million years ago	orthogneiss and foliated granite (**TRYXo**) *Note*: Of uncertain age.	The supercontinent Pangea is intact and achieves its greatest extent about 250 million years ago.	Quitobaquito Hills
Permian (P)	All P epochs	298.9 million to 251.9 million years ago	n/a	Permian rocks are probably present in the region but erode away before Jurassic time. Most of Arizona is part of a stable cratonic platform (part of a continent that is covered by flat-lying or gently tilted sedimentary rocks, underlain by a complex of rocks that were consolidated during earlier deformation) (Shafiqullah et al. 1980).	n/a
Pennsylvanian (PN)	All PN epochs	323.2 million to 298.9 million years ago	n/a	Pennsylvanian rocks are probably present in the region but erode away before Jurassic time.	n/a
Mississippian (M) and Devonian (D)	All M and D epochs	419.2 million 323.2 million years ago	Escabrosa and Martin Formations (**MDm**) *Note*: In Geolex, formal names are Escabrosa Group/Limestone and Martin Formation/ Limestone.	**MDm**, which consists of limestone, is deposited during a series of marine transgressions (sea level rise/land retreat).	Outcrops in San Cristobal Wash
Silurian (S)	All S epochs	443.8 million to 419.2 million years ago	n/a	no regional record of events	n/a
Ordovician (O)	All O epochs	485.4 million to 443.8 million years ago	n/a	no regional record of events	n/a
Cambrian (C)	All C epochs	541.0 million to 485.4 million years ago	Bolsa and Abrigo Formations (**Cs**) *Note*: In Geolex, formal names are Bolsa Quartzite and Abrigo Limestone.	Besides **TRYXo** (see below), **Cs** is the oldest rock unit in the monument. **Cs** is deposited during shallow sea transgression (spread of sea over land), likely in an intertidal or shallow subtidal environment.	Growler Mountains
Triassic? (TR) Mesoproterozoic? (Y) Paleoproterozoic? (X)	Unknown	Unknown	orthogneiss and foliated granite (**TRYXo**) *Note*: Of uncertain age.	Combined with **Xp**, **Xcg**, and **Ycs**, **TRYXo** represents early to middle Proterozoic continental crust formation and mountain building.	Quitobaquito Hills

Table 1, continued. Geologic time scale.

Period	Epoch	Age	Geologic Map Units	Geologic Events	Locations
Proterozoic Eon: Neoproterozoic (Z)	n/a	1.0 billion to 541 million years ago	n/a	no regional record of events	n/a
Proterozoic Eon: Mesoproterozoic (Y)	n/a	1.6 billion to 1.0 billion years ago	Chico Shunie Quartz Monzonite (**Ycs**) *Note*: Formally recognized in Geolex.	**Ycs** represents batholiths (large bodies of rock that cover an aerial extent of 40 mi2 [100 km2] or more and have no known floor) that intrude Earth's nascent crust about 1.4 billion years ago (Skinner et al. 2008).	Outcrops north of the monument
Proterozoic Eon: Paleoproterozoic (X)	n/a	2.5 billion to 1.6 billion years ago	Cardigan Gneiss (**Xcg**) Pinal Schist (**Xp**) *Note*: Formally recognized in Geolex.	Assembly of Earth's nascent crust. The oldest rocks preserved near the monument are about 1.7 billion years old (Skinner et al. 2008).	Outcrops north of the monument
Archean Eon	n/a	~4.0 billion to 2.5 billion years ago	None in Arizona	Formation of Earth's basement or foundation	Earth's oldest rocks (4.4 billion years old) occur in the Hudson Bay area, northern Quebec, Canada.
Hadean Eon	n/a	4.6 billion to 4.0 billion years ago	No representative Earth rocks	Earth forms about 4.6 billion years ago.	n/a

A Note About the Obsolete Tertiary Period

"Tertiary" is a widely used but obsolete term for the geologic period from 66.0 million to 2.6 million years ago. Following Skinner et al. (2008), GRI GIS data use the term "Tertiary" and symbol (**T**). In current geologic nomenclature, however, the Paleogene Period (66.0 million to 23.0 million years ago) and Neogene Period (23.0 million to 2.6 million years ago) replace the Tertiary. These two periods are further divided into five epochs, oldest to youngest, Paleocene, Eocene, Oligocene, Miocene, and Pliocene (see table 1). Geologic events significant for the monument took place during the Oligocene and Miocene Periods. These events include crustal extension and eruption of the Ajo volcanic field. Corresponding to the source map by Skinner et al. (2008), map unit symbols associated with the Ajo volcanic field include "**T**" for Tertiary (see table 1).

North American Cordillera

Associated map units: **Jga**, **Jgr**, **Jgrr**, **Jgd**, **Jag**, **Japs**, **Jap**, **Jaq**, **Jas**; thrust fault (Quitobaquito thrust); tectonic slide

The monument is part of the North American Cordillera (broad assemblage of more-or-less parallel mountain ranges together with their associated valleys, basins, plains, plateaus, rivers, and lakes). This "mighty set of mountain ranges that stretch from northern Alaska to southern Mexico" (Cannings and Cannings 2015, p. 11) formed through processes associated with plate tectonics—the unifying theory of how Earth works. Plate tectonics provides a context for why continents move, seafloors spread, mountains rise, volcanoes erupt, and earthquakes happen. According to plate tectonics, Earth's crust and upper mantle (fig. 13) form a carapace consisting of plates that are constantly in motion; some plates are growing while others are shrinking. In plate tectonic terminology, Earth's hard crust and relatively stiff upper mantle compose the lithosphere. Below the lithosphere, the asthenosphere consists of the molten part of the mantle. Lithospheric plates move around on the asthenosphere, and much of the "action" takes place at plate boundaries (where two, or even three, plates meet).

Although rocks in the vicinity of the monument, for example Pinal Schist (**Xp**) and Cardigan Gneiss (**Xcg**), are as old as 1.7 billion years (Paleoproterozoic; see table 1), 250 million years ago (Triassic Period) is a good starting place for the monument's geologic story. At that time, much of Earth's continental crust was joined together in a supercontinent called "Pangea," although an estimated 15% of the crust existed as terranes (detached microcontinents) adrift in a mega-ocean called "Panthalassa" and other smaller ocean basins (Blakey and Ranney 2018). Some terranes would ultimately make their way to the western edge of the North American plate, causing the continent to build outward and upward during orogenesis (mountain building) that incorporated uplift, faulting, folding, volcanic eruptions, igneous intrusions, and intense local and regional metamorphism.

About 200 million years ago (Early Jurassic Period), Pangea began breaking apart, eventually yielding today's familiar continental shapes and configuration. Fragmentation of Pangea heralded a worldwide plate reorganization that included the separation of the North American continent from the rest of the supercontinent as the Atlantic Ocean opened on Pangea's eastern side and the Gulf of Mexico began to open on the south (fig. 14).

As a result of continental breakup, the North American plate commenced a westward migration, which continues to the present day. Subduction (sinking of oceanic crust beneath continental crust; see fig. 13) was initiated along the western margin of the continent where the immense Panthalassa Ocean basin began to shrink as oceanic crust was consumed beneath the North American plate. At about the same time, the North American Cordillera started to form as terranes accreted and a magmatic arc (uplifted area above rising magma at a subduction zone; see fig. 13) formed near the western plate margin. Similarity of timing suggests that the breakup of Pangea and the migration of the North American plate to the west was the ultimate cause of Cordilleran mountain building (Mathews and Monger 2005). In addition, subduction of the Farallon plate (i.e., the oceanic plate underlying the Panthalassa Ocean) was arguably the single most important event of the present-day North American Cordillera because all accreted terranes now attached to western North America came either on the back or leading edge of that plate (Blakey and Ranney 2018).

In the monument, buildup of the North American Cordillera is represented by three geologic features: Jurassic rocks, Quitobaquito thrust, and tectonic slides.

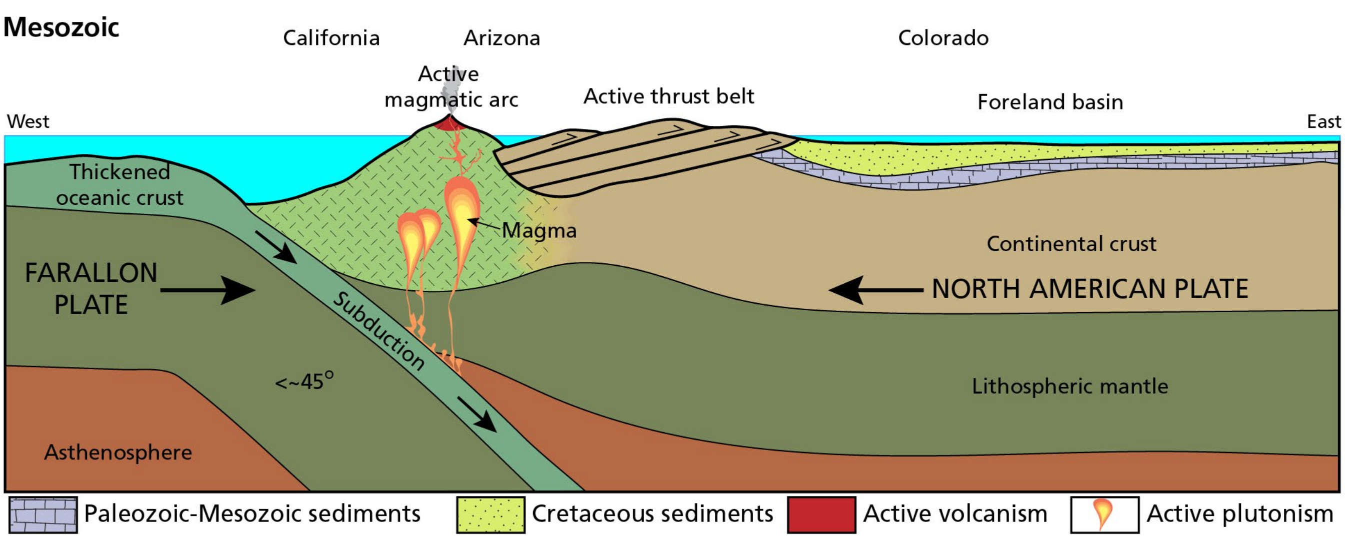

Figure 13. Schematic cross section of the Mesozoic western margin of North America. The eastward-moving Farallon plate (precursor of the Pacific plate) collides with the North American plate. The Farallon plate subducts beneath the North American plate; collision continues for almost 100 million years. As the subducting plate begins to melt, large magma chambers form in the crust many kilometers below the surface. Magma rises to the surface, creating a magmatic arc characterized by widespread plutonism and a chain of volcanoes. As a consequence of eastward-directed subduction combined with westward movement of the North American plate, friction increases and compression takes place across the Cordilleran region, producing an active thrust belt consisting of the Mojave–Sonora megashear (see fig. 14), including the Quitobaquito thrust in the monument. Figure by Trista Thornberry-Ehrlich (Colorado State University) after Blakey and Ranney (2018, figure 8.13).

Figure 14. Paleogeographic map of Jurassic North America.
From the Gulf of Mexico to Alaska, the Mexico–Alaska megashear runs west–northwesterly for 8,000 km (5,000 mi) and traces a subduction-related magmatic arc that bounded the southwestern margin of the North American plate between 170 million and 148 million years ago (Middle to Late Jurassic Period). Where the megashear crosses northern Mexico and southwestern Arizona, it is referred to as the "Mojave–Sonora megashear." In the monument, the Quitobaquito thrust is associated with the megashear. Figure by Trista Thornberry-Ehrlich (Colorado State University) using information from Anderson and Mahoney (2006) and Anderson (2015). Base paleogeographic map by Ron Blakey, "Paleogeography of Southwest North America," © 2012 Colorado Plateau Geosystems Inc, used under license; see https://deeptimemaps.com/.

Jurassic Rocks

The bulk of bedrock exposed in the monument and surrounding area consists of Jurassic rocks, both volcanic (extruded onto Earth's surface) and plutonic (intruded below Earth's surface) (Skinner et al. 2008). These rocks were part of a northwest-oriented continental margin and magmatic arc (see fig. 13) and formed as part of a single volcanic-plutonic complex during the Middle to Late Jurassic Period. The magmatic arc was the result of oblique subduction of the oceanic Farallon plate beneath the overriding North American plate (Tosdal et al. 1989; Tosdal and Wooden 2015).

Arc-magmatism and granitic plutonism produced the intrusive felsic ("felsic" is derived from feldspar + silica to describe an igneous rock having abundant light-colored minerals) volcanic rocks in the monument. Felsic volcanism is represented by dikes (narrow igneous intrusions that cut across preexisting rocks; fig. 15) and volcanic plugs (vertical, pipelike bodies of magma that represent the conduit to a former vent) (Skinner et al. 2008).

Mineralization (process by which a mineral or minerals are introduced into a rock, resulting in a valuable or potentially valuable deposit) is associated with intrusive felsic volcanism. Mineralization at the Milton Mine, for example, occurred in the rocks of La Abra, greenschist and metaconglomerate (**Jag**; see greenschist and metaconglomerate bullet, below). Typically, mineralization occurs within about 10 km (6 mi) below the ground surface. These deposits are commonly on the continental side of convergent oceanic–continental plate boundaries (Kyle Hinds, GRD, mining engineer, written communication, 14 May 2021).

Jurassic rocks are found in the Puerto Blanco Mountains and northern part of the Quitobaquito Hills in the monument (see fig. 3 and poster). They consist of the following units:

- rocks of La Abra, greenschist and metaconglomerate (**Jag**). Greenschist is a schistose (strongly foliated and having a silky sheen) metamorphic rock whose green color is due to the presence of the minerals chlorite, epidote, or actinolite. Metaconglomerate is a metamorphosed conglomerate (a coarse-grained, generally unsorted, sedimentary rock consisting of rounded clasts larger than 2 mm [0.08 in] in diameter).
- rocks of La Abra, intrusive rhyolite related to **Jgr** (**Jgrr**). Rhyolite is an igneous rock that is characteristically light in color, generally contains more than 72% silica, and is rich in potassium and sodium.
- rocks of La Abra, heterogeneous, altered granitic rocks (**Jgr**). Perhaps the best known of all igneous rocks, granite is a coarse-grained, intrusive igneous rock in which quartz constitutes 10%–50% of the felsic ("light-colored") components and the alkali feldspar/total feldspar ratio is generally restricted to the range of 65% to 90%.
- rocks of La Abra, granite of Agua Dulce Mountains (**Jga**). See bullet describing heterogeneous, altered granitic rocks (**Jgr**).
- rocks of La Abra, quartzofeldspathic phyllite and semischist (**Japs**). "Quartzofeldspathic" describes a rock rich in the minerals quartz and feldspar. Phyllite is a metamorphic rock, intermediate between slate and mica schist, with minute crystals of graphite, sericite, or chlorite that impart "schistosity" (a silky sheen). Semischist has a schistose texture but also contains relict clastic (rocks or sediments made of fragments of preexisting rock) components of the original parent rock.
- rocks of La Abra, Pozo Nuevo granite porphyry (**Jap**). For granite, see definition in bullet describing heterogeneous, altered granitic rocks (**Jgr**). Porphyry is an igneous rock consisting of abundant coarse-grained crystals in a fine-grained groundmass.
- rocks of La Abra, metamorphosed quartz porphyry (**Jaq**). See bullet describing Pozo Nuevo granite porphyry (**Jap**).
- rocks of La Abra, quartzofeldspathic semischist and phyllite (**Jas**). See bullet describing quartzofeldspathic phyllite and semischist (**Japs**).

Figure 15. Photograph of dike.
Dikes are igneous intrusions that cut across preexisting rock. As shown in this outcrop along Ajo Mountain Drive, a dike intruded the rhyolite of Montezuma's Head (Tmr), which erupted onto the landscape about 17.5 million to 16 million years ago (early Miocene Epoch). Photograph by Katie KellerLynn (Colorado State University), taken 2006.

Quitobaquito Thrust

The Quitobaquito thrust is the primary geologic feature in the monument linked to the buildup of the North American Cordillera. The local Quitobaquito thrust is associated with the regional Mojave–Sonora megashear, which, in turn, is associated with the continental-scale Mexico–Alaska megashear (see fig. 14). In 2006, scoping participants identified the Mojave–Sonora megashear as one of the two most significant geologic features at the monument (National Park Service 2006). The other "most significant" feature is the Ajo Range (see "Ajo Volcanic Field"). The Mojave–Sonora megashear bounded the southwestern margin of the North American plate during the Middle to Late Jurassic Period.

In general, the length of a megashear measures more than about 700 km (440 mi) (Neuendorf et al. 2005). The Mexico–Alaska megashear is 8,000 km (5,000 mi) long. Displacement (movement) within a megashear is measured in tens to hundreds of kilometers (Neuendorf et al. 2005). Movement along the principal strand of the Mexico–Alaska megashear is estimated to be about 800 km (500 mi) (Anderson 2015).

The Mojave–Sonora megashear was a system of sinistral (counterclockwise rotating) strike-slip faults (see fig. 20) that cut obliquely across the magmatic arc (see fig. 13) between 170 million and 148 million years ago (Anderson 2015). The focus of the Mojave–Sonora megashear was across northern Mexico, but secondary structures, for example the Quitobaquito thrust, formed a series of thrust faults (breaks in the Earth's crust, across which older rocks are pushed above younger rocks). Older continental crust—of undetermined age but possibly early to middle Proterozoic and Triassic—was thrust over Jurassic plutons by the Quitobaquito thrust, juxtaposing totally dissimilar and unrelated rock units. In the monument, the continental crust is represented by orthogneiss (gneiss formed from igneous rocks) and foliated granite (**TRYXo**). Plutons are represented by rocks of La Abra, quartzofeldspathic semischist and phyllite (**Jas**; see "Jurassic Rocks").

Compilation of multiples lines of evidence—including regional elements such as transtensional ("pull-apart") basins, overlapping magmatic belts, and terrane juxtapositions—by many investigators led Anderson (2015) to propose that the Mojave–Sonora megashear be extended northward to Alaska and called the "Mexico–Alaska megashear." Significant for the GRI, Anderson (2015) used work by Gordon Haxel, who was an author of the source map for the GRI GIS data (i.e., Skinner et al. 2008) and a scoping participant in 2006.

The Mexico–Alaska megashear separated the North American plate from the proto-Pacific plate and linked the axis of ocean-floor spreading within the developing Gulf of Mexico with a westward-facing subduction zone (see fig. 13) that ran along the western margin of the North American continent (see fig. 14). On the eastern side of the continent at that time, the Atlantic Ocean was born, growing in the rift between North America and Africa. Growth of the Atlantic Ocean basin propelled North America westward. These events mark the last stage of the breakup of Pangea, with North America separating from South America and Africa.

The Mexico–Alaska megashear is a "big picture" idea that may be of interest to the public and worthy of interpretation at the monument (see "Geologic Interpretation"). The megashear connects the countries of North America: Mexico, the United States, and Canada. Its trace extends west–northwest from the Gulf of Mexico across northern Mexico and southern Arizona to southern California, then runs northward along the entire continental margin (see fig. 14). In British Columbia, Canada, the megashear marks the boundary between the Insular and Intermontane terranes, two terranes that helped build the North American Cordillera. When the megashear was active (i.e., Late Jurassic Period), however, the Insular terrane was still west of North America, having not yet collided with the continent. In the United States, the megashear swings through Arizona, California, Oregon, Washington, and Alaska. As such, many NPS units are part of the megashear story. For example, in central California, the megashear curves east around the Great Valley (and rocks of the Great Valley sequence) thereby incorporating John Muir National Historic Site. Additionally, the well-known and widespread granite of Yosemite National Park represents plutons (i.e., the magmatic arc) within the megashear. In northern California and Oregon, the megashear corresponds to the Coast Range thrust, which marks where the Josephine ophiolite (an assemblage of oceanic crust) was thrust onto the continent, overriding the Franciscan Complex of rocks. As such, Redwood National and State Parks and Oregon Caves National Monument are part of the story. In Alaska, the megashear intersects Wrangell-St. Elias and Denali National Parks and Preserves (see fig. 14). Many of these park stories are recorded in GRI reports, for example, Thornberry-Ehrlich 2010; KellerLynn 2011, 2021a, 2020b; and Graham 2012.

Tectonic Slides

Tectonic slides are not slope movements and should not be confused with mass wasting (dislodgement and downslope transport of a mass of rock and/or unconsolidated material under the direct influence of gravity). Tectonic slides are a distinct class of fault (Hutton 1979), but unlike brittle faults, tectonic slides form in "ductile" environments at great depth within the crust and under high temperature and pressure. Ductile environments characterize metamorphic–orogenic belts of regional deformation.

The term "tectonic slide" does not have widespread use beyond the Caledonian Mountains of Europe, which run from the Arctic Circle through Scandinavia and Scotland to northwest Ireland, but the term was used by mappers in the monument (Haxel et al. 1984; Skinner et al. 2008). The term was introduced into the geologic literature by Bailey (1910) for his work in the Scottish Highlands. Whereas tectonic slides in the Caledonian Mountains record the Caledonian Orogeny, which was one of several mountain-building events associated with construction of the supercontinent Pangea, tectonic slides in the monument record the breakup of Pangea, as well as the building of the North American Cordillera.

In the monument, tectonic slides occur in the Quitobaquito Hills and are associated with rocks of La Abra (**Jaq**, **Jap**, **Jas**, and **Jag**). Additionally, tectonic slides occur in the Puerto Blanco Mountains where they also are found with rocks of La Abra (**Jaq**, **Jap**, **Jas**, and **Jga**). Moreover, a tectonic slide is located between the orthogneiss and foliated granite (**TRYXo**) and the Aguajita Spring granite (**Kga**) in the Quitobaquito Hills, though that tectonic slide is probably related to reactivation of the Quitobaquito thrust during the Laramide Orogeny (see "Laramide Orogeny"), not assemblage of the North American Cordillera.

Tectonic slides are marked by intensification of the regional metamorphic fabric (Haxel et al. 1984) and may include the appearance of flowing (e.g., mineral grains with wispy tails), intense stretching and flattening of mineral crystals, or ellipsoid-shaped mineral grains (fig. 16). Because tectonic slides commonly lie along lithologic contacts (between adjacent rock units), they may be difficult to detect in outcrops despite the large displacement (movement along a fault) that likely took place.

The tectonic slides in the Quitobaquito Hills are related to the Quitobaquito thrust. Unlike other thrust faults in south-central Arizona, which have a single lower block, the Quitobaquito thrust is underlain by a stack of at least eight imbricate (tilted and overlapping) structural sheets separated by zones of mylonite (foliated metamorphic rock that commonly has a flowlike appearance; see fig. 16), which characterize localized zones of ductile deformation. These mylonitic sheets, which are composed of rocks of La Abra (**Jaq**, **Jap**, **Jas**, and **Jag**), extend continuously from the lower part of the upper block of the Quitobaquito thrust down through the entire several-kilometer thickness of imbricate lower-block sheets. The tectonic/metamorphic fabric is most strongly developed within the mylonitic zones bounding the sheets and decreases in intensity into the interiors of the sheets. Because the contacts between sheets are shear zones marked by intensification of the regional metamorphic fabric, they are best referred to as "tectonic slides" following the definition of Hutton (1979) (Haxel et al. 1984).

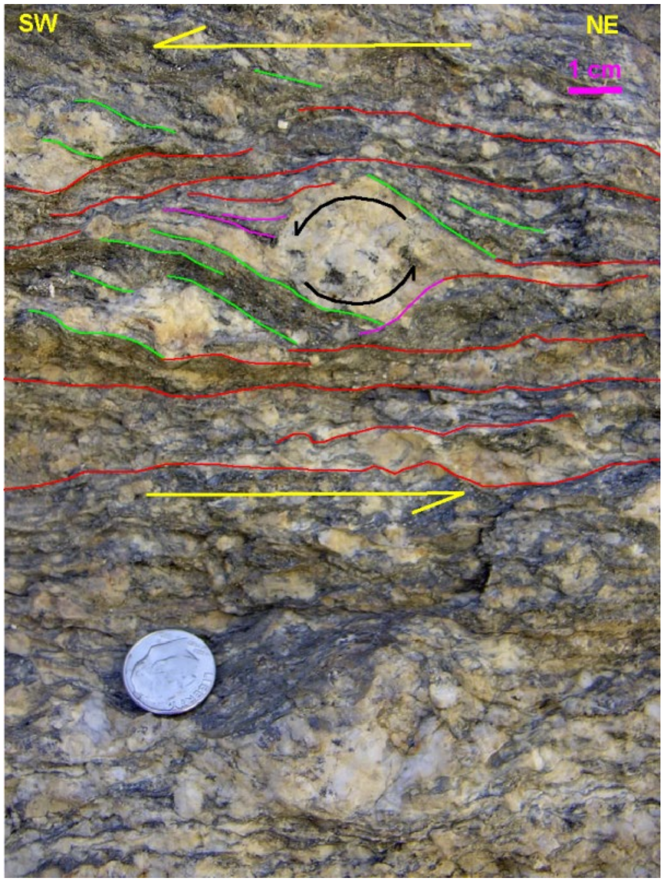

Figure 16. Photograph of a mylonitic shear zone. Although mylonitic rocks are found in the monument, the rock in the photograph is in the Santa Catalina Mountains, near Tucson, Arizona, northeast of the monument. The large white potassium feldspar crystal was rolled to the left in a shear zone; yellow arrows show the sense of shear. Red lines are shear surfaces. Green lines are surfaces that formed by mica (mineral group characterized by perfect cleavage, readily splitting into thin sheets) recrystallization in the plane of flattening. Purple lines are shear surfaces that were rotated into the pressure shadow of the hard, resistant, feldspar crystal. Photograph and annotations by Jon Spencer (AZGS), taken 2006 (see Spencer 2006).

Laramide Orogeny

Associated map units: **Kvu**, **Kga**, **Kgg**, **Kap**, **Kgb**, **TKgs**; thrust fault (i.e., reactivation of the Quitobaquito thrust)

The Laramide Orogeny was a seminal event of the North American Cordillera. The orogeny was responsible for the rise of the Rocky Mountains, the initial uplift of the Colorado Plateau, and rejuvenation of the "transition zone" of central Arizona (between the Colorado Plateau and Basin and Range physiographic provinces; see Peirce 1985 and GRI reports about Montezuma Castle, Tuzigoot, and Tonto National Monuments by KellerLynn 2019a, 2019b, and 2020, respectively). A commonly cited plate tectonics mechanism for the Laramide Orogeny is shallow-slab or flat-slab (low angle) subduction (Saleeby 2003) (fig. 17).

The Laramide Orogeny commenced about 80 million–70 million years ago (Late Cretaceous Period) and ended by about 60 million–58 million years ago (Paleogene Period). Orogenesis involved "uplift, volcanism, intense compressive deformation, and plutonism—in that order. This activity swept from southwest to northeast across the region" (Coney 1978, p. 287). As magmatic activity shifted eastward during the Laramide Orogeny, it emplaced rich ores of copper in the crust. "Mineral belts"—including the well-known Colorado Mineral Belt from Durango to Golden, Colorado—mark the track of mineral activity (Blakey and Ranney 2018).

The Laramide Orogeny was first recognized and named for sediments shed into the Laramie Basin in southern Wyoming. Over the years, however, uplifted mountain ranges have become the most recognizable Laramide feature (Blakey and Ranney 2018). Laramide mountains are referred to as "basement cored" uplifts because tectonic processes brought Earth's buried crust to the surface at the cores of these ranges. Now, billion-year-old rocks that compose the basement form many mountain summits as a result of Laramide uplift.

Deformation and uplift of the Laramide Orogeny were focused in a "belt" along a north–northeast-oriented corridor extending from Mexico to Canada. Events during the orogeny gave rise to the Laramide block uplifts in the United States, the Rocky Mountain fold-and-thrust belt in Canada and the United States, and the Sierra Madre Oriental fold-and-thrust belt in east-central Mexico (e.g., English and Johnston 2004). The Black Hills of South Dakota mark the easternmost extent of the Laramide belt (see GRI reports about Jewel Cave National Monument and Wind Cave National Park by KellerLynn 2009a, 2009b, respectively). Numerous national parks and monuments preserve the scenery created by the Laramide Orogeny, including alpine peaks in Rocky Mountain National Park (see GRI report by KellerLynn 2004) and spectacular folds in Grand Canyon National Park (see GRI report by Graham 2020) as well as Waterpocket Fold that runs the length of Capitol Reef National Park (see GRI report by Graham 2006a).

In the monument, features of the orogeny include evidence of volcanism (**Kvu**) in the Bates Mountains and plutonism (**Kga**, **Kgg**, **Kap**, **Kgb**, and **TKgs**) in the Quitobaquito Hills, Growler Mountains, Gunsight Hills, and Senita Basin. Moreover, Laramide-age deformation includes compressive deformation and probable reactivation of the Quitobaquito thrust (Skinner et al. 2008). Also, intense local metamorphism affected older rocks east of the monument (Shafiqullah et al. 1980; Haxel et al. 1984). In addition, samples of "Batamote Basalt", which were analyzed using X-ray fluorescence (see "Batamote Mountains Shield Volcano"), plot within the range of subduction-related melt involving the lithosphere as opposed to a melt origin within the asthenosphere; this geochemical signature suggests a shallower subducting slab (Bowles and Greeley 2013) characteristic of the western margin of the North American plate during the Cenozoic Era (see fig. 17).

Displayed at the mines and prospects in the monument, mineralization is closely associated with igneous activity, especially intrusive bodies such as plutons (Butler et al. 1938); many of these plutons were emplaced during the Laramide Orogeny when conditions were just right to produce an abundance of extremely rich copper ores, which fueled Arizona's mining industry. As highlighted and explained by Bezy et al. (2000), plutonic rocks at the monument, for example the granite of Senita Basin (**TKgs**), crystallized very slowly from magma at a depth of 10 to 15 km (6 to 9 mi). Remnant heat retained by the pluton provided energy to drive a thermal convection system consisting of hot fluids containing minerals in solution that circulated through fractures in the cooling pluton. The migrating fluids left evidence of their passage in the form of minerals deposited along fractures. The granite of Senita Basin (**TKgs**), for instance, has veins or seams of shiny, finely crystalline muscovite, as well as milky white quartz, that is representative of this mineralization. A few of the larger quartz veins bear minerals containing lead, silver, copper, gold, or zinc (Bezy et al. 2000).

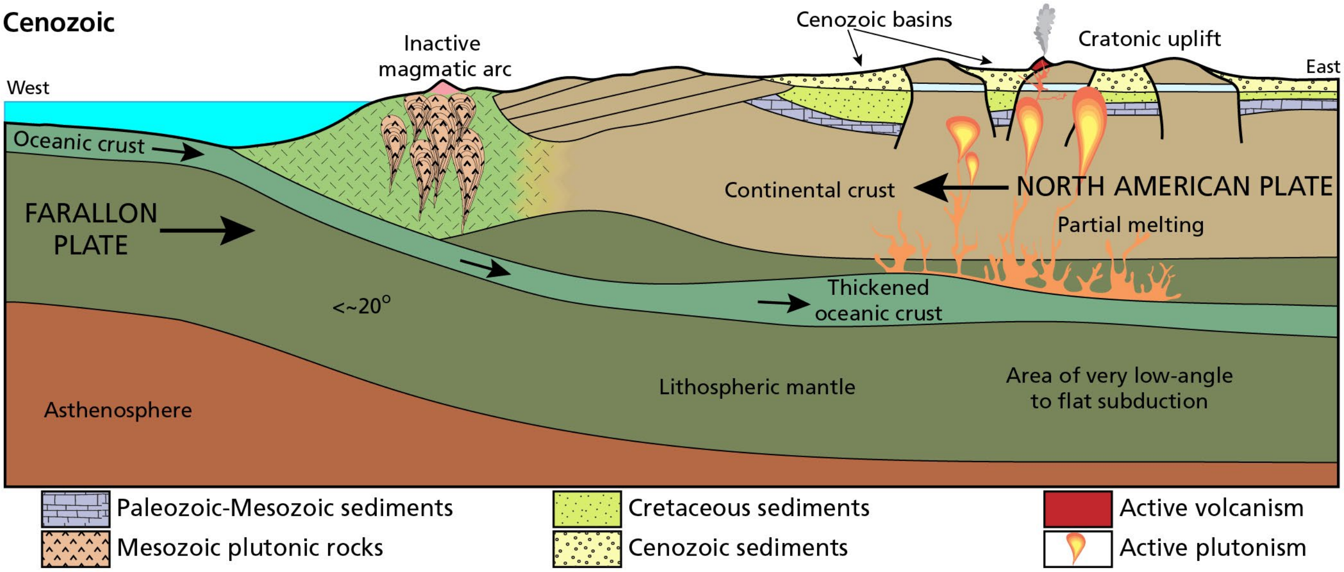

Figure 17. Schematic cross section of the Cenozoic western margin of North America.
The Laramide Orogeny takes place as a result of shallow-slab or flat-slab (low angle) subduction. About 80 million years ago, as the Farallon plate subducts beneath the North American plate, a large oceanic plateau (thickened oceanic crust) riding on the back of the Farallon plate approaches the southwestern corner of North America near southern California. As this thickened slab of volcanic oceanic crust subducts beneath the continent, it provides buoyancy to the Farallon plate and causes its angle of descent to become less steep. Because the depth at which the slab melts is pushed eastward, arc magmatism also migrates to the east. Mineralization of rocks mark the eastward migration. Figure by Trista Thornberry-Ehrlich (Colorado State University) after Blakey and Ranney (2018, figure 8.13).

