National Park Service
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Natural Resource Stewardship and Science

Casa Grande Ruins National Monument

Geologic Resources Inventory Report

Natural Resource Report NPS/NRSS/GRD/NRR—2018/1785

ON THE COVER

The Great House at Casa Grande Ruins National Monument towers above the underlying river terrace, a former floodplain of the Gila River. The river flowed through the monument area about 130,000 to 10,000 years ago. NPS photograph (from National Park Service 2017, cover).

THIS PAGE

The Santan Mountains north of the monument create a scenic backdrop consisting of rocks as old as 1.7 billion years. NPS photograph (from National Park Service 2017, p. 8).

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

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

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Executive Summary

The Geologic Resources Inventory (GRI) provides geologic map data and pertinent geologic information to support resource management and science-informed decision making in more than 270 natural resource parks throughout the National Park System. The GRI is one of 12 inventories—including geologic resources, vegetation mapping, natural resource bibliography, water resources, vertebrates and vascular plants, climate, base cartography, air quality, and soil resources (see https://www.nps.gov/im/inventories.htm)—funded by the National Park Service (NPS) Inventory and Monitoring Program. The Geologic Resources Division of the NPS Natural Resource Stewardship and Science Directorate administers the GRI.

This GRI report synthesizes discussions from a scoping meeting held in 2006 for Casa Grande Ruins National Monument (referred to as the "monument" throughout this report) and a follow-up conference call in 2018 (see Appendix A). Chapters of this report discuss the monument's geologic setting and significance and draw connections between geologic and cultural resources, outline the geologic history leading to the present-day landscape, describe geologic issues facing resource managers, suggest future geologic investigations pertinent to the monument's resources, and provide information about the previously completed GRI map data.

This report, and the interpretation of the monument's geologic history provided here, is supported by GRI GIS data of three compiled geologic maps of the Blackwater and Coolidge 7.5-minute quadrangles. The boundary of these two quadrangles runs through the monument. These geologic maps were produced by the Arizona Geological Survey (AZGS) and converted to the GRI GIS data model by the GRI team. A poster in the pocket of this report displays the GRI GIS data draped over a shaded relief image of the monument and surrounding area; it is the primary figure of this report. More information about the GRI GIS data is provided in the "Geologic Map Data" chapter.

The GRI GIS data comprise 16 bedrock and 14 surficial map units. Source maps provided descriptions for all of the surficial map units but only two of the bedrock map units. Thus for this report, descriptions for the bedrock map units without them were compiled from mapping projects in proximity to the Blackwater and Coolidge quadrangles, for example, the Superior quadrangle, Gila River Indian Reservation, the Goldfield and the northern part of the Superstition Mts. SW quadrangles, and the Santan and Sacaton Mountains. Descriptions of all of the map units are provided in table 1.

Figure 1 of this report is a geologic time scale based on the International Commission on Stratigraphy (ICS) international chronostratigraphic chart (International Commission on Stratigraphy 2018); the figure shows the associated geologic eras, periods, and epochs. Similarly, table 1 displays the map units of the GRI GIS data in a context of geologic time. Epochs listed in table 1 are from the GRI GIS data, with the exception of epochs associated with Tertiary ("**T**") map units, which are from the US Geologic Names Lexicon ("Geolex"), a national compilation of names and descriptions of geologic units. Table 1 includes numeric ages from the ICS international chronostratigraphic chart as well as numeric ages for specific map units provided by source maps and other references.

As discussed in the "Geologic Setting and Significance" chapter, a single map unit—river terrace and alluvium deposits (map unit **Qi3r**)—underlies the entire monument. This map unit is a late Pleistocene stream terrace (one of a series of flat or gently sloping surfaces in a stream valley, flanking the stream channel; a terrace is above the level of the stream and represents a former floodplain). The age of the monument's terrace (**Qi3r**) indicates that the middle Gila River was flowing across the monument area approximately 130,000–10,000 years ago (Klawon et al. 1998; Richard et al. 2006). The terrace now sits 3–6 m (10–20 ft) above the Holocene floodplain (**Qyr**) (Huckleberry 1992), which in turn is above the modern stream channel (**Qycr**). Today, the middle Gila River is characterized by a wide streambed with a braided pattern of sandy and gravelly bars and channels. The streambed is entrenched and flanked by a floodplain (**Qyr**) and terraces (e.g., **Qi3r**).

The Gila River is the unifying geomorphic feature of the monument and surrounding region (Huckleberry 1992). The seasonal flows and floods of the river set the rhythms of life for the Ancestral Sonoran Desert People (National Park Service 2011) who built the Great House and other prehistoric structures in the monument.
In this report, the "Casa Grande" is referred to as the

“Great House” so as not to confuse this structure with the monument itself.

As a major water source in the Sonoran Desert, the Gila River has been the locus of cultural activity for at least 2,000 years, as discussed in “Connections between Geologic and Cultural Resources.” The river’s origin, however, extends back several million years. Furthermore, the geologic story of the monument and surrounding area dates back even farther—more than a billion years.

A timeline, which makes a very long story short, is provided in the “Geologic History” chapter of this report. Pinal Schist (**Xp**), which formed about 1.7 billion years ago (Drewes 1980), marks the beginning of the long geologic story affecting the monument’s landscape. Pinal Schist is exposed north of the monument in the Santan Mountains (see poster, in pocket); it is one of the oldest rock formations in Arizona. The oldest rocks in the state, which are igneous and metamorphic, formed in an interval from about 1.8 billion to 1.6 billion years ago (during the early Proterozoic Era) (Livingston and Damon 1968; Silver 1978).

In addition to the Pinal Schist, bedrock in the Santan Mountains consists of voluminous middle Proterozoic (1.6 billion to 1.0 billion years ago) plutons (**Ygs**, **Yg**, and **Yge**); these large bodies of igneous rock intruded the Pinal Schist. Bedrock of the Santan Mountains also consists of rocks (**Kv**, **Kg**, and **Kd**) from a younger igneous episode that took place during the Cretaceous Period (approximately 145 million to 66 million years ago). These Cretaceous rocks record the onset of the most intense mountain-building event to have affected Arizona since early Proterozoic time—the Laramide Orogeny. In the Santan Mountains, dikes (**TKri**, **TKdi**, and **TKbi**) are representative of the Laramide Orogeny.

Another significant mountain-building event—the one that contributed most to the current topography (Gary Huckleberry, University of Arizona, adjunct researcher and lecturer, written communication, 26 May 2018)—was the result of Basin and Range extension (pulling apart of Earth’s crust) and tectonism (large-scale movement and deformation of Earth’s crust). The monument and surrounding region are part of the Sonoran Desert subprovince of the Basin and Range physiographic province. As the name implies, the province is composed of structural basins, which dropped down along normal faults (one of the three main types of faults; see figs. 5 and 6), as mountain ranges were uplifted along these same faults. The monument is in the down-dropped Picacho Basin. The monument’s physiographic setting is discussed in the “Geologic Setting and Significance” chapter.

In the “Geologic Resource Management Issues” chapter, management issues related to the monument’s geologic resources (features and processes) are ordered with respect to management priority and include the following: erosion; surrounding land use; windblown dust; geologic hazard assessment; climate change; earth fissures; groundwater level; interpretation and resource education relating to the monument’s geologic resources; paleontological resource inventory, monitoring, and protection; mining operations; seismic hazard; and flood potential. Discussions of issues are primarily based on the 2006 scoping summary (National Park Service 2006), but the monument’s foundation document (National Park Service 2017), 2018 conference call, and reviewers’ comments helped to update the list of geologic resource management issues since 2006 and guided research for this report.

“Future Geologic Investigations” provides suggestions for future studies related to the monument’s resources, including geoarchaeology (also spelled “geoarcheology”); vibration impact analysis; highly detailed spatial data; and biological and physical soil crusts, desert pavement, and desert varnish. This list is primarily an outcome of the discussion during the 2018 conference call; it is not a list of the highest priority research to support park management, though some of the studies would, of course, do that. In addition, “Future Geologic Investigations” includes a list of selected references for the Gila, Salt, Santa Cruz, and San Pedro Rivers (see “Geoarchaeology”). Although a thorough discussion of these river corridors is beyond the scope of this GRI report, an index of 1:24,000-scale geologic maps that intersect the Gila, Salt, Santa Cruz, and San Pedro Rivers and a bibliography of these geologic maps are provided. Also, tables 2 and 3 compile geologic information useful for future geoarchaeological studies related to the Ancestral Sonoran Desert People.

“Literature Cited” is a bibliography of references cited in this GRI report; many of these references are available online, as indicated by an Internet address included as part of the reference citation. If monument managers are interested in other investigations and/or a broader search of the scientific literature, the NPS Geologic Resources Division has collaborated with—and funded—the NPS Technical Information Center (TIC) to maintain a subscription to GEOREF (the premier online geologic citation database). Multiple portals are available for NPS staff to access this database. Monument staff should contact Tim Connors (NPS Geologic Resources Division) for instructions to access GEOREF.

“Additional Resources” provides online sources of information related to the geologic resource management issues discussed in this report, including mine data, climate change, earth fissures, active faults, and flood potential. The "Natural Hazards in Arizona" map viewer at http://data.azgs.az.gov/hazard-viewer/, which is maintained by the Arizona Geological Survey (AZGS), is particularly noteworthy. In addition, "Additional Resources" suggests online sources and books for geologic interpretation at the monument.

Appendix A of this report provides a list of people who participated in the scoping meeting for the monument in 2006 as well as those who participated in a follow-up conference call in 2018. The list serves as a legacy document and reflects participants' affiliations and positions at the time of scoping and the conference call.

Finally, Appendix B of this report lists laws, regulations, and NPS policies that specifically apply to geologic resources in the National Park System. The NPS Geologic Resources Division can provide policy assistance, as well as technical expertise, regarding the monument's geologic resources.

Products and Acknowledgments

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

GRI Products

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

Scoping meetings bring together park staff and geologic experts to review and assess available geologic maps, develop a geologic mapping plan, and discuss geologic features, processes, and resource management issues that should be addressed in the GRI report. Following the scoping meeting, the GRI map team converts the geologic maps identified in the mapping plan to GIS data in accordance with the GRI data model. After the map is completed, the GRI report team uses these data, as well as the scoping summary and additional research, to prepare the GRI report. The GRI team conducts no new field work in association with their products.

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

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

Acknowledgments

The GRI team thanks the **participants** of the **2006 scoping meeting** and **2018 conference call** (see Appendix A) for their assistance in this inventory. Thanks very much to the **Arizona Geological Survey** for its maps of the area; this report and accompanying GIS data could not have been completed without them. Thanks to **Tim Connors** (NPS Geologic Resources Division) for compiling data to create a geologic map index and bibliography for the Gila, Salt, Santa Cruz, and San Pedro Rivers; thanks to **Michael Barthelmes** (Colorado State University) and **Jason Kenworthy** (NPS Geologic Resources Division) for preparing the associated map index poster. This map index and accompanying bibliography provide geological information about the landscape inhabited by the Ancestral Sonoran Desert People. Thanks to **Trista Thornberry-Ehrlich** (Colorado State University) for creating many of the graphics in this report. Thanks to **Jake DeGayner** and **Matt Guebard** (NPS Southern Arizona Office) for their assistance in tracking down and answering questions about the highly detailed spatial data available for the monument. Thanks to **Karl Pierce** (Casa Grande Ruins National Monument) for reviewing the "first draft" of this report—twice.

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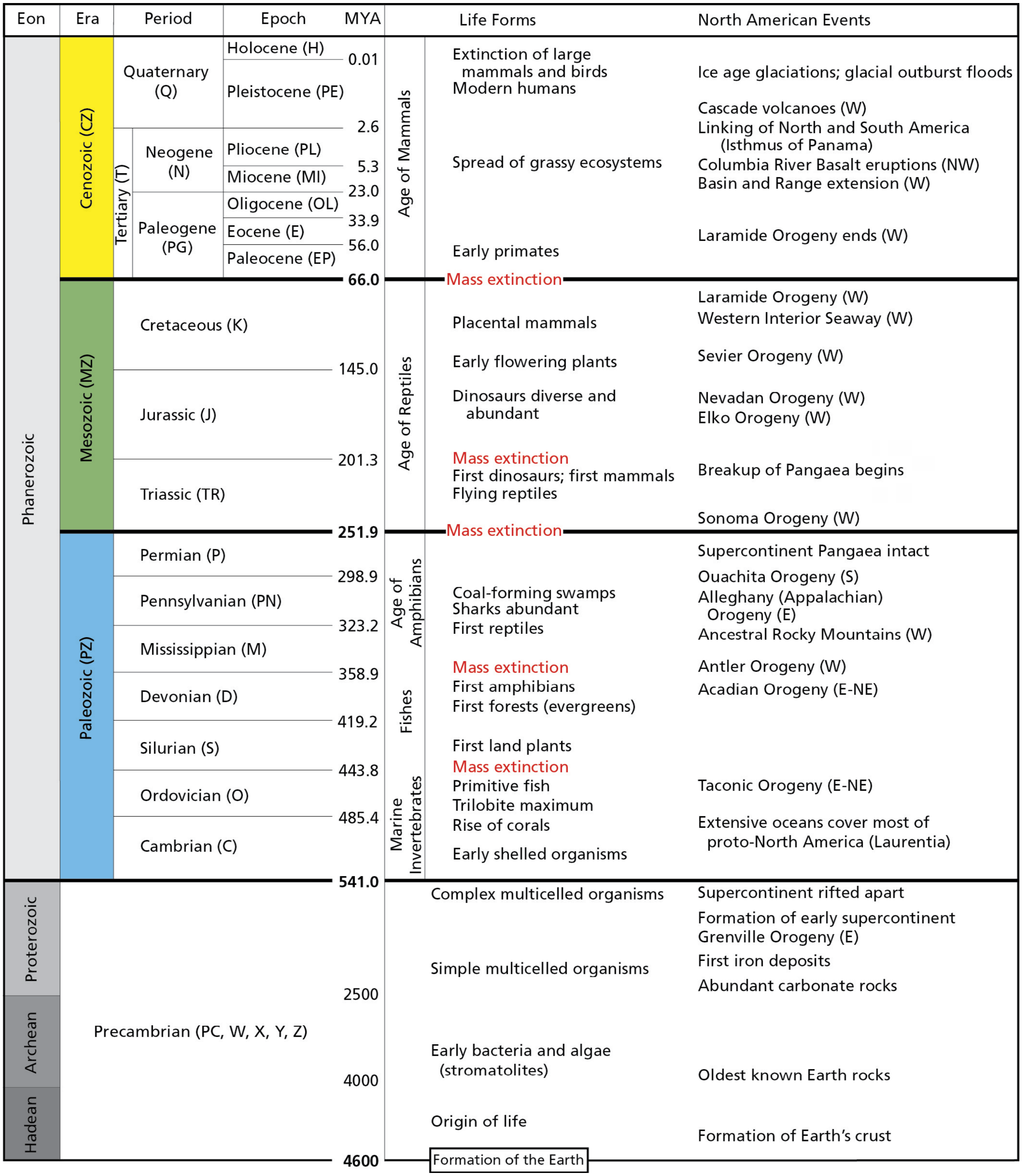

Figure 1. Geologic time scale.
The divisions of the geologic time scale are organized stratigraphically, with the oldest divisions at the bottom and the youngest at the top. GRI map abbreviations for each time division are in parentheses. Rocks and deposits of interest for the monument are from the Precambrian (X and Y), Cretaceous Period (K), Tertiary (T), and Quaternary Period (Q) (see table 1). Compass directions in parentheses indicate the regional locations of events. Boundary ages are millions of years ago (MYA). NPS graphic using dates from the International Commission on Stratigraphy (http://www.stratigraphy.org/index.php/ics-chart-timescale; accessed 15 August 2018).

Table 1. GRI GIS bedrock and surficial map units.

The source maps for the GRI GIS data (see "Geologic Map Data") did not provide descriptions for all of the map units. As indicated in this table, map unit descriptions for units without them were derived from Peterson (1969; geologic map of the Superior quadrangle, Pinal County), Wilson (1969; mapping of mineral deposits of the Gila River Indian Reservation), Skotnicki and Ferguson (1995; geologic map of the Goldfield and the northern part of the Superstition Mts. SW quadrangles), Ferguson and Skotnicki (1996; bedrock geologic map of the Santan Mountains), and Skotnicki and Ferguson (1996; bedrock geologic map of the Sacaton Mountains).

In this table, listed epochs associated with map units are from the GRI GIS data, with the exception of epochs associated with Tertiary ("T") map units, which were are from Geolex (http://ngmdb.usgs.gov/Geolex/search). Numeric ages for epochs or periods are from the ICS international chronostratigraphic chart (http://stratigraphy.org/index.php/ics-chart-timescale). Citations for more specific ages are provided in the "Map Unit Description" column. Geologic terms used in the map unit descriptions are defined below the table. The Quaternary, Tertiary (including Neogene and Paleogene) periods are all part of the Cenozoic Era (CZ). The Cretaceous Period is part of the Mesozoic Era (MZ).

The gray-highlighted unit (Qi3r) underlies the entire monument.

Geologic Time Unit(s) Age	Geologic Map Unit	Map Unit Description
Quaternary (Q) Period Holocene (H) Epoch 11,700 years ago to present day	Disturbed land (**Qd**)	Areas of significant recent surficial disruption due to various human activities. Includes dams, sand and gravel quarries, large cattle tanks, areas leveled for mining, and other development activity.
Quaternary (Q) Period Holocene (H) Epoch 11,700 years ago to present day	Modern river channel deposits (**Qycr**)	Deposits in active stream channels of major streams. Predominantly unconsolidated sand, pebbles, cobbles, and boulders. Clasts are subrounded to well-rounded and deposits typically contain diverse lithologies representing both local and non-local rock types. Age: generally less than 100 years (Richard et al. 2006).
Quaternary (Q) Period Holocene (H) Epoch 11,700 years ago to present day	Modern stream channel deposits (**Qyc**)	Denotes modern ephemeral streams draining piedmont. Composed of moderately sorted sand, gravel, and pebbles with some cobbles in the lower piedmont areas to poorly sorted sand, gravel, pebbles, and cobbles in the upper piedmont areas. Channels are generally incised less than 0.5 to 1 m (2 to 3 ft) below adjacent Holocene terraces. These channels tend to flow after locally heavy rainstorms. Age: less than 1,000 years (Huckleberry 1992).
Quaternary (Q) Period Holocene (H) and Pleistocene (PE) Epochs 2.6 million years ago to present day	Surficial deposits, undivided (**Qal**)	Poorly sorted sand- to cobble-sized material on pediment surfaces and other areas of low relief and along drainages where recent incision is not severe.
Quaternary (Q) Period Holocene (H) Epoch 11,700 years ago to present day	Piedmont alluvium, youngest (**Qy**)	Mostly alluvium; may include some eolian (windblown) deposits. Characterized by unconsolidated, stratified, poorly to moderately sorted sand, gravel, cobble, and boulder deposits that underlie small active channels, low terraces, and alluvial fans. Terraces and alluvial fan surfaces are 0 to 2 m (0 to 7 ft) above active tributary channels (**Qyc**). Age: less than 1,000 years (Huckleberry 1992).
Quaternary (Q) Period Holocene (H) Epoch 11,700 years ago to present day	River deposits, younger (**Qyr**)	Consists of sand and gravel equivalent to material in channel deposits, as well silt and clay deposited by overbank flow during floods. Generally includes young terrace deposits that are above the active channels. Locally includes **Qyc** or **Qycr**. Age: less than 10,000 years (Huckleberry 1992).
Quaternary (Q) Period Holocene (H) and Pleistocene (PE) Epochs 2.6 million years ago to present day	Colluvium and talus (**Qct**)	***No description provided in source data.*** According to Ferguson and Skotnicki (1996): deposits mantle steep slopes. Consists of locally derived, poorly sorted, angular to subrounded clasts. Age: less than 750,000 years (Richard et al. 2006).

Geologic Time Unit(s) Age	Geologic Map Unit	Map Unit Description
Quaternary (Q) Period Pleistocene (PE) to Holocene (H) Epochs 2.6 million years ago to present day	Alluvium (**Qyif**)	Fine-grained sheetflood and overbank deposits typically found in lower piedmont areas, possibly mantling older deposits. Consists of sand, silt, and clay, with some fine gravel. Differentiated from basin center deposits by sedimentological evidence of surface slope sufficient to keep water flowing on the depositional surface.
Quaternary (Q) Period Late to latest Pleistocene (PE) Epoch 126,000 to 11,700 years ago	Piedmont alluvium, younger (**Qi3**)	Alluvial fan surfaces and terraces located generally in proximal fan positions. Consists of moderately sorted, clast-supported sandstone and conglomerate with abundant granitic or metamorphic gravel clasts in a tan to brown sandy to silty matrix. Age: 20,000–10,000 years (Huckleberry 1992).
Quaternary (Q) Period Late Pleistocene (PE) Epoch 126,000 to 11,700 years ago	River terrace and alluvium deposits (**Qi3r**)	River terrace deposits; alluvium on river floodplains. Consists of pebbles, some cobbles, and sand. Situated 3–6 m (10–20 ft) above the Holocene floodplain (**Qyr**). Age: 130,000 to 10,000 years (Klawon et al. 1998; Richard et al. 2006).
Quaternary (Q) Period Middle to late Pleistocene (PE) Epoch 781,000 to 11,7000 years ago	River deposits, older (**Qmlr**)	River terraces and alluvial fans on the basin floor. In areas that have been cultivated, topographic differences between Pleistocene and Holocene surfaces may be undetectable, but on historical aerial photos, Pleistocene surfaces appear to be higher than surrounding younger surfaces. Age: 500,000 to 10,000 years (Klawon et al. 1998).
Quaternary (Q) Period Middle to late Pleistocene (PE) Epoch 781,000 to 11,7000 years ago	Piedmont alluvium, older (**Qi2**)	Preserved depositional surfaces in the upper piedmont that form flat ridges separated by incised channels in shallow valleys. Tends to be coarsely textured given the proximity to mountain slopes. Includes sand, loamy sand, gravely sand, and minor gravel; poorly sorted with sand- to boulder-sized clasts. Surfaces are typically 2 to 10 m (7 to 30 ft) above modern channels (**Qyc**).
Quaternary (Q) Period Middle to early Pleistocene (PE) Epoch 2.6 million to 126,000 years ago	River deposits, oldest (**Qor**)	Relict very old river terraces distinguished by strong carbonate accumulation. These surfaces are altered by agricultural activity. Age: 1 million to 500,000 years (Klawon et al. 1998).
Quaternary (Q) Period Early Pleistocene (PE) Epoch 2.6 million to 781,000 years ago	Piedmont deposits, oldest (**Qop**)	Alluvial fan surfaces and deposits that consist of typically very poorly sorted cobbles to clay, including angular to subangular cobbles and pebbles and clay. Occupies the highest topographic position on the piedmont and occurs only on the upper piedmont. Original fan surfaces have been removed by erosion, so the characteristic topographic expression is alternating ridges and valleys. Age: 1 million to 500,000 years (Klawon et al. 1998).
Tertiary (T): Neogene (N) Period Miocene (MI) to Pliocene? (PL) Epochs 23 million to 2.6 million years ago	Gila Group, basalt (**Tby**)	***No description provided in source data***. Geolex refers to the "Gila Group" as "Gila Conglomerate" and records a late Tertiary (Miocene to Pliocene?) age; elsewhere, the unit may be as young as Quaternary (Pleistocene). The unit is "basin fill" and includes volcaniclastic conglomerate, sandstone, siltstone, as well as interlayered basaltic to dacitic lava flows.
Tertiary (T): Neogene (N) Period Miocene (MI) Epoch 23 million to 5.3 million years ago	Apache Leap Tuff (**Talt**)	***No description provided in source data***. According to Peterson (1969): ash-flow sheet consisting of nonwelded light-gray tuff at the base that grades upward to densely welded black vitrophyre that is overlain by densely welded tuff with cryptocrystalline groundmass. Farther up in the unit, degree of welding gradually decreases and degree of devitrification and vapor-phase crystallization increase. Color progressively changes upward from light brown just about the vitrophyre through moderate red to very light gray near top. Abundant pumice fragments progressively less flattened towards the top. Phenocrysts constitute 40% of the rock. Age: Tertiary, based on 20-million-year-old K-Ar date (Creasey and Kistler 1962).

Geologic Time Unit(s) Age	Geologic Map Unit	Map Unit Description
Tertiary (T): Neogene (N) Period Miocene (MI) Epoch 23 million to 5.3 million years ago	Superstition Tuff, Miners Needle break (**Tsm**)	This unit is named for a package—referred to as a "break" less than 2 m (7 ft) thick (see Skotnicki and Ferguson 1995)—of several (2–5) thin, welded or poorly welded flow units that crop out through the middle of Miners Needle (in the Weavers Needle quadrangle). The flow units are bounded by sharp contacts.
Tertiary (T): Paleogene (PG) Period Oligocene (OL) Epoch 33.9 million to 23 million years ago	Whitetail Formation, sandstone and conglomerate (**Twsc**)	***No description provided in source data***. Geolex refers to the formation as "Whitetail Conglomerate." According to Peterson (1969): Whitetail Conglomerate consists of stream deposits derived from all older rocks. Fragments are angular to subrounded, pebble to boulder size, and coarsest near base. Fragments' composition generally is like nearby bedrock. Matrix is typically coarse-grained, poorly sorted, arkosic to lithic sandstone, but matrix of some beds is fine grained. Moderately to well cemented. Bedding plains are generally poorly defined, locally absent, but become distinct upward. Upper part locally interstratified with water-laid tuff, which is from pyroclastic eruptions that immediately preceded the ash-flow eruptions of the Apache Leap Tuff. Age: 32 million years, based on biotite collected from an air-fall tuff interbedded near the top of the conglomerate (Cornwall et al. 1971).
Tertiary (T): Paleogene (PG) Period Oligocene (OL) Epoch 33.9 million to 23 million years ago	Whitetail Formation, granite breccia (**Twx**)	***No description provided in source data***. See map unit description for **Twsc**.
Tertiary (T) and Cretaceous (K) Periods 145 million to 2.6 million years ago	Mafic dikes (**TKbi**)	***No description provided in source data***. According to Ferguson and Skotnicki (1996): fine-grained, dark greenish-gray mafic dikes. Mineral assemblages are dominated by plagioclase and fine-grained, unidentifiable mafic minerals.
Tertiary (T) and Cretaceous (K) Periods 145 million to 2.6 million years ago	Intermediate dikes (**TKdi**)	***No description provided in source data***. According to Ferguson and Skotnicki (1996): crystal-rich aphanitic-matrix and porphyritic holocrystalline dikes and lenticular intrusions. The porphyritic bodies are typically crystal rich, commonly with abundant coarse-grained quartz, and rarely include crystal-poor varieties. The average composition is probably quartz monzodiorite. Also contains variable amounts of biotite and hornblende. The rocks weather to a dark color, and the porphyritic varieties have a dark gray matrix. These dikes probably correlate to the Laramide dikes and elongate intrusions in the Poston Butte area, east of the Santan Mountains (Nason et al. 1982).
Tertiary (T) and Cretaceous (K) Periods 145 million to 2.6 million years ago	Felsic dikes (**TKri**)	***No description provided in source data***. According to Ferguson and Skotnicki (1996): light-colored, aphanitic-matrix, crystal-poor felsic dikes. Contain 5%–10%, 1–2 mm (0.04–0.08 in) phenocrysts of subhedral biotite, quartz, and minor chalky white K-feldspar. Age: 63.90 ± 2.30 million years based on K-Ar date (Ferguson and Skotnicki 1996).
Cretaceous (K) Period 145 million to 66 million years ago	Diorite (**Kd**)	***No description provided in source data***. According to Ferguson and Skotnicki (1996): mafic plutonic bodies, typically fine- to medium-grained, equigranular diorite and monzodiorite.
Cretaceous (K) Period 145 million to 66 million years ago	Quartz monzodiorite to quartz monzonite (**Kg**)	***No description provided in source data***. According to Ferguson and Skotnicki (1996): medium- to fine-grained, equigranular quartz monzonite to quartz monzodiorite, and locally monzodiorite with between 10% to 20% mafic minerals, mostly biotite and lesser hornblende. Age: 66.00 ± 0.90 and 72.l0 ± 1.40 million years (biotite K-Ar radiometric dates; recalculated by Reynolds et al. 1986 from Balla 1972).