Basin and Range

Associated map unit: normal faults

The monument is in the Basin and Range physiographic province—a sprawling area that stretches from southeastern Oregon to northern Mexico and involves eight US states: Arizona, California, Idaho, New Mexico, Nevada, Oregon, Utah, and Texas. 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, also referred to as "intermontane valleys," in between.

Rising above Salt Lake City and Provo, Utah, on the Wasatch fault, the Wasatch Front forms the eastern edge of the Basin and Range. Farther south, the eastern edge of the Basin and Range is marked by the Rio Grande rift, which is the single most striking topographic feature in New Mexico (Price 2010; Blakey and Ranney 2018). The western edge of the northern Basin and Range is located at the foot of the Sierra Nevada in California, where faulting has created one of the planet's most spectacular escarpments (fig. 18). The western edge of the southern Basin and Range is not as well-defined as the northern Basin and Range but is more-or-less where strike-slip faulting (see fig. 20) associated with the North American plate–Pacific plate boundary becomes dominant. Presently, the San Andreas Fault system characterizes that plate boundary.

The birth of the Basin and Range was no small event in the history of the North American Cordillera (Blakey and Ranney 2018). It arose during transition from subduction to transform plate motion at the western edge of the North American plate (fig. 19). As tensional forces increased, southwestern North America underwent extreme east–west extension, forming the Basin and Range (Blakey and Ranney 2018).

Earth's crust in the Basin and Range is characterized by east–west stretching and thinning. The region has been stretched nearly 100% from its Oligocene-Miocene dimension. For example, the straight-line distance between the Sierra Nevada and the Wasatch Front is currently 700 km (440 mi), but 36 million years ago (i.e., before extension began), the Sierra Nevada arc was perhaps only 350 km (220 mi) west of the Wasatch Front and Colorado Plateau. To the south, the eastern boundary of the Basin and Range is the Rio Grande rift, and the distance between it and the San Andreas Fault is nearly 900 km (560 mi), that is, approximately twice what it was before development of the Basin and Range (Blakey and Ranney 2018). This extraordinary amount of stretching has resulted in thinning of the crust to

Figure 18. Photograph of Owens Valley, California.
A stunning wall of rock forms the eastern escarpment of the Sierra Nevada. The wall marks the western edge of the Basin and Range physiographic province. Seen here with Owen Valley below, the escarpment is a horst whereas the valley is a graben. Mountain peaks, composing the horst—including the highest in California and the lower 48 states, Mount Whitney (4,413 m [14,479 ft] above sea level)—on either side of the valley or graben reach above 4,300 m (14,000 ft) in elevation. The floor of the valley is about 1,200 m (4,000 ft) above sea level, making it the deepest in the United States (Putnam and Smith 1995). Although timing of the raising of the Sierra Nevada is controversial, this relief was formed as part of Basin and Range extension during the Neogene Period. Tinemaha Reservoir is in the foreground. Photograph by G. Thomas, taken 2 June 2006; released into the public domain at Wikipedia, https://commons.wikimedia.org/wiki/File:SierraEscarpmentCA.jpg (accessed 27 June 2022).

28–35 km (17–22 mi) thick (Chulick and Mooney 2002). Outside the province, the crust averages about 50 km (30 mi) thick (Brown 1992).

Two episodes of crustal extension are recorded in the monument:

- 36 million–17 million years ago. An early period of extension in the southern Basin and Range lasted from the Oligocene Epoch until about the early Miocene Epoch. Until recently, this phase of extension was referred to as "mid-Tertiary" (see "A Note About the Obsolete Tertiary Period") but is now referred to as "Oligo-Miocene." This phase of extension included development of fault-block mountains and down-dropped basins accompanied by tilting, normal faulting, folding, and volcanism (Brown 1992). Significantly, the volcanic rocks in the monument were erupted at this time (see "Ajo Volcanic Field"). Rocks in the Ajo volcanic field overlap and are interbedded with clastic sedimentary rocks derived from underlying bedrock, such as Daniels Conglomerate (**Tdc**) and sedimentary and volcanic rocks, undivided (**Tsvu**), suggesting that volcanism and extension were synchronous (Skinner et al. 2008).
- 10 million–5 million years ago. A later period of extension, which is generally referred to as "Basin and Range" extension, commenced and finished in the late Miocene Epoch (Brown 1992). Although Basin and Range extension and associated subsidence ended in the Sonoran Desert region by about 5 million years ago, it continues to the present day in the eastern and central mountain regions of the Basin and Range physiographic province (Shafiqullah et al. 1980; e.g., see the GRI report about Great Basin National Park by Graham 2014).

Earth's crust in the Basin and Range is characterized by and breaking along normal faults (fig. 20). Most of the faults mapped by Skinner et al. (2008) in the monument (see poster) are normal faults.

Broadly speaking, normal faults separate the basins and ranges in the physiographic province. An uplifted block bounded by a normal fault is termed a "horst." Most of the mountain ranges in the monument—including the highest peak, Mount Ajo—are horsts. Mount Ajo is an asymmetric horst because the west side of the block has been lifted higher than the east side (Brown 1992). A down-dropped block between horsts is termed a "graben"; these make up the intervening basins or valleys.

Normal faults ripped the landscape apart, modifying preexisting landforms and transforming previous drainage and depositional patterns (Eberly and Stanley 1978). Faulting first appeared in central and southern Arizona and southeastern California, then progressed north into Nevada and western Utah, and southeast into Sonora, Mexico, New Mexico, and Texas. Over time, the forces of extension became elongated to the north and southeast (Blakey and Ranney 2018).

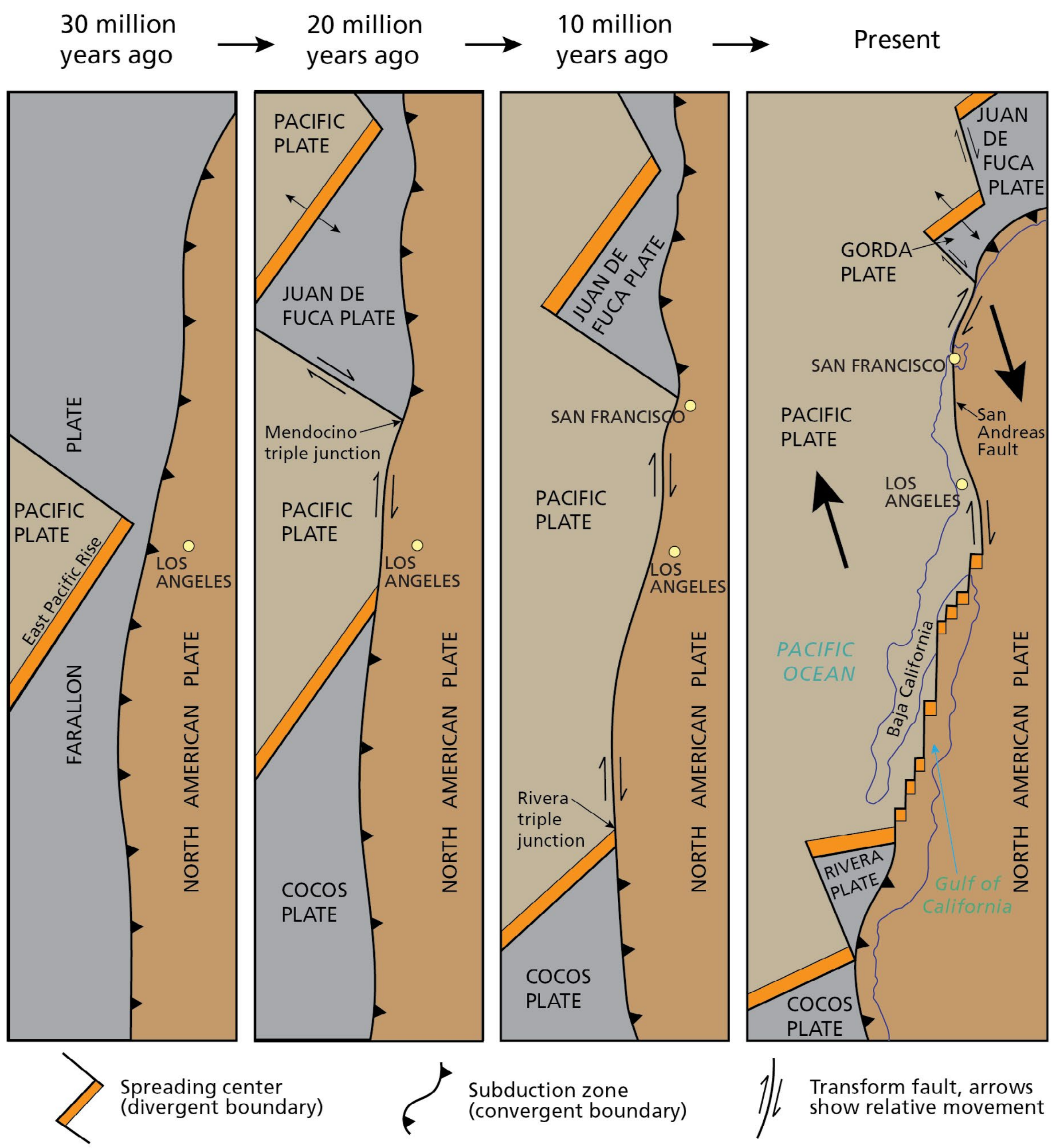

Figure 19. Schematic illustration of the North American plate boundary over time.
The four panels show subduction of the Farallon plate as it was progressively consumed beneath the North American plate. As the East Pacific Rise and North American plate made contact, the Farallon plate east of the rise began to fracture into microplates. The Mendocino triple junction formed where the North American, Pacific, and Juan de Fuca plates intersected. Farther south, the Rivera triple junction formed where the Pacific, North American, and Cocos plates intersect. Over millions of years, the triple junctions moved farther apart, and contact between the Pacific and North American plates lengthened. Consequently, the right-lateral transform margin of southwestern North America was born. The Pacific plate was moving rapidly to the northwest while the North American plate was moving slowly to the southwest. The pull between the two plates, as well as "capture" and northwestward movement of portions of the North American plate by the Pacific plate, caused extension in western North America (Basin and Range). At present, the San Andreas Fault takes up the bulk of the motion at the plate boundary and thus has come to be identified as the transform-plate boundary in popular scientific thought. In reality, many faults make up a broad zone of deformation that composes the plate boundary. Figure by Trista Thornberry-Ehrlich (Colorado State University) after Kious and Tilling (1996, p. 7).

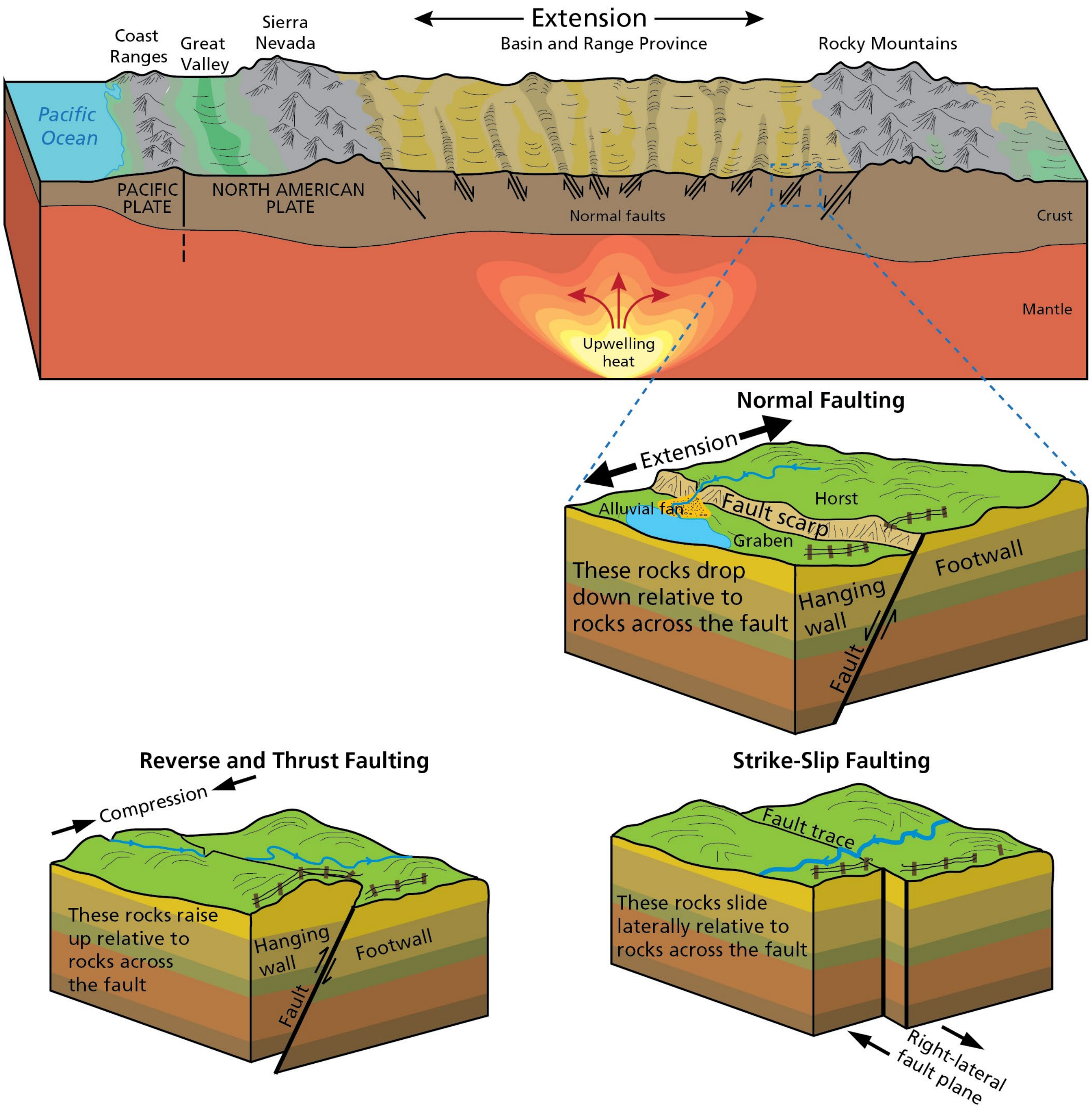

Figure 20. Block diagrams of Basin and Range extension, normal faults, and other fault types. As Earth's crust cracks, movement takes place along a fault plane. Footwalls are masses of rock below a fault. Hanging walls are masses of rock above a fault. Geologic forces in the Basin and Range physiographic province cause extension (pulling apart of Earth's crust). The crust thins and cracks as it pulls apart, creating normal faults in which the hanging wall drops down relative to the footwall. Mountain ranges lift up whereas basins drop down along these faults, producing the distinctive alternating pattern of parallel ranges (referred to as "horsts") and basins (referred to as "grabens"). In addition to 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. 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 shown in the figure. When movement is to the left, it is a left-lateral strike-slip fault. Figure by Trista Thornberry-Ehrlich (Colorado State University), incorporating a figure by Idaho Geologic Survey (2011, p. 2).

Ajo Volcanic Field

Associated map units: **Tvu**, “**Tp**” units, “**Tc**” units, **Ttu**, **Tru**, **Tdu**, **Tbu**, “**Tm**” units, “**Tb**” units, and **Td**

The monument includes part of the Ajo volcanic field, which surrounds the town of Ajo for which it was named. The volcanic field covers about 5,000 km^2 (1,930 mi^2) and preserves a stratigraphic thickness of volcanic rocks of at least 1,200 m (3,900 ft) (Brown 1992; Eddy et al. 2004).

The Ajo volcanic field erupted in a brief but intense burst of volcanic activity between 22 million and 14 million years ago (Bezy et al. 2000; Skinner et al. 2008). Dates from the analysis of potassium-argon isotopes in rocks from the volcanic field indicate that volcanic activity lasted for about 8 million years. Volcanism took place during Oligo-Miocene extension (see “Basin and Range”); faulting and tilting of crustal blocks provided avenues for magma to spread upwards—creating dikes, volcanic necks or plugs, and domes—and onto the surface. In addition, basaltic magma exploded at vents creating cinder cones in the Cipriano Hills, northern Bates Mountains, and southern Growler Mountains of the monument (Brown 1992).

Volcanic Rocks

The volcanic rocks in the monument (fig. 21) encompass an incredible compositional range (table 2). From effusive (emitted as fluid lava onto Earth’s surface) basalt to explosive rhyolite, these rocks vary widely in characteristics such as eruption explosivity and lava viscosity. For example, when basalts (low viscosity and effusive) erupt onto the landscape, their nature causes them to spread out, forming mesa-capping flows. The recently recognized Batamote Mountains shield volcano (see “Batamote Mountains Shield Volcano”) displays many characteristics of basaltic volcanism (Bowles and Greeley 2013). By contrast, rhyolites (high viscosity and explosivity), which are substantially more viscous than basalt, travel shorter distances from their eruptive vents and develop short, thick, bulbous lava flows.

The general volcanic stratigraphy used by Skinner et al. (2008) in mapping the monument was first delineated in the Ajo Range by May et al. (1981). It has since been extended throughout 12 mountain ranges in the region (Eddy et al. 2004). From oldest to youngest, the volcanic rocks mapped in the monument are as follows:

- Tertiary dikes, undivided (**Td**). These rocks represent extension (see “Basin and Range”). Following Skinner et al. (2008), the term “Tertiary” is included here (see “A Note About the Obsolete Tertiary Period”). Dikes are associated with all the volcanic rock units in the monument, from oldest to youngest: rhyolite of Pinkley Peak, Childs Latite, rhyolite of Montezuma’s Head, and Batamote Andesite complex (see poster). Within the monument, Tertiary dikes, undivided (**Td**) intruded Aguajita Spring granite (**Kga**), rhyolite of Pinkley Peak (**Tpr**), Childs Latite (**Tcl**), and rhyolite of Montezuma’s Head (**Tmr**).
- volcanic and volcaniclastic rocks (**Tvu**). These rocks mark the beginning of volcanic activity in the Ajo volcanic field, approximately 28.4 million to 16 million years ago (late Oligocene to early Miocene Epochs). These rocks are primarily north of the monument in the Growler and Little Ajo Mountains. Within the monument, they occur near the US–Mexico border.
- rhyolite of Pinkley Peak (“**Tp**” map units). These rocks erupted onto the landscape between about 22 million and 18 million years ago (early Miocene Epoch). The rhyolite of Pinkley Peak was informally named and first described in the Puerto Blanco Mountains (D. M. Miller, unpublished data, 1984, *cited in* Skinner et al. 2008; Tosdal et al. 1986) where Pinkley Peak is the highest peak (952 m [3,124 ft]; see fig. 21). Informal use and description of the map unit was extended to include rocks of similar lithology and stratigraphic position in the Gunsight Hills and isolated exposures in the northernmost Ajo Range (Skinner et al. 2008). The rhyolite of Pinkley Peak forms that basal part of the Ajo volcanic field and is unconformably (with breaks in deposition) overlain by Childs Latite (Brown 1992). Skinner et al. (2008) divided the rhyolite of Pinkley Peak into eight stratigraphic units based on rock type, including rhyolite, rhyodacite, and dacite, which make up flows, domes, and tuffs, as well as minor andesite and basalt flows with interbedded sandstone and conglomerate. Pinkley Peak, and the rhyolite that composes it, was named for Frank “Boss” Pinkley (1881–1940), who was an archeologist, park ranger, and the NPS regional superintendent of the Southwestern National Monuments. Pinkley administered 27 national monuments in four states and was excitedly planning the development of Organ Pipe Cactus National Monument at the time of his death (National Park Service 2020b).

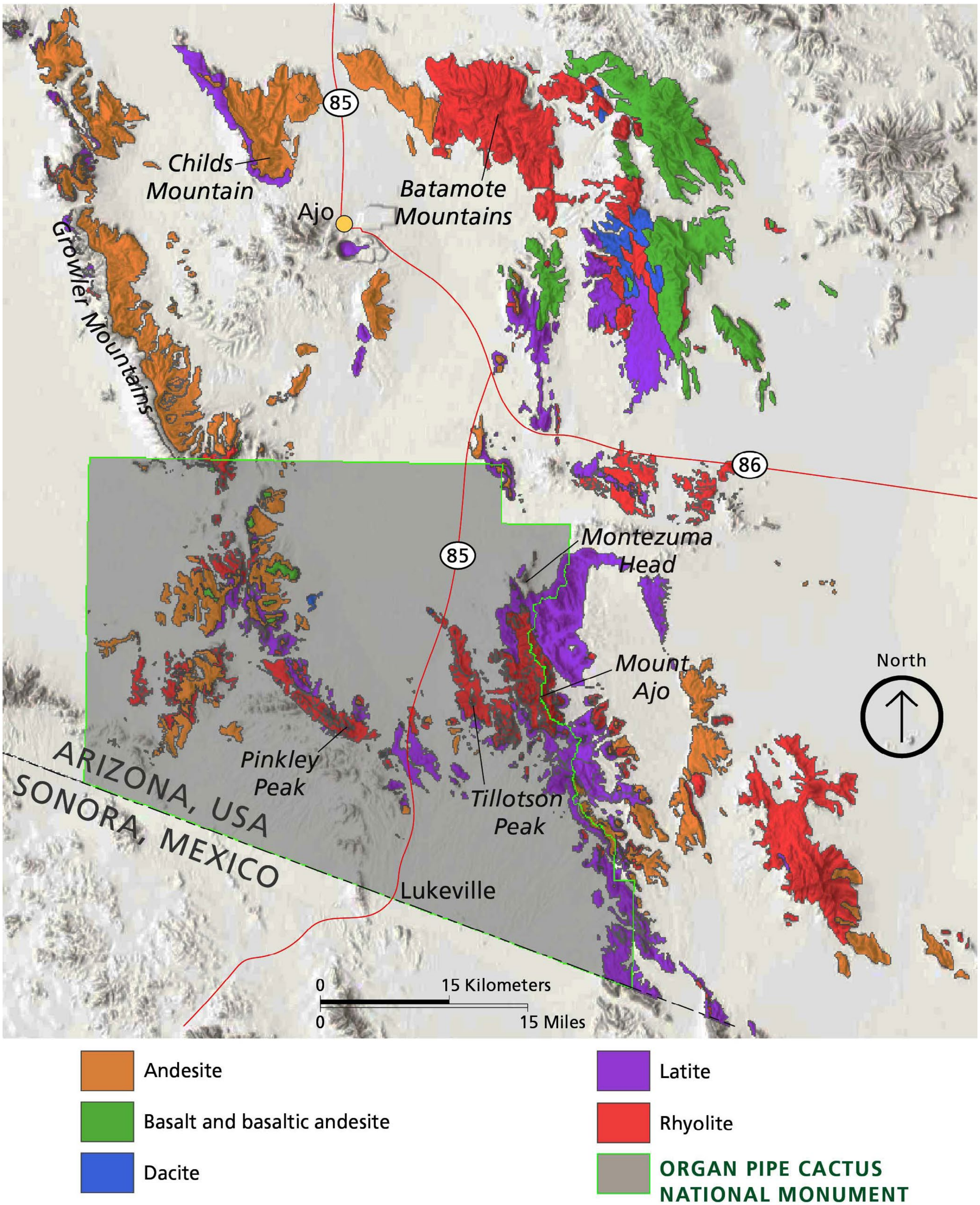

Figure 21. Location map with volcanic rock types.
The monument contains part of the Ajo volcanic field, which hosts a remarkable variety of volcanic rocks. Map by Trista Thornberry-Ehrlich (Colorado State University) using GRI GIS data (source map by Skinner et al. 2008) and base map by Tom Patterson (NPS).

Table 2. Volcanic rocks.

Sources: La Bas and Streckeisen (1991), Neuendorf et al. (2005), and Clynne and Muffler (2010).
Note: "Batamote Basalt" of Bowles and Greeley (2013) is 51.78%–52.81% silica (see "Batamote Mountains Shield Volcano").

Name	Percentage Silica (SiO_2)	Viscosity	Explosivity
Rhyolite	>72%	High	More
Rhyodacite	68%–72%	Lower than rhyolite	Less than rhyolite
Dacite	63%–68%	Lower than rhyodacite	Less than rhyodacite
Andesite	57%–63%	Lower than dacite	Less than dacite
Latite ("trachyandesite")	~58%	Lower than andesite	Less than andesite
Basaltic andesite	53%–57%	Lower than latite	Less than latite
Basalt	<53%	Low	Less

- Childs Latite ("**Tc**" map units). These rocks erupted onto the landscape more than 18 million years ago (early Miocene Epoch). Childs Latite was named by Gilluly (1937) for exposures on the west slope of Childs Mountain (near Ajo, north of the monument; see fig. 21) but crops out in more than a dozen mountain ranges in southwestern Arizona and northwestern Sonora (May et al. 1981; Bezy et al. 2000). The thickest section of Childs Latite, 500 m (1,640 ft) thick, occurs in the Ajo Range. Childs Latite is characterized by large (1–4 cm [0.5–1.5 in] across) crystals called "phenocrysts" (fig. 22). Geochronologic, chemical, and petrologic data indicate that Childs Latite was erupted from two shallow crustal chambers, one underlying the Crater Range (north of Ajo) and a second larger chamber underlying the monument (Miller 1988).
- welded tuff (**Ttu**; consists of shards of volcanic glass welded together), rhyolite (**Tru**), dacite (**Tdu**), and basalt and basaltic andesite (**Tbu**). As mapped by Skinner et al. (2008), these rocks represent other early Miocene volcanic activity in the Ajo volcanic field. More recent studies now associate these rocks with the Batamote Mountains shield volcano (see "Batamote Mountains Shield Volcano").
- rhyolite of Montezuma's Head ("**Tm**" map units). These rocks erupted onto the landscape about 17.5 million to 16 million years ago (early Miocene Epoch). In addition to composing the feature known as Montezuma Head (see "Geologic Connections to Cultural Resources"), the rhyolite of Montezuma's Head makes up much of the Ajo Range, including Arch Canyon and Mount Ajo, as well as the Mesquite Mountains east of the monument. Skinner et al. (2008) divided the rhyolite of Montezuma's Head into eight stratigraphic units depending on rock type. These consist of thick, stubby rhyolite flows, plugs, and associated tuff and tuff breccia and include minor dacite and andesite flows, rare ash-flow tuffs, and sedimentary rocks (Skinner et al. 2008). Unit **Tmr** (rhyolite of Montezuma's Head, rhyolite, rhyodacite, and minor dacite flows, flow breccias, and plugs) consists of red-brown rhyolite and ranges in thickness from 443 to 673 m (1,454 to 2,208 ft) in the main Ajo Range (Brown 1992). Unit **Tmr** forms massive, nearly vertical cliffs, steep slopes, flat benches, and ledges throughout the Ajo Range.

Figure 22. Photograph of Childs Latite.
More than 18 million years ago, a volcanic eruption produced the distinctive Childs Latite. Phenocrysts (large crystals) enclosed in a matrix of much smaller crystals characterize the rock unit. The phenocrysts are composed of plagioclase, one of the most common rock-forming minerals. During the 2006 scoping meeting and field trip, participants noted the distinctive "chunky" nature of the rock, which once cut and polished, would result in a nice set of bookends; hence, collection of Childs Latite by "rock hounds" could be a minor concern for resource protection (National Park Service 2006). Photograph by Katie KellerLynn (Colorado State University), taken 2006.

- Batamote Andesite complex ("**Tba**" map units). These rocks represent the most recent volcanic eruption in the Ajo volcanic field. Gilluly (1946) was the first to map Batamote Andesite in the Batamote Mountains (northeast of the monument). The pulse of volcanic activity creating these rocks took place about 16 million to 14 million years ago (middle Miocene Epoch). Gray to black or reddish brown (oxidized) basalt, basaltic andesite, and andesite form mesa-capping flows, flow breccias (coarse-grained rock consisting of angular clasts), agglomerates (consolidated rock consisting of ejected lava, typically "bombs"), and rare dikes (Skinner et al. 2008). Individual flows are discontinuous and interrupted; some include paleosols (ancient soils), indicating a period of quiescence and soil formation between eruptions (Brown 1992).

Batamote Mountains Shield Volcano

The Batamote Mountains, for which the Batamote Andesite was named (Gilluly 1946), are northeast of the monument, though rocks of the Batamote Andesite complex ("**Tba**" units) occur within the monument (see "Volcanic Rocks"). The source map for the GRI GIS data (Skinner et al. 2008) mapped the Batamote Mountains as consisting of two units: (1) Batamote Andesite complex, basaltic andesite flows and flow breccias (**Tba**); and (2) rhyolite flows, dikes, and felsic pyroclastic rocks, undivided (**Tru**). The rhyolite was not mapped as part of the Batamote Andesite complex. Skinner et al. (2008) also mapped basalt and basaltic andesite, undivided (**Tbu**) in the vicinity of the Batamote Mountains (fig. 23).

Since mapping by Skinner et al. (2008), other investigators (i.e., Bowles and Greeley 2013) have recognized the Batamote Mountains as a shield volcano. Shield volcanoes appear as broad domed hills with gently sloping sides. They form where basaltic to andesitic lavas erupt effusively, flowing far from a vent. Prolonged volcanism at a single site may produce a sizeable edifice. The Batamote Mountains shield volcano is 15 km (9 mi) wide, 23 km (14 mi) long, and 960 m (3,150 ft) high; slopes of 1°–2° radiate out from the summit region (Bowles and Greeley 2013).

Using remote sensing (e.g., color variations of earth materials in imagery), analysis of Landsat 7 Enhanced Thematic Mapper "Plus" data, and fieldwork, Bowles and Greeley (2013) mapped the Batamote Mountains in greater detail than Skinner et al. (2008). Mapping and analysis by Bowles and Greeley (2013) concluded that the Batamote Mountains represent a 16-million-to-14-million-year-old shield volcano, which corresponds to the age of volcanic activity provided by Skinner et al. (2008) for the Batamote Andesite complex. However, X-ray fluorescence chemical analyses, also by Bowles and Greeley (2013), support renaming the rocks exposed in the Batamote Mountains as "Batamote Basalt" in accordance with the Le Bas total alkali-silica volcanic rock classification (Le Bas et al. 1986), which plots the percentage of sodium oxide (Na_2O) and potassium oxide (K_2O) in relation to silica (SiO_2) of volcanic rocks.