Geologic Time Unit(s) Age	Geologic Map Unit	Map Unit Description
Cretaceous (K) Period 145 million to 66 million years ago	Vein arrays (**Kv**)	***No description provided in source data***. According to Ferguson and Skotnicki (1996): hematite-stained clastic dikes, cataclastic zones and/or copper-mineralized quartz vein arrays.
Proterozoic Eon: Mesoproterozoic ["Middle Proterozoic"] (Y) Era 1.6 billion to 1.0 billion years ago	Diabase (**Yd**)	Dark gray-green diabase composed of 1–5 mm (0.04–0.2 in), interlocking, tabular, subhedral phenocrysts of green to black pyroxene, clear to white plagioclase, and 1–3 mm (0.04–0.12 in) opaque minerals (magnetite?). Opaque minerals commonly altered to red iron oxide.
Proterozoic Eon: Mesoproterozoic ["Middle Proterozoic"] (Y) Era 1.6 billion to 1.0 billion years ago	K-feldspar porphyritic granite (**Yg**)	***No description provided in source data***. According to Skotnicki and Ferguson (1996): outcrops form steep hills covered with large spheroidal boulders, as well as expansive dissected pediments in the west half of the Sacaton Mountains. Consists of K-feldspar porphyritic granite to quartz monzonite containing about 15%–20% clear to milky gray quartz, light gray to light pink K-feldspar, and variable amounts of biotite (between 5%–15%). The matrix is medium- to coarse-grained. K-feldspar phenocrysts are subhedral and are as much as 5 cm (2 in) long. Biotite is anhedral to subhedral, fresh, and occurs in loose, felty masses. Exposures with less abundant biotite (about 5%) are lighter in color than more biotite-rich outcrops. The rock is medium to light gray on fresh surfaces. Weathered surfaces are rusty tan and locally moderately varnished. **Yge** and **Yg** are considered cogenetic phases of a larger pluton. Age: 1.240 billion years (Balla 1972).
Proterozoic Eon: Mesoproterozoic ["Middle Proterozoic"] (Y) 1.6 billion to 1.0 billion years ago	Granite, equigranular phase (**Yge**)	***No description provided in source data***. According to Ferguson and Skotnicki (1996): medium- to slightly coarse-grained granite with 5%–10% biotite exposed at Cholla Butte. The granite is mostly equigranular but locally slightly porphyritic (quartz and K-feldspar). On the west side of Cholla Butte the rock is coarser grained and quartz porphyritic, where quartz occurs as 5–12 mm (0.2–0.5 in), spherical, anhedral phenocrysts. **Yge** and **Yg** are considered cogenetic phases of a larger pluton.
Proterozoic Eon: Mesoproterozoic ["Middle Proterozoic"] (Y) Era 1.6 billion to 1.0 billion years ago	Silicified granite (**Ygs**)	***No description provided in source data***. According to Wilson (1969): granite with coarse- to medium-grained texture. Samples of these rocks, examined microscopically, were found generally to contain 54%–70% orthoclase, 1%–14% oligoclase, 15%–18% quartz, 6%–10% biotite, and 4% or less muscovite. Age: "older Precambrian" (i.e., probably "Early Proterozoic") but unit may include some younger granites (Wilson 1969).
Proterozoic Eon: Paleoproterozoic ["Early Proterozoic"] (X) Era 2.5 billion to 1.6 billion years ago	Pinal Schist, undifferentiated (**Xp**)	***No description provided in source data***. According to Skotnicki and Ferguson (1996): Pinal Schist, which is exposed in small isolated hills, is medium- to coarse-grained quartz-muscovite schist. Age: 1.715 billion years (Drewes 1980).

- **alluvium**. Stream-deposited sediment.
- **anhedral**. A grain lacking well-developed crystal faces.
- **aphanitic**. Describes the texture of fine-grained igneous rock in which different components are not distinguishable by the unaided eye.
- **arkose**. A commonly coarse-grained, pink or reddish sandstone consisting of abundant feldspar minerals.
- **ash flow**. A density current, generally a hot mixture of volcanic gases and tephra that travels across the ground surface; produced by the explosive disintegration of viscous lava in a volcanic center, or from a fissure or group of fissures. The solid materials contained in a typical ash flow are generally unsorted and ordinarily include volcanic dust, pumice, scoria, and blocks in addition to ash.
- **basalt**. Volcanic rock that is characteristically dark in color (gray to black), contains ≤ 53% silica (silicon dioxide [SiO_2], an essential constituent of many minerals), and is rich in iron and magnesium.
- **biotite**. A dark-colored, shiny silicate mineral (silicon + oxygen) of the mica group composed of magnesium and/or iron, $K(Mg,Fe)Si_3O_{10}(OH)_2$; characterized by perfect cleavage, readily splitting into thin sheets.
- **boulder**. A detached rock fragment, generally somewhat rounded or otherwise distinctively shaped by abrasion during transport, greater than 256 mm (10 in) in diameter; the largest rock fragment recognized by sedimentologists.
- **breccia**. A coarse-grained, generally unsorted sedimentary rock consisting of cemented angular clasts more than 2 mm (0.08 in) across.
- **cataclastic**. Describes a structure in a rock, such as bending, breaking, or crushing of minerals, resulting from extreme stress during metamorphism.
- **clast**. An individual constituent, grain, or fragment of a rock or unconsolidated deposit, produced by the mechanical or chemical disintegration of a larger rock mass.
- **clay**. A detrital particle that is less than 0.004 (1/256) mm (0.00015 in) in diameter.
- **cobble**. A rock fragment ranging from 64 to 256 mm (2.5 to 10 in) in diameter, thus larger than a pebble and smaller than a boulder; generally rounded by abrasion.
- **colluvium**. A general term applied to loose and incoherent deposits, usually at the foot of a slope or cliff and brought there chiefly by gravity.
- **conglomerate**. A coarse-grained, generally unsorted, sedimentary rock consisting of cemented, rounded clasts larger than 2 mm (0.08 in) in diameter.
- **cryptocrystalline**. Describes a rock texture in which individual crystals are too small to be recognized or distinguished with an ordinary microscope.
- **dacite**. A volcanic rock that is characteristically light in color and contains approximately 63%–68% silica and moderate amounts of sodium and potassium.
- **devitrification**. Conversion of glass to crystalline material.
- **diabase**. An intrusive igneous rock consisting primarily of the minerals labradorite and pyroxene.
- **dike**. A narrow igneous intrusion that cuts across bedding planes or other geologic structures.
- **diorite**. A coarse-grained, intrusive igneous rock characteristically containing plagioclase, as well as dark-colored amphibole (especially hornblende), pyroxene, and sometimes a small amount of quartz; diorite grades into monzodiorite with the addition of alkali feldspar.
- **equigranular**. Said of the texture of a rock having crystals of the same or nearly the same size.
- **euhedral**. A grain bounded by perfect crystal faces; well-formed.
- **felsic**. Derived from feldspar + silica to describe an igneous rock having abundant light-colored minerals such as quartz, feldspars, or muscovite; also, describes those minerals.
- **felty**. Said of the texture of the groundmass of a holocrystalline (composed entirely of crystals) igneous rock in which lath-shaped microlites (microscopic crystals that polarize light; typically plagioclase) are interwoven in an irregular unoriented fashion.
- **granite**. 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%; perhaps the best known of all igneous rocks.
- **gravel**. An unconsolidated, natural accumulation of rock fragments that are greater than 2 mm (0.08 in) in diameter; deposits may contain boulders, cobbles, or pebbles.
- **hematite**. An oxide mineral composed of oxygen and iron, Fe_2O_3.
- **hornblende**. A silicate (silicon + oxygen) mineral of sodium, potassium, calcium, magnesium, iron, and aluminum; commonly black and occurring in distinct crystals or in columnar, fibrous, or granular forms in hand specimens.

- **igneous**. Describes a rock or mineral that solidified from molten or partly molten material; also, describes processes leading to, related to, or resulting from the formation of such rocks. One of the three main classes or rocks—igneous, metamorphic, and sedimentary.
- **intermediate**. Said of an igneous rock that is transitional between felsic and mafic, generally having a silica content of 54%–65%.
- **K-feldspar or potassium feldspar**. A feldspar mineral rich in potassium such as orthoclase, microcline, and sanidine.
- **lithic**. Described a medium-grained sedimentary rock or pyroclastic deposit that contains abundant fragments of previously formed rocks.
- **lithology**. The physical description or classification of a rock or rock unit based on characteristics such as color, mineral composition, and grain size.
- **loam**. A rich permeable soil composed of a mixture of clay, silt, sand, and organic matter.
- **mafic**. Derived from magnesium + ferric (Fe is the chemical symbol for iron) to describe an igneous rock having abundant dark-colored, magnesium- or iron-rich minerals such as biotite, pyroxene, or olivine; also, describes those minerals.
- **metamorphic rock**. Any rock derived from preexisting rocks that was altered in response to marked changes in temperature, pressure, shearing stress, and chemical environment. One of the three main classes of rock—igneous, metamorphic, and sedimentary.
- **monzodiorite**. An intrusive igneous rock intermediate in composition between monzonite and diorite and containing nearly equal amounts of plagioclase and alkali feldspar. The presence of alkali feldspar distinguishes monzodiorite from diorite.
- **monzonite**. An intrusive igneous rock, intermediate in composition between syenite and diorite, containing approximately equal amounts of alkali feldspar and plagioclase and very little quartz. Monzonite contains less quartz and more plagioclase than granite.
- **muscovite**. A light-colored silicate (silicon + oxygen) mineral of the mica group, $KAl_3Si_3O_{10}(OH)_2$, characterized by perfect cleavage in one direction and the ability to split into thin, clear sheets.
- **oligoclase**. A silicate (silicon + oxygen) mineral of the plagioclase group, intermediate in chemical composition and crystallographic and physical characteristics between albite ($NaAlSi_3O_8$) and anorthite ($CaAl_2Si_2O_8$).
- **orthoclase**. A colorless, white, cream-yellow, flesh-pink, or gray silicate (silicon + oxygen) mineral of the alkali feldspar group, $KAlSi_3O_8$, characterized by potassium ions in its crystal structure.
- **pebble**. A rock fragment ranging from approximately 4 to 64 mm (0.16 to 2.5 in) in diameter and generally rounded by abrasion.
- **pumice**. A highly vesicular pyroclast with very low bulk density and thin vesicle walls.
- **phenocryst**. A coarse-grained crystal in a porphyritic igneous rock.
- **plagioclase**. A silicate (silicon + oxygen) mineral of the feldspar group that contains both sodium and calcium ions that freely substitute for one another; characterized by striations (parallel lines) in hand specimens.
- **plutonic**. Describes an igneous rock or intrusive body formed at great depth beneath Earth’s surface.
- **porphyry**. An igneous rock consisting of abundant coarse-grained crystals in a fine-grained groundmass.
- **pyroclast**. An individual particle ejected during a volcanic eruption; usually classified according to size.
- **pyroxene**. A group of silicate (silicon + oxygen) minerals composed of magnesium and iron with the general formula $(Mg,Fe)SiO_3$; characterized by short, stout crystals in hand specimens.
- **quartz**. Silicon dioxide, SiO_2. The only silicate (silicon + oxygen) mineral consisting entirely of silicon and oxygen. Synonymous with “crystalline silica.”
- **sand**. A detrital particle ranging from 0.06 (1/16) to 2 mm (0.0025 to 0.08 in) in diameter.
- **sandstone**. Clastic sedimentary rock composed of predominantly sand-sized grains, 1/16–2 mm (0.0025–0.08 in).
- **schist**. A medium- to coarse-grained, strongly foliated, metamorphic rock with eminently visible mineral grains, particularly mica, which are arranged parallel, imparting a distinctive sheen or “schistosity” to the rock.
- **sedimentary rock**. A rock resulting from the consolidation of loose sediment that has accumulated in layers; it may be “clastic,” consisting of mechanically formed fragments of older rock; “chemical,” formed by precipitation from solution; or “organic,” consisting of the remains of plants and animals. One of the three main classes of rock—igneous, metamorphic, and sedimentary.
- **sheetflood**. A broad expanse of moving, storm-borne water that spreads as a thin, continuous, relatively uniform film over a large area in an arid region and that is not concentrated into well-defined channels; its distance of flow is short and its duration is measured in minutes or hours, commonly occurring after a period of sudden and heavy rainfall.
- **silt**. A detrital particle ranging from 0.004 (1/256) to 0.06 (1/16) mm (0.00015 and 0.0025 in) in diameter, thus smaller than sand.
- **siltstone**. A clastic sedimentary rock composed of silt-sized grains.

- **subhedral**. A grain partly bounded by crystal faces; intermediate between euhedral and anhedral.
- **subrounded**. Said of a sedimentary particle showing considerable abrasion and an original general form that is still discernable; many of its edges and corners are considerable rounded off to smooth curves.
- **tabular**. Said of a feature having two dimensions that are much larger or longer than the third.
- **talus**. Rock fragments, usually coarse and angular, lying at the base of a cliff or steep slope from which they have fallen.
- **tuff**. Consolidated or cemented volcanic ash and lapilli (pyroclastic materials ranging between 2 and 64 mm [0.08 and 2.5 in] across with no characteristic shape; may be either solidified or still viscous upon landing).
- **vapor-phase crystallization**. The crystallization of minerals from hot gases escaping through a volcanic body. Cooling of the escaping gases, which carry elements in solution, promotes the crystallization of mineral in rock cavities.
- **vitrophyre**. Any porphyritic igneous rock with a glassy groundmass.
- **volcaniclastic**. Pertaining to all clastic volcanic materials formed by any process of fragmentation, dispersed by any kind of transporting agent, deposited in any environment, or mixed in any significant portion with nonvolcanic fragments.

Geologic Setting and Significance

This chapter describes the regional geologic setting of Casa Grande Ruins National Monument and summarizes connections among geologic resources, other monument resources, and monument stories.

Park Establishment

The monument is in Pinal County, Arizona, which is the third most populous county in the state after Maricopa and Pima Counties (US-Places.com 2018). Maricopa County is north and west of Pinal County, and Pima County is south (fig. 2). Phoenix, which is in Maricopa County, is northwest of the monument. Tucson, which is in Pima County, is southeast of the monument. The largest city in Pinal County is Casa Grande. The county seat is Florence. The monument lies within the city limits of Coolidge (fig. 3).

In 1892 (20 years before Arizona became a state), President Benjamin Harrison set aside "480 acres more or less, including Casa Grande Ruin" in Arizona Territory, as "Casa Grande Ruin Reservation." This designation created the nation's first archeological (also spelled "archaeological") reserve and initiated the US government's archeological preservation movement. It also sparked national interest and awareness of archeological preservation in the Southwest. Because of the early establishment of the preserve, the integrity of the archeological resources in the monument remains high (National Park Service 2011).

In 1918 (25 years after establishment of the archeological reserve), President Woodrow Wilson proclaimed "Casa Grande Ruins National Monument." At that time, management, which had been the responsibility of the General Land Office, was transferred to the National Park Service. Frank "The Boss" Pinkley, who had been the first onsite custodian for the General Land Office, stayed on at the monument and eventually became the superintendent of all Southwest national monuments. Later, Pinkley served in the Legislature of the State of Arizona as representative from Pinal County (Van Valkenburgh 1971).

In 1932, the second (and current) shelter covering the Great House was erected. The structure was designed by renowned landscape architect Frederick Law Olmsted Jr. (1870–1957) and NPS landscape architect Thomas Vint (1894–1967). For nearly 90 years this shelter has been instrumental in protecting the Great House from harsh environmental elements of the Sonoran Desert. The shelter itself reflects an enduring style of architecture that combines form and function (National Park Service 2017) and is listed in the National Register of Historic Places.

The monument encompasses 191.2 ha (472.5 ac) and contains 62 documented prehistoric cultural sites, including a ballcourt, platform mound, irrigation canals, and the only surviving example of a multistory, freestanding earthen Hohokam great house (see cover photo and fig. 4). Notably, Hohokam is an archeological term for a cultural period, not the name of a tribe or people. The Hohokam cultural pattern existed from the first years of the common era (CE, preferred to AD) through about 1450 CE (National Park Service 2018). The Great House was completed in about 1350 CE and represents the final evolution of architecture of the Hohokam cultural period (National Park Service 2017), which is exemplified by large-scale, well-engineered irrigation canal systems, densely populated walled communities, and large multistoried structures (National Park Service 2011).

The monument embodies early adaptation by the Ancestral Sonoran Desert People to the desert environment, including use of the middle Gila River and other rivers, for creating the most extensive prehistoric irrigation-based agricultural desert society in North America (National Park Service 2017). The middle Gila River valley has experienced at least 2,000 years of irrigation agriculture (Haury 1976). Although investigators have yet to find irrigation canals in the Gila River floodplain dating back 2,000 years, Gary Huckleberry (University of Arizona, adjunct researcher and lecturer) suspects that they are either there [but have not been found yet] or have eroded away. This suspicion is based on the age of nearby canals in the Tucson Basin to the south, which date as early as 1500 BCE (before common era). The absence of evidence for early canals on the Gila and Salt Rivers may be a matter of geologic preservation (Gary Huckleberry, written communication, 26 May 2018).

Six American Indian Tribes are traditionally associated with the monument: Ak-Chin Indian Community of the Maricopa (Ak-Chin) Indian Reservation, Arizona; Gila River Indian Community of the Gila River Indian Reservation, Arizona; Hopi Tribe of Arizona; Salt River Pima-Maricopa Indian Community of the Salt River Reservation, Arizona; Tohono O'odham Nation of Arizona; and Zuni Tribe of the Zuni Reservation, New Mexico (National Park Service 2017). People of today's tribes are descendants of the Ancestral Sonoran Desert People.

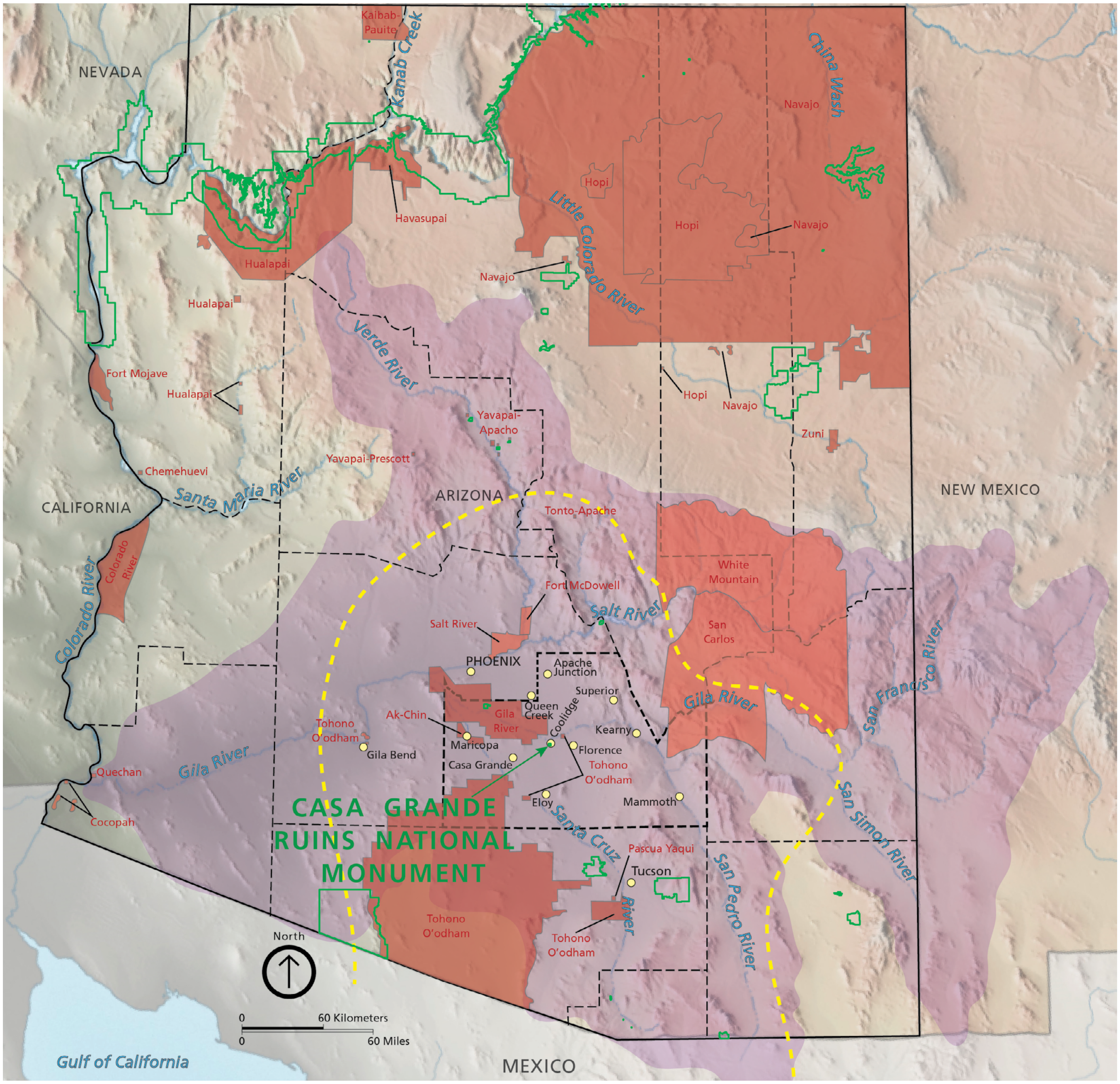

Figure 2. Location map.
The monument is in Pinal County, Arizona. It lies within the city limits of Coolidge and is between Phoenix (Maricopa County) and Tucson (Pima County). Hashed black lines delineate counties. Pinal County contains parts of the Tohono O'odham Nation, the Gila River Indian Community, and the San Carlos Apache Indian Reservation, as well as the entire the Ak-Chin Indian Community (represented by orange on the map). The lavender shading on the map represents the Gila River drainage basin. The Gila River, which is a major tributary of the Colorado River, drains about 150,000 km^2 (58,000 mi^2). The Gila River drainage basin, which is the primary drainage basin for southern Arizona, extends across Arizona into western New Mexico and northern Sonora. During the Hohokam cultural period, the Ancestral Sonoran Desert People lived throughout the drainage basin, primarily occupying terraces along the Gila, Salt, Santa Cruz, and San Pedro Rivers, though they also are known to have lived on small alluvial fans in pediment areas (see Waters and Field 1986). The dashed yellow line delineates the Hohokam cultural boundary. Green outlines delineate National Park Service areas. Graphic by Trista Thornberry-Ehrlich (Colorado State University). The area of the Gila River drainage basin and the Hohokam cultural boundary are from Waters (2008, figure 1). Base map by Tom Patterson (National Park Service).

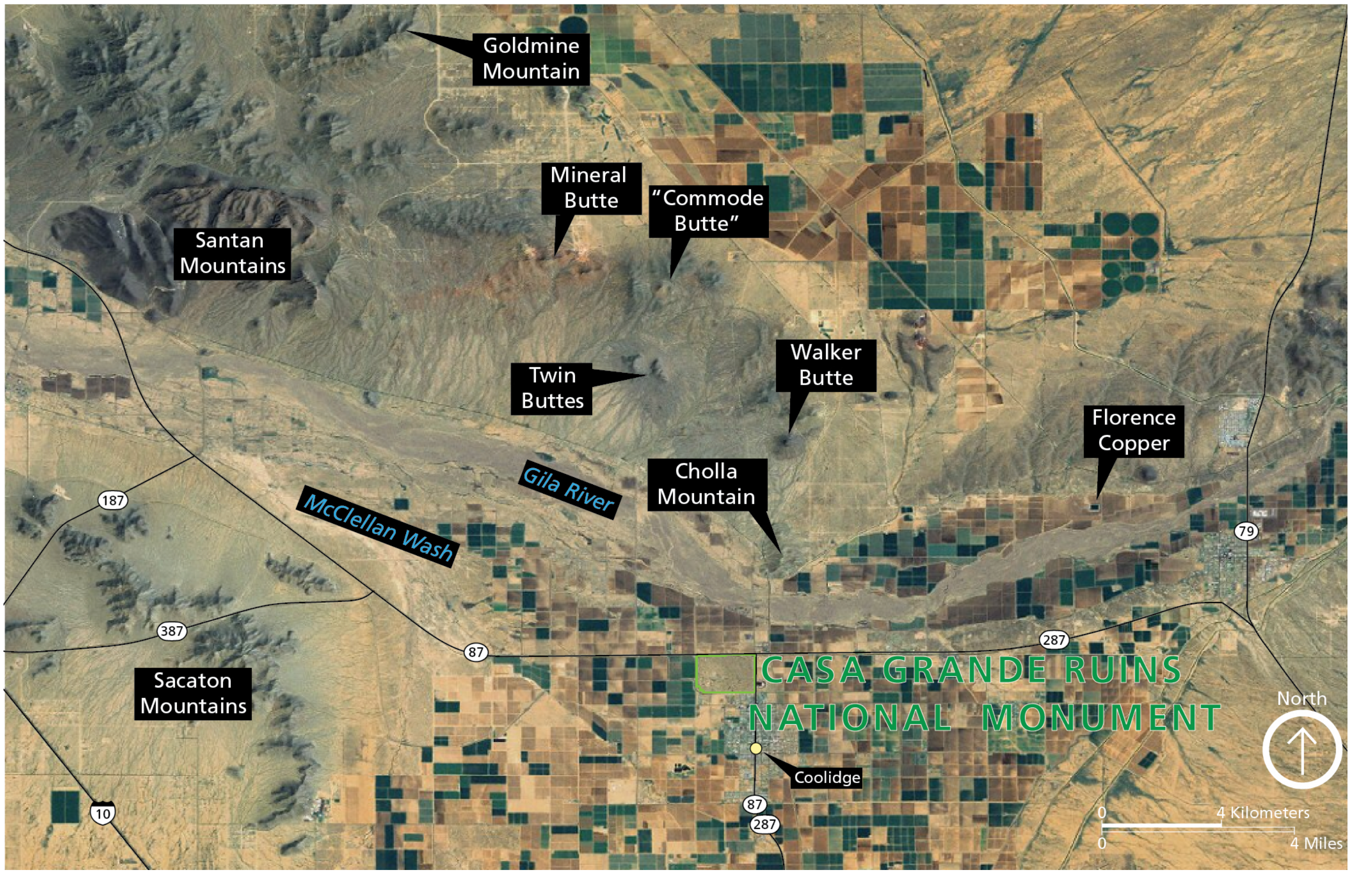

Figure 3. Satellite imagery of the monument and surrounding area.
The boundary of the monument is outlined in green. The Santan Mountains are north of the monument; geologic mapping of a portion of these mountains are part of the GRI GIS data. Note the red staining around Mineral Butte, which is indicative of mineralization. The Sacaton Mountains are west of the monument. The monument sits on a former floodplain, referred to as a "terrace," of the Gila River. Agriculture and urban development, which surround the monument, are land uses associated with the terrace. Graphic by Trista Thornberry-Ehrlich (Colorado State University). Base imagery from ESRI ArcGIS World Imagery (accessed 25 July 2018).

Because the Ancestral Sonoran Desert People left behind no written language, the original name of the Great House is unknown; the O'odham and Hopi refer to it as "Sivan Vah'Ki" and "Naasavi," respectively (National Park Service 2011). "Casa Grande" is the Spanish name for the Great House, and though the term is a misnomer, it has long been associated with the national monument and has historical value dating back to the first written account of the structure in 1694 by Padre Eusebio Francisco Kino, a Jesuit missionary to the Indians of the Sonoran Desert.

Over the years, the Great House has been the focus of preservation efforts because of its integrity and uniqueness. However, it is just one feature of a much larger irrigation-based society of the Ancestral Sonoran Desert People. Caliche-walled communities (see "Connections between Geologic and Cultural Resources") related to Casa Grande Ruins follow the Gila River from upstream east of Florence to downstream as far west as Gila Bend (fig. 2). Hohokam archeological sites also occur along the Salt (east of Phoenix), Santa Cruz (Tucson area), and San Pedro Rivers (joins the Gila River at Winkleman, Arizona) (fig. 2).