According to Bowles and Greeley (2013), the Batamote Mountains shield volcano initially built up from mildly explosive eruptions from at least six vents (see fig. 23, namely areas of units Tbi and Tbv of Bowles and Greeley [2013]). The associated lava flows (unit Tbb of Bowles and Greeley 2013) (see fig. 23) partly cover the pre-Batamote basement rocks (e.g., Sauceda rhyolite [Tsr], Sikort Chuapo dacite [Tsd], and Childs Latite [Tcl]), which consist of silica-rich volcanic rocks (i.e., containing the mineral quartz; see table 2). The next eruptive sequence involved effusive stages (unit Tbb) of the central source vent and, likely, several other presently buried sources. At least three subsequent effusive phases emplaced multiple flows on cinder-cone deposits and lava flows of earlier eruptions (unit Tbb). Finally, fire fountains around a central vent produced several short, thin, agglutinated flows (composed of welded and fused fragments of volcanic glass), which form the steeper summit of the volcano (units Tbi and Tbv). Subsequent erosion of summit material left the amphitheater morphology seen today.

Basin Fill

Associated map unit: **QTal**

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" (Scarborough 1981, p. 5). The process of basin filling consists of erosion of rocks exposed in the mountains and deposition of sediments such as gravel, sand, silt, and clay in deep intermontane basins. Since about 5 million years ago (late Miocene or Pliocene Epoch), basin filling has been the main geologic process operating at the monument. The mountains are "literally burying themselves with their own debris" (Houk 2000, p. 12). Growler Valley, for example, contains deposits as thick as 1,500 m (4,800 ft). Basin fill in the Valley of the Ajo is as much as 980 m (3,200 ft) thick. In the Sonoyta Valley and La Abra Plain, deposits are as much as 240 m (800 ft) thick (Richard et al. 2007).

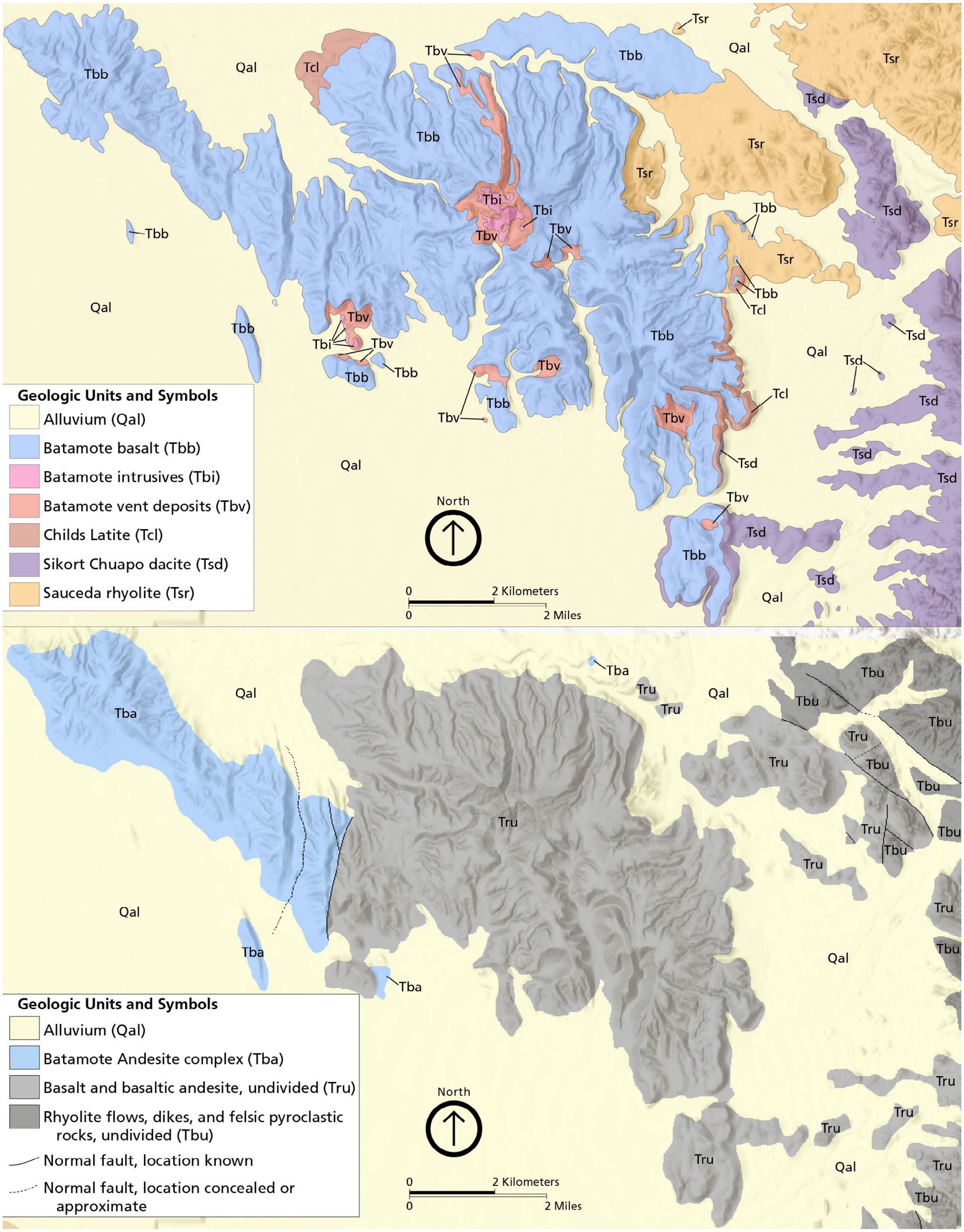

Figure 23. Geologic maps of the Batamote Mountains.
Since mapping by Skinner et al. (2008), investigation has revealed a shield volcano. Top: Plate 1 of Bowles and Greeley (2013). Bottom: GRI GIS data of the monument; source map by Skinner et al. (2008). Figure by Trista Thornberry-Ehrlich (Colorado State University).

Groundwater Basin/Aquifer

Associated map unit: **QTal** and surrounding bedrock

Thick deposits of basin fill (**QTal**) are important because they serve as the major aquifer (body of permeable rock that contains and/or transmits groundwater) in the Basin and Range province (Barnett and Sharrow 1992). In addition to basin fill, two other types of aquifers may be present at the monument. First, recent stream alluvium probably serves as another major aquifer in the Lower Gila basin, which underlies the northern part of the monument (Arizona Department of Water Resources 2009). Second, the active channel of the Rio Sonoyta, which is likely connected to the groundwater system of the southern part of the monument, is an aquifer (Goodman 1992).

Geohydrologic features of the basin fill determine where and how groundwater is stored and where and how groundwater moves through the subsurface. Types of now-buried sedimentary deposits (e.g., alluvial fan, stream channel, delta, and lake) and the composition of materials (e.g., clay vs. sand/gravel) govern water-yielding properties and have the potential to serve as barriers to groundwater flow; for example, impermeable basin-center lakebed clay deposits (see Hollett 1985) will affect storage and movement of groundwater.

The "joint term" basin/aquifer is used in this report to emphasize the relationship between bedrock and basin fill (see "Groundwater Assessment"). A basin is like a large bedrock-enclosed bathtub. Over the past 5 million years, these "bathtubs" have been filling with hundreds or even thousands of feet of sediment (see "Basin Fill"). The sedimentary material filling the bathtubs is an aquifer.

The characteristics of the groundwater basin/aquifer associated with the monument are not completely known (see "Groundwater Assessment"), but the monument's groundwater system is likely connected to at least five named groundwater basins/aquifers (fig. 24). Using descriptions provided by the Arizona water atlas (Arizona Department of Water Resources 2009), the monument is connected to (1) Lower Gila basin/aquifer in the northern part of the monument, (2) Western Mexican Drainage basin/aquifer in the southern part of the monument, and (3) San Simon Wash basin/aquifer in the eastern part of the monument. In addition, based on work by Sanchez et al. (2016), the Western Mexican Drainage basin/aquifer (north of the US–Mexico border) is associated with the (4) Los Vidrios basin/aquifer and the (5) Sonoyta-Puerto Peñasco basin/aquifer (south of the US–Mexico border). The San Simon Wash basin/aquifer (north of the US–Mexico border) is also associated with the Sonoyta-Puerto Peñasco basin/aquifer (south of the US–Mexico border).

Except for the Lower Gila basin/aquifer, which underlies the northern part of the monument, the other groundwater systems associated with the monument suffer from "blank map" syndrome, in which a transboundary aquifer is mapped by an entity in the United States but because US researchers lack access to Mexican data, the portion of the aquifer south of the border shows up completely blank on the map; the same problem occurs north of the border for Mexican researchers (Good Neighbor Environmental Board 2010). Notably, US Geological Survey investigators currently conducting geophysical surveys at the monument, which will feed an updated groundwater conceptual model, are collaborating with Mexican colleagues (Rijk Moräwe, Organ Pipe Cactus National Monument, chief of Natural and Cultural Resources Management, written communication, 27 October 2021).

The plethora of aquifer names associated with the monument can be simplified into the Rio Sonoyta basin/aquifer, which harkens back to usage by Brown (1991). The boundaries of the Rio Sonoyta basin/aquifer can be imagined as coinciding with the Rio Sonoyta surface-water catchment area, also referred to as a "watershed" or "drainage basin" (fig. 25). Flow within the Rio Sonoyta basin/aquifer, however, may not coincide with the surface-water catchment area. If a gradient and pathway exist, groundwater may move large distances beneath several surface drainages and divides (Barnett and Sharrow 1992).

Some characteristics of the groundwater basin/aquifer are known. For example, the Arizona water atlas (Arizona Department of Water Resources 2009) includes simple maps that show generalized flow directions, consolidated crystalline and sedimentary rocks, and unconsolidated sediments for the Lower Gila, San Simon Wash, and Western Mexican Drainage basins/aquifers. Groundwater flow between these basins north of the US–Mexico border and among the associated basins south of the border is not known, however. Yet, recent findings by Zamora et al. (2020) suggest that the source of the groundwater at Quitobaquito Springs originated in the Bavoquivari Mountains (east of the monument; see fig. 25). Thus, at least the Western Mexican Drainage basin/aquifer (associated with Quitobaquito Springs) and the San Simon Wash basin/aquifer (associated with the Bavoquivari Mountains) seem to be connected (see "Groundwater Assessment"). As proposed in the model by Carruth (1996), a likely pathway of groundwater flow between basins is through highly fractured bedrock (see

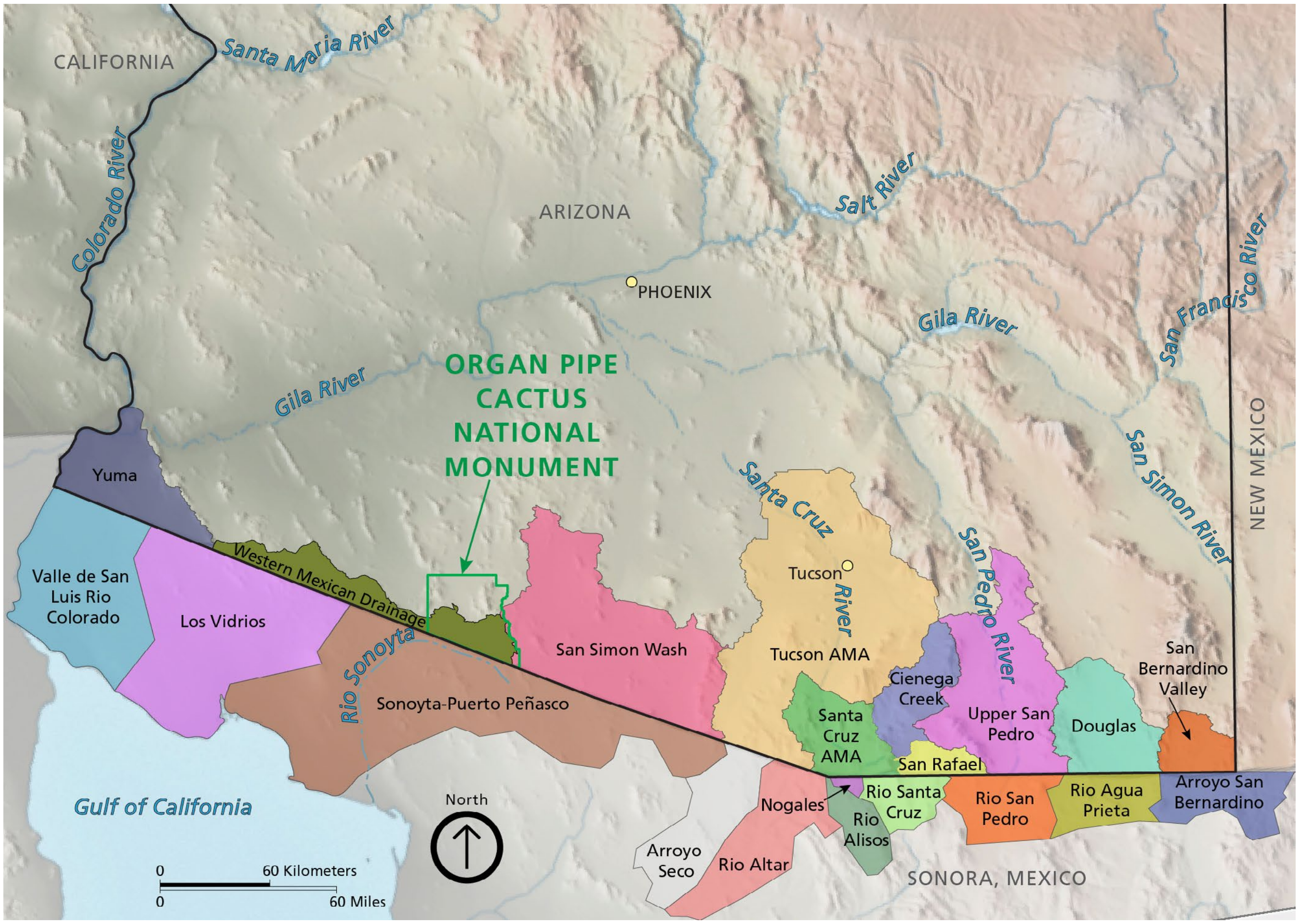

Figure 24. Map of transboundary aquifers between Arizona and Sonora.
The monument is outlined in green on the figure. The Lower Gila aquifer (not labeled) underlies the northern part of the monument. The southern part of the monument overlies the Western Mexican Drainage aquifer (Arizona Department of Water Resources 2009). This aquifer borders the Los Vidrios and Sonoyta-Puerto Peñasco aquifers in Mexico. The groundwater at the monument also may be connected to the San Simon Wash aquifer in Arizona. Figure by Thornberry-Ehrlich (Colorado State University) using NPS base map by Tom Patterson and information from Sanchez et al. (2016, figure 3).

fig. 8). This model, however, was proposed for a "local" system (i.e., La Abra Plain) and its applicability to a "regional" system is not known.

Although more information is needed to generate a satisfactory understanding of the monument's groundwater system (see "Groundwater Assessment"), past geohydrologic (e.g., Hollett 1985) or hydrogeologic (e.g., Carruth 1996) studies provide a picture of the groundwater basin/aquifer connected to the monument as consisting of broad, deep, sediment-filled basins bounded by low, jagged, fault-block mountains (see "Geologic Setting"). Groundwater is thought to enter the sediment-filled basins principally as underflow beneath washes and as recharge along the mountain fronts (Hollett 1985).

Hollett (1985) is a source of geohydrologic information for a portion of the eastern part of the San Simon Wash basin/aquifer. Carruth (1996) is a source of geohydrologic information for La Abra Plain, which covers a portion of the Western Mexican Drainage basin/aquifer. Also, Haxel et al. (1984) mapped geologic structures such as faults, which affect groundwater storage and movement; these faults are included in the GRI GIS data. A listing of these and other investigations related to the geohydrology of the Quitobaquito–La Abra Plain–Rio Sonoyta valley area of the monument was provided by Goodman (1992).

At the present time, the NPS is working with the US Geological Survey on an updated evaluation of the Quitobaquito aquifer (Organ Pipe Cactus National Monument 2020; Macey et al. 2021). A better

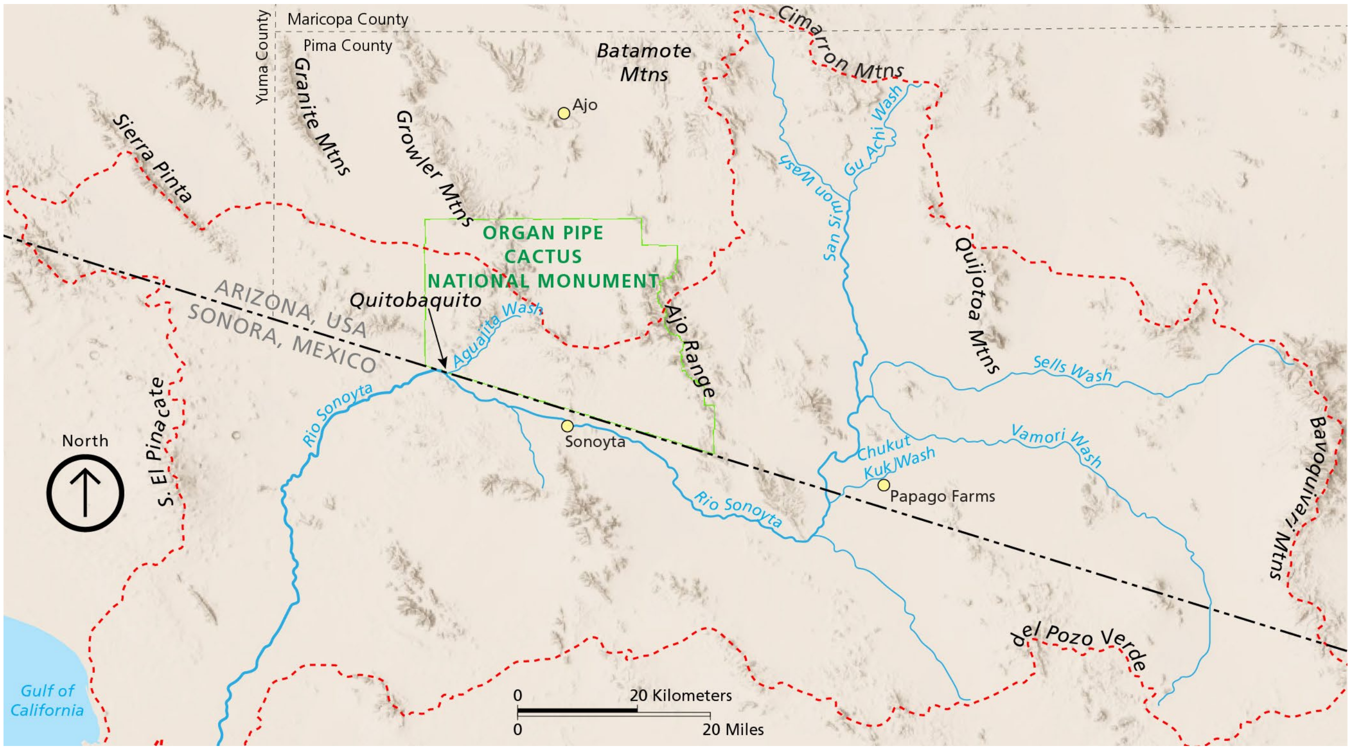

Figure 25. Location map of the Rio Sonoyta watershed.
The Rio Sonoyta watershed is outlined with a dashed red line. The southern part of the monument is within the watershed. The monument is outlined in green on the figure. Map by Trista Thornberry-Ehrlich (Colorado State University). Base map is World Hillshade (WGS84), downloaded from ESRI ArcGIS online.

understanding of the source of Quitobaquito Springs will provide the NPS with information necessary to manage this important resource and ensure sustainability for the species that depend on a secure and stable water source (see "Groundwater Assessment" and "Threats to Quitobaquito"). Investigators are considering previous conceptual models by Carruth (1996), which has the source of groundwater to Quitobaquito Springs as coming from La Abra Plain, and Zamora et al. (2020), which has the source of groundwater coming from the Mexican portion of the aquifer. The current working hypothesis is that some groundwater comes from each area, but the proportion is unknown and likely changing with climate and pumping (Macey et al. 2021).

Streams and Washes

Associated map unit: **QTal**

In much of Arizona, development of the present-day landscape is heralded by stream incision and dissection of basin fill by through-flowing rivers. Arizona parks in the National Park System with good examples of river development during the Pleistocene Epoch (2.6 million to 11,700 years ago) include Casa Grande Ruins, Montezuma Castle, Tuzigoot, and Tonto National Monuments (see GRI reports by KellerLynn 2018, 2019a, 2019b, and 2020, respectively).

In most parts of Organ Pipe Cactus National Monument, however, very little incision has taken place during the past 2.6 million years (Quaternary Period) (Pearthree et al. 2012). Rather, washes (broad, gravelly, normally dry stream beds, occasionally filled by a deluge of water) dominate the valley floors (see "Flash Flooding").

Washes in the monument drain toward the Rio Sonoyta, which is an incised river (fig. 26). The segment of the Rio Sonoyta south of the monument is distinctive because the river does not follow the longitudinal axis of the northwest–southeast valley but drains across it, breaching many topographic features. This breaching is a result of the formation of an integrated drainage pattern (multiple drainages coalescing into a single, lower base level). The timing of this event is speculative but may coincide with integration of drainage on the lower Colorado and Gila River systems, which have been estimated as taking place in the late Miocene and early Pliocene Epochs (Eberly and Stanley 1978; Goodman 1992).

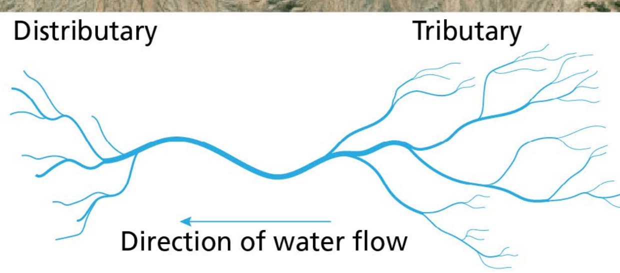

Figure 26. Satellite image showing washes.
The stream pattern of Cherioni and Alamo Washes is distributary (downstream branching). By comparison, the stream pattern of Aguajita Wash is tributary (downstream joining). Like Aguajita Wash, other ephemeral streams that flow across La Abra Plain and the Sonoyta Valley are tributary. These stream systems flow to the Rio Sonoyta (south of the monument). The green outline on the figure delineates the boundary of the monument. Figure by Trista Thornberry-Ehrlich (Colorado State University). Base imagery by ESRI World Aerial Imagery, taken 5 April 2021.

In many drainage systems in southern and central Arizona, the channel network changes from tributary (“downstream joining”) to distributary (“downstream branching”) (see fig. 26). In the stream networks at the monument, tributary patterns characterize the water- and sediment-gathering parts of the fluvial systems. Distributary portions of these same systems are common in areas of recent deposition such as alluvial fans or widening downstream reaches. The tributary patterns along most washes in the monument indicate that most valley areas are currently being eroded, with active deposition characterized by distributary channel networks being quite limited. Nevertheless, parts of Alamo Wash east and west of State Road 85 are definitely distributary (i.e., having active deposition), as was obvious after the large flood in 2012 (Phil Pearthree, AZGS, director and state geologist, written communication, 29 June 2021).

Another means of transporting surficial material across a valley floor, across flat portions of alluvial fans, or on flat or nearly flat areas is overland flow, referred to as “sheet flow” or a “sheetflood.” These broad movements of water, which are heavily laden with rock debris, may be local or regional, may reach 30 cm (12 in) or more in depth, and can travel considerable distances. Sheetfloods are short-lived but can be very destructive to any obstacles in their path (Keith 1971). AZGS mapping projects by Pearthree et al. (2012), Youberg and Pearthree (2012), and Young and Pearthree (2012) identified sheetflood deposits in the Valley of the Ajo and Sonoyta Valley (see “Surficial Geologic Mapping”).

Terrace Gravels or Relict Alluvial Fan Deposits

Associated map unit: **QTg**

Terraces are high remnants of old valley floors. They can be thought of as abandoned floodplains. Various terrace levels show where a river paused in its downcutting, and multiple terraces indicate that incision of a valley was not steady. Based on 2012 mapping by the AZGS (see “Surficial Geologic Mapping”), the so-called “terraces” in the monument are more likely relict (abandoned) alluvial fans (Phil Pearthree, AZGS, director and state geologist, written communication, 29 June 2021).

As mapped by Skinner et al. (2008), terrace gravels (**QTg**) consist of tan to brown, pebble- and boulder-conglomerate and volcaniclastic sandstone. Individual strata are poorly to well-bedded with well-developed channels and crossbedding; coarse beds are poorly sorted (Skinner et al. 2008).

With respect to mapping by Skinner et al. (2008), terrace gravels (**QTg**) are one of two surficial units mapped in the monument. The other surficial unit mapped by Skinner et al. (2008) is alluvium and colluvium (**QTal**). Notably, Skinner et al. (2008) focused on bedrock geology (see “Surficial Geologic Mapping”).

The map unit symbol, **QTg**, indicates that terrace gravels are Quaternary (“**Q**”) and/or Tertiary (“**T**”), that is, deposited in the past 66 million years and, thereby, including the Paleocene, Eocene, Oligocene, Miocene, Pliocene, Pleistocene, and Holocene Epochs (see table 1). As such, “**QT**” represents a very conservative age designation for terrace gravels. Some of the highest “terraces” could be as old as late Pliocene, but none in this map unit are as young as Holocene (Phil Pearthree, AZGS, director and state geologist, written communication, 29 June 2021).

The best examples of terrace gravels in the monument are found in Aguajita Wash, between the Bonita Well picnic area and Cipriano Hills (Bezy et al. 2000). Mapping by Skinner et al. (2008) included these deposits (see poster). According to Bezy et al. (2000), which highlighted these deposits as feature 8 in *A Guide to the Geology of Organ Pipe Cactus National Monument and the Pinacate Biosphere Reserve*, terraces are evidence of dramatic changes in the flow of Aguajita Wash. Sediment, which washed down from the Cipriano Hills, Bates Mountains, and Puerto Blanco Mountains, once filled this valley to the level of the highest terrace, which is an estimated 550 m (1,800 ft) above sea level. For comparison, Bonita Well, which is at the bottom of today’s valley floor, is at about 410 m (1,350 ft) above sea level. Thus, faster moving waters than at present cut down through an estimated 140 m (450 ft) of basin fill, sweeping much of it away. The process of downcutting halted at least five times, allowing the stream to erode laterally and produce floodplains, which are represented by the stair-like flight of cobble capped terraces displayed along the southeastern margins of the Cipriano Hills (Bezy et al. 2000).

Bajada

Associated map unit: **QTal**

Originating in the humid Piedmont district of Italy, the term “piedmont” is used to designate the “foot of the mountain” region (Italian: ai piede della montagne). In arid regions like the southwestern United States, the term “bajada” (meaning “descent” or “slope” in Spanish) is commonly used. While some researchers use “bajada” as equivalent to “piedmont,” others apply “bajada” specifically to coalescing alluvial fans (fig. 27).

The continuum of rocky slopes, alluvial fans, and fine-grained material on the valley floors constitutes a significant natural feature that is important for both

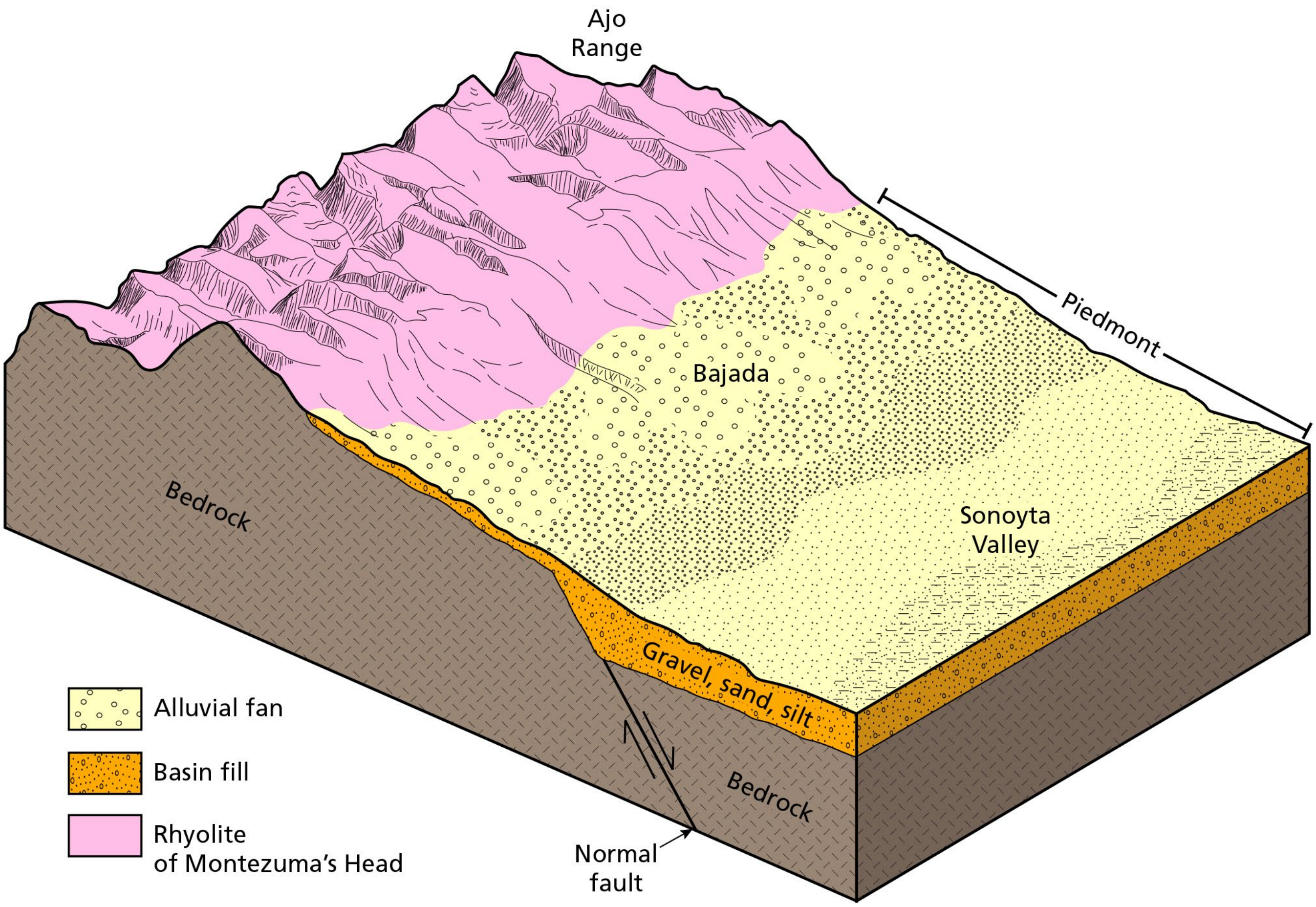

Figure 27. Block diagram of bajada.
The figure depicts the southwestern margin of the Ajo Range and Sonoyta Valley. Piedmont means "foot of the mountain." In the US Southwest, the terms "piedmont" and "bajada" are used interchangeably, though some geomorphologists limit the use of "bajada" to mean coalescing alluvial fans. Alluvial fans and other surficial deposits lie atop basin fill (gravel, sand, and silt) that accumulated in a structural basin as it dropped down along normal faults. The geologic episode of basin filling ended about 5 million years ago, but deposition of sediments across the bajada and on the valley floor continues to the present day. Graphic by Trista Thornberry-Ehrlich (Colorado State University) after Bezy et al. (2000, figure 7-2).

plant and animal diversity (National Park Service 2006). The following are some examples: The bajada influences where columnar cacti grow (i.e., the valley floor regularly experiences sub-freezing temperatures in the winter and is less rocky, so cacti prefer to grow higher up on the bajada). In general, for saguaro cactus (*Carnegiea gigantea*), numbers increase upslope; they are most prolific in the upper middle to upper bajada, where organ pipe cactus also grow. The bajada also influences where different wildlife species tend to range (Rijk Moräwe, Organ Pipe Cactus National Monument, chief of Natural and Cultural Resources Management, written communication, 7 April 2021; email communication 3 January 2022). For example, the entrenched, shallow stream channels that radiate across the surfaces of alluvial fans are natural corridors for animals and, thereby, good places for visitors to spy wildlife such as the collared peccary, also known as javelina (*Pecari tajacu*). This pig-like animal snuffles along searching for tubers to eat (Houk 2000). Additionally, active alluvial fans support dense stands of vegetation important to wildlife (Skinner et al. 2008). Where slopes are less than 1.5°, sheet flow (overland, non-channelized flow) creates two-phase plant communities that may be important to pronghorn habitat (Mary Kralovec, Organ Pipe Cactus National Monument, chief of Resource Management, written communication, 16 March 2006, *cited in* National Park Service 2006).

Upper Bajada

At the monument, the upper margins of the bajada are generally covered by hillslope deposits and regolith (layer of unconsolidated rocky material that covers bedrock), which includes weathered bedrock, locally derived hillslope colluvium (poorly sorted rock fragments at the base of slopes), and coarse boulder and cobble talus (accumulations of rock fragments, typically in a heap or mass). The upper bajada is dominated by Pleistocene alluvial fan deposits (Pearthree et al. 2012; Youberg and Pearthree 2012; Young and Pearthree 2012), which have moderate soil and desert-pavement development (see "Desert Pavement").

Middle Bajada

The middle bajada is characterized by an extensive and complex distributary ("downward branching") drainage system (see fig. 26) composed of alluvial fans and terrace deposits. Alluvial-fan deposits are slightly dissected by stream courses, which are characterized by entrenched walls along stream channels and dominantly coarse-grained materials in the streambed (Brown 1992). Terrace deposits (in contrast to terrace gravels, **QTg**) are found on floodplains and low terraces adjacent to active channels or in drainageways that receive occasional inundation.

Lower Bajada

The lower bajada is covered by young, relatively fine-grained deposits from active washes. Stream channels have not incised the washes (Pearthree et al. 2012; Youberg and Pearthree 2012; Young and Pearthree 2012).

In some locations, alluvial fans form relatively far out into valleys if washes have cut into older fan deposits that are closer to the mountain fronts. This is generally the case in the monument (Phil Pearthree, AZGS, director and state geologist, written communication, 29 June 2021).

Paleontological Resources

Tweet et al. (2008) completed a paleontological resource inventory and monitoring report for the Sonoran Desert Network. That report included a summary of the monument's paleontological resources. Based on Tweet et al. (2008), the scoping summary (National Park Service 2006), and reviewers' comments of the draft GRI report, the following four types of paleontological resources are worthy of mention: (1) packrat (*Neotoma* spp.) middens; (2) an unidentified, fossiliferous conglomerate; (3) specimens in museum collections; and (4) Quaternary fossils. These are listed by potential significance, not age.

Packrat Middens

Fossil packrat middens are the most common and important fossil resource at the monument (Tweet et al. 2008). Middens consist of plant material, food waste, coprolites (fossil dung), bones, and other biological materials collected by packrats and cemented by their viscous urine.

Middens are important tools for reconstructing the ecology and climate of the southwestern United States during the latest Pleistocene and Holocene Epochs (Strickland et al. 2001). Analysis of middens at the monument has provided a detailed picture of the vegetation, climate, and terrestrial microfauna over the past 35,000 years (Tweet et al. 2012).

Analysis of middens from the Ajo Range indicates that the monument was characterized by pinyon–juniper–oak woodland about 18,000 years ago. Analysis of middens from the Puerto Blanco Mountains indicates that the monument was characterized by juniper–Joshua tree woodland about 17,000 years ago, juniper–Sonoran desertscrub about 11,000 years ago, a cool Sonoran desertscrub about 8,400 years ago, and a subtropical Sonoran desertscrub about 2,400 years ago (Van Devender et al. 1991; Tweet et al. 2008). Today, biotic communities in the monument include Arizona Upland desertscrub, Lower Colorado Valley desertscrub, temperate woodlands and scrub, xeroriparian woodlands and scrub, and a small wetland (Organ Pipe Cactus National Monument 2006).

Fossil packrat middens also are the best studied fossil resource at the monument (Tweet et al. 2008). Work by T. R. Van Devender is notable; for instance, Van Devender (1990) is probably the most extensive published survey of middens in the Sonoran Desert. Van Devender (1982) and Van Devender et al. (1991) provided documentation specific to the monument.

Another source of information about the monument's packrat middens is the North American Packrat Midden Database (US Geological Survey 2016), which includes 32 records from the monument. Within the monument, 11 middens have been studied from the Ajo Range (seven from Alamo Canyon and four from Montezuma Head) and 21 from the Puerto Blanco Mountains (10 from Ajo Loop, seven from Twin Peaks, and four from Cholla Pass). Furthermore, a series of 21 publications titled *Ajo Peak to Tinajas Altas: Flora of Southwestern Arizona* (Felger et al. 2013a–e, 2014a–c, 2015a–h, 2016; Felger and Rutman 2016a–d) described plant fossils from middens in the monument.

Middens at the monument have yielded the following fossils: plant macrofossils (Van Devender 1977, 1982, 1987, 1990; Spaulding 1983; Van Devender et al. 1990); pollen (Anderson et al. 1987; Davis 1990); arthropod fossils including beetle, ant, antlion, burrowing bug, kissing bug, soldier fly, millipede, and scorpion (Hall et al. 1989, 1990); and vertebrates fossils such as lizard, bird, shrew, rodent, and rabbit (Mead et al. 1983; Van Devender et al. 1991).

Fossiliferous Conglomerate

During the scoping meeting, Gordon Haxel (US Geological Survey–Flagstaff) showed a picture of a hand-sized specimen of a Tertiary conglomerate that contained fossils (e.g., shells, crinoid stems, and brachiopods). Although Haxel assumed that these fossils were rather insignificant, post-meeting correspondence with Jason Kenworthy—who was the paleontology technician for the GRD at that time (February 2006)—revealed that this picture was the first documentation of a fossil in bedrock at the monument.

In conjunction with review of the draft GRI report, Vince Santucci attempted to track down the original photograph (Vince Santucci, NPS, paleontologist, email communication to Gordon Haxel, US Geological Survey–Flagstaff, geologist, 10 March 2021). Unfortunately, this and other attempts were unsuccessful.

The fossiliferous conglomerate is thought to have come from along the western boundary of the monument (Peter Holm, Organ Pipe Cactus National Monument, resource program manager, personal communication, May and September 2008, *cited in* Tweet et al. 2008, p. 69). Based on that general location, the most likely source is the Escabrosa and Martin Formations (**MDm**). The Escabrosa and Martin Formations consist of limestone deposited under shallow marine conditions during the Mississippian and Devonian Periods (419 million to 323 million years ago), and the conglomerate is likely reworked Paleozoic cobbles (National Park Service 2006; Tweet et al. 2008). The rock unit (**MDm**) shares a solitary bedrock exposure with the Cretaceous and Jurassic conglomerate at Scarface Mountain (**KJc**) in an isolated hill in the Growler Valley (see poster). Normal faulting brought the Escabrosa and Martin Formations to the surface.

In an attempt to identify the so-called Tertiary conglomerate for the GRI, map unit descriptions of Skinner et al. (2008) were searched, resulting in a list of five Tertiary-age units that contain conglomerate: (1) Daniels Conglomerate and associated lake deposits (**Tdc**); (2) Childs Latite (**Tca**); (3) sedimentary and volcanic rocks, undivided (**Tsvu**); (4) Batamote Andesite complex (**Tbau**); and (5) rhyolite of Pinkley Peak (**Tps**). However, none of these units appear to have outcrops on the western side of the monument, though the Daniels Conglomerate crops out in the northwestern corner (southern end of the Growler Mountains; see poster). Daniels Conglomerate also occurs in the Ajo Range on the eastern side of the monument. Childs Latite (**Tca**) occurs in the Bates Mountains (central part of the monument). Sedimentary and volcanic rocks, undivided (**Tsvu**) occur on the eastern side of the monument (Ajo Range). Batamote Andesite complex (**Tbau**) is in the southwestern part of the monument (Cipriano Hills). The conglomerate-containing unit of the rhyolite of Pinkley Peak (i.e., arkosic and volcaniclastic sandstone, **Tps**) does not occur in the monument, though other units of rhyolite of Pinkley Peak do (see table 1).

Considering both age and location of these five map units, the Daniels Conglomerate is the most likely candidate (Justin Tweet, GRD, associate, email communication, 6 April 2021). Notably, however, Gilluly (1946, p. 43), who was the first to describe the Daniels Conglomerate in the southwestern part of Chico Shunie Hills (north of the monument), stated that "no fossils have been found" in it. At that location, which is just north of Daniels Arroyo, the Daniels Conglomerate forms a belt about 2.4 km (1.5 mi) wide (Gilluly 1937).

Field reconnaissance is needed to identify the source of this paleontological material in the monument. Determining the age of a random conglomerate, particularly in the field, may be difficult (Justin Tweet, GRD, associate, email communication, 6 April 2021) but could be an interesting project for a Scientists in the Parks (SIP) participant (see "Guidance for Resource Management"). A small area of conglomerate at Scarface Mountain (**KJc**) near the western boundary of the monument is an intriguing possibility (Justin Tweet, GRD, associate, email communication, 6 April 2021), though this unit is of Jurassic and Cretaceous, not Tertiary.

Fossils in Museum Collections

Reanalysis of specimens in museum collections has the potential to reveal yet unidentified paleontological resources. Museum specimens also illustrate the connection between geology and archeology (see "Geologic Connections to Cultural Resources"). As defined by the NPS Archeology Program, archeological resources are any physical evidence of past human activity at least 100 years old. Humans often used fossils or other geologic materials to make things such as tools, jewelry, or ceremonial items. In many cases, these artifacts date back thousands of years while the source of the artifact itself (i.e., fossil) may be millions of years old. Kenworthy and Santucci (2006) cited examples of NPS fossils as archeological resources. Additionally, fossils may occur in other cultural resource contexts such as ethnographic stories and legends; prehistoric and historic structures; and historic research, collections, and displays.

Tweet et al. (2008) documented 12 paleontological specimens in the monument's museum collection. Most of these specimens were collected by Charles B. Hunt in 1970. Those collected by Hunt include four specimens (ORPI 4802, 4803, 4804, and 4805) of rugose corals (a type of coral that became common in the Ordovician Period and went extinct at the end of the Permian Period; also known as horn corals when solitary). The type of coral suggests that the rocks in the monument most likely to have yielded these fossils are the Escabrosa and Martin Formations (**MDm**). Hunt also collected five brachiopod specimens (ORPI 4806, 4807, 4808, 4809, and 4810). The other three specimens of the 12 in the monument's museum collection are a beetle (*Phyllotreta*; ORPI 6624), an ant (*Pseudomymex apache*; ORPI 6646), and a wasp (*Eumenes bolli*; ORPI 7103). These were collected by R. Bailowitz and E. Draeger in 1987.

The collection housed by the NPS Western Archeological and Conservation Center (WACC) also contains fossils associated with the monument. These are two bivalve specimens (ORPI 9006 and 13664); the former is fragmented into 17 pieces (fig. 28; Justin Tweet, GRD, associate, email communication, 3 November 2020).

Quaternary Fossils

Rocks or sediments from the Quaternary Period (the past 2.6 million years) may contain isolated remains of fauna such as testudines (turtles and tortoises), equids (horses), camelids (camels), and proboscideans (mammoths and elephants) (Robert McCord, Arizona Museum of Natural History, paleontologist, personal communication, May 2008, *cited in* Tweet et al. 2008, p. 75). Investigators have found fossil testudinind material near Pozo Nuevo and possible vertebrate remains along the strike of the seep that forms Quitobaquito Springs (Tweet et al. 2008, p. 75).

Rocks or sediments from the Quaternary Period also may contain the remains of ancient flora. Possible plant fossils occur in the Sonoyta Valley, northwest of the Salsola weather station. These are "root or stem-like fossils made of a caliche-like material" (Peter Holm, Organ Pipe Cactus National Monument, resource program manager, personal communication, May and September 2008, *cited in* Tweet et al. 2008, p. 75). Using radiocarbon dating, plant fossils and charcoal from two Quaternary deposits in the monument yielded calendar ages of 17,800 ± 100 years ago and 2,552 ± 199 years ago (Pohl 1995).

Additionally, plant scar mounds and depressions (alterations to the terrain that remain for thousands of years after the death of a large perennial plant in desert settings) are a paleontological resource at the monument. After a plant dies, modifications occur to the location over time, leading first to a light-colored mound 2–6 m (7–20 ft) across and 0.3 m (1 ft) tall surrounded by a ring of larger cobbles, then a light-colored ringed depression with a desert pavement surface (see "Desert Pavement"). Mounds occur near modern water courses; depressions are only found farther out. Depressions likely correspond to a change in climate during the Pleistocene-Holocene transition (about 11,700 years ago). The mounds likely correspond to another episode of climate change a few thousand years ago. These features, if not true trace fossils, are close enough to bear mentioning in a paleontological inventory; they are certainly large, easily observed records of past life (McAuliffe and McDonald 2006; Tweet et al. 2008).

Desert Pavement

Desert pavement is a distinctive geologic feature found throughout the monument, commonly in areas of smooth, gently sloping surfaces on relict (abandoned) alluvial fans and terraces. Notable examples of desert pavement occur along Ajo Mountain Drive southwest of the Diablo Canyon picnic area.

Desert pavement consists of an armored surface of angular or rounded rock fragments, usually one or two stones thick, which caps underlying fine-grained material (i.e., silt and sand). Desert pavement protects the fragile underlying substrate from further erosion by wind or water (Brown 1992).

Various mechanisms have been suggested for the formation of desert pavement including deflation (wind erosion of fine-grained material); rain wash and overland flow (i.e., water erosion of fine-grained material); cycles of freezing and thawing or wetting and drying, which were thought to cause coarse fragments to migrate upwards; and upward migration of stones through a slowly formed, clayey soil horizon. Research over the past 30 or 40 years has demonstrated, however, that the surface gravel layer typically overlies fine soil horizons (usually silt and clay with some sand and minor gravel). Thus, soil scientists and geomorphologists have ruled out other mechanisms and concluded that the surface gravel layer traps eolian dust that is then moved down into the soil profile during major wetting events (McFadden et al. 1987).

Figure 28. Photograph of bivalve fossils.
The NPS Western Archeological and Conservation Center (WACC) collection contains fossils associated with the monument. The photograph shows specimen ORPI 9006, which is a shell fragmented into pieces. NPS photograph courtesy of Vince Santucci (GRD), taken 2015.

Biological Soil Crusts

Depending on the expertise of past scoping participants and the interest and need of park managers, some GRI reports have included a discussion of biological soil crusts, for example, Canyonlands National Park (KellerLynn 2005), Colorado National Monument (KellerLynn 2006), White Sands National Monument (KellerLynn 2012), and Casa Grande Ruins National Monument (KellerLynn 2018). In general, however, biological soil crusts are beyond the scope of the GRI because they are "alive" and associated with soils and, thereby, addressed by other inventories (e.g., Soil Resources Inventory). Nevertheless, a brief account is included here because biological soil crusts are an important "soil binder" likened to desert pavement (Rijk Moräwe, Organ Pipe Cactus National Monument, chief of Natural and Cultural Resources Management, written communication, 7 April 2021).

Biological soil crusts—also known as "cryptogamic," "microbiotic," "cryptobiotic," or "microphytic"—are formed by living organisms and their byproducts. The various names are all meant to indicate common features of the organisms that compose the crusts, which consists of an interwoven community of cyanobacteria, lichens, mosses, green algae, microfungi, and bacteria. The most inclusive term is probably "biological soil crust" because it distinguishes these crusts from physical or chemical crusts without limiting the crust components to plants.

The Sonoran Desert Network monitors the cover and frequency of biological soil crusts in the monument (see "Guidance for Resource Management"). Information gathered during monitoring is used to track soil function and improve current understanding of ecosystem health. Monitoring protocols are specifically designed to minimize impact to these fragile communities.

Geologic Resource Management Issues

This chapter highlights issues (geologic features, geologic processes, and human activities affecting or affected by geology) that may require management for human safety, protection of infrastructure, or preservation of natural and cultural resources. GRD staff provides technical and policy assistance for these issues (see "Guidance for Resource Management").

During the 2006 scoping meeting, 2020 conference call, and GRI report review process, participants and reviewers (see "Acknowledgements") identified the following geologic resource management issues. As suggested by Rijk Moräwe (Organ Pipe Cactus National Monument, chief of Natural and Cultural Resources Management, written communication, 17 May 2021), the issues of greatest concern for human safety are discussed first then important resource concerns followed by extremely rare geologic events. An additional issue not represented in this ordering scheme is the need for geologic interpretation at the monument; this is discussed last.

- Flash Flooding
- Erosion
- Groundwater Assessment
- Threats to Quitobaquito
- Climate Change Impacts to Geologic Resources
- Abandoned Mineral Lands
- Mining
- Mineral and Energy Development
- Slope Movements
- Active Faults and Earthquakes
- Giant Desiccation Cracks vs. Earth Fissures
- Geologic Interpretation

Flash Flooding

The monument contains many washes (see "Streams and Washes"), which are part of a south-flowing drainage system. Heavy local showers—an estimated 8 cm (3 in) per hour (National Park Service 2006)—can change innocent-looking washes into raging torrents capable of carrying away anything in their path. Where roads pass through these "dips," travelers should not attempt to pass through them at such times. Fortunately, flooding is normally short-lived and usually only a short wait on higher ground is necessary before a wash can be safely crossed (Keith 1971).

"Stream capture" by roads during flooding events is an issue for public safety and resource management (National Park Service 2006). The smooth, impermeable surface of paved roads concentrates and swiftly transports floodwaters, causing exacerbated erosion such as gullies where floodwaters "exit" the roadway. Moreover, unpaved roads and trails, as well as undesignated vehicle routes, can serve as linear entrenchments that capture water, promoting accelerated erosion (see "Erosion").

Another flooding-related issue is the construction of infrastructure along the international border between the United States and Mexico (fig. 29). In 2008, for example, a pedestrian fence was constructed along 8.4 km (5.2 mi) of the monument's southern boundary; a typical fence section stood about 5 m (15 ft) high and consisted of a wire mesh panel. From 2019 to 2021, the so-called border "wall" was constructed, resulting in alteration of 45.9 km (28.5 mi; 95%) of the monument's southern boundary. Infrastructure now includes a 9-m- (30-ft-) tall bollard-style fence that replaced a vehicle barrier and two-track dirt road; footers extend 2 m (8 ft) into the ground. In addition, lights, 12 m (40 ft) high and spaced every 45 m (150 ft), and a utility corridor, 0.9–1.2 m (3–4 ft) deep, run the entire length of the Roosevelt Reservation, which is an 18-m- (60-ft-) wide strip of land along the international border that in 1907 President Roosevelt withdrew from the public domain for use by customs personnel. As part of the 2019–2021 construction process, the full width of the Roosevelt Reservation was bladed (cleared and flattened), stripping all vegetation and changing the way water flows from north to south.

What this infrastructure will do in a heavy rain event is yet to be seen, but monument staff anticipates that the culverts, roadbed, altered washes, and exposed soils will result in problems for the Department of Homeland Security and NPS (Rijk Moräwe, Organ Pipe Cactus National Monument, chief of Natural and Cultural Resources Management, written communication, 17 May 2021). Findings from a study following a major storm event on 12 July 2008 suggest what could happen: The mainstem drainage channels will contain flood flows until reaching the border fence/wall. Debris blockages will form at the upstream side of the fence/wall, restricting water flow and causing significant water elevation rise. Footers and/or foundation walls will stop subsurface sediment flow, adding to the water elevation rise. Backwater flooding will occur in most washes. Floodwaters will flow laterally (east–west) along the fence/wall, resulting in erosion and scouring as well as damage to the structural integrity of the fence/wall. Riparian vegetation will change in response to changes in rainfall retention or runoff. Channel morphology and floodplain function will change. Channelized waters will initiate gullying with the potential to transform land surfaces in the affected watersheds (see Organ Pipe Cactus National Monument 2008).

The Sonoran Desert Network has established six monitoring sites on washes at the border to study the effects of border infrastructure on natural processes (Sonoran Desert Network 2019a). Five of these sites were monitored in 2011 and one was monitored in 2020; no mitigation was needed at that time. With the extension of the border fence/wall, the Sonoran Desert Network had plans to add a seventh monitoring site at Aquajita Wash, but COVID has thus far prevented that work (Kara Raymond, NPS Southern Arizona Office, hydrologist, written communication, 29 April 2021).

Figure 29. Photograph of flood-damaged pedestrian fence.
Near Lukeville, an intense rainstorm resulted in flooding and damage to the pedestrian fence and surrounding area on 7 August 2011. The fence crosses washes that span the international border. NPS photograph, taken 2011.

Erosion

Early in the history of the monument, problems of managing livestock and accelerated erosion attracted a great deal of management attention. Starting in the 1940s, references to the following six “erosion sites” appear repeatedly in NPS documents: (1) Dos Lomitas Ranch (southern boundary of the monument, east of Lukeville), (2) Kuakatch Wash near Armenta Ranch (north-central monument), (3) Growler Canyon (east of the Bates Mountains in the western Valley of the Ajo), (4) Cherioni Wash (southern Valley of the Ajo), (5) Growler Valley (west of Bates Well/Bates Mountains), and (6) Palo Verde Camp (northwest corner of the monument) (Rutman 1997).

These “erosion sites” occur on sandy loams (soil type composed of sand with varying amounts of silt and clay, as well as organic matter) of the Gilman Series (Rutman 1997), which consists of very deep, well drained soils that formed in stratified stream alluvium. Gilman soils are on floodplains and alluvial fans and have slopes of 0% to 3% (National Cooperative Soil Survey 2009).

Around 2013, the AZGS studied the “gully system” near Armenta Ranch to understand triggers and rates of soil loss (National Park Service 2013). Although the monument’s state of the park report (National Park Service 2013) noted this study and GRI conference call participants mentioned it, no formal report was produced (Phil Pearthree, AZGS, director and state geologist, email communication, 9 October 2021). As part of the GRI, attempts were made to find an informal report or memorandum that documented that study, but nothing was found. Because of the lack of documentation, findings of that study are not included in this GRI report.

Because the monument issued its last grazing permit in 1968, and all livestock was removed by 1979 (Rutman 1997), livestock grazing and its association with accelerated soil erosion is less of a management concern than it once was. Moreover, trespass of cattle from ranches south of the border is now rare (National Park Service 2016), though it does take place from time to time (GRI conference call, 23 November 2020). However, trespass of cattle, horses, and burrows from the Tohono O’odham Nation takes place because of fence cutting by US Customs and Border Protection (CBP) agents during interdiction efforts. Thus, livestock trespass is a continuing problem for resource protection at the monument. In addition, it has the potential to be a life-and-death issue as animals make their way to Highway 85 (Rijk Moräwe, Organ Pipe Cactus National Monument, chief of Natural and Cultural Resources Management, written communication, 28 May 2021).

In recent years, management attention on erosion has shifted to roads. Areas where roads bisect arroyos are particularly susceptible to erosion. Incision can be 0.9–2 m (3–6 ft) or more. “Death Star Trench” (a road used by CBP agents at the north boundary of the monument) and Bates Well Road each have significant erosion. In these areas, the road has become the new arroyo, changing the hydrology of the area (GRI conference call, 23 November 2020). The effects are far-reaching and include lateral erosion left and right of the road, loss of archeological resources, fall threats to endangered species, off-road drive-arounds by CBP agents to avoid sumps and water flow, and death of downstream riparian areas that are starved of water (Rijk Moräwe, Organ Pipe Cactus National Monument, chief of Natural and Cultural Resources Management, written communication, 28 May 2021).

Undesignated vehicle routes (UVRs) are a significant erosion-related issue. UVRs are the result of cross-border traffic and law-enforcement interdiction efforts. An estimated 4,108 km (2,553 mi) of UVRs cross the monument's wilderness (Howard et al. 2014).

In addition to impairing wilderness values, UVRs damage soils and impact archeological resources, vegetation, and wildlife habitat, including habitat for the endangered Sonoran pronghorn (*Antilocapra americana sonoriensis*). Other effects of UVRs are dust deposition on biological soil crusts; linear entrenchments that capture, block, or channelize sheet flow; and alteration of life-sustaining hydrologic processes (National Park Service 2013; Howard et al. 2014).

In 2011, the NPS entered into an interagency agreement with the Department of Homeland Security to map and assess UVRs in the monument, Cabeza Prieta National Wildlife Refuge, and on Bureau of Land Management (BLM) lands within or in proximity to the Secure Border Initiative Ajo-1 Tower (SBI*net* Ajo-1) project area, which is a network of surveillance towers that monitor human activity across the international border. Using GIS, investigators mapped UVRs shown on high-resolution aerial photography from two years—2008 and 2010. Analysis of the imagery allowed investigators to identify areas of concentrated vehicle use, provide information for ongoing Sonoran pronghorn recovery efforts, and form the foundation for planned habitat restoration activities (Howard et al. 2014).

The Growler Valley in the northwest part of the monument and Cabeza Prieta National Wildlife Refuge had the highest UVR density in the project area (Howard et al. 2014). Interestingly, this high-density area is an estimated 50 km (30 mi) north of the international border.

Geomorphic features in the project area influenced UVRs in several ways. In the Growler Valley, broad, flat stretches with little topographic relief have very few obstacles to restrict vehicles. In the Sonoyta Valley (southeastern part of the monument), UVRs were primarily restricted to the high terraces of dissected bajadas, where low plant cover and flat, hard surfaces lend themselves to easier vehicle access. Other features of the landscape add to the complexity of spatial patterns in UVRs; for example, despite being surrounded by relatively flat terrain, vehicle travel on the Christmas Pass Road in Cabeza Prieta National Wildlife Refuge is restricted in some places to the main road alignment, where the road itself is too far below the surrounding ground surface to allow vehicles to exit (Susan Rutman, Organ Pipe Cactus National Monument, plant ecologist, personal communication, 5 July 2012, *cited in* Howard et al. 2014, p. 25).

Investigators (Howard et al. 2014) developed a classification system to describe relative rates of use and environmental impacts in the project area (fig. 30). The classification system ranged from Class 1 (route used one or two times) to Class 4 (well-used routes). Most UVRs (92%) were Class 1. The average width of a Class-1 UVR was 2.2 m (7.2 ft) with a range of 1.5–2.7 m (4.9–8.9 ft). The least common UVRs (0.2%) were Class 4. The average width of a Class-4 UVR was 45.2 m (148.3 ft) with a range of 8–147 m (26.2–482.2 ft).

Figure 30. Photograph of undesignated vehicle route.
As categorized in a study by Howard et al. (2014), undesignated vehicle routes (UVRs) in the monument range between Class 1 (routes used one or two times) to Class 4 (well-used routes), though most (92%) are Class 1. The UVR in the photograph is a Class 3, which has an average width of 2.6 m (8.4 ft) but can range from 1.8 to 3.4 m (5.9 to 11.1 ft) across. This UVR is in the San Cristobal Valley of the monument. Photograph in Howard et al. (2014, figure 2.3), taken 2010.

Class 4 routes are normally associated with multiple, parallel routes all going in the same direction to the same location. Formation of Class 4 routes is a result of poor soils that cannot sustain the heavy use and aggressive driving employed by CBP agents. Blowouts are common in Class 4 areas, especially during sustained droughts, and result in virtually impassible pits filled with dust (referred to as "moon dust"), which agents drive around to avoid getting stuck (Rijk Moräwe, Organ Pipe Cactus National Monument, chief of Natural and Cultural Resources Management, written communication, 28 May 2021).

According to Howard et al. (2014), the higher the UVR class, the more complex and difficult restoration will be. The following factors influence restoration potential: soil particle size and composition, soil moisture, soil slope and aspect, vegetation presence or absence, plant species composition, and short- and long-term climate patterns. Also, frequency and intensity of exposure to foot and vehicular traffic and associated degrees of compaction, entrenchment or incision, area accessibility, land designations, and environmental compliance are factors in restoration potential.

Erosion Management Plan

As a preliminary step toward restoration, about 320 km (200 mi) of UVRs in the monument's wilderness, previously used by CBP agents, had been closed to vehicle traffic as agreed upon by the US Department of the Interior and CBP. Although this restoration effort has lessened the impact of incursions to wilderness from cross-border activity (National Park Service 2016), about a third of the restored park roads have been re-used by CBP agents (Rijk Moräwe, Organ Pipe Cactus National Monument, chief of Natural and Cultural Resources Management, written communication, 28 May 2021).

An erosion abatement plan/backcountry roads management plan remains a high-priority management need at the monument. Such a plan will help guide local management of erosion and impacts on backcountry roads, provide information for developing temporary and long-term routes for public and/or CBP use, and establish best strategies for maintaining such routes. In conjunction with the plan, National Environmental Policy Act (NEPA) and National Historic Preservation Act (NHPA) compliance needs to be completed for all approved "tactical infrastructure" routes. Once completed, the CBP will consider these routes to be "Green Green" (i.e., receiving approval from the land manager, in this case the NPS, and completing compliance for the proposed action), then money can be spent on tactical maintenance and repair. This would help to correct deficiencies in roadbed integrity and will help reduce or eliminate blowouts, drive-arounds, and the proliferation of parallel routes (Rijk Moräwe, Organ Pipe Cactus National Monument, chief of Natural and Cultural Resources Management, written communication, 28 May 2021, and email communication, 15 October 2021).

Applying disturbed land restoration practices, GRD staff may be able to provide technical assistance at the monument (see "Guidance for Resource Management"). A joint NPS GRD–Water Resources Division (WRD) project also may be possible. Another option is receiving technical assistance from the Natural Resource Conservation Service, which has worked cooperatively with the NPS in the monument since the 1940s (Rutman 1997). The GRD also maintains a partnership with the Natural Resource Conservation Service and has a signed memorandum of understanding, which should facilitate a technical assistance request by monument managers.

Once an erosion management plan has been developed and implemented, monitoring will help determine the effectiveness of restoration efforts and inform needed changes to future restoration approaches. The Sonoran Desert Network would likely conduct monitoring.

Past monitoring efforts may be applicable to future monitoring. For example, Marsh (1981) established monitoring sites at three gullies west of Dos Lomitas Ranch; methods established, data collected, and photos taken for that study may serve as a baseline or provide a useful comparison for present-day monitoring efforts.

Groundwater Assessment

The monument's foundation document (National Park Service 2016) identified a groundwater assessment as a low-priority data need, though current resource managers identify issues related to groundwater as a high priority (Rijk Moräwe, Organ Pipe Cactus National Monument, chief of Natural and Cultural Resources Management, written communication, 28 May 2021; see "Threats to Quitobaquito"). Based on research of the scientific literature and NPS documents associated with preparation of this GRI report, the low-priority rating reported in the foundation document undervalues this need. Also, depending on the meaning of "assessment" (possibly, an evaluation of a body of scientific or technical knowledge), a groundwater assessment is likely only a single step in addressing this need. Before an assessment can be conducted, compilation of information is required; after an assessment, development of a conceptual model (discussed below) is required. Compilation and evaluation of existing information could be conducted by a Scientist in Parks (SIP) participant with possible guidance from the NPS WRD (see "Guidance for Resource Management").

To better understand and properly manage the groundwater system connected to the monument, an updated groundwater conceptual model is needed. Without an updated groundwater conceptual model, the following questions, proposed elsewhere in this

GRI report, cannot be answered: Is groundwater withdrawal in the Sonoyta Valley of Sonora, Mexico, impacting Quitobaquito Springs and pond? (see "Threats to Quitobaquito"). Will earth fissures form in the monument? (see "Giant Desiccation Cracks vs. Earth Fissures"). What is the source of uranium in the water at Williams Spring? (see "Mineral and Energy Development"). Do the mine tailings at the Ajo Mine pose a threat to monument resources? (see "Mining").

Development of an updated groundwater conceptual model is well beyond the scope of the GRI, and resource managers are encouraged to contact the NPS WRD for technical assistance (see "Guidance for Resource Management"). The 2016 report about the San Pedro aquifer (Callegary et al. 2016), which is east of the monument, provides information as well as possible guidance and objectives for such a project. The San Pedro aquifer project is part of the Transboundary Aquifer Assessment Program (see "Guidance for Resource Management").