Physiographic Setting

The monument and surrounding region are part of the Basin and Range physiographic province—a sprawling area that stretches from southeastern Oregon into northwestern Mexico. The province encompasses more than half of Arizona, the entire state of Nevada, about half of New Mexico and Utah, and parts of California, Idaho, Oregon, and Texas (Kiver and Harris 1999). As the name implies, the province has mountain ranges—more than 400, if all the small ranges are included—with

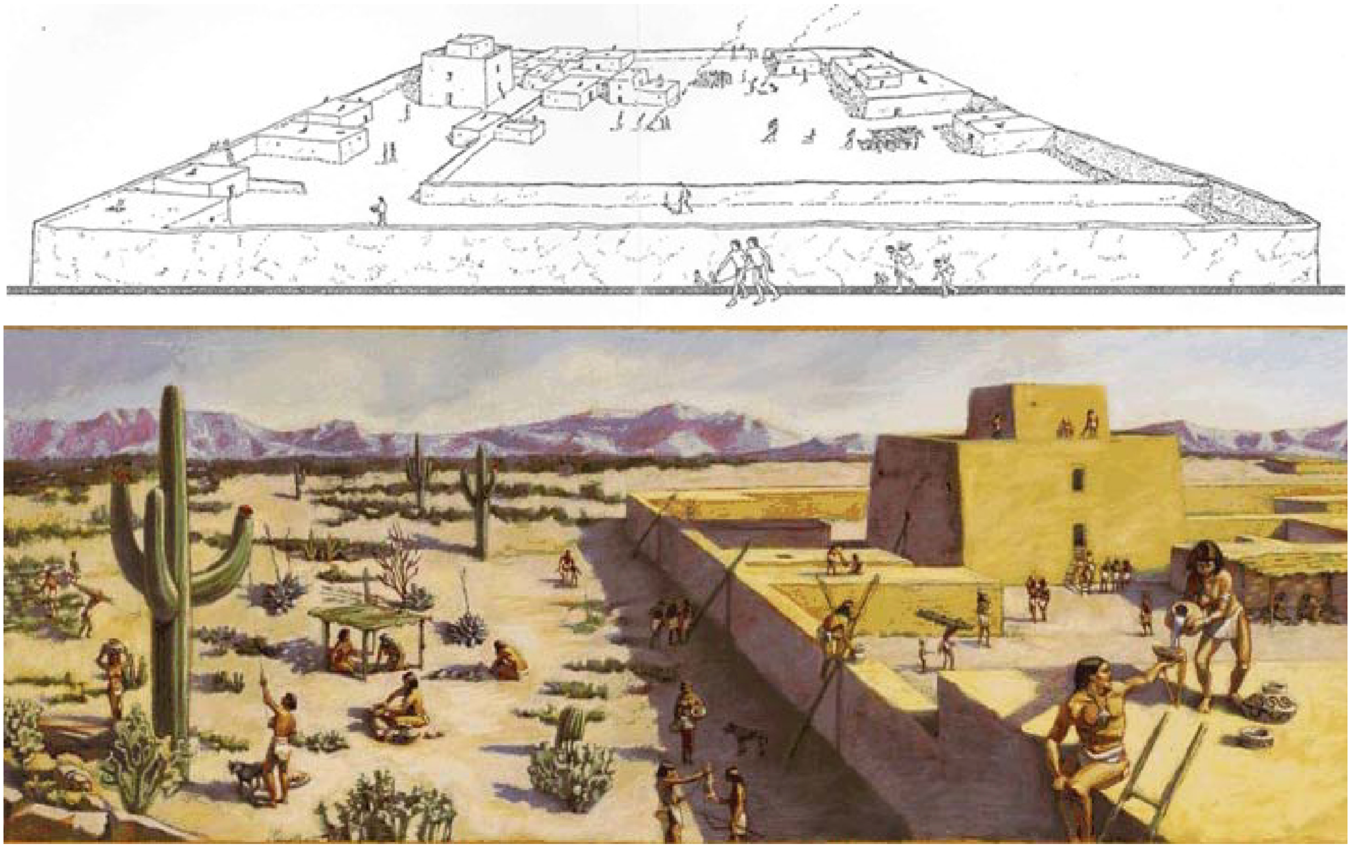

Figure 4. Artists' depictions of Casa Grande Ruins as it may have appeared around 1350 CE. During the Hohokam cultural period, caliche-walled communities were densely populated and contained large multistoried structures. The caliche-walled community associated with the monument's Great House was occupied from about 1150 to 1450 CE. Top: NPS graphic available at https://www.nps.gov/cagr/learn/historyculture/index.htm (accessed 19 December 2017). Bottom: NPS graphic from National Park Service (2011) available at https://www.nps.gov/hfc/pdf/ip/CAGR_3.10.11.pdf (accessed 20 December 2017).

basins between them. The alternating pattern of linear mountain ranges and valleys bounded by roughly north–south-trending normal faults is characteristic of the Basin and Range (fig. 5). The monument is located in the Sonoran Desert subprovince of the Basin and Range physiographic province.

Three features distinguish the Arizona Basin and Range from the Great Basin and Rio Grande rift areas of the province. First, the mountain ranges and intervening basins are oriented northwest to southeast, in contrast to a more north–south orientation in the Great Basin and Rio Grande rift areas. Second, greatly eroded roots of mountain ranges stand less than 300 m (1,000 ft) above wide, almost level, inter-range plains (sediment-filled basins). The inter-range plains are composed of structural (down-dropped) basins filled with alluvial debris, which is the accumulation of millions of years of sediment eroded from higher elevations and transported by water. The fill may be 600 m (2,000 ft) deep near basin centers. Third, extensive bedrock pediments (erosional surfaces) developed mountainward from buried range-front faults. This difference results from an earlier cessation of extensional deformation (pulling apart of Earth's crust) in Arizona relative to the Great Basin and Rio Grande rift (see, e.g., Eaton 1979, 1982).

In Arizona, the Basin and Range landscape developed during two periods of extension (pulling apart of Earth's crust) and tectonism (large-scale movement of Earth's crust), referred to as "mid-Tertiary" and "Basin and Range." A long period of mid-Tertiary extensional tectonism (approximately 32 million to 20 million years ago) preceded the more recent and better known Basin and Range extensional tectonism (15 million to 8 million years ago). Mid-Tertiary faulting is characterized by low angle, normal faults, whereas later Basin and Range extension is characterized by high-angle, normal faults. In other parts of the Basin and Range, faulting (and associated uplift of mountain ranges and dropping down of basins) is ongoing and continues to produce

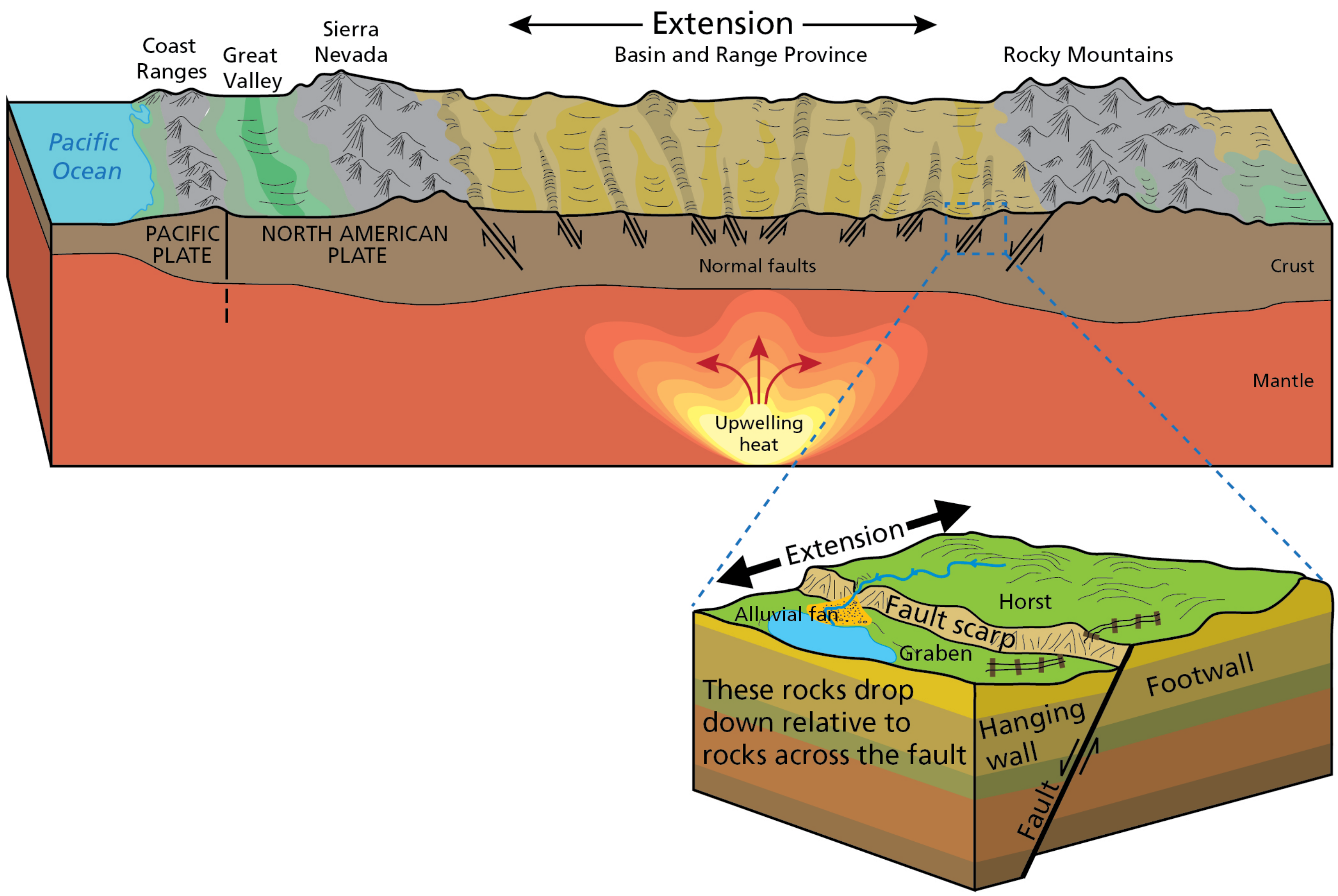

Figure 5. Graphic of Basin and Range extension.
The Basin and Range physiographic province has been subjected to extension (pulling apart of Earth's crust). Earth's crust (and upper mantle) has been stretched up to 100% of its original width. The crust thinned and cracked as it pulled apart, creating normal faults, which are oriented northwest to southeast in the Arizona Basin and Range. Mountains were uplifted and valleys dropped down along these faults, producing the distinctive alternating pattern of linear mountain ranges (referred to as "horsts") and valleys/basins (referred to as "grabens") of the Basin and Range province. Graphic by Trista Thornberry-Ehrlich (Colorado State University) after Idaho Geologic Survey (2011, p. 2).

earthquakes. Although normal faults occur in the nearby Santan Mountains (see poster, in pocket), none are considered active.

Regional Geologic Features

Huckleberry (1992)—one of the source maps for the GRI GIS data (see "Geologic Map Data")—divided the monument and surrounding area into two principal zones: (1) river valley/basin floor and (2) mountain upland/piedmont. The landforms in these zones are the major geologic features in the monument area and record the evolution of the landscape.

River Valley

The term "river valley" is associated with the middle Gila River, which emerges from a bedrock gorge 26 km (16 mi) east of Florence and flows west over a broad desert basin to its junction with the Salt River. The landforms associated with "river valley" are stream channel, floodplain, and terrace. In the vicinity of the monument, the following map units are associated with the development of the middle Gila River valley: river deposits, oldest (**Qor**); river deposits, older (**Qmlr**); river terrace and alluvium (**Qi3r**); river deposits, younger (**Qyr**); and modern river channel deposits (**Qycr**) (see table 1).

The monument lies about 2.5 km (1.6 mi) south of the present-day middle Gila River channel (**Qycr**; see poster, in pocket), but as recently as the end of the Pleistocene Epoch (2.6 million–11,700 years ago), the river flowed across the monument area. Since that time the river has shifted and cut downward, leaving abandoned floodplains, referred to as "terraces." Terraces represent responses of fluvial systems to climatic

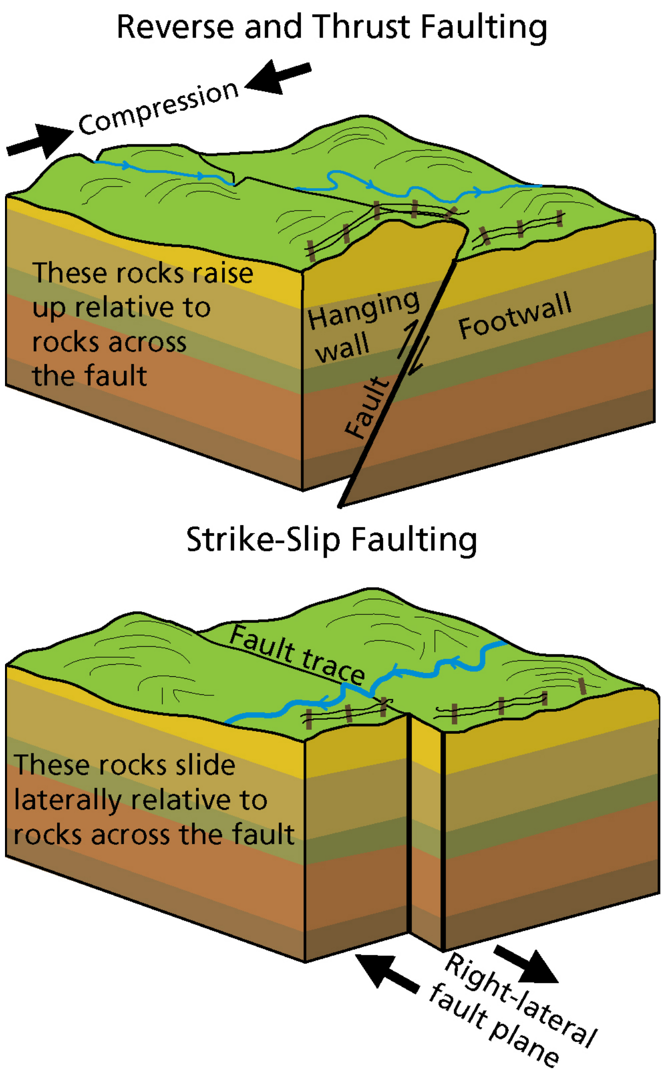

Figure 6. Graphic of fault types.
The three principal fault types are strike-slip, reverse, and normal (see fig. 5). Movement occurs along a fault plane. Footwalls are below the fault plane, and hanging walls are above. In a normal fault (see fig. 5), crustal extension (pulling apart) moves the hanging wall down relative to the footwall. Faults mapped in the vicinity of the monument are normal faults. In a reverse fault, crustal compression (squeezing together) moves the hanging wall up relative to the footwall. A thrust fault is a type of reverse fault that has a dip angle of less than 45°. In a strike-slip fault, movement is horizontal. When movement across a strike-slip fault is to the right, it is a right-lateral strike-slip fault, as illustrated above. When movement is to the left, it is a left-lateral strike-slip fault. Graphic by Trista Thornberry-Ehrlich (Colorado State University).

fluctuations during the Quaternary Period (Menges and Pearthree 1989). Another factor in terrace formation is tectonics. In this part of Arizona, more terraces formed in tectonically active areas than tectonically stable ones. In tectonically stable areas, the Gila River primarily deposited sediment (Huckleberry 1996).

The monument is on a terrace (**Qi3r**) that according to Klawon et al. (1998) and Richard et al. (2006) formed between 130,000 and 10,000 years ago; Huckleberry (1992) provided a somewhat older age, 200,000–20,000 years ago. In the vicinity of the monument, two other terrace levels are older/higher (**Qor** and **Qmlr**) than the monument's terrace (**Qi3r**) and one (**Qyr**) is lower/younger. Multiple terraces indicate that incision of a valley was not steady (Connell et al. 2005) and because the river was incising (cutting downward) over time, older terraces are higher than younger terraces. Terraces stair step upward and outward from the modern river (**Qycr**), which is characterized by a wide streambed with a braided pattern of sandy and gravelly bars and channels. These five map units in the Gila River valley represent as much as a million years of channel change and floodplain development.