In order to be useful for resource management, a groundwater conceptual model needs to include two fundamental elements: (1) characteristics of the basin such as geometry, extent, and boundaries, as well as defining the hydrogeologic units that compose the basin and the structures that affect it; and (2) characteristics of the basin fill, as well as the systems of deposits they represent, which must include thickness, grain-size, lateral variations, hydraulic properties, barriers, and boundaries of the subsurface flow and hydrogeologic basement (Callegary et al. 2016).

At present, the fundamental elements needed to develop a groundwater conceptual model for the monument are not known. For instance, even the extent of the groundwater basin/aquifer connected to the monument is not known (see "Groundwater Basin/Aquifer"). Findings by Zamora et al. (2020), however, suggest that the source of the groundwater at Quitobaquito Springs is not "local" (i.e., rain falling on or adjacent to La Abra Plain) as previously thought (Carruth 1996). Zamora et al. (2020) found that values of oxygen and hydrogen isotopes of Quitobaquito waters are too low to have been derived from local discharge. Rather, waters discharged at Quitobaquito Springs are similar to groundwater in the Rio Sonoyta or its alluvial aquifer, which originate in the Bavoquivari Mountains (east of the monument; see fig. 25). Zamora et al. (2020), however, failed to describe a mechanism that would allow for the transport of groundwater from the Rio Sonoyta to Quitobaquito Springs.

Following completion of a groundwater conceptual model, previously collected data could help inform a groundwater budget, which is needed for management of the groundwater system. Data include those collected by monument staff at nine wells and four springs (see Raymond et al. 2019). Data collected at the wells provide a record of mean depth to water, mean elevation, annual and long-term change in water level, and lowest recorded water level. Monument staff also records water quality (temperature, dissolved oxygen, pH, specific conductivity, and total dissolved solids) and water chemistry (alkalinity, calcium, chloride, magnesium, potassium, and sulfate) for each of the monitored springs.

The Sonoran Desert Network collaborates on the groundwater monitoring effort at the monument; network staff assists with technical issues, data management, and trend analysis. Analysis of data shows that six of the nine monitored wells have an ongoing downward trend with respect to water level. Three wells have been more variable, with periods of recovery occurring outside seasonal cycles (Raymond et al. 2019). In water year 2018 (the last year with recorded data at the time of writing of this report), water levels declined in all nine monitored wells; changes from water year 2017 were between -5.49 cm (-2.16 in) and -77.42 cm (-30.48 in) (see table 3-2 in Raymond et al. 2019). Moreover, monitoring data show that discharge at Quitobaquito Springs has reduced from 114 L (25 gal) per minute in the 1980s to between 32 and 55 L (7 and 12 gal) per minute today (Kara Raymond, NPS Southern Arizona Office, hydrologist, written communication, 2 November 2021).

Managing a regional groundwater system to protect monument resources will require cooperation and collaboration among many stakeholders. Once the extent of the groundwater basin/aquifer connected to the monument is identified, individuals and groups affected can be identified to form a stakeholder group. Potential members include Organ Pipe Cactus National Monument and existing partners Cabeza Prieta National Wildlife Refuge, Tohono O'odham Nation, and Reserva de la Biosfera El Pinacate y Gran Desierto de Altar (see "Park Setting"). Other potential government entities include Secretaría de Agricultura y Recursos Hidráulicos (SARH, meaning "Ministry of Agriculture and Water Resources") in Mexico, International Boundary and Water Commission (IBWC), Comisión Nacional del Agua (CONAGUA, meaning "Mexican National Water Commission"), and the US Geological Survey. Collaborators in the development of a groundwater conceptual model include researchers at the US Geological Survey; University of Arizona, Department of Geosciences, Department of Hydrology, and/or Water Resources Research Center; Universidad de Sonora ("University of Sonora," abbreviated as Unison); Sonoran Desert Network; and NPS WRD.

Formation and management of such a group may seem daunting, but a binational study of the transboundary San Pedro aquifer (east of the monument) shows that completion of a groundwater conceptual model (see Callegary et al. 2016) and establishment of a working group (see Callegary et al. 2018) are possible. The 1992 water resources management plan (Barnett and Sharrow 1992) as well as work by Gabriel E. Eckstein (Texas Wesleyan University School of Law) and Rosario Sanchez (Texas A&M University) provide guidance for transboundary management. Work by Eckstein and Sanchez (see Eckstein 2013; Sanchez et al. 2016; Sanchez and Eckstein 2017) emphasizes the utility of a "local approach" of collaboration. Other units in the National Park System that share a boundary with Mexico—including Coronado National Memorial in Arizona and Big Bend National Park, Amistad National Recreation Area, and Chamizal National Memorial in Texas—also may be able to provide support and guidance on transboundary relationships. Monument managers are encouraged to contact the GRD about policy related concerns (see "Guidance for Resource Management").

Threats to Quitobaquito

Quitobaquito is a fundamental resource and value of the monument (see "Geologic Connections to Cultural Resources") and an area of particular resource-management concern because it is designated critical habitat for the endangered Quitobaquito pupfish (*Cyprinodon eremus*) and Sonoyta mud turtle (*Kinosternon sonoriense longifemorale*), as well as the likely soon-to-be designated Quitobaquito spring snail (*Tryonia quitobaquitae*; Rijk Moräwe, Organ Pipe Cactus National Monument, chief of Natural and Cultural Resources Management, written communication, 17 May 2021).

A resource management and restoration plan for Quitobaquito is a high-priority planning need. According to the monument's foundation document (National Park Service 2016), planning would include management strategies related to the failing cottonwood tree, reengineering of the 60-year-old pond stabilization efforts (e.g., the clay pond liner was emplaced in 1962), increased interpretation at the site, and the protection of federally listed endangered and threatened species that depend on Quitobaquito Springs and pond for their survival.

Following publication of the foundation document, the NPS removed the cottonwood tree in 2016 and is launching a project, which is slated to start in March 2022, to replace the pond containment system with a geomembrane (Rijk Moräwe, Organ Pipe Cactus National Monument, chief of Natural and Cultural Resources Management, email communication, 27 October 2021). This restoration plan is also taking into account declining spring discharge (Kara Raymond, NPS Southern Arizona Office, hydrologist, written communication, 2 November 2021).

Current State of Knowledge of the Groundwater System

Notably, a better understanding of the groundwater system that feeds Quitobaquito is not part of the restoration plan as listed in the foundation document (National Park Service 2016). Such a lack of understanding, however, may be deemed a threat because it limits the ability of monument managers to make science-based decision and respond to public concern. For example, construction of border infrastructure (see "Flash Flooding") resulted in contractors of the Department of Homeland Security and US Army Corps of Engineers drilling three new wells in the monument. More than 300,000 L (70,000 gal) of water per day was extracted throughout the duration of the project (2019–2021) for cement, dust abatement, and other construction-related needs. This use of water exacerbated concerns of groundwater extraction, increasing fears that further loss of spring outflow would result. Interested parties and entities, without direct evidence, claimed the project was adversely affecting groundwater that supplies the Quitobaquito aquifer. This misinformation and lack of knowledge was used to garner media attention and the consternation of numerous tribal members and the public (Organ Pipe Cactus National Monument 2020).

For many years—at least since the early 1990s (see Brown 1991; Barnett and Sharrow 1992; Goodman 1992)—the NPS has been concerned that the natural flow from Quitobaquito Springs could be reduced by groundwater withdrawal in the adjacent State of Sonora, Mexico (Carruth 1996). In Sonora, groundwater is used primarily for agriculture (Barnett and Sharrow 1992). The most heavily exploited aquifer there is fluvial channel and floodplain deposits along the margins of the Rio Sonoyta. Numerous irrigation and stock wells have been developed in this aquifer owing to the shallow depth to water and its excellent transmissive properties (Goodman 1992). In addition, urbanization and development in the Sonoyta Valley also demand groundwater to support tourism, including facilities such as hotels, condominiums, and trailer parks, in the port city of Puerto Peñasco, as well as for a growing population in the town of Sonoyta (Brown 1991; Pearson and Conner 2000).

In the early 1990s, two studies—Goodman (1992) and Carruth (1996)—both concluded that groundwater withdrawals south of the international border did not appear to be affecting water-level conditions in the flow system or discharge to Quitobaquito Springs. Significantly, this conclusion was based on rates of groundwater withdrawal at that time. Moreover, at that time, the groundwater system supplying Quitobaquito was thought to be "local," but findings by Zamora et al. (2020) suggest that the groundwater supplying Quitobaquito Springs is "regional," originating in the Bavoquivari Mountains (see fig. 25).

In addressing groundwater withdrawal at the monument, at least three NPS entities have the potential to collaborate. In addition to monument managers, the Water Rights Branch (WRB) of the NPS WRD would likely serve as the lead at the national level, and the Sonoran Desert Network would be the lead at the local level. The role of the Water Rights Branch is to secure and protect water rights for the preservation and management of the National Park System through all available local, state, and federal authorities. A basic function of the Water Rights Branch is to measure and analyze groundwater and surface water data. The Water Rights Branch, which has expertise in hydrogeology, groundwater modeling, groundwater sustainability, and water rights, has provided technical assistance to many parks in the Sonoran Desert Network (Water Resources Division 2019).

Disruption of Surface-Water Flow

The disruption of surface-water flow is another threat to Quitobaquito. In particular, the construction of border infrastructure (e.g., bollard-style fence, lights, and associated loss of vegetation) is a significant disturbance to the hydrology (see "Flash Flooding").

Additionally, the roadbed at Quitobaquito has been raised some 0.9 m (3 ft), a water conveyance channel has been constructed, and the natural connections between the bosque (cluster or group of trees) and the ancestral drainage has been altered. Water from the bosque now flows from the bosque to the road, then to the west, joining another channel that originates west of Quitobaquito pond. This alteration removed the southern 12 m (40 ft) of lands designated as critical habitat for two endangered species (Rijk Moräwe, Organ Pipe Cactus National Monument, chief of Natural and Cultural Resources Management, written communication, 17 May 2021).

Climate Change Impacts to Geologic Resources

Although climate change planning is beyond the scope of the GRI, a discussion of climate change is included in this report because of its relevance to geologic features and processes. Notably, the monument's foundation document (National Park Service 2016) identified adaptation to climate change at Quitobaquito as a planning need. Monument managers are directed to the NPS Climate Change Response Program to address planning related to climate change (see "Guidance for Resource Management").

Geologic features and processes potentially affected by climate change include the following:

- Dust accumulation and dust storms. Increased deposition of windblown silt could result in enhanced dust accumulation in doorways and deposition of silt on biological soil crusts. One of the effects of long-term droughts is dry roads that increase dust deposition on plants (Rijk Moräwe, Organ Pipe Cactus National Monument, chief of Natural and Cultural Resources Management, written communication, 28 May 2021). Also, dust storms can cause lower visibility and safety hazards for drivers on roads.
- Erosion. An increase in storm frequency/intensity, which is projected (Wuebbles et al. 2017), could accelerate current erosion rates.
- Flooding. More frequent or intense floods could increase the vulnerability of park infrastructure and resources along washes.
- Groundwater. Future climate scenarios predict declines in recharge of varying magnitudes in the southwest region of the United States (Meixner et al. 2016). Declines in recharge could lower the groundwater table and decrease discharge at springs and in wells. On the Tohono O'odham Nation, for example, some villages are facing the prospects of drilling deeper wells because shallow aquifers are declining (Rijk Moräwe, Organ Pipe Cactus National Monument, chief of Natural and Cultural Resources Management, written communication, 28 May 2021). A groundwater assessment would help monument managers determine the causes of diminishing groundwater, which may be exacerbated due to climate change (National Park Service 2016).
- Groundwater and surface water. The Sonoran Desert Network monitors several vital signs that will likely show the effects of climate change (Sonoran Desert Network 2010); some of these vital signs also are geologic indicators of change, for example, seeps, springs, and tinajas; streams; washes; and groundwater.
- Groundwater and surface water. In the heart of the Sonoran Desert, along the international border, ecological systems and human settlements heavily rely on and compete for water resources that are

expected to decline as the climate warms and becomes more arid (Barnett et al. 2008).

- Landform development. Climate plays a role in the development of many desert landforms. Changes in climate could impact the development of landforms such as desert pavement and alluvial fans.
- Slope movements. Moritz et al. (2012) predicted a global increase in fire frequency as much as 25% by 2100. Changes in the pattern of wildland fire may cause a greater frequency of slope movements (see GRI reports about Bandelier National Monument and Redwood National and State Parks by KellerLynn 2015a and 2021b, respectively).
- Tinajas. Changing precipitation patterns could decrease surface water, affecting tinajas.
- Wind erosion. A drier landscape due to climate change may result in increased wind erosion, including "sand blasting" of cultural and natural resources such as building facades, petroglyphs, tree bark, epidermis (outer layer) of cactus, and new plant growth, as well as NPS infrastructure including signage.

Abandoned Mineral Lands

According to *Abandoned Mineral Lands in the National Park System—Comprehensive Inventory and Assessment* (Burghardt et al. 2014), the monument contains 789 AML features at 25 sites. Of these, 410 AML features require mitigation; 407 of these features are high priority and three are low priority. The estimated cost of mitigation is $3,694,109 (Burghardt et al. 2014).

The Abandoned Mineral Lands (AML) Program, which is administered by the GRD, is in the process of updating and pulling together a summary sheet that will help shed light on these statistics (Kyle Hinds, GRD, mining engineer, written communication, 14 May 2021). The GRD in in the process of updating and will maintain an AML database.

Some AML features pose a safety hazard whereas others have cultural significance (see "Historic Mines"). AML features in the monument include glory holes, tunnels, adits, ore-cart runouts, leaching vats, and thousands of prospect pits. Ruins include the infrastructure associated with mining camps such as supply stores, blacksmith shops, miner's outdoor kitchens and quarters that are constructed of ocotillo and cactus ribs plastered with mud, cisterns, and dynamite storage bunkers (National Park Service 2013). Monument managers are encouraged to contact the GRD for assistance in managing these resources (see "Guidance for Resource Management").

Mining

At present, no active mining is taking place at the monument or in Ajo (Arizona Geological Survey 2020a). During the 2006 scoping field trip, a brief discussion ensued about the Ajo Mine (also known as the New Cornelia Pit), which includes the pit, tailings, and dump piles and covers approximately 5 km^2 (2 mi^2). According to Steve Richard (AZGS), who attended the scoping meeting in 2006, the high carbonate content in the soils probably buffers the metals in the piles; moreover, groundwater in the Ajo area, which is part of the Lower Gila basin/aquifer, flows north (away from the monument) (Arizona Department of Water Resources 2009) and is unlikely to affect park resources (National Park Service 2006).

Freeport-McMoRan Copper and Gold Inc. (renamed Freeport-McMoRan, Inc., in July 2014) acquired the Ajo Mine through its merger with the Phelps Dodge Corporation in March 2007. Freeport-McMoRan, Inc., continues to periodically assess the economic feasibility of returning the Ajo project to production (Briggs 2017). If copper prices rise in the future, interest in mining north of the monument could occur (National Park Service 2006). In the event of a "boom," discussions between the Bureau of Land Management and NPS would be significant for the protection of monument resources near its northern boundary. Monument managers may contact the GRD for assistance (see "Guidance for Resource Management").

Mineral and Energy Development

Beside the potential for returning the Ajo Mine to production (see "Mining"), neither the scoping meeting in 2006 nor the follow-up conference call in 2020 revealed any additional issues related to mineral or energy resources within or in the vicinity of the monument. The following issues are mentioned in response to review comments but are not known to require the attention of resource managers:

Geothermal Energy Development

A thermal well in Arizona is defined as one in which the surface discharge temperature is both 20°C (68°F) or greater and at least 10°C (18°F) higher than the mean annual air temperature (Witcher et al. 1982).

Quitobaquito Springs is classified as a warm spring (Anderson and Laney 1978) but is not considered thermal because although the mean annual surface discharge temperature at Quitobaquito Springs is 25.71°C (78.28°F) (Goodman 1992), the long-term average (1949–2010) air temperature is 21.2°C (70.1°F) (Organ Pipe Cactus National Monument 2011). On 2 February 1982, Phillips Petroleum drilled seven temperature gradient/geothermal resource wells north of the monument (Arizona Oil and Gas Conservation Commission 2021), but geothermal energy production did not take place at any of these wells. The scoping summary (National Park Service 2006) reported that although the aquifer underlying the monument has increased temperatures, these "warmish" temperatures are not high enough to warrant interest in geothermal energy development, which would have the potential to impact park resources.

Oil and Gas

Arizona is not a major oil and gas producing state (Arizona Geological Survey 2021b). Most production stems from small oil fields in northeastern Arizona. *Arizona Has Oil & Gas Potential!* (Rauzi 2001) is an excellent starting point for learning about the state's oil and gas resources. Also, "Want to Drill an Oil Well"? (Rauzi 2003) describes the process of exploring for oil, natural gas, carbon dioxide (e.g., used in carbonated drinks, as a refrigerant, and in fire extinguishers), or helium in the state.

Over the past 100 years, more than 1,100 oil and gas exploration wells have been drilled in Arizona. The locations of wells and well logs of those drilled since the 1920s are online at the Arizona Oil and Gas Conservation Commission (AOGCC) map viewer (see "Additional References, Resources, and Websites"). According to the map viewer/database, nine wells have been drilled in Pima County; seven of these are the aforementioned shallow temperature gradient wells drilled by Phillips Petroleum (see "Mineral and Energy Development"). In addition, Nano'Ltex drilled a dry ("unsuccessful") well, and a well drilled by New Cornelia Copper served as a "strat test" (exploration of the strata [rock formations] below the surface). The Arizona Oil and Gas Conservation Commission webpage, which is maintained by the Arizona Department of Environmental Quality (ADEQ), provides information about oil and gas in Arizona (see "Additional References, Resources, and Websites").

Uranium

During water years 2003 and 2004, scientists at the US Geological Survey, Arizona Water Science Center in Tucson, Arizona, collected water samples and other water quality information at 30 sites in nine NPS areas in west-central New Mexico and southern and central Arizona, including Organ Pipe Cactus National Monument. The expected range of uranium in natural waters is 0.1 to 10 µg/L (Hem 1985). In October 2003, however, the concentration of dissolved uranium at Williams Spring in the monument was 32 ug/L. This is slightly above the maximum contaminant level (MCL) of 30 mg/L set by the US Environmental Protection Agency for drinking water quality (Brown 2005).

Water-Quality Data for Selected National Park Units, Southern and Central Arizona and West-Central New Mexico, Water Years 2003 and 2004 (Brown 2005) did not provide a source for the uranium at Williams Spring. In general, economic uranium deposits in Arizona are associated with vertical, pipe-shaped bodies of highly fractured rock called "breccia pipes" that collapsed into voids created by the dissolution of underlying rock due to groundwater flow (Richardson et al. 2019). Such deposits occur in the rocks of the Grand Canyon region (Spencer and Wenrich, 2011) but are not known from the monument area. Moreover, although Oligocene and Miocene volcanic rocks in the Basin and Range are known to contain anomalous concentrations of uranium (Scarborough 1980), and these rocks occur in the monument (see "Ajo Volcanic Field"), Williams Spring issues from Aguajita Spring granite (**Kga**), which is not known to be a source of uranium, as per the description provided by Skinner et al. (2008). Thus, further study is required to determine the source of uranium in Williams Spring.

Slope Movements

At a scale of 1:24,000, Skinner et al. (2008) did not map any landslide deposits (**QTls**) within the monument. However, surficial mapping by the AZGS in the Valley of the Ajo and Sonoyta Valley delineates young debris flow deposits (map unit Qyd of Pearthree et al. 2012, Youberg and Pearthree 2012, and Young and Pearthree 2012). These debris flows were deposited less than 12,000 years ago and consist of coarse-grained, very poorly sorted deposits on steep hillslopes and along some washes within and near the mountains. Deposits consist primarily of small to medium boulders, cobbles, pebbles, and sand. Typically, the coarse deposits form linear levees that parallel small washes or irregularly shaped piles that represent debris flow snouts. Unit Qyd of Pearthree et al. (2012), Youberg and Pearthree (2012), and Young and Pearthree (2012) may include areas of erosion (debris flow scars) on hillslopes that are spatially associated with debris flow deposits.

North of the monument, Skinner et al. (2008) mapped landslide deposits (**QTls**) consisting of massive slump blocks. These deposits range from 200 to 1,500 m (660 to 5,000 ft) wide on the west flank of the Growler Mountains and are composed of unconsolidated, unstratified, and unoriented coarse-grained rubble, which locally reflects the underlying bedrock (primarily basalt). Slumping in these deposits is the result of the instability of poorly consolidated Daniels Conglomerate (**Tdc**) that underlies lava flows (Skinner et al. 2008).

In 2006, scoping participants identified the area below Twin Peaks (northwest of the Kris Eggle Visitor Center) as a potentially hazardous zone for rockfall because park housing and the water tank are located there. Mapping by Young and Pearthree (2012) shows this area covered by hillslope deposits and regolith (map unit Rtc; "R" stands for "rock," not a unit of geologic time; Phil Pearthree, AZGS, director and state geologist, email communication, 9 October 2021). Unit Rtc includes several different types of weathered bedrock such as granite, felsic volcanic rocks and associated volcanoclastic sediments, and basalt, as well as extensive areas of locally derived colluvium and talus. This and other areas mapped as Rtc have experienced rockfall in the past, and the deposition of colluvium and talus in these areas is likely ongoing. Conference call participants did not consider the area below Twin Peaks to be an area of "high safety concern," however.

During the 2020 conference call, participants noted debris flows in the vicinity of Diaz Spire and Diaz Peak (near the eastern boundary of the monument). Although surficial mapping (Youberg and Pearthree 2012) does not cover this easternmost part of monument, the AZGS investigated these slope movements in 2010 and confirmed that they are recent debris flows.

Conference call participants proposed that the area of highest concern for slope movements in the monument is along the western side of the Ajo Range. Mapping by the AZGS (Pearthree et al. 2012) confirms this. Other areas of potential concern are around Diablo Peak, Tillotson Peak, and the ridge running north of Tillotson Peak (see Pearthree et al. 2012).

With respect to roads, Highway 85, which runs north–south through the monument, does not appear to have been impacted by slope movements. Rockfall, however, occurs along the southern and western segments of Ajo Mountain Drive (see Pearthree et al. 2012 and Youberg and Pearthree 2012).

Common natural landslide triggers include heavy rain, rapid snow melt, earthquakes, volcanic eruptions, and freeze and thaw cycle (i.e., physical weathering) (Arizona Geological Survey 2020b). Chemical weathering also may weaken slope materials. Moreover, groundwater circulating along potential failure surfaces may weaken natural cohesive forces, and excessive pore water pressure within the slope-forming materials or along a potential failure surface may decrease slope stability. In addition, human activities can initiate slope movements; mechanisms include removal of the toe (lower end) of a potentially unstable slope, removal of lateral support material adjacent to an unstable area, placement of additional material on the upper portion of an unstable area, or weakening of clay or other fine-grained materials by wetting. The most common human-induced mechanisms include excavations such as road cuts, quarries, pits, utility trenches, site grading, landfill operations, and stockpiling of earth, rock, or mine waste; alternation of natural drainage, which may lead to increased runoff and erosion or to local ponding and saturation of potentially unstable slopes; and vibrations from blasting or heavy vehicular traffic (Rogers et al. 1979).

Active Faults and Earthquakes

Faults that are considered "active" have moved during the past 2.6 million years (Quaternary Period) and have some chance to generate an earthquake. None of the faults mapped in the monument are considered active. Most of the faults in the monument are normal faults that moved about 5 million years ago (Miocene Epoch) in association with Basin and Range extension (see "Basin and Range"). The two other types of faults in the monument—thrust faults and tectonic slides—were active during the Jurassic Period (between 170 million and 148 million years ago; see "Building the North American Cordillera"). In addition, movement on the Quitobaquito thrust may have been reactivated during the Laramide Orogeny, ending by about 60 million–58 million years ago (Paleocene Epoch) (see "Laramide Orogeny").

Two active faults are relatively close to the monument:

- Sand Tank fault. Movement on the Sand Tank fault, near Gila Bend (north of the monument; fig. 31), has occurred since 200,000–70,000 years ago (latest Pleistocene Epoch). The Sand Tank fault, which is a normal fault, has a total length (obvious fault scarp) of about 3 km (2 mi), but lineaments (linear topographic features of regional extent, in this case, fault lines; other examples are aligned volcanoes and straight stream courses) extend for about 5 km (3 mi) north and southwest of the fault scarp on Pleistocene alluvial surfaces with no discernible offset. The length of a fault is significant because the longer the fault, the larger the potential earthquake can be (Wells and Coppersmith 1994). Total late Quaternary displacement across the fault zone is less than 2 m (7 ft) (Pearthree 1995).
- Tinajas Altas fault zone. The Tinajas Altas fault zone, which is in southwestern Arizona and Sonora (west of the monument; see fig. 31), is classified as undifferentiated Quaternary, having moved less than 1.6 million years ago (Pearthree 1998). The fault zone is composed of two, short (less than 5-km- [3-mi-] long), linear, northwest-trending faults on

the southwest side of the Tinajas Altas Mountains. Bedrock on the west side of the Tinajas Altas fault zone has similar lithology to the main mountain mass, suggesting that normal displacement across the fault is not great, or that the fault zone is a very narrow graben (Tucker 1980). Alternatively, the orientation of the Tinajas Altas fault zone, which is subparallel with the San Andreas fault system, suggests that it may have accommodated primarily dextral (right-lateral, strike-slip; see fig. 20) displacement (P. K. Knuepfer, oral communication, 1981, *cited in* Pearthree 1998 [no page number]).

In addition to the distribution of Quaternary faults, seismic hazard can be evaluated with respect to the distribution and size of historical earthquakes. The historical seismic record of Arizona indicates that the state is subject to a low to moderate seismic hazard from earthquakes originating within its borders, but a seismic hazard posed by earthquakes occurring near Arizona is probably greater (Beyer and Pearthree 1994). The largest historical earthquake to affect Arizona was the 1887 Sonoran earthquake, which originated on the Pitaycachi fault, a 104-km- (65-mi-) long normal fault (Pearthree 2012) near the Arizona-Sonora border (southeast of the monument). That earthquake predated establishment of the monument, which occurred in 1937, as well as the state of Arizona, which occurred in 1912, but was felt throughout the Southwest, including Phoenix and Tucson.

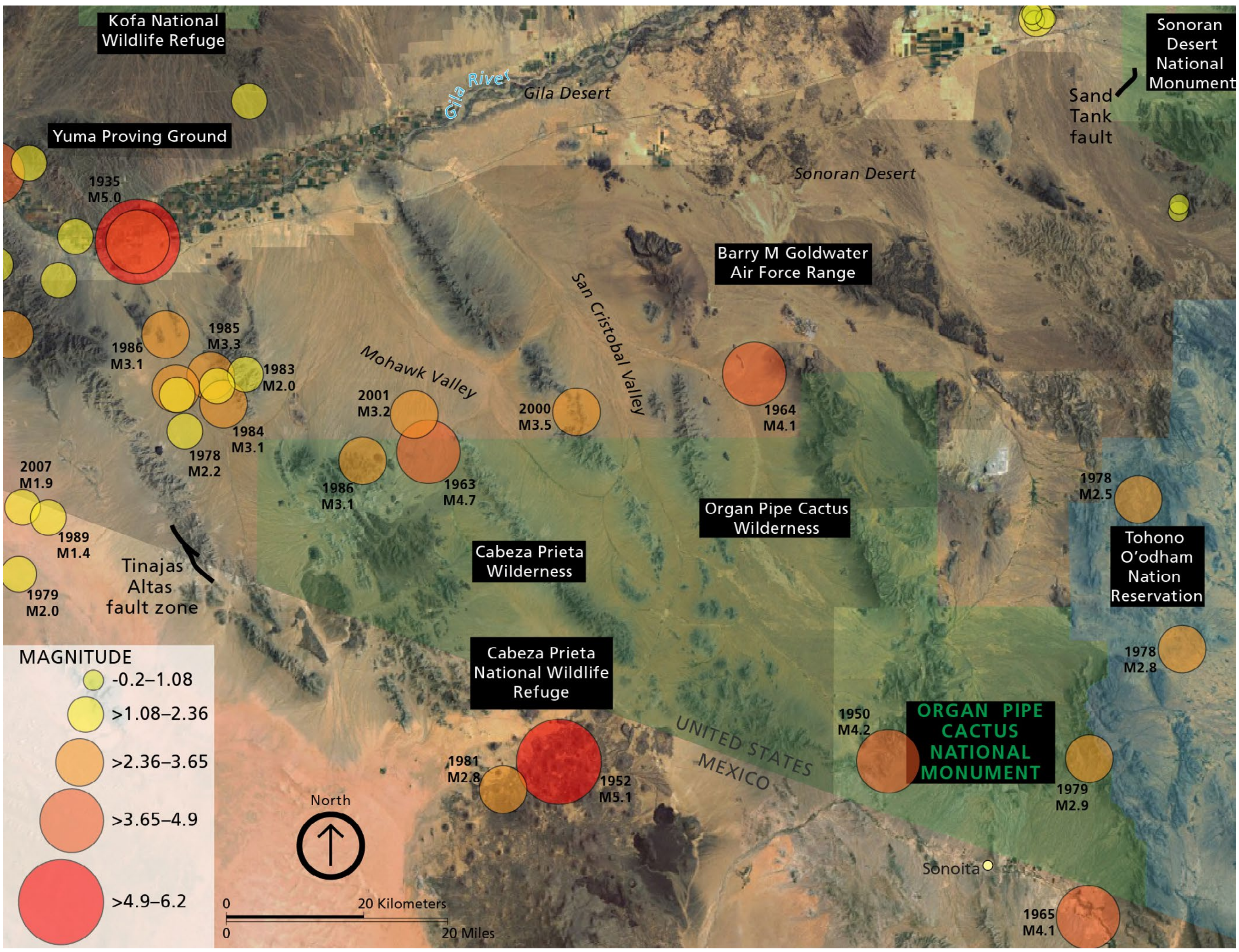

Figure 31. Satellite image showing active faults and earthquakes.
The closest active faults to the monument are the Sand Tank fault to the north and the Tinajas Altas fault zone to the west. Many recorded seismic events have occurred near the monument. The size of the circle on the figure represents the relative size of the event. The largest earthquake in recent history took place in 1952; it was a magnitude (M) 5.1. The epicenter was south of the international border. Figure by Trista Thornberry-Ehrlich (Colorado State University) using data from the "Natural Hazards in Arizona" map viewer (Arizona Geological Survey 2021c), accessed 15 December 2020. Base imagery by ESRI Imagery World 2D.

Shaking during the Sonoran earthquake was estimated by Scarborough and Pearthree (1988) as level VI on the Modified Mercalli Intensity Scale. The scale has 12 levels (I–XII) that quantify shaking and damage based on eyewitness accounts and post-earthquake assessments. Earthquakes are widely felt starting at intensity level IV. Significant structural damage begins at level VII. Damage and destruction are total at intensity level XII (US Geological Survey 2000). Intensity level VI (the estimated intensity of the Sonoran earthquake) is described as having been felt by all people, frightening many. Also, heavy furniture would have moved, and some plaster would have fallen, though overall damage would have been slight.

Based on the Modified Mercalli Intensity Scale, buildings, historic structures, and mines at the monument may experience some damage starting at intensity level VI but, more likely, damage would take place starting at intensity level VII.

Today, the Richter Scale is widely used to measure the magnitude (energy released) of an earthquake. The Sonoran earthquake was magnitude 7.6 on the Richter Scale (Arizona Geological Survey 2018). Using seismograph oscillations, the Richter Scale provides a numeric expression. The scale is logarithmic, and a difference of one represents an approximate thirtyfold difference in magnitude. Destructive earthquakes typically have magnitudes between about 5.5 and 8.9 on the scale.

Many earthquakes ranging in magnitude up to about 6 have occurred within Arizona (Beyer and Pearthree 1994). The largest recent (1952) earthquake in the vicinity of the monument was magnitude 5.1 (see fig. 31).

Giant Desiccation Cracks vs. Earth Fissures

Several reviewers of the draft GRI report proposed "giant desiccation cracks" as a potential geologic issue at the monument. To properly address this concern, a clarification of terminology is needed. Simply stated, a desiccation crack is a crack in sediment produced by drying. A familiar type of desiccation crack is a mud crack (an irregular fracture in a crudely polygonal pattern, formed by shrinkage of clay, silt, or mud, which, in general, is drying under the influence of atmospheric conditions). Giant desiccation cracks are mud cracks but on an enormous scale; the polygons of giant desiccation cracks can be 45–180 m (150–600 ft) across. By comparison, typical mud cracks form polygons 10–20 cm (4–8 in) across. A giant desiccation crack may be as much as 1 m (3 ft) wide and 3 m (9 ft) deep (apparent depth) (Harris 2004).

In a strict sense, the formation of giant desiccation cracks is not a soil process because it takes place at depths well below soil horizons. The desiccation occurs in clay-rich layers deposited in lakes or playas in internally drained basins. Ironically, desiccation cracks open after heavy rains (Harris 2004).

In Cabeza Prieta Wildlife Refuge (west of the monument), Harris (2004) documented giant desiccation cracks at Las Playas, which occupies a small internally drained basin adjacent to the international border. This region—halfway between Yuma and Lukeville—is one of the driest in Arizona. In March 2021, managers at Cabeza Prieta Wildlife Refuge contacted the AZGS about the reoccurrence of giant desiccation cracks; the AZGS investigated the cracks on 1 April 2021 (Joe Cook, AZGS, research geologist, letter to Sid Slone, Cabesa Prieta National Wildlife Refuge, 5 April 2021).

On the Tohono O'odham Nation (east of the monument), Harris (2004) documented giant desiccation cracks in the Pisinemo District. These cracks are largely concentrated at the toe of a bajada surrounding the Kupk Hills. In addition, desiccation cracks near Mission San Xavier were mapped and described in published reports by Konieczki et al. (1996) and Hoffman et al. (1997, 1998).

Although giant desiccation cracks have developed on lands west and east of the monument, none have developed in the monument. The AZGS provided the following explanation:

> Giant desiccation cracks (GDCs) form in areas with fine-grained soils with significant clay and/or salt content [that] are subjected to repeat wetting and drying. These areas are often found within the limits of former pluvial lake highstands which include modern playas and the surrounding areas. Low-relief fine-grained swales in undissected alluvial environments and disturbed ground including dirt roads may also be prone to GDC formation. Although no GDCs are currently mapped within [the monument], they are present nearby in the vicinity of Las Playas in the Cabeza Prieta Wilderness west of [the monument] and along the base of low alluvial fans in Tohono O'odham lands to the east. Similar low-relief terrain is located along the western edge of [the monument] west of the Bates Mountains and along some low-relief areas along Cherioni Wash in the north-central [part]

of the monument [fig. 32]. Based on the similar geomorphic setting and appearance on aerial photos to areas affected by GDCs nearby, these areas seem the most likely to be prone to GDC formation within [the monument]. Even if the geomorphic setting and soil conditions are conducive for GDC formation, the areas must be subject to repeat wetting and drying for GDCs to form (Joe Cook, AZGS, research scientist, email communication, 21 October 2021).

Figure 32. Satellite image showing potential areas for giant desiccation cracks at the monument. At present, no giant desiccation cracks (GDCs) have formed within the monument. Areas most prone to GDC formation are Growler Wash and San Cristobal Wash in the western part of the monument and Cherioni Wash in the central part of the monument; these areas are outlined in yellow on the figure. Even if the geomorphic setting and soil conditions are conducive for GDC formation, however, the areas must be subject to repeat wetting and drying for GDCs to form. The green outline is the monument boundary. Annotated image by Trista Thornberry-Ehrlich (Colorado State University) with information from Joe Cook (AZGS). Base imagery by ESRI World Aerial Imagery, taken 5 April 2021.

Although lowering of the groundwater table has been cited as a trigger for the formation of giant desiccation cracks, this is no longer the case (Harris 2004). Groundwater withdrawal may have been a factor in the development of giant desiccation cracks around the turn of the last century, but groundwater levels in the areas with desiccation cracks studied by Harris (2004) have water levels typically 30 m (100 ft) deep or more. Once groundwater levels drop below 15–30 m (50–100 ft) deep, further groundwater declines are essentially irrelevant to near-surface desiccation. In places where groundwater levels began to drop by the 1950s (e.g., Casa Grande area; see GRI report about Casa Grande Ruins National Monument by KellerLynn 2018), the development of giant desiccation cracks in the past 40 years can no longer be blamed on groundwater declines. In several places (e.g., San Simon and Willcox), giant desiccation cracks appeared before major groundwater pumping (Harris 2004).

At present, the geologic feature formed by groundwater withdrawal in Arizona is earth fissures. As the ground settles into the space no longer filled by groundwater, fissures form at depth and propagate upward towards the surface. Earth fissures threaten people, property, infrastructure (e.g., roads, gas lines, and canals), and livestock (Arizona Geological Survey 2021a).

According to the AZGS, earth fissures are an unlikely hazard in the monument because there has been no significant land subsidence. The Arizona Department of Water Resources monitors land subsidence throughout Arizona and its records do not show measurable subsidence near the monument. The closest known earth fissures are in Avra Valley, approximately 150 km (90 mi) northeast of the monument (Arizona Geological Survey 2015). Unless significant long term groundwater withdrawal was to commence in or near the monument, earth fissures are not a concern (Joe Cook, AZGS, research scientist, email communication, 21 October 2021). The "Natural Hazards in Arizona" map viewer shows the locations of all known earth fissures in the state (see "Guidance for Resource Management").

Geologic Interpretation

An interpreter (also called an "interpretive ranger") is a professional communicator who facilitates audience understanding and appreciation of park resources (National Park Service 2021a). Interpreters engage visitors in ways that attempt to bring meaning to each person, enriching his, her, or their experience.

Significantly, "[interpretation] goes beyond summarizing interesting facts about [a] park" (Kenworthy 2010, p. 31). In the NPS, interpretation is formally defined as a "catalyst in creating opportunities for audience members to make their own intellectual and emotional connections to the meanings of park resources" (National Park Service 2021a). The National Association for Interpretation defines interpretation as "a purposeful approach to communication that facilitates meaningful, relevant, and inclusive experiences that deepen understanding, broaden perspectives, and inspire engagement with the world around us" (National Association for Interpretation 2021, no page number/online information).

The monument's foundation document has four interpretive themes; none of these themes is specific to the monument's geology, though "sense of place," "dynamic landscapes," and "mountains" are mentioned (National Park Service 2016, p. 7). Geology, as an individual theme, may seem impersonal, but a trained interpreter can make connections between Earth's natural processes and the daily lives of visitors because many visitors can identify with geologic events such as earthquakes, tsunamis, floods, landslides, or erosion that have taken place near their homes or within their lifetimes. Moreover, geologic, place-based stories that relate to daily human experiences may allow visitors to appreciate how present-day forces forming the landscape might shape their own lives (Natoli and Lillie 2006).

Geologic interpretation steps beyond the scope of the GRI, but many sections of this GRI report may be useful to interpreters in preparing "walks," "talks," or site brochures. An example of an existing guide that may be useful for interpretation at the monument is *A Guide to the Geology of Organ Pipe Cactus National Monument and the Pinacate Biosphere Reserve* (Bezy et al. 2000). That publication discusses geologic topics (e.g., bajadas; alluvial terraces; desert pavement; rock varnish; fault-controlled springs; and outcrops of rhyolite, latite, mylonite, and granite) and provides specific fieldtrip stops along Ajo Mountain and Puerto Blanco Drives where these features are found.

A long-term partnership between the GRD and the Geological Society of America has provided geologic expertise in parks that lack park geologists. Formerly known as the Geoscientists-in-the-Parks (GIP) program, the Scientists in Parks (SIP) program is an avenue for receiving assistance with geologic interpretation (see "Guidance for Resource Management"). Projects may include training for interpreters and other staff, development of site bulletins, help in design of wayside exhibits, and onsite interpretation at visitor centers or in the field.

Guidance for Resource Management

Information in this chapter will assist resource managers in addressing geologic resource management issues and applying NPS policy. The compilation and use of natural resource information by park managers is called for in the 1998 National Parks Omnibus Management Act (§ 204), Management Policies 2006, and the Natural Resources Inventory and Monitoring Guideline (NPS-75).

Access to GRI Products

- GRI products (scoping summaries, GIS data, reports, and posters) are available at the Geologic Resources Inventory—Products website: http://go.nps.gov/gripubs or https://www.nps.gov/subjects/geology/geologic-resources-inventory-products.htm
- GRI products also are available through the NPS Integrated Resource Management Applications (IRMA) portal: https://irma.nps.gov/. Enter "GRI" as the search text and select a park from the unit list.
- Additional information regarding the GRI, including contact information: https://www.nps.gov/subjects/geology/gri.htm
- GRI geodatabase model: http://go.nps.gov/gridatamodel

Four Ways to Receive Geologic Resource Management Assistance

- Contact the GRD (https://www.nps.gov/orgs/1088/contactus.htm). GRD staff 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. The GRD can assist with resource inventories, assessments, and monitoring; impact mitigation, restoration, and adaptation; hazards risk management; law, policy, and guidance; resource management planning; and geologic data and information management.
- Formally request assistance at the Solution for Technical Assistance Requests (STAR) webpage: https://irma.nps.gov/Star/ (available on the Department of the Interior [DOI] network only). NPS employees (from a park, region, or any other office outside of the Natural Resource Stewardship and Science [NRSS] Directorate) can submit a request for technical assistance from NRSS divisions and programs.
- Contact the program manager and/or submit a proposal to receive geologic expertise through the Scientists in Parks (SIP) program: https://doimspp.sharepoint.com/sites/nps-scientistsinparks (available on the DOI network only). Proposals may be for assistance with research, interpretation and public education, inventories, and/or monitoring. Formerly the Geoscientists-in-the-Parks (GIP) program, the SIP program (https://www.nps.gov/subjects/science/scientists-in-parks.htm) places scientists (typically undergraduate students) in parks to complete geoscience-related projects that may address resource management issues. The Geological Society of America (https://www.geosociety.org/GSA/Education_Careers/Field_Experiences/sip/GSA/fieldexp/sip/home.aspx) and Environmental Stewards are partners of the SIP program.
- Refer to *Geological Monitoring* (Young and Norby 2009), which provides guidance for monitoring vital signs (measurable parameters of the overall condition of natural resources). Each chapter covers a different geologic resource and includes detailed recommendations for resource managers, suggested methods of monitoring, and case studies. Chapters are available online at https://www.nps.gov/subjects/geology/geological-monitoring.htm.

Assistance with Water-Related Issues

Although water is a geologic agent, some water-related issues are best addressed by the NPS Water Resources Division, rather than the NPS Geologic Resources Division. Such issues include groundwater hydrology, water quality, water supply, floodplains, wetlands, and water rights. Park managers are directed to WRD webpages for program specifics (https://home.nps.gov/orgs/1439/index.htm) and contact information (https://home.nps.gov/orgs/1439/contactus.htm). Park managers can formally request assistance from the Water Resources Division via https://irma.nps.gov/Star/ (available on the DOI network only).

Park-Specific Documents

The monument's foundation document (National Park Service 2016) and state of the park report (National Park Service 2013) are primary sources of information for resource management. These were used in writing the GRI report. A resource stewardship strategy has not been completed. The monument's general management plan (National Park Service 1997) was completed in July 1997 but was not used in writing this report.

Other sources on park-specific information include the following:

- NPS History eLibrary hosts historical information and management documents: http://www.npshistory.com/
- NPS Integrated Resource Management Applications (IRMA) is a repository of park-specific documents: https://irma.nps.gov/DataStore/
- NPS Planning, Environment and Public Comment (PEPC) provides information about park planning: https://parkplanning.nps.gov/parks.cfm
- NPS Technical Information Center (TIC) is a repository for technical documents (eTIC online): https://www.nps.gov/orgs/1804/dsctic.htm

NPS Resource Management Guidance and Documents

- NPS *Management Policies 2006* (Chapter 4: Natural Resource Management): https://www.nps.gov/policy/index.cfm
- National Parks Omnibus Management Act of 1998: https://www.congress.gov/bill/105th-congress/senate-bill/1693
- NPS-75: Natural Resources Inventory and Monitoring guideline: https://irma.nps.gov/DataStore/Reference/Profile/622933
- NPS Natural Resource Management Reference Manual #77: https://irma.nps.gov/DataStore/Reference/Profile/572379
- Resist-Accept-Direct (RAD)—A Framework for the 21st-Century Natural Resource Manager: https://doi.org/10.36967/nrr-2283597

Geologic Resource Laws, Regulations, and Policies

The following table (table 3), which was developed by the GRD, summarizes 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.

Table 3. Geologic resource laws, regulations, and policies.

Resource	Resource-Specific Laws	Resource-Specific Regulations	NPS 2006 Management Policies
Rocks and 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.

Table 3, continued. Geologic resource laws, regulations, and policies.

Resource	Resource-Specific Laws	Resource-Specific Regulations	NPS 2006 Management Policies
Paleontology	**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—t**he 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.

Table 3, continued. Geologic resource laws, regulations, and policies.

Resource	Resource-Specific Laws	Resource-Specific Regulations	NPS 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, including climate change. **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.
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).

Table 3, continued. Geologic resource laws, regulations, and policies.

Resource	Resource-Specific Laws	Resource-Specific Regulations	NPS 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.

Additional References, Resources, and Websites

AZGS Reference Tools

- AZGS: https://azgs.arizona.edu/
- AZGS Document Repository (more than 1,000 publications dating from 1915 to the present): http://repository.azgs.az.gov/

Biological Soil Crusts

- *Biological Soil Crusts: Webs of Life in the Desert* (Belnap 2001): https://pubs.usgs.gov/fs/2001/0065/
- *Biological Soil Crusts: Ecology and Management* (Belnap et al. 2001): https://www.blm.gov/learn/blm-library/agency-publications/technical-references
- Jayne Belnap's (US Geological Survey, research ecologist) work on biological soil crusts is notable (see McMurdo 2021). Belnap has been a cooperator

of the NPS, including participation in the geologic resource evaluation (precursor to the GRI) scoping meeting at Canyonlands National Park.

- *A Field Guide to Biological Soil Crusts of Western US Drylands* (Rosentreter et al. 2007): https://www.usgs.gov/centers/sbsc/science/a-field-guide-biological-soil-crusts-western-us-drylands?qt-science_center_objects=0#qt-science_center_objects
- *Field Guide to Classify Biological Soil Crusts for Ecological Site Evaluation* (Pietrasiak 2014): http://www.nrcs.usda.gov/wps/portal/nrcs/main/soils/ref/#field_guides. *Note*: This guide is a Natural Resources Conservation Service (NRCS) technical reference.
- Sonoran Desert Network monitors biological soil crust cover: https://www.nps.gov/im/sodn/vegetation-soils.htm
- Many parks in the Sonoran Desert and Chihuahuan Desert Networks have biological soil crusts: Big Bend National Park, Carlsbad Caverns National Park, Casa Grande Ruins National Monument, Chiricahua National Monument, Coronado National Memorial, Fort Bowie National Historic Site, Fort Davis National Historic Site, Gila Cliff Dwellings National Monument, Guadalupe Mountains National Park, Montezuma Castle National Monument, Saguaro National Park, Tonto National Monument, and White Sands National Park. Managers at these parks may be able to provide guidance or collaborate with monument managers.
- US Forest Service, Rocky Mountain Research Station, information about biological soil crusts: https://www.fs.usda.gov/rmrs/dont-bust-biological-soil-crust-preserving-and-restoring-important-desert-resource

Climate Change Planning

According to the monument's foundation document (National Park Service 2016), planning for adaptation to climate change is a medium-priority management need. Planning for adaptation to climate change at Quitobaquito is a particular need. The following existing weather and climate change information, which is listed from specific (to the monument) to general, will support climate change planning:

- In 2007, the Sonoran Desert Network completed a weather and climate inventory (Davey et al. 2007) that identified weather and climate stations within the boundaries of the monument. At that time, all 13 stations in the monument were active. As of October 2021, the monument still had 13 weather stations, however, only 12 were active; the one on Mount Ajo was down and awaiting some repairs (Rijk Moräwe, Organ Pipe Cactus National Monument, chief of Natural and Cultural Resources Management, email communication, 15 October 2021). As of 2007, the Cooperative Observer Program (COOP) station "Organ Pipe Cactus NM" was located near park headquarters and had a very reliable climate record, going back to 1944. The National Atmospheric Deposition Program (NADP) station "Organ Pipe Cactus NM" was also located at park headquarters and had been active since 1980. In addition to these two stations, a network of 11 near real-time weather stations were in operation across the monument; many of these stations had been operating since the 1990s. Outside the monument, the only active station within 40 km (25 mi) was the COOP station "Ajo," which was 19 km (12 mi) north of the monument. "Ajo" had been active since 1914, and its data record was very reliable except for a lack of weekend observations starting in the mid-1980s.
- A climate change summary for the monument (Gonzalez 2015) provided climate trends in temperature and precipitation, reporting that temperature has increased at a statistically significant rate between 1950 and 2010. The summary found no statistically significant change in precipitation since 1950. The summary also provided projections of precipitation and temperature changes under four different emission scenarios. Notably, under all emissions scenarios, reduced snowfall and rainfall and increased temperature could reduce the flow of springs, streams, and rivers.
- A climate change resource brief for the monument (Monahan and Fisichelli 2014) analyzed temperature and precipitation and identified "extreme" conditions (exceeding 95% of the historical range). No temperature variables were "extreme cold." Two temperature variables were "extreme warm"—annual mean temperature and mean temperature of the warmest quarter.
- A status update of climate and water resources at the monument for water year 2018 (Raymond et al. 2019) provided data and analysis about precipitation; temperature; groundwater levels (in nine monitored wells); as well as water quantity, water quality, and site condition (noting anthropogenic and natural disturbances) at monitored springs (Dripping, Bull Pasture, and Quitobaquito) and tinajas (East Arroyo and Snake Pit).
- *Climate Change Impacts on Cultural Resources* (Morgan et al. 2016) provided an "impacts table" with succinct descriptions of 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.
- NPS Climate Change Response Program: http://www.nps.gov/subjects/climatechange/resources.htm
- US Global Change Research Program: http://www.globalchange.gov/home
- Fourth National Climate Assessment (Reidmiller et al. 2018)—climate change impacts, risks, and adaptation information for the US Southwest: https://nca2018.globalchange.gov/chapter/front-matter-guide/
- Intergovernmental Panel on Climate Change: http://www.ipcc.ch/

Days to Celebrate Geology

- The first Sunday in April (e.g., 3 April 2022)—Geologist Day (marks the end of the winter and beginning of preparation for summer field work; formally celebrated in Ukraine, Kazakhstan, Belarus, Kyrgyzstan, and Russia).
- 6 October—International Geodiversity Day: https://www.geodiversityday.org/
- Typically the second full week of October (e.g., 9–15 October 2022)—Earth Science Week: https://www.earthsciweek.org/
- The Wednesday of Earth Science Week (e.g., 12 October 2022)—National Fossil Day: https://www.nps.gov/subjects/fossilday/index.htm

Earth Fissures

- Arizona Department of Water Resources—the latest in land subsidence: https://new.azwater.gov/news/articles/2018-27-06
- Arizona's Earth Fissure Center: http://www.azgs.az.gov/EFC.shtml
- AZGS earth fissure brochure: http://www.azgs.az.gov/efresources.shtml (scroll down the page)
- AZGS earth fissure study area maps: http://www.azgs.az.gov/efresources.shtml
- AZGS mitigation tips for reducing the occurrence of earth fissures and their associated effects: https://azgs.arizona.edu/earth-fissures-ground-subsidence/more-arizonas-earth-fissures
- "Natural Hazards in Arizona" map viewer maintained by the AZGS includes earth fissures: https://uagis.maps.arcgis.com/apps/webappviewer/index.html?id=98729f76e4644f1093d1c2cd6dabb584

Earthquakes

- Earthquake monitoring in Arizona occurs at seismograph stations throughout the state. Most of these stations are maintained by two seismograph networks: (1) Northern Arizona Network (https://www.fdsn.org/networks/detail/AR/), operated by Northern Arizona University; and (2) Arizona Broadband Seismic Network (http://www.fdsn.org/networks/detail/AE/), operated by the AZGS.
- Arizona Earthquake Information Center: https://aeic.nau.edu/index.html
- 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
- *Geological Monitoring* chapter about earthquakes and seismic activity (Braile 2009) described the following methods and vital signs for understanding earthquakes and monitoring seismic activity: (1) monitoring earthquakes, (2) analysis and statistics of earthquake activity, (3) analysis of historical and prehistoric earthquake activity, (4) earthquake risk estimation, (5) geodetic monitoring and ground deformation, and (6) geomorphic and geologic indications of active tectonics.
- US Geological Survey, Earthquake Hazards Program (information by region—Arizona): https://earthquake.usgs.gov/

Erosion

- Disturbed land restoration in the National Park System: https://www.nps.gov/articles/geoconservation-disturbed-land-restoration.htm
- State standards for rangeland health (Arizona): https://www.blm.gov/programs/natural-resources/rangeland-and-grazing/rangeland-health/arizona
- *Upland Soil Erosion Monitoring and Assessment: An Overview* (Ypsilantis 2011): https://www.blm.gov/documents/national-office/blm-library/technical-note/upland-soil-erosion-monitoring-and-assessment. *Note*: Former NPS soil scientist, Pete Biggam, reviewed this document, which is BLM Technical Note 438. It provides prudent land management practices that will help reduce erosion, including maintaining adequate plant,

litter, and biological soil crust cover; diminishing soil compaction; maintaining soil aggregate stability; applying good road building practices; reducing catastrophic wildfire conditions; and managing off-highway vehicle use. Other practices include concurrent reclamation of areas disturbed by mining and energy development, proper road maintenance, and implementing sound livestock grazing management practices. Information in the document will aid resource specialists in evaluating and selecting techniques for monitoring and assessing upland soil surface erosion.

- Web Soil Survey—a powerful online tool to access and use soil data for all 50 states—hosted by the NRCS: https://websoilsurvey.sc.egov.usda.gov/App/HomePage.htm

Geologic Heritage

- In 2015, GRD in cooperation with the American Geosciences Institute published a booklet introducing the American experience with geoheritage, geodiversity, and geoconservation: *America's Geologic Heritage: An Invitation to Leadership* (National Park Service and American Geosciences Institute 2015). That publication introduced key principles and concepts of America's geoheritage, which are the focus of ongoing collaboration and cooperation on geologic conservation in the United States.
- NPS Geologic Heritage: https://www.nps.gov/subjects/geology/geoheritage-conservation.htm

Geologic Interpretation, Education, and Outreach

- American Geosciences Institute, educational resources: https://www.americangeosciences.org/education/resources
- Ask a Geologist (most commonly asked questions and online form for submitting questions to AZGS geologists): http://azgs.arizona.edu/ask-a-geologist
- AZGS "Arizona Geology" blog (more than 4,500 posts since 2007): http://blog.azgs.arizona.edu/
- 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 page: https://www.facebook.com/AZ.Geological.Survey/
- AZGS Flickr: https://www.flickr.com/photos/azgs/
- AZGS Twitter: https://twitter.com/AZGeology
- AZGS YouTube channel: 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
- GRD, geoscience concepts: http://go.nps.gov/geoeducation

Geologic Maps

- American Geosciences Institute, information about geologic maps and their uses: http://www.americangeosciences.org/environment/publications/mapping
- The National Map: https://www.usgs.gov/programs/national-geospatial-program/national-map is hosted by the US Geological Survey, National Geospatial Program: https://www.usgs.gov/programs/national-geospatial-program

Geological Surveys and Societies

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

Geology of NPS Areas

- GRD: Energy and Minerals; Active Processes and Hazards; Geologic Heritage: http://go.nps.gov/geology
- NPS Geodiversity Atlas: https://www.nps.gov/articles/geodiversity-atlas-map.htm
- NPS Geologic Resources Inventory: http://go.nps.gov/gri
- *Parks and Plates: The Geology of Our National Parks, Monuments, and Seashores* (Lillie 2005)

Groundwater

- Arizona Department of Water Resources (ADWR): http://www.azwater.gov/azdwr/
- ADWR groundwater site inventory data: http://gisweb.azwater.gov/waterresourcedata/
- *Engineering Diplomacy, The Politics of Transboundary Water Resources Management Along the United States-Mexico Boundary, 1945–2015* (upcoming book by Stephen Mumme, Colorado State University, Political Science Department; see Nick 2021a)
- *Environmental Isotope Geochemistry in Groundwaters of Southwestern Arizona, USA, and Northwestern Sonora, Mexico: Implications for Groundwater*

Recharge, Flow, and Residence Time in Transboundary Aquifers (Zamora 2018, dissertation): https://repository.arizona.edu/handle/10150/631319

- Findings and lessons learned from the assessment of the Mexico-United States transboundary San Pedro and Santa Cruz aquifers (Callegary et al. 2018): https://doi.org/10.1016/j.ejrh.2018.08.002
- *Groundwater Depletion in the United States (1900–2008)* (Konikow 2013): http://pubs.usgs.gov/sir/2013/5079
- "Indicators in the Groundwater Environment of Rapid Environmental Change" (Edmunds 1996). In *Geoindicators: Assessing Rapid Environmental Changes in Earth Systems* (Berger and Iams 1996).
- International Boundary and Water Commission (IBWC): https://ibwc.gov/
- International Groundwater Resources Assessment Centre: https://www.un-igrac.org/
- Maps showing water-level declines, land subsidence, and earth fissures in south-central Arizona (Laney et al. 1978): https://pubs.er.usgs.gov/publication/wri7883
- "Rethinking Transboundary Ground Water Resources Management: A Local Approach Along the Mexico-US Border" (Eckstein 2013): https://ssrn.com/abstract=2254081
- Sonoran Desert Network, groundwater information: https://www.nps.gov/im/sodn/groundwater.htm
- Transboundary Aquifer Assessment Program (TAAP): https://wrrc.arizona.edu/TAAP (University of Arizona) or https://webapps.usgs.gov/taap/priority-aquifers.html (US Geological Survey). *Note*: TAAP used Coronado National Memorial weather station data in the San Pedro aquifer project (see Callegary et al. 2016).
- User-friendly groundwater modeling tool to inform decision-making in Arizona-Sonora transboundary aquifers (Rosebrough 2020): https://repository.arizona.edu/handle/10150/641692
- US Geological Survey, groundwater information: https://water.usgs.gov/ogw/
- US-Mexico Transboundary Aquifer Assessment Program as a model for transboundary groundwater collaboration (Tapia-Villaseñor and Megdal 2021): https://doi.org/10.3390/w13040530

Mining in Arizona

- AZGS "Mining in Arizona": https://azgs.arizona.edu/minerals/mining-arizona (includes map of major mines in the state, compiled in 2015)
- 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* (Richardson et al. 2019): http://repository.azgs.az.gov/uri_gin/azgs/dlio/1916
- NPS Abandoned Mineral Lands (AML): https://www.nps.gov/subjects/abandonedminerallands/index.htm

Oil and Gas in Arizona

- Arizona Oil and Gas Conservation Commission (AOGCC): http://azogcc.az.gov/
- AOGCC oil and gas well, online map viewer (provides location, operator, geologic formation, and depth of oil and gas wells across the state): https://adeq.maps.arcgis.com/apps/webappviewer/index.html?id=4d53e4cd05b6404f9b1ee5f067f55c04
- AOGCC permits and reporting data (maintained by the Arizona Department of Environmental Quality): https://azdeq.gov/databases

Packrat Middens

- NOAA [National Oceanic and Atmospheric Administration]/USGS [US Geological Survey] North American Packrat Midden Database (version 4, June 2016), originally by Laura Strickland (Strickland et al. 2001) and more recently maintained by Randy Schumann (US Geological Survey–Denver). As of 16 November 2020, the database included 11 records from the Ajo Range and 21 records from the Puerto Blanco Mountains; some national parks are listed as localities (e.g., Arches, Big Bend, Canyon de Chelly, Canyonlands, and Capital Reef), but not the monument: https://geochange.er.usgs.gov/midden/

Slope Movements and other Geologic Hazards

- *Geological Monitoring* chapter about slope movements (Wieczorek and Snyder 2009): https://www.nps.gov/articles/monitoring-slope-movements.htm
- *The Landslide Handbook—A Guide to Understanding Landslides* (Highland and Bobrowsky 2008): http://pubs.usgs.gov/circ/1325/
- "Natural Hazards in Arizona" map viewer maintained by the AZGS includes landslides: https://uagis.maps.arcgis.com/apps/webappviewer/index.html?id=98729f76e4644f1093d1c2cd6dabb584
- GRD employs three rockfall management strategies: (1) an Unstable Slope Management Program (USMP) for transportation corridor risk reduction, (2) quantitative risk estimation for specific rockfall

hazards, and (3) monitoring of potential rockfall areas. Monument managers can contact the GRD to discuss these options and determine if submitting a technical request is appropriate.

- GRD, geohazards: http://go.nps.gov/geohazards
- GRD, slope movement monitoring: http://go.nps.gov/monitor_slopes
- US Geological Survey, debris-flow forecasting (before fires): https://landslides.usgs.gov/research/featured/2018/before-fire-forecasts/
- US Geological Survey, landslides: http://landslides.usgs.gov/
- US Landslide Inventory (maintained by the US Geological Survey, Landslide Hazard Program) includes landslides and other slope movements mapped by the AZGS: https://usgs.maps.arcgis.com/apps/webappviewer/index.html?id=ae120962f459434b8c904b456c82669d

Tinajas

- The Sonoran Desert Network monitors tinajas, as well as springs and seeps, at the monument: https://www.nps.gov/im/sodn/orpi.htm

United Nations Educational, Scientific and Cultural Organization (UNESCO)

- Biosphere reserves: https://en.unesco.org/biosphere/wnbr
- World heritage sites: https://whc.unesco.org/en/list/

US Geological Survey Reference Tools

- National Geologic Map Database (NGMDB): http://ngmdb.usgs.gov/ngmdb/ngmdb_home.html
- US Geologic Names Lexicon ("Geolex"; national compilation of names and descriptions of geologic units): http://ngmdb.usgs.gov/Geolex/search
- Geographic Names Information System (GNIS; official listing of place names and geographic features): https://www.usgs.gov/us-board-on-geographic-names
- Publications Warehouse (provides more than 160,000 publications written by geologists at the US Geological Survey): http://pubs.er.usgs.gov
- US Geological Survey Store (find maps by location or by purpose): http://store.usgs.gov

Literature Cited

These references are cited in this report. Contact the GRI team for assistance in obtaining them.

Altschul, J. H., and A. G. Rankin, editors. 2008. Fragile patterns: the archaeology of the western Papaguería. SRI Press, Tucson, Arizona.

Anderson, L. W., L. A. Piety, and R. C. LaForge. 1987. Seismotectonic investigation, Theodore Roosevelt Dam, Salt River Project, Arizona (scale 1:48,000), with appendix, stratigraphy and tectonic significance of Cenozoic basin-fill sediments, Tonto Basin, Arizona, by J. D. Nations. Seismotectonic Report 87-5. US Bureau of Reclamation, Lower Colorado Region, Phoenix Office, Phoenix, Arizona.

Anderson, T. H. 2015. Jurassic (170–150 Ma) basins: the tracks of a continental-scale fault, the Mexico-Alaska megashear, from the Gulf of Mexico to Alaska. Pages 107–188 *in* T. H. Anderson, A. N. Didenko, C. L. Johnson, A. I. Khanchuk, and J. H. MacDonald Jr., editors. Late Jurassic margin of Laurasia—a record of faulting accommodating plate rotation. Special Paper 513. Geological Society of America, Boulder, Colorado. doi:10.1130/2015.2513(03).

Anderson, T. W., and R. L. Laney. 1978. Reconnaissance of ground-water conditions in the Quitobaquito Spring and La Abra Plain area, Organ Pipe Cactus National Monument, Arizona. Administrative Report 1978. US Geological Survey, Reston, Virginia.