The channel of the middle Gila River (**Qycr**) fluctuates in width depending on flood regime. The Holocene floodplain (**Qyr**) is an active geologic surface prone to periodic flooding and spatial shifts in channel position (see poster, in pocket). During the floods of 1983 and 1993, units **Qycr** and **Qyr** were inundated. In addition, ethnographic records indicate that floods in 1833 and 1868 covered **Qycr** and **Qyr** (Russell 1908) (see "Historic Flooding and Flood Potential").

Basin Floor

The landforms associated with the basin floor are surfaces that grade to Pleistocene terraces. The basin floor commonly has less than a meter (only a few feet) of relief, cloaking a thick package of sediment that underlies the basin-floor surface. This underlying material consists of basin-filling sediment and associated volcanic rock deposited during mid-Tertiary extensional tectonism (approximately 32 million to 20 million years ago) and Basin and Range extensional tectonism (15 million to 8 million years ago). In the vicinity of the monument, the following map units are associated with the development of the basin floor: Whitetail Formation, granite breccia (**Twx**); Whitetail Formation, sandstone and conglomerate (**Twsc**); Superstition Tuff, Miners Needle break (**Tsm**); Apache Leap Tuff (**Talt**); and Gila Group, basalt (**Tby**) (see table 1).

The Whitetail Formation sandstone and conglomerate (**Twsc**) (a coarse-grained, generally unsorted, sedimentary rock consisting of cemented, rounded clasts) is associated with development of depositional basins that were partially filled with sediments during mid-Tertiary extension. Based on the age of the Whitetail Conglomerate, sedimentation related to mid-Tertiary extension was taking place about 32 million years ago (Cornwall et al. 1971). "Commode Butte" is composed of the Whitetail Formation sandstone and conglomerate (see fig. 3; and poster, in pocket). "Commode Butte" is an informal name used by Ferguson and Skotnicki (1996) for a distinctive, double butte in the Santan Mountains north of the monument.

Mid-Tertiary crustal extension was accompanied by widespread, dominantly silicic magmatism. This episode of magmatism migrated from east to west across Arizona (Spencer and Reynolds 1989) and is characterized by deposits of pyroclastic flows called "ignimbrites." These flows would have been spectacular displays of swiftly flowing ash and other pyroclastic materials exploding as turbulent, incandescent clouds. The Superstition Welded Tuff (**Tsm**) and Apache Leap Tuff (**Talt**), which cover the Whitetail Formation near Commode Butte, represent this episode of silicic magmatism. Apache Leap Tuff (**Talt**) was deposited 20 million years ago (Creasey and Kistler 1962). Outcrops of mid-Tertiary ignimbrites in southeastern Arizona can be regarded as erosional outliers of the vast ignimbrite plateau of the Sierra Madre Occidental farther south (Dickinson 1989). The Mogollon–Datil volcanic field in New Mexico also was part of this violent volcanic episode (see GRI report about Gila Cliff Dwellings National Monument by KellerLynn 2014).

Following mid-Tertiary extension and sedimentation, Basin and Range extension is represented by the Gila Group, formally known as "Gila Conglomerate," which was originally described by G. K. Gilbert (1875) for the clastic deposits in the upper Gila River drainage. Gila Conglomerate has been widely recognized in Arizona and New Mexico as basin-filling sedimentary rocks that include volcaniclastic conglomerate, sandstone, siltstone, as well as interlayered basaltic to dacitic lava flows and associated intrusions (see GRI report about Gila Cliff Dwellings National Monument by KellerLynn 2014). Ratté et al. (1994) provided the most recent description of Gila Conglomerate recorded in the US Geologic Names Lexicon (Geolex; http://ngmdb.usgs.gov/Geolex/search). In the GRI GIS data, Gila Group, basalt (**Tby**) is associated with basin filling. Remnants of this basalt occur atop Walker Butte (see poster, in pocket). Notably, basalt is the least explosive, most mobile, and hottest (as much as 1,160°C [2,120°F]; Price 2010) of volcanic rock types. Basalt generally erupts onto the surface in effusive lava flows. Thus, basaltic volcanism during Basin and Range extension was much less violent than that of mid-Tertiary volcanism.

Mountain Upland

The landforms associated with the mountain upland/piedmont zone are mountains (discussed in this section), as well as pediments, alluvial fans, and tributary stream–channel deposits (see "Piedmont"). The Santan Mountains make up the mountain upland in the vicinity of the monument. These mountains are part of the monument's historic/prehistoric viewshed. They are fundamental to the monument's significance (National Park Service 2011) and considered a fundamental resource and value (National Park Service 2017).

The Santan Mountains are composed of a variety of metamorphic and igneous rocks, including early Proterozoic schist (**Xp**) and middle Proterozoic granites (**Ygs**, **Yge**, and **Yg**). The core of the Santan Mountains also consists of two ancient plutons (igneous intrusions): silicified granite (**Ygs**) represents one pluton; another pluton consists of two types of granite—(1) K-feldspar porphyritic granite (**Yg**), which was emplaced about 1.2 billion years ago (Balla 1972), and (2) granite, equigranular phase (**Yge**). Cholla Mountain (also referred to as "Cholla Butte") is composed of granite, equigranular phase (**Yge**) that is cut by felsic dikes (**TKri**) (see fig. 3; and poster, in pocket).

Bedrock of the Santan Mountains also consists of rocks from a younger igneous episode that took place during the Cretaceous Period (145 million to 66 million years ago). These rocks are characterized by vein arrays (**Kv**) that intruded the middle Proterozoic granitic rocks (**Yg**), as well as a pluton composed of quartz monzodiorite to quartz monzonite (**Kg**) and associated diorite (**Kd**) dikes. Twin Buttes is composed of quartz monzodiorite to quartz monzonite (**Kg**) (see poster, in pocket, and table 1). Most of the colluvium and talus (**Qct**) in the mountain uplands lies at the base of slopes composed of quartz monzodiorite to quartz monzonite (**Kg**) (see poster, in pocket).

In addition, dikes associated with the Laramide Orogeny (mountain-building event) intruded the rocks of the Santan Mountains. These dikes consist of a range of rocks types: felsic (**TKri**), intermediate (**TKdi**), and mafic (**TKbi**) (see table 1). The felsic dikes were intruded approximately 64 million years ago (Ferguson and Skotnicki 1996). Igneous intrusions responsible for most of the important copper mineralization within the state are associated with the Laramide Orogeny (Titley 1982). The deposition of copper minerals was probably associated in time and space with the intrusion of the biotite quartz monzonite during the Late Cretaceous Period about 70 million years ago (Balla 1972). Most of the copper minerals are concentrated in granite (**Ygs**) near the granite (**Ygs**)–quartz monzonite (**Kg**) contact (Chaffee 1976). Deposition took place in Earth's crust, deep below ground surface. The rich metal deposits were subsequently exposed millions of years later by faulting and erosion.

The summits of some of the buttes in the Santan Mountains consist of remnants of mid-Tertiary or younger lava flows (**Talt** and **Tby**) that are associated with mid-Tertiary and Basin and Range extension. These rocks were uplifted along normal faults. Deformation along these faults resulted in the placement of unmetamorphosed mid-Tertiary and Cretaceous rocks together with deep-seated Proterozoic plutons and metamorphic rocks (see poster, in pocket). Movement along some of these faults—for example, in the vicinity of Commode Butte—resulted in the occurrence of the Whitetail Formation breccia (**Twx**). The formation of breccia, namely breakage into angular fragments of rock, was a result of movement along faults.

All the faults mapped in the vicinity of the monument are normal faults associated with extension (fig. 5). A few fault segments in the GRI GIS data are high-angle normal faults (see poster, in pocket). High-angle normal faulting is indicative of more recent Basin and Range–style faulting, though neither these high-angle faults nor the other normal faults mapped in the vicinity of the monument are considered active by either Scarborough et al. (1983; map of Basin and Range [post–15 million years ago] faults, grabens, and basalt-dominated volcanism) or the AZGS "Natural Hazards in Arizona" map viewer (http://data.azgs.az.gov/hazard-viewer/) (see "Seismic Hazards").

Piedmont

"Piedmont" is a generic term for the gently sloping surface extending from the base of mountains towards the valley (basin) floor. It is defined largely by topography rather than genesis and can be composed of both erosional surfaces (pediments) and depositional surfaces (alluvial fans). The term is commonly used in surficial geologic mapping because it is often difficult to identify the boundary between pediment and coalesced alluvial fans (Gary Huckleberry, University of Arizona, adjunct researcher and lecturer, written communication, 26 May 2018).

An extensive granitic pediment, primarily eroded into middle Proterozoic granite (**Yg**), underlies the piedmont area of the Santan Mountains. North of the monument, the pediment around Mineral Butte and the one adjacent to Commode Butte consist of Pinal Schist (**Yg**) (see poster, in pocket). Bedrock pediments may be 1–10 km (0.6–6 mi) wide (Menges and Pearthree 1989). Their size is defined by the distance between the range-bounding fault and the mountain front (Huckleberry 1994b). The pediment at the base of the Santan Mountains extends all the way to the Gila River.

The following map units are associated with the piedmont in the vicinity of the monument: piedmont deposits, oldest (**Qop**); piedmont alluvium, older (**Qi2**); piedmont alluvium, younger (**Qi3**); alluvium (**Qyif**); piedmont alluvium, undivided (**Qy**); surficial deposits, undivided (**Qal**); and modern stream channel deposits (**Qyc**). This youngest unit (**Qyc**) is deposited by tributary streams on the piedmont, rather than in the river valley (see poster, in pocket). These deposits range in age from 1 million to less than 1,000 years old (Huckleberry 1992). In the upper piedmont areas near Stanfield (west of the monument), Klawon et al. (1998) mapped similar deposits (map unit **Qo** in the source data) as old as 2 million years. Piedmont deposits were transported and deposited by ephemeral tributary streams. Stream activity in the piedmont area north of the monument is clearly shown in satellite imagery (fig. 3).

Connections between Geologic and Cultural Resources

Many connections exist between the geologic and cultural resources at the monument. An entire field of study known as "geoarchaeology" applies techniques and methods of the earth sciences to examine topics that inform archeological knowledge and thought, and vice versa. A few of the primary connections are discussed here. The "Geoarchaeology" section of this report provides more information and suggests some topics for future study.

Gila River Drainage Basin

The story of the monument goes back farther than written history (National Park Service 2011). The Ancestral Sonoran Desert People left no written record, but clues to their lifeways are preserved in the stratigraphic sequences along the middle Gila River (table 2) as well as other rivers in the Gila River drainage basin (i.e., Salt, Santa Cruz, and San Pedro Rivers) (table 3). Synchronicity in the timing of channel entrenchment across southern Arizona suggests that terrace deposits might be correlative throughout the Gila River drainage basin (Waters and Haynes 2001) and beyond; for example, Cook et al. (2010a) mapped the monument's terrace level (**Qi3r**) in the Castle Unit of Montezuma Castle National Monument (see "Geoarchaeology" and the GRI report about Montezuma Castle National Monument by KellerLynn in progress).

Table 2. Correlation of Quaternary map units along the middle Gila River

*Calendar years calculated from 15,000 radiocarbon ([14]C) years BP (a date reported in Waters 2008) using OxCal 4.3 manual (University of Oxford 2018).

Landform	GRI GIS data symbol	Huckleberry (1992)	Klawon et al. (1998)	Richard et al. (2006)	Waters and Ravesloot (2000, 2001)
Active channel (1–3 m [3–10 ft] below adjacent terrace/Holocene floodplain)	Qycr	Y2 <1,000 years ago	Qy2r <100 years ago	Qycr <100 years ago	T-0 and T-1 (Holocene) T-0 is modern streambed alluvium. Terrace 1 (T-1) is inundated during large floods
Holocene floodplain (above active channel)	Qyr	Y1 <10,000 years ago	Qy1r <10,000 years ago	Qyr No date provided Locally includes Qycr	T-2 Terrace 2 is underlain by sediments dating from 16,130 cal BP*
Late Pleistocene river terrace (3–6 m [10–20 ft] above Holocene floodplain)	Qi3r	M 200,000–20,000 years ago	Qlrg 130,000–10,000 years ago	Qi3r 130,000–10,000 years ago	T-3 Before 16,130 cal BP, the Gila River abandoned its floodplain and cut into its alluvium creating Terrace 3
River terraces and alluvial fans on basin floor (middle to late Pleistocene)	Qmlr	Not mapped	Qmlr 500,000–10,000 years ago	Not mapped	Not mapped
Relict, very old river terraces (early to middle Pleistocene)	Qor	Not mapped	Qor 500,000–1 million years ago	Not mapped	Not mapped

Table 3. Geoarchaeological information for the Gila River drainage basin

Sources: Waters (2008), Huckleberry et al. (2013), and Onken et al. (2014).

River:	Middle Gila	Salt	Santa Cruz	San Pedro
Fluvial setting	Major (trunk) stream	Headwater stream	Arroyo	Arroyo
Stratigraphic sequence	Entrenched streambed flanked by a floodplain and three terraces: (1) late Pleistocene, (2) late Pleistocene and Holocene, and (3) Holocene (Waters 2008)	Modern floodplain (Holocene) with three Pleistocene terraces, one each—early, middle, and late Pleistocene (Huckleberry et al. 2013)	Seven major stratigraphic units: unit 1 (late Pleistocene) and units 2–7 (Holocene) (Waters 2008)	Three Pleistocene terraces (early to middle, middle to late, and late Pleistocene), four sets of Holocene deposits and associated alluvial surfaces, and the active channel (Onken et al. 2014)
Ages of cultural sites	Hohokam Potential for Archaic	Hohokam Archaic	Hohokam Archaic	Hohokam Archaic Clovis

The most likely geologic surface in the Casa Grande Ruins area to contain buried, cultural resources is the Holocene floodplain (**Qyr**) (Huckleberry 1994b). Table 2 is an attempt to correlate the map units of the three source maps (see "Geologic Map Data") with geoarchaeological studies (Waters and Ravesloot 2000, 2001) in order that geoarchaeological interpretations, such as the one by Waters (2008; see "Selected Geoarchaeology References"), can be more easily applied to the monument's geologic story.