Anderson, T. H., and J. B. Mahoney. 2006. Late Jurassic basins: the tracks of a continental-scale transform from the Gulf of Mexico to Alaska. Pages 369–375 *in* J. W. Haggart, R. J. Enkin, and J. W. H. Monger, editors. Paleogeography of the North American Cordillera: evidence for and against large-scale displacements. Special Paper 46. Geological Association of Canada, Toronto, Ontario, Canada.

Arizona Department of Water Resources. 2009. Arizona water atlas: volume 7—lower Colorado River planning area. Arizona Department of Water Resources, Tucson, Arizona. https://prism.lib.asu.edu/items/43170.

Arizona Geological Survey. 2015. Earth fissure study area of Avra Valley, Pima County, Arizona (scale 1:24,000). Digital Map Earth Fissure Series DM-EF-27. Arizona Geological Survey, Tucson, Arizona. http://repository.azgs.az.gov/uri_gin/azgs/dlio/1593.

Arizona Geological Survey. 2018. Earthquakes. Online information. Arizona Geological Survey, Tucson, Arizona. http://azgs.arizona.edu/center-natural-hazards/earthquakes (accessed 5 March 2018).

Arizona Geological Survey. 2020a. Active mines in Arizona. Online information and interactive Arizona mines map. Arizona Geological Survey, Tucson, Arizona. https://uagis.maps.arcgis.com/apps/webappviewer/index.html?id=9eceb192cd86497e8eed04113302db8b (accessed 18 November 2020).

Arizona Geological Survey. 2020b. Landslides & debris flows. Online information. Arizona Geological Survey, Tucson, Arizona. https://azgs.arizona.edu/center-natural-hazards/landslides-debris-flows (accessed 24 November 2020).

Arizona Geological Survey. 2020c. Mining in Arizona. Online information. Arizona Geological Survey, Tucson, Arizona. https://azgs.arizona.edu/minerals/mining-arizona (accessed 24 November 2020).

Arizona Geological Survey. 2021a. Earth fissures & ground subsidence. Online information. Arizona Geological Survey, Tucson, Arizona. https://azgs.arizona.edu/center-natural-hazards/earth-fissures-ground-subsidence (accessed 17 August 2021).

Arizona Geological Survey. 2021b. Energy resources of Arizona. Online information. Arizona Geological Survey, Tucson, Arizona. https://azgs.arizona.edu/energy-resources-arizona (accessed 24 August 2021).

Arizona Geological Survey. 2021c. Natural hazards in Arizona. Online map viewer. Arizona Geological Survey, Tucson, Arizona. https://uagis.maps.arcgis.com/apps/webappviewer/index.html?id=98729f76e4644f1093d1c2cd6dabb584 (accessed 8 November 2021).

Arizona Oil and Gas Conservation Commission. 2021 [access date]. Oil & gas wells. Online information. Arizona Department of Environmental Quality, Arizona Oil and Gas Conservation Commission, Phoenix, Arizona. https://adeq.maps.arcgis.com/apps/webappviewer/index.html?id=4d53e4cd05b6404f9b1ee5f067f55c04 (accessed 31 August 2021).

Bailey, E. B. 1910. Recumbent folds in the schists of the Scottish Highlands. The Quarterly Journal of the Geological Society of London 66:586–608.

Barnett, T. P., D. W. Pierce, H. G. Hidalgo, C. Bonfils, B. D. Santer, T. Das, G. Bala, A. W. Wood, T. Nozawa, A. A. Mirin, D. R. Cayan, and M. D. Dettinger. 2008. Human-induced changes in the hydrology of the western United States. Science 319(5866):1080–1083. https://science.sciencemag.org/content/319/5866/1080.

Barnett, J. J., and D. Sharrow. 1992. Water resources management plan, Organ Pipe Cactus National Monument. NPS D-77. National Park Service, Western Region, San Francisco, California. https://irma.nps.gov/DataStore/DownloadFile/442483.

Belnap, J. 2001. Biological soil crusts—webs of life in the desert. Fact Sheet 065-01. US Geological Survey, Southwest Biological Science Center, Canyonlands Field Station, Moab, Utah. https://pubs.usgs.gov/fs/2001/0065/.

Belnap, J., J. Hilty Kaltenecker, R. Rosentreter, J. Williams, S. Leonard, and D. Eldridge. 2001. Biological soil crusts: ecology and management. Technical Reference 1730-2. United States Department of the Interior, Bureau of Land Management, National Science and Technology Center, Information and Communications Group, Denver, Colorado. https://www.blm.gov/learn/blm-library/agency-publications/technical-references.

Bennett, P. S., and M. R. Kunzmann. 1989. A history of the Quitobaquito resource management area, Organ Pipe Cactus National Monument, Arizona. Technical Report 26. Cooperative National Park Resources Studies Unit, University of Arizona, Tucson, Arizona. http://www.npshistory.com/publications/orpi/#documents.

Berger, A. R., and W. J. Iams. 1996. Geoindicators: assessing rapid environmental changes in Earth systems. A. A. Balkema, Rotterdam, The Netherlands.

Beyer, S., and P. S. Pearthree. 1994. Bibliography of earthquake hazards in Arizona Open-File Report OFR-94-03. Arizona Geological Survey, Tucson, Arizona. http://repository.azgs.az.gov/uri_gin/azgs/dlio/929.

Bezy, J. V., J. Gutmann, and G. B. Haxel. 2000. A guide to the geology of Organ Pipe Cactus National Monument and the Pinacate Biosphere Reserve. Down-to-Earth 9. Arizona Geological Survey, Tucson, Arizona. http://repository.azgs.az.gov/uri_gin/azgs/dlio/1685.

Blakey, R. C., and W. D. Ranney. 2018. Ancient landscapes of western North America: a geologic history with paleogeographic maps. Springer International Publishing, Cham, Switzerland.

Bolton, H. E. 1936. Rim of Christendom: a biography of Eusebio Francisco Kino, Pacific Coast pioneer. MacMillan Company, New York, New York.

Bowles, Z., and R. Greeley. 2013. Reconnaissance volcanic geology of the Batamote Mountains, Ajo, Arizona. Journal of the Arizona-Nevada Academy of Science 45(1):37–51. https://doi.org/10.2181/036.045.0101.

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

Briggs, D. F. 2017. History of the Ajo Mining District, Pima County, Arizona. Contributed Report CR-17-A. Arizona Geological Survey, Tucson, Arizona. http://repository.azgs.az.gov/uri_gin/azgs/dlio/1710.

Brown, B. 1991. Land use trends surrounding Organ Pipe Cactus National Monument. Technical Report 39. Cooperative National Park Resources Studies Unit, University of Arizona, School of Renewable Natural Resources, Tucson, Arizona. https://irma.nps.gov/DataStore/DownloadFile/442326.

Brown, B. T., L. P. Hendrickson, R. R. Johnson, and W. Werrell. 1983. An inventory of surface water resources at Organ Pipe Cactus National Monument. Technical Report 10. Cooperative National Park Resources Studies Unit, University of Arizona, Tucson, Arizona.

Brown, B. T., and R. R. Johnson. 1983. The distribution of bedrock depressions (tinajas) as sources of surface water in Organ Pipe Cactus National Monument, Arizona. Journal of the Arizona-Nevada Academy of Science 18:61–68.

Brown, J. G. 2005. Water-quality data for selected national park units, southern and central Arizona and west-central New Mexico, water years 2003 and 2004. Open-File Report 2005-1291. US Geological Survey, Reston, Virginia. https://doi.org/10.3133/ofr20051291.

Brown, J. L. 1992. Interpretive geologic map of Mt. Ajo quadrangle, Organ Pipe Cactus National Monument, Arizona (scale 1:24,000). Open-File Report 92-23. Department of the Interior, US Geological Survey, prepared in cooperation with the US National Park Service, Washington, DC. https://pubs.er.usgs.gov/publication/ofr9223.

Bryan, K. 1920. Origin of rock tanks and charcos. Article XIV. American Journal of Science, Fourth Series, Volume L, Number 297, 188–206.

Bryan, K. 1923. Wind erosion near Lees Ferry, Arizona. Article XXVII. American Journal of Science, Series 5, Volume 6, Number 34, 291–307.

Bryan, K. 1925. The Papago country, Arizona: a geographic, geologic, and hydrologic reconnaissance, with a guide to desert watering places. Water-Supply Paper 499. US Geological Survey, Washington, DC. https://pubs.er.usgs.gov/publication/wsp499.

Burghardt, J. E., E. S. Norby, and H. S. Pranger II. 2014. Abandoned mineral lands in the National Park System—comprehensive inventory and assessment. Natural Resource Technical Report NPS/NRSS/GRD/NRTR—2014/906. National Park Service, Fort Collins, Colorado. https://irma.nps.gov/DataStore/Reference/Profile/2215804.

Butler, B. S., E. D. Wilson, R. E. Heineman, C. Trischka, L. E. R. Reber Jr., G. R. Rubly, J. Gilluly, M. N. Short, R. M. Hernon, S. K. Garrett, G. M. Fowler, N. P. Peterson, T. H. Kuhn, S. G. Lasky, and B. N. Webber. 1938. Some Arizona ore deposits. Geological Series 12. Bulletin 145. University of Arizona, Arizona Bureau of Mines, Tucson, Arizona. http://repository.azgs.az.gov/uri_gin/azgs/dlio/1242.

Callegary, J. B., S. B. Megdal, E. M. Tapia Villaseñor, J. D. Petersen-Perlman, I. Minjárez Sosa, R. Monreal, F. Gray, F. Grijalva Noriega. 2018. Findings and lessons learned from the assessment of the Mexico-United States transboundary San Pedro and Santa Cruz aquifers: the utility of social science in applied hydrologic research. Journal of Hydrology: Regional Studies 20:60–73. https://doi.org/10.1016/j.ejrh.2018.08.002.

Callegary, J. B., I. Minjárez Sosa, E. M. Tapia Villaseñor, P. dos Santos, R. Monreal Saavedra, F. J. Grijalva Noriega, A. K. Huth, F. Gray, C. A. Scott, S. B. Megdal, L. A. Oroz Ramos, M. Rangel Medina, and J. M. Leenhouts. 2016. Binational study of the transboundary San Pedro aquifer. International Boundary and Water Commission, Transboundary Aquifer Assessment Program, United States and Mexico. https://isarm.org/publication/binational-study-transboundary-san-pedro-aquifer.

Cannings, R., and S. Cannings. 2015. British Columbia: a natural history of its origins, ecology, and diversity with a new look at climate change. Revised and expanded third edition. Greystone Books, Vancouver, British Columbia, and Berkeley, California.

Carruth, R. L. 1996. Hydrogeology of the Quitobaquito Springs and La Abra Plain area, Organ Pipe Cactus National Monument, Arizona, and Sonora, Mexico. Water Resources Investigations Report 95-4295. US Geological Survey, Tucson, Arizona. https://irma.nps.gov/DataStore/DownloadFile/442667.

Chan, M. A., T. E., Cerling, and J. Gosse. 2006. Weathering of Jurassic sandstones: cosmogenic nuclide dating of geomorphic surfaces in southern Utah. Geological Society of America Abstracts with Programs 38(7):439. https://gsa.confex.com/gsa/2006AM/webprogram/Paper109390.html.

Chan, M. A., K. Moser, J. M. Davis, G. Southam, K. Hughes, and T. Graham. 2005. Desert potholes: ephemeral aquatic microsystems. Aquatic Geochemistry 11:279–302.

Chan, M. A., G. Southam, K. Moser, J. M. Davis, and T. Graham. 2001. Desert potholes: life in the fast pool. Geological Society of America Abstracts with Programs 33(6):1671. https://gsa.confex.com/gsa/2001AM/webprogram/Paper26095.html.

Chulick, G. S., and W. D. Mooney. 2002. Seismic structure of the crust and uppermost mantle of North America and adjacent oceanic basins: a synthesis. Bulletin of the Seismological Society of America 92(6):2478–2492.

Clynne, M. A., and L. J. P. Muffler. 2010. Geologic map of Lassen Volcanic National Park and vicinity, California (scale 1:50,000). Scientific investigations map 2899. US Geological Survey, Menlo Park, California, USA. http://pubs.er.usgs.gov/publication/sim2899.

Coney, P. J. 1978. Mesozoic–Cenozoic Cordilleran plate tectonics. Pages 33–50 *in* R. B. Smith and G. P. Eaton, editors. Cenozoic tectonics and regional geophysics of the western Cordillera. Memoir 152. Geological Society of America, Boulder, Colorado.

Cunningham, S. C. 1982. Aspects of the ecology of peninsular desert bighorn sheep (*Ovis canadensis cremobates*) in Carrizo Canyon, California. Thesis. Arizona State University, Tempe, Arizona.

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

Davis, O. K. 1990. Caves as sources of biotic remains in arid western North America. Palaeogeography, Palaeoclimatology, Palaeoecology 76:331–348.

Dickerson, R. 2011. Desert varnish—nature's smallest sedimentary formation. Geology Today 27(6):216–219.

Eberly, L. D., and T. B. Stanley Jr. 1978. Cenozoic stratigraphy and geologic history of southwestern Arizona. Geological Society of America Bulletin 89:921–940.

Eckstein, G. E. 2013. Rethinking transboundary ground water resources management: a local approach along the Mexico-US border. Georgetown International Environmental Law Review 25(1):95–128. https://ssrn.com/abstract=2254081.

Eddy, A. C., G. B. Haxel, D. J. May, R. J. Miller, D. W. Peterson, and R. M. Tosdal. 2004 [original mapping completed in 1988]. Geological reconnaissance at Organ Pipe Cactus National Monument, Arizona (scale 1:62,500 [digital data—scale 1:24,000]). Digitization was completed under a cooperative agreement between the University of Arizona, Cooperative Park Studies Unit, Tucson, Arizona, and Organ Pipe Cactus National Monument, Ajo, Arizona.

Edmunds, W. M. 1996. Indicators in the groundwater environment of rapid environmental change. Pages 121–136 *in* A. R. Berger and W. J. Iams, editors. Geoindicators: assessing rapid environmental changes in Earth systems. A. A. Balkema, Rotterdam, The Netherlands.

English, J. M., and S. T. Johnston. 2004. The Laramide Orogeny: what were the driving forces? International Geology Review 46:833–838.

Felger, R. S., S. Rutman, and J. Malusa. 2013a. Ajo Peak to Tinajas Altas: flora of southwestern Arizona. Part 5: Monocots except grasses. Phytoneuron 2013-76:1–59.

Felger, R. S., S. Rutman, J. Malusa, and T. R. Van Devender. 2013b. Ajo Peak to Tinajas Altas: flora of southwestern Arizona. Introduction. Phytoneuron 2013-5:1–40.

Felger, R. S., S. Rutman, J. Malusa, and T. R. Van Devender. 2013c. Ajo Peak to Tinajas Altas: flora of southwestern Arizona. Part 2: Checklist. Phytoneuron 2013-27:1–30.

Felger, R. S., S. Rutman, J. Malusa, and T. R. Van Devender. 2013d. Ajo Peak to Tinajas Altas: flora of southwestern Arizona. Part 3: Ferns, lycopods, and gymnosperms. Phytoneuron 2013-37:1–46.

Felger, R. S., S. Rutman, J. Malusa, and T. R. Van Devender. 2013e. Ajo Peak to Tinajas Altas: flora of southwestern Arizona. Part 4: Magnoliids. Phytoneuron 2013-38:1–9.

Felger, R. S., S. Rutman, M. A. Baker, and J. Malusa. 2014a. Ajo Peak to Tinajas Altas: flora of southwestern Arizona. Part 7: Cactaceae (cactus family). Phytoneuron 2014-69:1–95.

Felger, R. S., S. Rutman, and J. Malusa. 2014b. Ajo Peak to Tinajas Altas: flora of southwestern Arizona. Part 6: Poaceae (grass family). Phytoneuron 2014-35:1–139.

Felger, R. S., S. Rutman, and J. Malusa. 2014c. Ajo Peak to Tinajas Altas: flora of southwestern Arizona. Part 8: Acanthaceae–Apocynaceae. Phytoneuron 2014-85:1–74.

Felger, R. S., and S. Rutman. 2015a. Ajo Peak to Tinajas Altas: flora of southwestern Arizona. Part 14: Fabaceae—legumes. Phytoneuron 2015-58:1–83.

Felger, R. S., and S. Rutman. 2015b. Ajo Peak to Tinajas Altas: flora of southwestern Arizona. Part 15: Fagaceae to Lythraceae. Phytoneuron 2015-59:1–53.

Felger, R. S., S. Rutman, M. Costea, D. F. Austin, and J. Malusa. 2015c. Ajo Peak to Tinajas Altas: flora of southwestern Arizona. Part 9: Convolvulaceae (morning glory family). Phytoneuron 2015-2:1–22.

Felger, R. S., S. Rutman, C. J. S. Davis, and R. Lindley. 2015d. Ajo Peak to Tinajas Altas: flora of southwestern Arizona. Part 16: Malpighiaceae to Moraceae. Phytoneuron 2015-60:1–54.

Felger, R. S., S. Rutman, C. M. Guillams, and J. Malusa. 2015e. Ajo Peak to Tinajas Altas: flora of southwestern Arizona. Part 10: Berberidaceae, Bignoniaceae, and Boraginaceae. Phytoneuron 2015-1:1–60.

Felger, R. S., S. Rutman, and J. Malusa. 2015f. Ajo Peak to Tinajas Altas: flora of southwestern Arizona. Part 12: Campanulaceae to Cucurbitaceae. Phytoneuron 2015-21:1–39.

Felger, R. S., S. Rutman, A. Salywon, and J. Malusa. 2015g. Ajo Peak to Tinajas Altas: flora of southwestern Arizona. Part 11: Brassicaceae and Burseraceae. Phytoneuron 2015-6:1–48.

Felger, R. S., S. Rutman, and N. C. Taylor. 2015h. Ajo Peak to Tinajas Altas: flora of southwestern Arizona. Part 13: Euphorbiaceae—spurges. Phytoneuron 2015-26:1–65.

Felger, R. S., and S. Rutman. 2016a. Ajo Peak to Tinajas Altas: flora of southwestern Arizona. Part 17: Eudicots—Nyctaginaceae to Plumbaginaceae. Phytoneuron 2016-34:1–77.

Felger, R. S., and S. Rutman. 2016b. Ajo Peak to Tinajas Altas: flora of southwestern Arizona. Part 19: Eudicots—Polygalaceae [to] Simmondsiaceae. Phytoneuron 2016-47:1–71.

Felger, R. S., and S. Rutman. 2016c. Ajo Peak to Tinajas Altas: flora of southwestern Arizona. Part 20: Eudicots—Solanaceae [to] Zygophyllaceae. Phytoneuron 2016-52:1–66.

Felger, R. S., and S. Rutman. 2016d. Ajo Peak to Tinajas Altas: flora of southwestern Arizona. Part 21: Eudicots—Asteraceae (aster family). Phytoneuron 2016-77:1–164.

Felger, R. S., S. Rutman, and J. M. Porter. 2016. Ajo Peak to Tinajas Altas: flora of southwestern Arizona. Part 18: Eudicots—Polemoniaceae (phlox family). Phytoneuron 2016-35:1–24.

Galinier, J. 1991. From Montezuma to San Francisco: the Wi:gita ritual in Papago [Tohono O'odham] religion. Journal of the Southwest 33 (4):486–538.

Gilluly, J. 1937. Geology and ore deposits of the Ajo quadrangle, Arizona (scale 1:62,500). Bulletin 141. Arizona Bureau of Mines, Tucson, Arizona.

Gilluly, J. 1946. The Ajo mining district, Arizona. Professional Paper 209. US Geological Survey, Reston, Virginia. https://pubs.er.usgs.gov/publication/pp209.

Goodman, B. S. 1992. Hydrogeology of the Quitobaquito Springs area, La Abra Plain, and Rio Sonoita Valley, Organ Pipe Cactus National Monument, Arizona and Sonora, Mexico. Thesis. University of Arizona, Tucson, Arizona. http://hdl.handle.net/10150/278243.

Good Neighbor Environmental Board. 2010. A blueprint for action on the US-Mexico border. Thirteenth report of the Good Neighbor Environmental Board to the president and Congress of the United States. US Environmental Protection Agency, Good Neighbor Environmental Board, Washington, DC. https://19january2017snapshot.epa.gov/faca/gneb-13th-report-blueprint-action-us-mexico-border_.html.

Gonzalez, P. 2015. Climate Change trends, impacts, and vulnerabilities, Organ Pipe Cactus National Monument, Arizona. NPS Climate Change Response Program, Washington, DC. https://irma.nps.gov/DataStore/Reference/Profile/2224663.

Gonzalez, P., F. Wang, M. Notaro, D. J. Vimont, and J. W. Williams. 2018. Disproportionate magnitude of climate change in United States national parks. Environmental Research Letters 13(10): doi:10.1088/1748-9326/aade09. https://iopscience.iop.org/article/10.1088/1748-9326/aade09/meta.

Graham, J. P. 2004. Arches National Park: geologic resource evaluation report. Natural Resource Report NPS/NRPC/GRD/NRR—2004/005. National Park Service, Geologic Resources Division. Denver, Colorado. http://go.nps.gov/gripubs.

Graham, J. P. 2006a. Capitol Reef National Park: geologic resource evaluation report. Natural Resource Report NPS/NRPC/GRD/NRR—2006/005. National Park Service, Denver, Colorado. http://go.nps.gov/gripubs.

Graham, J. P. 2006b. Dinosaur National Monument: geologic resource evaluation report. Natural Resource Report. NPS/NRPC/GRD/NRR—2006/008. National Park Service, Denver, Colorado. http://go.nps.gov/gripubs.

Graham J. P. 2010. Saguaro National Park: geologic resources inventory report. Natural Resource Report. NPS/NRPC/GRD/NRR—2010/233. Natural Resource Program Center. Fort Collins, Colorado. http://go.nps.gov/gripubs.

Graham J. P. 2012. Yosemite National Park: geologic resources inventory report. Natural Resource Report. NPS/NRSS/GRD/NRR—2012/560. National Park Service. Fort Collins, Colorado. http://go.nps.gov/gripubs.

Graham, J. P. 2014. Great Basin National Park: geologic resources inventory report. Natural Resource Report NPS/NRSS/GRD/NRR—2014/762. National Park Service, Fort Collins, Colorado. http://go.nps.gov/gripubs.

Graham, J. P. 2020. Grand Canyon National Park: geologic resources inventory report. Natural Resource Report NPS/NRSS/GRD/NRR—2020/2195. National Park Service, Fort Collins, Colorado. http://go.nps.gov/gripubs.

Greene, J. A. 1977a. Historic resource study: Organ Pipe Cactus National Monument, Arizona (September 1977). National Park Service, Denver Service Center, Historic Preservation Division, Denver, Colorado. http://npshistory.com/publications/orpi/index.htm.

Greene, J. A. 1977b. National Register of Historic Places Inventory—nomination form: Bull Pasture, Organ Pipe Cactus National Monument. National Park Service, Historic Preservation Division, Denver, Colorado. https://catalog.archives.gov/id/75610387.

Greene, J. A. 1977c. National Register of Historic Places Inventory—nomination form: Growler Mine Area, Organ Pipe Cactus National Monument. National Park Service, Historic Preservation Division, Denver, Colorado. https://catalog.archives.gov/id/75610383.

Greene, J. A. 1977d. National Register of Historic Places Inventory—nomination form: Milton Mine, Organ Pipe Cactus National Monument. National Park Service, Historic Preservation Division, Denver, Colorado. https://catalog.archives.gov/id/75610556.

Greene, J. A. 1977e. National Register of Historic Places Inventory—nomination form: I'itoi Mo'o (I'itoi's/Montezuma's Head) and 'Oks Daha (Old Woman Sitting), Organ Pipe Cactus National Monument. National Park Service, Historic Preservation Division, Denver, Colorado. https://catalog.archives.gov/id/75610550.

Greene, J. A. 1977f. National Register of Historic Places Inventory—nomination form: Victoria Mine, Organ Pipe Cactus National Monument. National Park Service, Historic Preservation Division, Denver, Colorado. https://catalog.archives.gov/id/75610554.

Hall, W. E., C. A. Olson, and T. R. Van Devender. 1989. Late Quaternary and modern arthropods from the Ajo Mountains of southwestern Arizona. Pan Pacific Entomologist 65:322–347.

Hall, W. E., T. R. Van Devender, and C. A. Olson. 1990. Arthropod history of the Puerto Blanco Mountains, Organ Pipe National Monument, southwestern Arizona. Pages 363–379 *in* J. L. Betancourt, T. R. Van Devender, and P. S. Martin, editors. Packrat middens: the last 40,000 years of biotic change. University of Arizona Press, Tucson, Arizona.

Harris, R. C. 2004. Giant desiccation cracks in Arizona. Open File Report OFR-04-01. Arizona Geological Survey, Tucson, Arizona. http://repository.azgs.az.gov/uri_gin/azgs/dlio/1059.

Haxel, G. B., R. M. Tosdal, D. J. May, and J. E. Wright. 1984. Latest Cretaceous and early Tertiary orogenesis in south-central Arizona: thrust faulting, regional metamorphism, and granitic plutonism. Geological Society of America Bulletin 95(6):631–653. https://doi.org/10.1130/0016-7606(1984)95<631:LCAETO>2.0.CO;2.

Hem, J. D. 1985. Study and interpretation of the chemical characteristics of natural water. Water-Supply Paper 2254. US Geological Survey, Reston, Virginia. https://pubs.usgs.gov/wsp/wsp2254/.

Henry, R. S., and L. K. Sowls. 1980. White-tailed deer of the Organ Pipe Cactus National Monument, Arizona. Technical Report 6. Cooperative National Park Resources Studies Unit, University of Arizona, Tucson, Arizona. https://irma.nps.gov/DataStore/Reference/Profile/137253 (access from NPS computers only).

Hensley, M. M. 1950. Results of a herpetological reconnaissance in extreme southwestern Arizona and adjacent Sonora, with a description of a new subspecies of the Sonoran whipsnake, Masticophis bilineatus. Transactions of the Kansas Academy of Science 53(2):270–288.

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

Hoffman, J. P, D. R. Pool, A. D. Konieczki, and M. C. Carpenter. 1997. Investigation of the causes of sinks in the San Xavier District, Tohono O'odham Nation, Pima County, Arizona (scales 1:6,000, and 1:12,000). Open-File Report OFR-97-19. US Geological Survey, Water Resources Division, Tucson, Arizona. https://pubs.er.usgs.gov/publication/ofr9719.

Hoffman, J. P, D. R. Pool, A. D. Konieczki, and M. C. Carpenter. 1998. Causes of sinks near Tucson, Arizona, USA. Hydrogeology Journal 6:349–364.

Hollett, K. J. 1985. Geohydrology and water resources of the Papago Farms-Great Plain area, Papago Indian Reservation, Arizona, and the upper Rio Sonoyta area, Sonora, Mexico. Water-Supply Paper 2258. Prepared in cooperation with the US Bureau of Indian Affairs. United States Geological Survey, Alexandria, Virginia. https://doi.org/10.3133/wsp2258.

Houk, R. 2000. Sonoran Desert. American Deserts Handbook. Southwest Parks and Monuments Association, Tucson, Arizona.

Howard, S. M. S., S. Rutman, R. Tietjen, and M. Sturm. 2014. Inventory and assessment of unauthorized vehicle routes on Department of the Interior lands in the SBInet Ajo-1 project area and vicinity, southwestern Arizona: August 2014. Natural Resource Technical Report NPS/ORPI/NRTR—2014/900. National Park Service, Fort Collins, Colorado. https://irma.nps.gov/DataStore/Reference/Profile/2214834.

Hoy, W. E. 1976. Three volumes: Organ Pipe Cactus National Monument administrative historical research. Organ Pipe Cactus National Monument early period historical research. Organ Pipe Cactus National Monument frontier period historical research. Organ Pipe Cactus National Monument, Ajo, Arizona.

Hutton, D. H. W. 1979. Tectonic slides: a review and reappraisal. Earth-Science Reviews 15(2):151–172. https://doi.org/10.1016/0012-8252(79)90025-4.

Idaho Geological Survey. 2011. Putting down roots in earthquake country: your handbook for earthquakes in Idaho, version 3/19/11. Idaho Geological Survey, Boise, Idaho. https://www.idahogeology.org/geologic-hazards/earthquake-hazards.

International Commission on Stratigraphy. 2021. International chronostratigraphic chart (v2021/10). Drafted by K. M. Cohen, D. A. T. Harper, P. L. Gibbard, and N Car, October 2021. International Union of Geological Sciences (IUGS), International Commission on Stratigraphy (ICS), Durham, England [address of current ICS chair]. https://stratigraphy.org/chart (accessed 28 December 2021).

Keith, S. B. 1971. Highways of Arizona: Arizona highways 85, 86, and 386. Geologic Guidebook 3. University of Arizona, Bureau of Mines, Tucson, Arizona. http://repository.azgs.az.gov/uri_gin/azgs/dlio/1271.

KellerLynn, K. 2004. Rocky Mountain National Park: geologic resource evaluation report. Natural Resource Report NPS/NRPC/GRD/NRR—2004/004. National Park Service, Denver, Colorado. http://go.nps.gov/gripubs.

KellerLynn, K. 2005. Canyonlands National Park: geologic resource evaluation report. Natural Resource Report NPS/NRPC/GRD/NRR—2005/003. National Park Service, Denver, Colorado. http://go.nps.gov/gripubs.

KellerLynn, K. 2006. Colorado National Monument: geologic resource evaluation report. Natural Resource Report NPS/NRPC/GRD/NRR—2006/007. National Park Service, Denver, Colorado. http://go.nps.gov/gripubs.

KellerLynn, K. 2009a. Jewell Cave National Monument: geologic resources inventory report. Natural Resource Report NPS/NRPC/GRD/NRR—2009/084. National Park Service, Denver, Colorado. http://go.nps.gov/gripubs.

KellerLynn, K. 2009b. Wind Cave National Park: geologic resources inventory report. Natural Resource Report NPS/NRPC/GRD/NRR—2009/087. National Park Service, Denver, Colorado. http://go.nps.gov/gripubs.

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

KellerLynn, K. 2011. Oregon Caves National Monument: geologic resources inventory report. Natural Resource Report NPS/NRSS/GRD/NRR—2011/457. National Park Service, Fort Collins, Colorado. http://go.nps.gov/gripubs.

KellerLynn, K. 2012. White Sands National Monument: geologic resources inventory report. Natural Resource Report NPS/NRSS/GRD/NRR—2012/585. National Park Service, Fort Collins, Colorado. http://go.nps.gov/gripubs.

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

KellerLynn, K. 2014b. Lava Beds National Monument: geologic resources inventory report. Natural Resource Report NPS/NRSS/GRD/NRR—2014/804. National Park Service, Fort Collins, Colorado. http://go.nps.gov/gripubs.

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

KellerLynn, K. 2015b. Lake Meredith National Recreation Area and Alibates Flint Quarries National Monument: geologic resources inventory report. Natural Resource Report NPS/NRSS/GRD/NRR—2015/1046. National Park Service, Fort Collins, Colorado. http://go.nps.gov/gripubs.

KellerLynn, K. 2017. Petroglyph National Monument: geologic resources inventory report. Natural Resource Report NPS/NRSS/GRD/NRR—2017/1547. National Park Service, Fort Collins, Colorado. http://go.nps.gov/gripubs.

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

KellerLynn, K. 2019a. Montezuma Castle National Monument: geologic resources inventory report. Natural Resource Report NPS/NRSS/GRD/NRR—2019/2022. National Park Service, Fort Collins, Colorado. http://go.nps.gov/gripubs.

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

KellerLynn, K. 2020. Tonto National Monument: geologic resources inventory report. Natural Resource Report NPS/NRSS/GRD/NRR—2020/2212. National Park Service, Fort Collins, Colorado. http://go.nps.gov/gripubs.