Table 3 highlights the fluvial settings and stratigraphic sequences of the middle Gila, Salt, Santa Cruz, and San Pedro Rivers. The stratigraphic sequences of these rivers represent deposition and erosion along a major (trunk) stream (middle Gila River), in a headwater stream (Salt River), and in arroyos (Santa Cruz and San Pedro

Rivers). Each of these rivers has a complex history of deposition, erosion, and landscape change, as recorded in its stratigraphic sequence. Geoarchaeological studies can determine if landscape changes (e.g., channel cutting and erosion) correlate with significant cultural changes (e.g., crop failure, loss of farmland, and the need to abandon older canal systems and construct new ones). Both correlation and non-correlations between landscape and cultural change help to explain major transitions in the lifeways of the Ancestral Sonoran Desert People (Waters and Ravesloot 2001).

Caliche

Geologically, caliche—referred to as "hardpan" in *The History of Casa Grande Ruins National Monument* (Van Valkenburgh 1971), also referred to as "duricrust" and "calcrete"—may have been the material most affecting the lives of the prehistoric inhabitants at Casa Grande Ruins (Van Valkenburgh 1971). Caliche (layers of calcium carbonate, commonly cementing together sand and gravel) provided material for lasting and massive house construction in a land without suitable building stone (e.g., the granite exposed in nearby mountainous areas commonly crumbles; see "Mountain Upland"). Also, caliche provided foundational support for built structures (see "The Great House"). As an impervious underground layer, however, caliche also may result in puddling of irrigated top soil (a condition that is corrected in modern farming by deep-plowing to break up the hardpan), which may have forced ancestral inhabitants to abandon waterlogged, unproductive farms, and extend their canal system to new lands. Van Valkenburgh (1971) hypothesized that an imbalance between crop production and canal efficiency was ultimately reached and resulted in the departure of the inhabitants from the "caliche-walled" communities they built.

Other possible factors for the departure of these ancient inhabitants include soil salinization, floods, and/or droughts, disease, social conflict (National Park Service 2011), and even earthquakes. Geoarchaeological studies suggest that for these irrigation-based farmers, landscape changes such as channel cutting and floodplain erosion correlated with significant cultural changes such as crop failure, loss of farmland, and the need to abandon older canal systems and construct new ones (Waters and Ravesloot 2000, 2001).

In soil science terms, caliche comprises K, Bk, or calcic soil horizons, which can be almost pure calcium carbonate, or may consist of gravel, sand, and silt grains cemented together by calcium carbonate into an essentially continuous medium. Factors in the formation of calcic horizons are the amount, seasonal distribution, and concentration of calcium ions (Ca^{++}) in rainfall, and the calcium-carbonate ($CaCO_3$) content and net influx of airborne dust, silt, and sand (Machette 1985).

Because calcium carbonate accumulates over time, geologists use the aggregation of this material as a dating method for geomorphic surfaces such as alluvial fans and terraces (see Gile et al. 1966; Machette 1985). This method was important for dating the terraces in the vicinity of the monument (Huckleberry 1992). Simply stated, more advanced stages of calcium carbonate accumulation correspond to older geomorphic surfaces (e.g., see tables 1 and 2 in Huckleberry 1992).

Various map unit descriptions in the GRI GIS data note the presence of calcium carbonate (see cagr_geology.pdf). Notably, colluvium and talus deposits (**Qct**; see "Mountain Upland") are locally cemented by laminar caliche, in some places greater than 1 m (3 ft) thick.

The map unit that underlies the monument—river terrace and alluvium deposits (**Qi3r**)—has calcic soil horizons with Stage II–III carbonate morphology (Huckleberry 1992); that is, pebbles may be coated with calcium carbonate, carbonate nodules may have formed, and calcium carbonate may be filling the spaces between nodules (Gile et al. 1966). Klawon et al. (1998) also noted calcium carbonate accumulations in unit **Qi3r**, including calcium carbonate–coated clasts (fragments from a preexisting, larger, rock mass) and medium-soft carbonate nodules at a starting depth of 36–76 cm (14–30 in), as well as extremely gravelly soils with silica lime–cemented caliche fragments at an average depth of 61 cm (24 in). In addition, Appendix A in Huckleberry (1992) provides descriptions of soils associated with alluvial surfaces in the piedmont area (see "Piedmont"); some of these have Stage III or greater carbonate concentrations, that is, having many nodules and filling between nodules.

Further information about calcium carbonate accumulation is available from a soils resources inventory (SRI) for the monument, which was completed in 2010. The monument has two soils: (1) Coolidge sandy loam covers about 80% of the monument, including the area under the Great House; (2) Laveen loam covers the remainder. Both of these soils have Bk horizons, and up to 30% calcium carbonate in the soil profile. This and other soils information may be obtained from the Natural Resources Conservation Service Web Soils Survey at https://websoilsurvey.nrcs.usda.gov/app/HomePage.htm.

Figure 7. Photographs of caliche walls. Structures at the monument were built using a technique referred to as "English cob" or "puddled adobe" where stiff caliche mud is piled up by hand to form a wall. When the mud dries, it becomes like concrete. Top: NPS photograph (from National Park Service 2017, p. 6). Bottom: Photograph by Katie KellerLynn (Colorado State University).

The Great House

Since about 1350 CE when Ancestral Sonoran Desert builders completed it, the Great House has dominated the landscape. The structure rises 13 m (45 ft) from its foundation, towering above a late Pleistocene river terrace (**Qi3r**). Details of wall load, weight distribution, and room dimensions were evidently well considered before construction of the Great House (Van Valkenburgh 1971). The excellence of both design and construction is proven by the structure's present existence, that is, a "dirt" building, four stories high, still standing after more than 600 years of continuous exposure to harsh desert conditions.

The more than 1-m- (4-ft-) thick walls of the Great House are composed of calcareous adobe—a mixture of calcium carbonate derived from local calcic horizons (see "Caliche") and sediments from other less calcareous sources (Gary Huckleberry, University of Arizona, adjunct researcher and lecturer, written communication, 26 May 2018). The walls taper upwards from a five-room base. The Great House structure, which is about 20 m (60 ft) long, consists of an estimated 3 million kg (3,000 tons) of caliche mud, built up in layers called "courses" (Wilcox and Shenk 1977). The building technique—referred to as "English cob" (Wilcox and Shenk 1977) or "puddled adobe" (National Park Service 2017)—consists of stiff mud piled up by hand to form a wall. Once the mud dried, the walls became hardened like concrete (fig. 7).

In addition to geologic materials, hundreds of timbers supported the ceiling and floors of the Great House; *The Architecture of Casa Grande and Its Interpretations* (Wilcox and Shenk 1977) estimated 640 beams. Juniper, ponderosa pine, white fir, mesquite, and an unidentified non-conifer tree were used in construction. Some of these trees were gathered from more than 100 km (60 mi) away (National Park Service 2017). Wilcox and Shenk (1977) discussed possible source areas for these trees and transport methods of the timber.

Within the monument's terrace (**Qi3r**), caliche provides underlying support to the walls of the Great House (Van Valkenburgh 1971). Van Valkenburgh (1971) reported that a hardpan layer accumulated 2 m (5 ft) below the present ground level (A. T. Bicknell, based on trenching done by Charlie Steen, personal communication, *in* Van Valkenburgh 1971 [first page of "Archaeological History of the Area" chapter]). During review of this GRI report, however, Gary Huckleberry (University of Arizona, adjunct researcher and lecturer, written communication, 26 May 2018) suggested that the hardpan may be much closer to the surface than reported by Van Valkenburgh (1971). Although Huckleberry has not looked at the soil beneath the Great House, he pointed out that elsewhere in the soils associated with unit **Qi3r**, Stage II–III+ carbonates occur much closer to the modern surface, for example, within the upper 1 m (3 ft). The depth of this well-developed carbonate layer has significance for understanding how the Great House is supported as well as determining localities of calcium-carbonate layers as possible sources of building material for the Great House and other structures at the monument (see "Highly Detailed Spatial Data").

Geologic History

This chapter describes the chronology of geologic events that formed the present landscape. It incorporates all the map units in the GRI GIS data.

The following timeline makes a very long story short:

- Earth formed about 4.6 billion years ago.
- Earth's nascent crust developed during the early Proterozoic Era (2.5 billion to 1.6 billion years ago). Rocks of interest for the monument's geologic story span back to this period. The oldest rocks, composed of Pinal Schist, are 1.7 billion years old. Map unit associated with this event: **Xp** (see poster, in pocket; and table 1).
- Plutons (deep-seated igneous intrusions) added more crust during the middle Proterozoic Era (1.6 billion to 1.0 billion years ago). Map units associated with this event: **Ygs**, **Yge**, and **Yg**.
- Diabase (**Yd**) dikes intruded the 1.2-billion-year-old granitic pluton (**Yg**).
- Following intrusions, subsequent crustal stability lasted more than 1.1 billion years.
- A younger igneous episode augmented earlier crust via vein arrays, plutons, and dikes during the Cretaceous Period (145 million to 66 million years ago). These rocks record the onset of the most intense mountain-building event, known as the Laramide Orogeny, to have affected Arizona since early Proterozoic time.
- The Laramide Orogeny in Arizona began about 80 million to 75 million years ago and ended about 55 million years ago (Dickinson 1989). In the Santan Mountains, some dikes are indicative of this orogeny, for example, felsic dikes were intruded approximately 64 million years ago (Ferguson and Skotnicki 1996). Map units associated with this event: **TKri**, **TKdi**, and **TKbi**.
- Two periods of extensional tectonism took place to form the Basin and Range in Arizona; basin-filling sedimentation is associated with both periods. Mid-Tertiary tectonism and extension took place approximately 32 million to 20 million years ago. Map units associated with this event: **Twx**, **Twsc**, **Tsm**, and **Talt**. Basin and Range tectonism and extension took place approximately 15 million to 8 million years ago. Consequently, the Santan Mountains have been tectonically stable for approximately 8 million years (Huckleberry 1994b). Map unit associated with this event: **Tby**. Normal faults (polylines in the GRI GIS data) are associated with both periods of extension.
- Stream incision by the Gila River followed basin filling. Once drainage became integrated, the Gila River and its tributaries gained the power to incise into basin fill, forming terraces. Development of the Gila River drainage started in the late Pliocene or early Pleistocene Epoch (approximately 3.6 million to 1.8 million years ago). Map units associated with this event: **Qor**, **Qmlr**, and **Qi3r.**
- Ephemeral tributary streams began to develop as early as basins dropped and slopes were created (Miocene Epoch). At first, these streams flowed into internally closed basins resulting in lake and evaporite deposits. Then, as basins filled and drainages became integrated, these tributary streams on the piedmonts began to connect with axial streams on the basin floor. Changes in tributary drainages continue to the present day. Map units associated with this event: **Qop**, **Qi2**, and **Qi3**.
- Formation of pediments resulted in at least 120 m (400 ft) of granite being eroded from the top of the present surface (Chaffee 1976). The age of pediments (3 million to 2 million years old) indicates a period of relative tectonic quiescence (Huckleberry 1992). Map unit associated with this event: **Yg**.
- In places where pediments are buried by mid-to-late Pleistocene alluvial fans, pedimentation (erosion) ended about 2 million to 750,000 years ago. Elsewhere, pediments at the surface continue to form. The end of pedimentation can be correlated with the beginning of sediment accumulation on these surfaces (Klawon et al. 1998).
- Channel and overbank sedimentation continues along the Gila River and its tributaries. Map units associated with sedimentation along the Gila River: **Qyr** and **Qycr**. Map units associated with sedimentation along tributaries: **Qy** and **Qyc**.
- Some deposits such as sheetflood alluvium and talus continue to accumulate to the present day on pediment surfaces. Map units associated with this event: **Qyif**, **Qct**, and **Qal**.
- Humans become a notable geologic agent on the landscape. Map unit associated with this event: **Qd**.

Geologic Resource Management Issues

Some geologic features, processes, or human activities may require management for human safety, protection of infrastructure, and preservation of natural and cultural resources.

The NPS Geologic Resources Division (GRD) (see http://go.nps.gov/geology) can provide technical and policy support for geologic resource management issues or direct monument managers to other resources, such as for climate change, groundwater monitoring, and interpretation and resource education relating to the monument's geologic resources (discussed below). GRD programs and staff focus on three areas of emphasis: (1) geologic heritage, which would address paleontological resource inventory, monitoring, and protection (discussed below); (2) active processes and hazards, which would address erosion, surrounding land use, windblown dust, geologic hazard assessment, earth fissures, seismic hazards, and flood potential (discussed below); and (3) energy and minerals management, which would address mining operations (discussed below).

Resource managers may find *Geological Monitoring* (Young and Norby 2009) useful for addressing geologic resource management issues. The manual, which is available online at http://go.nps.gov/geomonitoring, provides guidance for monitoring vital signs (measurable parameters of the overall condition of natural resources). Each chapter of *Geological Monitoring* covers a different geologic resource and includes detailed recommendations for resource managers, suggested methods of monitoring, and case studies. Where applicable, those chapters are highlighted in the following discussion. Notably, the Sonoran Desert Network is currently monitoring two vital signs related to the geologic resources in the monument: groundwater and soils (see https://www.nps.gov/im/sodn/cagr.htm).

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

- Fluvial features and processes (including the effect of water erosion on archeological resources),
- Wind erosion (of archeological resources),
- Earth fissures (caused by groundwater withdrawal), and
- Seismic features and processes (especially the effect on prehistoric structures).

Since scoping in 2006, the National Park Service completed a foundation document for the monument (National Park Service 2017). Because the foundation document is a primary source of information for resource management within the monument, it was used in preparation of this report to draw connections between geologic features and "core components" such as "fundamental resources and values" and "other important resources and values."

In 2018, a follow-up conference call with monument staff, an Arizona Geological Survey (AZGS) geologist, and GRI team members (see Appendix A) verified the present-day pertinence of the issues identified in 2006. In addition, the call helped to update the list of geologic resource management issues and guide research of this report.

The following updated list of geologic resource management issues is based on the 2006 scoping summary, 2017 foundation document, 2018 conference call discussion, and reviewers' comments. The issues are ordered based on management priority.

- Erosion
- Surrounding land use
- Windblown dust
- Geologic hazard assessment
- Climate change
- Earth fissures
- Groundwater level
- Paleontological resource inventory, monitoring, and otection
- Interpretation and resource education relating to the monument's geologic resources
- Mining operations
- Seismic hazards
- Historic flooding and flood potentia

Erosion

Erosion is the highest management priority in the monument (Karl Pierce, Casa Grande Ruins National Monument, superintendent, written communication, 17 July 2018). Over the years, the focus of preservation efforts has been the Great House, but many other prehistoric structures and sites, as well as historic adobe buildings, including the monument's visitor center and administrative buildings, also are of management concern (Karl Pierce, Casa Grande Ruins National

Monument, superintendent, written communication, 17 July 2018).