KellerLynn, K. 2021a. John Muir National Historic Site: geologic resources inventory report. Natural Resource Report NPS/NRSS/GRD/NRR—2021/2333. National Park Service, Fort Collins, Colorado. http://go.nps.gov/gripubs.

KellerLynn, K. 2021b. Redwood National and State Parks: geologic resources inventory report. Natural Resource Report NPS/NRSS/GRD/NRR—2021/2314. National Park Service, Fort Collins, Colorado. http://go.nps.gov/gripubs.

Kenworthy, J. P. 2010. Changes in landscape, climate, and life during the age of mammals: interpreting paleontology, evolving ecosystems, and climate change in the Cenozoic fossil parks. Thesis. Oregon State University, Corvallis, Oregon.

Kenworthy, J. P., and V. L. Santucci. 2006. A preliminary inventory of National Park Service paleontological resources in cultural resource contexts, part 1: general overview. Pages 70–76 *in* S. G. Lucas, J. A. Spielmann, P. M. Hester, J. P. Kenworthy, and V. L. Santucci, editors. Fossils from federal lands. Bulletin 34. New Mexico Museum of Natural History and Science, Albuquerque, New Mexico. https://www.nps.gov/subjects/fossils/thematic-inventories.htm.

Kious, W. J., and R. I. Tilling. 1996. This dynamic Earth: the story of plate tectonics. US Geological Survey, Washington, DC. http://pubs.usgs.gov/gip/dynamic/dynamic.html.

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

Konieczki, A. D., J. P. Hoffman, and D. R. Pool. 1996. Methods of investigation of the causes of sinkholes on the farmlands of the San Xavier Di Nation, Pima County, Arizona. Abstract (pages 187–189) *in* Wanted: water for rural Arizona, Proceedings of the Ninth Annual Symposium, 12–14 September 1996. Arizona Hydrological Society, Tucson, Arizona.

Konikow, L. F. 2013. Groundwater depletion in the United States (1900–2008). Scientific Investigations Report 2013-5079. US Geological Survey, Reston, Virginia. http://pubs.usgs.gov/sir/2013/5079.

Le Bas, M. J., R. W. Le Maitre, A. Streckeisen, and B. Zanettin. 1986. A chemical classification of volcanic rocks based on total alkali-silica diagram. Journal of Petrology 27(3):745–750.

Le Bas, M. J., and A. L. Streckeisen. 1991. The IUGS systematics of igneous rocks. Journal of the Geological Society 148(5):825–833.

Laney, R. L., R. H. Raymond, and C. C. Winikka. 1978. Maps showing water-level declines, land subsidence, and earth fissures in south-central Arizona. Water-Resources Investigations Report WRI-78-83. US Geological Survey, Reston, Virginia. https://doi.org/10.3133/wri7883.

Lillie, R. J. 2005. Parks and plates: the geology of our national parks, monuments, and seashores. W. W. Norton and Company, New York, New York, and London, England.

Macey, J., J. Callegary, L. Wildermuth, J. Leenhouts, and K. Eherenberg. 2021. Geophysical investigation of the Quitobaquito Hills and La Abra Plain, Organ Pipe Cactus National Monument: preliminary findings. US Geological Survey, Tucson, Arizona.

Marsh, T. 1981. A photopoint soil erosion study of Gilman sandy loam in Organ Pipe Cactus National Monument. North Central College, Department of Biology, Naperville, Illinois. https://irma.nps.gov/DataStore/Reference/Profile/92129 (available on NPS computers only).

Mathews, B., and J. Monger. 2005. Roadside geology of southern British Columbia. Mountain Press Publishing Company, Missoula, Montana.

May, D. J., D. W. Peterson, R. M. Tosdal, R. A. LeVeque, and R. J. Miller. 1981. Miocene volcanic rocks of the Ajo Range, south central Arizona. Pages 65–66 *in* K. A. Howard, M. D. Carr, and D. M. Miller, editors. Tectonic framework of the Mojave and Sonoran Deserts, California and Arizona. Open-File Report 81-503. US Geological Survey, Menlo Park, California. https://pubs.er.usgs.gov/publication/ofr81503.

McAuliffe, J. R., and E. V. McDonald. 2006. Holocene environmental change and vegetation contraction in the Sonoran Desert. Quaternary Research 65(2):204–215.

McFadden, L. D., S. G. Wells, and M. J. Jercinovich. 1987. Influences of eolian and pedogenic processes on the origin and evolution of desert pavements. Geology 15(6):504–508.

McIntyre, C., K. Gallo, E. Gwilliam, J. A. Hubbard, J. Christian K. Bonebrake, G. Goodrum, M. Podolinsky, L. Palacios, B. Cooper, and M. Isley. 2018. Springs, seeps, and tinajas monitoring protocol: Chihuahuan and Sonoran Desert Networks. Natural Resource Report NPS/CHDN/NRR—2018/1796. National Park Service, Fort Collins, Colorado. https://www.nps.gov/im/reports-nrr.htm.

McKee, E. D. 1966. Structures of dunes at White Sands National Monument, New Mexico (and a comparison with structures of dunes from other selected areas). Sedimentology 7(1, special issue):1–69.

McMurdo, D. 2021. Jayne Belnap admitted to National Academy of Sciences, Moab's guru of soils. Online article. The Times-Independent, Moab, Utah. https://www.moabtimes.com/articles/jayne-belnap-admitted-to-national-academy-of-sciences/ (accessed 25 October 2021).

Mead, J. I., T. R. Van Devender, and K. L. Cole. 1983. Late Quaternary small mammals from Sonoran Desert packrat middens, Arizona and California. Journal of Mammalogy 64:173–180.

Meixner, T., A. H. Manning, D. A. Stonestrom, D. M. Allen, H. Ajami, K. W. Blasch, A. E. Brookfield, C. L. Castro, J. F. Clark, D. J. Gochis, A. L. Flint, K. L. Neff, R. Niraula, M. Rodell, B. R. Scanlon, K. Singha, and M. A. Walvoord. 2016. Implications of projected climate change for groundwater recharge in the western United States. Journal of Hydrology 534:124–138. https://doi.org/10.1016/j.jhydrol.2015.12.027.

Miller, R. J. 1988. Geology, geochemistry, and regional significance of the Childs Latite: a Miocene index unit in the Ajo volcanic field. Page 20 *in* F. Gray, compiler. Abstracts of the symposium of the geology and mineral deposits of the Ajo and Lukeville 1° by 2° quadrangle, Arizona. Open-File Report 88-217. US Geological Survey, Menlo Park, California. https://pubs.er.usgs.gov/publication/ofr88217.

Monahan, W. B., and N. A. Fisichelli. 2014. Recent climate change exposure of Organ Pipe Cactus National Monument. Climate change resource brief. National Park Service, Fort Collins, Colorado. https://irma.nps.gov/DataStore/Reference/Profile/2212893.

Morgan, M., M. Rockman, C. Smith, and A. Meadow. 2016. Climate change impacts on cultural resources. National Park Service, Cultural Resources Partnerships and Science, Washington, DC. https://www.nps.gov/subjects/climatechange/culturalimpactstable.htm.

Moritz, M. A., M. A. Parisien, E. Batllori, M. A. Krawchuk, J. Van Dorn, D. J. Ganz, and K. Hayhoe. 2012. Climate change and disruptions to global fire activity. Ecosphere 3(6), article 49. doi:10.1890/ES11-00345.1. https://esajournals.onlinelibrary.wiley.com/doi/10.1890/ES11-00345.1.

Muhs, D. R., R. Reynolds, J. Been, and G. Skipp. 2003. Eolian sand transport pathways in the southwestern United States: importance of the Colorado River and local sources. Quaternary International 104:3–18. https://doi.org/10.1016/S1040-6182(02)00131-3.

Nabhan, G. P. 2003. Destruction of an ancient indigenous cultural landscape: an epitaph from Organ Pipe Cactus National Monument. Ecological Restoration 21(4):290–295. https://doi.org/10.3368/er.21.4.290.

National Association for Interpretation. 2021. Mission, vision, and core values. Online information. National Association for Interpretation, Fort Collins, Colorado. https://www.interpnet.com/NAI/interp/About/About_NAI/What_We_Believe/nai/_About/Mission_Vision_and_Core_Values.aspx?hkey=ef5896dc-53e4-4dbb-929e-96d45bdb1cc1 (accessed 28 December 2021).

National Cooperative Soil Survey. 2009. Gilman Series. Online information. Classified according to Soil Taxonomy, Second Edition, 1999; Keys to Soil Taxonomy, Tenth Edition, 2006. Revised for the correlation of AZ661, 01/2009, WWJ. US Department of Agriculture, Natural Resources Conservation Service, Lincoln, Nebraska. https://soilseries.sc.egov.usda.gov/OSD_Docs/G/GILMAN.html (accessed 15 March 2021).

National Park Service. 1997. Final general management plan/development concept plans environmental impact statement, Organ Pipe Cactus National Monument, Pima County, Arizona (July 1977). Organ Pipe Cactus National Monument, Ajo, Arizona. http://www.npshistory.com/.

National Park Service. 2006. Geologic resource evaluation scoping summary, Organ Pipe Cactus National Monument, Arizona. National Park Service, Geologic Resources Division, Lakewood, Colorado. http://go.nps.gov/gripubs.

National Park Service. 2013. State of the park report for Organ Pipe Cactus National Monument. State of the Park Reports, Series Number 3. National Park Service, Washington, DC. https://www.nps.gov/nature/state-of-the-park.htm.

National Park Service. 2016. Foundation document, Organ Pipe Cactus National Monument, Arizona. ORPI 157/132289. Organ Pipe Cactus National Monument, Ajo, Arizona, and Intermountain Regional Office, Denver, Colorado.

National Park Service. 2018. Quitobaquito Springs. Online information. Organ Pipe Cactus National Monument, Ajo, Arizona. https://www.nps.gov/orpi/learn/historyculture/quitobaquito-springs.htm (accessed 10 March 2021).

National Park Service. 2020a. National natural landmarks directory. Online information. National Park Service, National Natural Landmarks Program, Washington, DC. https://www.nps.gov/subjects/nnlandmarks/nation.htm (accessed 1 December 2020).

National Park Service. 2020b. Peaks and people. Online information. Organ Pipe Cactus National Monument, Ajo, Arizona. https://www.nps.gov/orpi/learn/historyculture/peaks-and-people.htm (accessed 3 November 2020).

National Park Service. 2020c. Plan your visit: hiking. Online information. Organ Pipe Cactus National Monument, Ajo, Arizona. https://www.nps.gov/orpi/planyourvisit/hiking.htm (accessed 6 October 2020).

National Park Service. 2021a [access date]. NPS fundamentals essentials: interpretation and education. Online information. National Park Service, Common Learning Portal, Washington, DC. https://mylearning.nps.gov/library-resources/nps-essentials-interpretation-education/# (accessed 27 September 2021).

National Park Service. 2021b [access date]. Photo gallery: petroglyphs. Online information. Organ Pipe Cactus National Monument, Ajo, Arizona. https://www.nps.gov/media/photo/gallery.htm?pg=2139902&id=01C0A5C9-155D-451F-67C7BA9D5ABA739A (accessed 8 November 2021).

National Park Service and American Geosciences Institute. 2015. America's geologic heritage: an invitation to leadership (August 2015). NPS 999/129325. National Park Service, Geologic Resources Division, Denver, Colorado, and American Geosciences Institute, Alexandria, Virginia. https://www.nps.gov/subjects/geology/americas-geoheritage.htm.

Natoli, J. A., and R. J. Lillie. 2006. Shake, rattle, and roll—awaking the public's curiosity of geology via interpretation: a geology training manual for Redwood National and State Parks, California. Oregon State University, Department of Geosciences, Corvallis, Oregon.

Neuendorf, K. K. E., J. P. Meh. Jr., and J. A. Jackson. 2005. Glossary of geology. Fifth edition. American Geological Institute, Alexandria, Virginia.

Nick, S. 2021a. Navigating borders: could water be a bridge between US and Mexico? Online information. Colorado State University, Fort Collins, Colorado. https://libarts.source.colostate.edu/navigating-borders-could-water-be-a-bridge-between-u-s-and-mexico/?utm_source=newsletter&utm_medium=email&utm_campaign=m102521 (accessed 25 October 2021).

Nick, S. 2021b. The legacy of Quitobaquito Springs, a tiny place with a long history. Online information. Colorado State University, college of Fort Collins, Colorado. https://libarts.source.colostate.edu/the-legacy-of-quitobaquito-springs-a-tiny-place-with-a-long-history/ (accessed 27 December 2021).

Organ Pipe Cactus National Monument. 2006. Ecological monitoring program report 1997–2005. Organ Pipe Cactus National Monument, Ajo, Arizona. https://www.nps.gov/orpi/learn/nature/orpi-ecological-monitoring-report.htm.

Organ Pipe Cactus National Monument. 2008. Effects of the international boundary pedestrian fence in the vicinity of Lukeville, Arizona, on drainage systems and infrastructure, Organ Pipe Cactus National Monument, Arizona, prepared August 2008. National Park Service, Organ Pipe Cactus National Monument, Ajo, Arizona. https://ia803105.us.archive.org/3/items/6245820-ORPI-Analysis-of-2008-Flooding/6245820-ORPI-Analysis-of-2008-Flooding.pdf.

Organ Pipe Cactus National Monument. 2011. Organ Pipe Cactus National Monument: superintendent's 2010 report on natural resource vital signs. National Park Service, Ajo, Arizona.

Organ Pipe Cactus National Monument. 2020. Geophysical surveys at Quitobaquito. Project Management Information System (PMIS) 315535. National Park Service, Ajo, Arizona.

Pate, A., and C. Filippone. 2006. Water quality. Pages 14-1–14-10 *in* Organ Pipe Cactus National Monument, ecological monitoring report, 1997–2005. National Park Service, Intermountain Region, Organ Pipe Cactus National Monument, Ajo, Arizona.

Pearson, G., and C. W. Conner. 2000. The Quitobaquito desert pupfish, an endangered species within Organ Pipe Cactus National Monument: historical significance and management challenges. Natural Resources Journal 40 (2):379–410. https://digitalrepository.unm.edu/cgi/viewcontent.cgi?article=1641&context=nrj.

Pearthree, P. A., compiler. 1995. Fault number 943, Sand Tank fault in Quaternary fault and fold database of the United States. Online information. US Geological Survey, Earthquake Hazards Program, Golden, Colorado. https://earthquakes.usgs.gov/hazards/qfaults (accessed 25 November 2020).

Pearthree, P. A., compiler. 1998. Fault number 1019, Tinajas Altas fault zone in Quaternary fault and fold database of the United States. Online information. US Geological Survey, Earthquake Hazards Program, Golden, Colorado. https://earthquakes.usgs.gov/hazards/qfaults (accessed 25 November 2020).

Pearthree, P. A. compiler. 2012. Fault number 4000, Pitaycachi fault in Quaternary fault and fold database of the United States. Online information. US Geological Survey, Earthquake Hazards Program, Golden, Colorado. https://earthquakes.usgs.gov/hazards/qfaults (accessed 25 November 2020).

Pearthree, P. A., A. Youberg, and J. J. Young. 2012. Geologic map of the Tillotson Peak 7 1/2' quadrangle and part of the Mount Ajo 7 1/2' quadrangle, Organ Pipe Cactus National Monument, Pima County, Arizona (scale 1:24,000). Digital Geologic Map DGM-73. Arizona Geological Survey, Tucson, Arizona. http://repository.azgs.az.gov/uri_gin/azgs/dlio/1396.

Peirce, H. W. 1985. Arizona's backbone: the transition zone. Arizona Bureau of Geology and Mineral Technology Fieldnotes 15(3):1–6. http://www.azgs.az.gov/arizonageology_archive.shtml.

Pietrasiak, N. 2014. Field guide to classify biological soil crusts for ecological site evaluation. John Carroll University, Biology Department, University Heights, Ohio. http://www.nrcs.usda.gov/wps/portal/nrcs/main/soils/ref/#field_guides.

Pohl, M. M. 1995. Radiocarbon ages on organics from piedmont alluvium, Ajo Mountains, Arizona. Physical Geography 16(4):339–353.

Price, L. G. 2010. The geology of northern New Mexico's parks, monuments, and public lands. New Mexico Bureau of Geology and Mineral Resources, Socorro, New Mexico.

Putnam, J., and G. Smith. 1995. Deepest valley: a guide to Owens Valley, its roadsides and mountain trails. Second edition. Spellbinder Books, Bishop, California.

Rankin, A. G. 1995. Archeological survey at Organ Pipe Cactus National Monument, southwestern Arizona: 1989–1991. National Park Service, Western Archeological and Conservation Center, Tucson, Arizona. https://irma.nps.gov/DataStore/Reference/Profile/2181790.

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

Rauzi, S. L. 2003. Want to drill an oil well? Arizona Geology 33(1):1–4. http://azogcc.az.gov/.

Raymond, K., L. Palacios, C. McIntyre, and E. L. Gwilliam. 2019. Status of climate and water resources at Organ Pipe Cactus National Monument: water year 2018. Natural Resource Report NPS/SODN/NRR—2019/2029. National Park Service, Fort Collins, Colorado. https://irma.nps.gov/DataStore/Reference/Profile/2266975.

Reidmiller, D. R., C. W. Avery, D. R. Easterling, K. E. Kunkel, K. L. M. Lewis, T. K. Maycock, and B. C. Stewart, editors. 2018. Impacts, risks, and adaptation in the United States: fourth national climate assessment, volume II. US Global Change Research Program, Washington, DC. doi:10.7930/NCA4.2018.

Richard, S. M., T. C. Shipman, L. C. Greene, and R. C. Harris. 2007. Estimated depth to bedrock in Arizona, v. 1.0 (scale 1:100,000). Digital Geologic Map 52. Arizona Geological Survey, Tucson, Arizona. http://repository.azgs.az.gov/facets/results/DGM-52.

Richardson, C. A., L. Swartzbaugh, T. Evans, and F. M. Conway. 2019. Directory of active mines in Arizona: FY 2019. Open-File Report-19-04. Arizona Geological Survey, Tucson, Arizona. http://repository.azgs.az.gov/uri_gin/azgs/dlio/1916.

Rogers, W. P., L. R. Ladwig, A. L. Hornbaker, S. D. Schwochow, S. S. Hart, D. C. Shelton, D. L. Scroggs, and J. M. Soule. 1979. Guideline and criteria for identification and land-use controls of geologic hazards and mineral resource areas. Special Publication 6. Colorado Geological Survey, Denver, Colorado.

Rosebrough, A. 2020. A user-friendly groundwater modeling tool to inform decision-making in Arizona-Sonora transboundary aquifers. Thesis. University of Arizona, Tucson, Arizona. https://repository.arizona.edu/handle/10150/641692.

Rosentreter, R., M. Bowker, and J. Belnap. 2007. A field guide to biological soil crusts of western US drylands. US Government Printing Office, Denver, Colorado. https://www.usgs.gov/centers/sbsc/science/a-field-guide-biological-soil-crusts-western-us-drylands?qt-science_center_objects=0#qt-science_center_objects.

Rutman, S. 1997. Dirt is not cheap: livestock grazing and a legacy of accelerated soil erosion on Organ Pipe Cactus National Monument, Arizona. Pages 360–375 *in* Proceedings of Symposium on Environmental, Economic, and Legal Issues Related to Rangeland Water Developments, 13–15 November 1997, Arizona State University, College of Law, Tempe, Arizona. https://irma.nps.gov/DataStore/Reference/Profile/629650 (available on NPS computers only).

Saleeby, J. 2003. Segmentation of the Laramide slab—evidence from the southern Sierra Nevada region. Geological Society of America Bulletin 115(6):655–668. https://doi.org/10.1130/0016-7606(2003)115%3C0655:SOTLSF%3E2.0.CO;2.

Sanchez, R., and G. Eckstein. 2017. Aquifers shared between Mexico and the United States: management perspectives and their transboundary nature. Groundwater 55(4):495–505. https://ngwa.onlinelibrary.wiley.com/doi/10.1111/gwat.12533.

Sanchez, R., V. Lopez, and G. Eckstein. 2016. Identifying and characterizing transboundary aquifers along the Mexico-US border: an initial assessment. Journal of Hydrology 535:101–119. http://dx.doi.org/10.1016/j.jhydrol.2016.01.070.

Scarborough, R. B. 1980. Uranium in Arizona. Fieldnotes from the State of Arizona, Bureau of Geology and Mineral Technology 10(4):1–5.

Scarborough, R. B. 1981. Reconnaissance geology: Salt River—from Roosevelt Dam to Granite Reef Dam, central Arizona (scale 1:24,000). Open File Report OFR-81-30. Arizona Geological Survey, Tucson, Arizona. http://repository.azgs.az.gov/facets/results/OFR-81-30.

Scarborough, R. B., and P. A. Pearthree. 1988. Reconnaissance assessment of Quaternary faulting in the Gila River region from San Carlos Reservoir to Coolidge, Arizona (scale 1:250,000). Open-File Report OFR-88-15. Arizona Geological Survey, Tucson, Arizona. http://repository.azgs.az.gov/uri_gin/azgs/dlio/887.

Sellers, W. D., and R. H. Hill, editors. 1974. Arizona climate, 1931–1972. Second edition. University of Arizona Press, Tucson, Arizona.

Shafiqullah, M., P. E. Damon, D. J. Lynch, S. J. Reynolds, W. A. Rehrig, and R. H. Raymond. 1980. K-Ar geochronology and geologic history of southwestern Arizona and adjacent areas. Arizona Geological Society Digest 12:201–242.

Skinner, L. A., G. Haxel, and P. J. Umhoefer. 2008. Geological reconnaissance at Organ Pipe Cactus National Monument, Arizona (scale 1:24,000). Unpublished digital data. Northern Arizona University, Flagstaff, Arizona.

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

Sonoran Desert Network. 2019a. Natural resources monitoring at Organ Pipe Cactus National Monument: key issues. Online information. National Park Service, Sonoran Desert Network Inventory and Monitoring Program, Tucson, Arizona. https://www.nps.gov/im/sodn/orpi.htm (accessed 21 December 2021).

Sonoran Desert Network. 2019b. Sonoran Desert Network ecosystems. Online information. Park Service, Sonoran Desert Network Inventory and Monitoring Program, Tucson, Arizona. https://www.nps.gov/im/sodn/ecosystems.htm (accessed 4 January 2022).

Spamer, E. E. 1999. Rock Stars: grand vision of Edwin D. McKee. GSA Today 9(11):18–19. https://www.geosociety.org/GSA/Publications/GSA_Today/features/GSA/GSAToday/rockstars/archive.aspx.

Spaulding, W. G. 1983. Late Wisconsin macrofossil records of desert vegetation in the American Southwest. Quaternary Research 19:256–264.

Spencer, J. E. 2006. Macroscopic view of a mylonized shear zone. Online information. Arizona Geological Survey, Tucson, Arizona. https://azgs.arizona.edu/photo/macroscopic-view-mylonized-shear-zone (accessed 3 January 2022).

Spencer, J. E., and K. Wenrich. 2011. Breccia-pipe uranium mining in the Grand Canyon region and implications for uranium levels in Colorado River water. Open-File Report OFR-11-04. Arizona Geological Survey, Tucson, Arizona. http://repository.azgs.az.gov/uri_gin/azgs/dlio/1000.

Strickland, L. E., R. S. Thompson, and K. H. Anderson. 2001. USGS/NOAA North American packrat midden database data dictionary. Open-File Report 01-022. US Geological Survey, Denver, Colorado. https://geochange.er.usgs.gov/midden/.

Tapia-Villaseñor, E. M., and S. B. Megdal. 2021. The US-Mexico Transboundary Aquifer Assessment Program as a model for transborder groundwater collaboration. Water 13(4):530 [20 pages]. https://doi.org/10.3390/w13040530.

Thornberry-Ehrlich, T. L. 2010. Denali National Park and Preserve: geologic resources inventory report. Natural Resource Report. NPS/NRPC/GRD/NRR—2010/244. Natural Resource Program Center. Fort Collins, Colorado. http://go.nps.gov/gripubs.

Tohono O'odham Nation. 2016. Official web site of the Tohono O'odham Nation. Online information. Tohono O'odham Nation, Sells, Arizona. http://www.tonation-nsn.gov/districts/ (accessed 18 October 2021).

Tosdal, R. M., G. B. Haxel, and J. E. Wright. 1989. Jurassic geology of the Sonoran Desert region, southern Arizona, southeastern California, and northernmost Sonora: construction of a continental-margin magmatic arc. Pages 397–434 *in* J. P. Jenney and J. Reynolds, editors. Geologic evolution of Arizona. Digest 17. Arizona Geological Society, Tucson, Arizona.

Tosdal, R. M., D. W. Peterson, D. J. May, R. A. LeVegue, and R. J. Miller. 1986. Reconnaissance geologic map of the Mount Ajo and part of the Pisinimo quadrangles, Pima County, Arizona (scale 1:62,500). Miscellaneous Field Studies Map MF-1820. US Geological Survey, Reston, Virginia. https://ngmdb.usgs.gov/Prodesc/proddesc_7798.htm.

Tosdal, R. M., and J. L. Wooden. 2015. Construction of the Jurassic magmatic arc, southeast California and southwest Arizona. Pages 189–221 *in* T. H. Anderson, A. N. Didenko, C. L. Johnson, A. I. Khanchuk, J. H. MacDonald Jr., editors. Late Jurassic margin of Laurasia: a record of faulting accommodating plate rotation. Special Paper 513. Geological Society of America, Boulder, Colorado.

Tucker, W. C. Jr. 1980. Tectonic geomorphology of the Luke Air Force Range, Arizona. Pages 63–88 *in* J. P. Jenney and C. Stone, editors. Studies in western Arizona. Digest 12. Arizona Geological Society, Tucson, Arizona.

Tweet, J. S., V. L. Santucci, and A. P. Hunt. 2012. An inventory of packrat (Neotoma spp.) middens in National Park Service areas. Pages 355–368 *in* A. P. Hunt, J. Milàn, S. G. Lucas, and J. A. Spielmann, editors. Vertebrate coprolites. Bulletin 57. New Mexico Museum of Natural History and Science, Albuquerque, New Mexico. https://www.nps.gov/subjects/fossils/thematic-inventories.htm.

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

Underhill, R. M. 1969 [reprint; first published in 1946 by Columbia University Press, New York, New York]. Papago Indian religion. AMS Press, New York, New York.

US Board on Geographic Names. 1984. Summary report, feature details [for] Quitobaquito. Feature ID: 23947. Online information. Geographic Names Information System (GNIS), maintained by US Geological Survey, Washington, DC. https://www.usgs.gov/core-science-systems/ngp/board-on-geographic-names/domestic-names (accessed 17 August 2021).

US Geological Survey. 1981. Summary report, feature details [for] Montezuma Head. Feature ID: 8226. Online information. Geographic Names Information System (GNIS), maintained by US Geological Survey, Washington, DC. https://www.usgs.gov/us-board-on-geographic-names/domestic-names (accessed 20 December 2021).

US Geological Survey. 2000. The severity of an earthquake. General Interest Publication [unnumbered]. US Geological Survey, Reston, Virginia. https://pubs.er.usgs.gov/publication/7000035.

US Geological Survey. 2016. NOAA/USGS North American packrat midden database (version 4, June 2016). Online information. US Geological Survey, Denver, Colorado. https://geochange.er.usgs.gov/midden/ (accessed 5 October 2021).

US Geological Survey. 2020. National water information system: web interface. USGS current conditions for USGS 09535900 Quitobaquito Spring near Lukeville, AZ. https://waterdata.usgs.gov/nwis/uv?site_no=09535900 (accessed 23 November 2020).

US Geological Survey and US Board on Geographic Names. 1980. Summary report, feature details [for] Quitobaquito Springs. Feature ID: 9885. Online information. Geographic Names Information System (GNIS), maintained by US Geological Survey, Washington, DC. https://www.usgs.gov/core-science-systems/ngp/board-on-geographic-names/domestic-names (accessed 30 August 2021).

Van Devender, T. R. 1977. Holocene woodlands in the Southwestern deserts. Science 198:189–192.

Van Devender, T. R. 1982. The vegetation and climate of Organ Pipe Cactus National Monument: the view from the Ice Age. Report completed for the National Park Service. University of Arizona, Tucson, Arizona.

Van Devender, T. R. 1987. Holocene vegetation and climate in the Puerto Blanco Mountains, southwestern Arizona. Quaternary Research 27:51–72.

Van Devender, T. R. 1990. Late Quaternary vegetation and climate of the Sonoran Desert, United States and Mexico. Pages 134–163 *in* J. L. Betancourt, T. R. Van Devender, and P. S. Martin, editors. Packrat middens: the last 40,000 years of biotic change. University of Arizona Press, Tucson, Arizona.

Van Devender, T. R., A. M. Rea, and W. E. Hall. 1991. Faunal analysis of late Quaternary vertebrates from Organ Pipe Cactus National Monument, southwestern Arizona. The Southwestern Naturalist 36:94–106.

Van Devender, T. R., L. J. Toolin, and T. L. Burgess. 1990. The ecology and paleoecology of grasses in selected Sonoran Desert plant communities. Pages 326–349 *in* J. L. Betancourt, T. R. Van Devender, and P. S. Martin, editors. Packrat middens: the last 40,000 years of biotic change. University of Arizona Press, Tucson, Arizona.

Water Resources Division. 2019. Water Rights Branch. Online information. National Park Service, Water Resources Division, Fort Collins, Colorado. https://www.nps.gov/orgs/1439/wrb.htm (accessed 21 December 2021).

Wells, D. L., and K. J. Coppersmith. 1994. New empirical relationships among magnitude, rupture length, rupture width, rupture area, and surface displacement. Bulletin Seismological Society America 84:974–1002.

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

Witcher, J. C., C. Stone, and W. R. Hahman Sr. 1982. Geothermal resources of Arizona (scale 1:500,000). Map 15. Arizona Geological Survey, Tucson, Arizona. http://repository.azgs.az.gov/uri_gin/azgs/dlio/1718.

Wuebbles, D. J., D. W. Fahey, K. A. Hibbard, D. J. Dokken, B. C. Stewart, and T. K. Maycock, editors. 2017. Climate science special report: fourth national climate assessment, volume I. US Global Change Research Program, Washington, DC. http://doi.org/10.7930/J0J964J6.

Youberg, A., and P. A. Pearthree. 2012. Geologic map of parts of the Lukeville, Diaz Peak, South of Lukeville and Blankenship Wells 7 1/2' quadrangles, Organ Pipe Cactus National Monument, Pima County, Arizona (scale 1:24,000). Digital Geologic Map DGM-74. Arizona Geological Survey, Tucson, Arizona. http://repository.azgs.az.gov/uri_gin/azgs/dlio/1397.

Young, J. J, and P. A. Pearthree. 2012. Geologic map of the Armenta Well 7 1/2' quadrangle and part of the Gunsight 7 1/2' quadrangle, Organ Pipe Cactus National Monument, Pima County, Arizona (scale 1:24,000). Digital Geologic Map DGM-72. Arizona Geological Survey, Tucson, Arizona. http://repository.azgs.az.gov/uri_gin/azgs/dlio/1395.

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

Ypsilantis, W. G. 2011. Upland soil erosion monitoring and assessment: an overview. Technical Note 438. Bureau of Land Management, National Operations Center, Denver, Colorado. https://www.blm.gov/documents/national-office/blm-library/technical-note/upland-soil-erosion-monitoring-and-assessment.

Zamora, H. A. 2018. Environmental isotope geochemistry in groundwaters of southwestern Arizona, USA, and northwestern Sonora, Mexico: implications for groundwater recharge, flow, and residence time in transboundary aquifers. Dissertation. University of Arizona, Tucson, Arizona. https://repository.arizona.edu/handle/10150/631319.

Zamora, H. A., C. J. Eastoe, B. T. Wilder, J. C. McIntosh, T. Meixner, and K. W. Flessa. 2020. Groundwater isotopes in the Sonoyta River watershed, USA-Mexico: implications for recharge sources and management of the Quitobaquito Springs. Water [MDPI] 12(12):3307 [20 pages]. https://doi.org/10.3390/w12123307.

NPS 157/181564, June 2022

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