As discussed below, various types of erosion (water, wind, salt, and animal) likely affect the built structures at the monument. However, no known laboratory tests on the observed effects of erosion have been conducted on puddled caliche mud from the monument. Methods employed by Bass Rivera and Meyer (2006, 2009) and Riggens et al. (2009) on the Bandelier Tuff associated with the cavates at Bandelier National Monument may be of interest to monument managers in drafting a plan for testing environmental effects (see GRI report by KellerLynn 2015a). Testing could include simulations that replicate rainwater flowing over walls, raindrops landing on or pelting against walls, sandblasting, extreme temperatures, and freeze-thaw processes. Results of such a study could improve protection of these resources and enhance visitor understanding and experience of them.

A valuable resource in the protection of the Great House and, by association, other structures and sites at the monument is *The Architecture of the Casa Grande and Its Interpretation* (Wilcox and Shenk 1977). Chapter 8 in Wilcox and Shenk (1977) addressed natural and human-caused erosion process.

Water Erosion

In general, flowing water is not considered a geologic resource management issue at the monument because the monument sits higher than the Holocene floodplain (**Qyr**) and active channel (**Qycr**) (see "Historic Flooding and Flood Potential"). However, washing by rainwater is a possible threat to the exterior surface of the Great House (see National Park Service 2017, p. 12) and, presumably, other prehistoric and historic adobe structures. Notably, Wilcox and Shenk (1977, p. 106) considered washing by rainwater as a "relatively minor natural erosion process." According to them, the calcium carbonate bonds that hold puddled caliche mud together are "simply not easily disintegrated by water alone" (p. 136).

With respect to human manipulation of overland water flow, no culverts—which concentrate flow during heavy rain events—drain the monument area, though scoping participants in 2006 noted the potential for gully erosion as a result of concentrated flow originating at the gutters of the shelter over the Great House (National Park Service 2006). In addition, the monument's foundation document (National Park Service 2017, p. 26) noted a lack of proper exterior drainage away from some of the historic adobe structures and features.

The monument's foundation document (National Park Service 2017) identified a GIS layer of topographic data to address drainage issues as a data need; these data would assist with landscaping strategies and preventive maintenance of trails and structures. The Geologic Resources Division could provide an evaluation and assist with planning to address flowing water and drainage issues at the monument.

Wind Erosion

The monument appears to be an accumulation site, rather than a deflation site, for windblown silt (GRI conference call, 21 February 2018). Nevertheless, the monument's foundation document noted sandblasting from frequent high winds as a possible threat to the exterior surface of the Great House (see National Park Service 2017, p. 12) and, presumably, other prehistoric and historic earthen structures at the monument. Wilcox and Shenk (1977, p. 136) reported some abrasion of the upper walls of the Great House caused by sand carried by wind, but concluded the effects of windblown-sand abrasion as minimal.

Because seasonal haboobs (sand storms) are occurring with increasing frequency as a result of climate change (National Park Service 2017), a study of the effects of sandblasting on walls of the Great House and other structures in the monument may be warranted.

The chapter by Lancaster (2009) in *Geological Monitoring* described the following methods and vital signs for monitoring eolian (spelled "aeolian" by Lancaster 2009) features and processes: (1) frequency and magnitude of dust storms, (2) rate of dust deposition, (3) rate of sand transport, (4) wind erosion rate, (5) changes in total area occupied by sand dunes, (6) areas of stabilized and active dunes, (7) dune morphology and morphometry, (8) dune field sediment state (supply, availability, and mobility), (9) rates of dune migration, and (10) erosion and deposition patterns on dunes. Not all of these vital signs are applicable, but monument managers may find this discussion useful in clarifying the effects of sand and dust transport and potential eolian erosion on the Great House and other standing structures.

Salt Erosion

According to Wilcox and Shenk (1977), the two most serious erosion processes are (1) salt erosion, which undercuts the base of the walls, and (2) cracking, which has partitioned the walls into a series of vertical columns (see "Vibration Impact Analysis"). Salt erosion is also referred to as "salt weathering," "salt crystallization," and "efflorescence." Scoping participants in 2006 noted salt efflorescence—which appears as a whitish, fluffy or crystalline powder—as causing accelerated erosion on structures, especially between mortar and walls. Monument managers would like to determine whether salt efflorescence has increased in modern times or is a property of the original building materials. They have a baseline measurement of salt efflorescence for the Great House (National Park Service 2006).

Monument managers may find Doehne (2002) useful for the study and mitigation of salt efflorescence. That publication noted more than 1,800 references in the scientific literature (e.g., geomorphology, geochemistry, environmental science, geotechnical and material sciences, and architectural conservation) on the topic of salt weathering, and provided a review of recent work, focusing on articles about conservation. Additionally, Doehne (2002) supplied an organizing framework for considering the complexity of salt weathering. Monument managers also may find the knowledge of staff at Chaco Culture National Historical Park of interest and use on the topic of efflorescence (see GRI report by KellerLynn 2015b).

Animal Erosion

Natural Resources Monitoring at Casa Grande Ruins National Monument (Sonoran Desert Network 2018b) identified round-tailed ground squirrels (*Spermophilus tereticaudus*), house finches (*Carpodacus mexicanus*), common pigeons (*Columba livia*), and European starlings (*Sturnus vulgaris*), which might not normally be considered pests, as threats to archeological resources as a result of burrowing, nesting, feeding, and roosting on or near these resources. In addition, the acidic urine and fecal matter of birds damage the monument's archeological sites by reacting with alkaline walls. Damage caused by animal urine and fecal matter also may impact historic adobe structures.

Conference call participants noted erosion by animals, such as ground squirrels (followed by badgers and foxes attracted by this "food source") as a problem for the integrity of the Great House and buried archeological resources at the monument (GRI conference call, 21 February 2018). Erosion by animals probably affects other standing prehistoric structures and historic structures at the monument.

Burrowing round-tailed ground squirrels began to become problematic in the mid-20th century. The number of birds roosting and nesting in the Great House increased dramatically during the 1990s, when 20 L (5 gal) of bird debris fell onto the ruin floors every week. Efforts to control native species illustrate a conflict between management objectives, that is, preserving the ruins versus protecting the native species and ecosystem processes (Sonoran Desert Network 2018b).

Surrounding Land Use

Regional geologic features (i.e., river valley, basin floor, mountain upland, and piedmont; see "Regional Geologic Features") support surrounding land use (fig. 3). The monument is situated in the river valley/basin floor zone. Most of the Holocene floodplain (**Qyr**) is now agriculturally developed, and basin floor areas have been substantially altered for agricultural fields (Huckleberry 1992). Urban areas, including the City of Coolidge, commonly are situated in the river valley/basin floor zone (Klawon et al. 1998). Piedmont and mountain uplands are generally used for grazing and mining, though in some locations, for example at the City of Casa Grande west of the monument, rapid development is occurring in piedmont areas, as well as on the basin floor (Klawon et al. 1998).

Between 2010 and 2016, Coolidge was the 15th fastest growing city in Arizona; Queen Creek (north of Coolidge) was the fastest (Kolmar 2017). The Arizona Department of Transportation projects that the area of greatest growth in Arizona over the next 20 to 30 years will take place between Tucson and Queen Creek, which would include the area surrounding the monument (Karl Pierce, Casa Grande National Monument, superintendent, written communication, 4 September 2018).

The monument is surrounded by a variety of land uses on all sides. Highway 87 runs along northern boundary, and Highway 87/287 runs along the eastern boundary. Pima Lateral (irrigation canal) runs along the southern and lower western boundary. Agricultural land is on the north and west. Current development associated with the City of Coolidge is on the south, with areas of proposed residential development to the south and east (fig. 3).

The transport of water via irrigation canals is a notable land use in the vicinity of the monument. The Pima Lateral irrigation canal, which runs along the monument's boundary, is part of the Bureau of Indian Affairs, San Carlos Irrigation Project, which conveys water from the Gila River and Central Arizona Project to agricultural lands in the San Carlos Irrigation and Drainage District and Gila River Indian Community. Canals are maintained by the DOI Bureau of Reclamation. Future development of irrigation canals is anticipated in the area. For example, the people who now reside within the reservation of the Gila River Indian Community (i.e., the Pima and Maricopas) are in the planning stages of an irrigation project of monumental proportions—the Pima-Maricopa

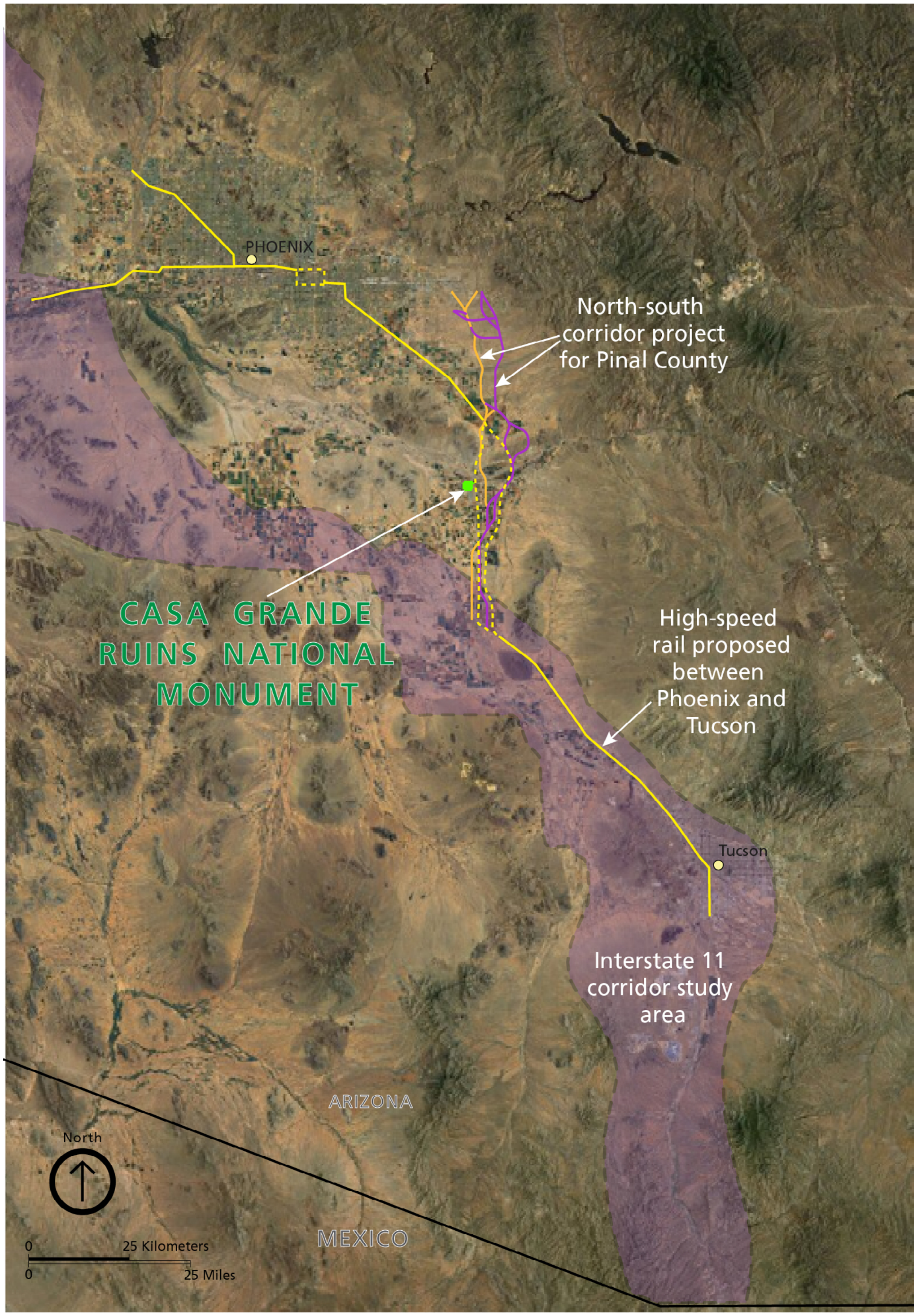

Figure 8. Map of proposed transportation projects.
Currently, three major transportation projects, which are in various stages of planning and development, could impact the monument: (1) north-south corridor project in Pinal County, (2) high-speed train between Phoenix and Tucson, and (3) Interstate-11 corridor project. Graphic by Trista Thornberry-Ehrlich (Colorado State University) using Arizona Department of Transportation and Federal Highway Administration graphics available at https://www.azdot.gov/planning/transportation-studies/PassengerRail (accessed 22 February 2017), https://www.azdot.gov/planning/transportation-studies/north-south-corridor-study/maps (accessed 4 April 2018), and http://www.i11study.com/Arizona/index.asp (accessed 4 April 2018). Base imagery from ESRI ArcGIS World Imagery (accessed 19 April 2018).

Irrigation Project (Gila River Indian Community 2015). The plan, part of the Gila River Indian Community's master plan for land and water use, is the development of a large distribution system designed to convey about 213 million m3 (173,100 acre-feet) of water annually to 59, 210 ha (146,300 ac) of rehabilitated existing agricultural lands and new agricultural lands as part of a Indian water rights settlement. This distribution system will consist of open channel conveyance, check structures, flow measurement structures, turnouts, settling basins, siphons, road crossings, pump systems, wells, and multiple other irrigation delivery components. This project is currently the single largest agricultural development project in the United States and will take many years to complete (George Cairo Engineering, Inc. 2018).

An overall shift in land use from agricultural to single-family residential is projected for the Coolidge area (Maricopa Association of Governments 2016). Three new housing developments are currently under construction; this current construction is the first new housing construction in the City of Coolidge in several years (Karl Pierce, Casa Grande National Monument, superintendent, written communication, 4 September 2018).

On the eastern boundary, across the highway, new commercial development of a large retail complex is attracting new housing prospects. Residential development and housing density are expected to increase in the area surrounding the monument (Sonoran Desert Network 2018b). Residential development is a concern for resource management because of the associated increased water use, which affects groundwater withdrawal (see "Groundwater Levels") and in turn increases the potential for earth fissure development (see "Earth Fissures").

Development of manufacturing facilities is also taking place in the vicinity of the monument. For example, a 1-million-square-foot plant of the Nikola Corporation is to be located near Houser and Vail Roads (south of the monument along Highway 87/287). The plant, which has the potential to create 2,000 jobs, will produce hydrogen-electric vehicles designed for Class 8, or heavy truck, transportation (Khairalla 2018).

During the follow-up conference call, participants noted three major transportation projects near the monument boundaries: (1) North-South Corridor, a proposed new transportation route in Pinal County (https://www.azdot.gov/planning/transportation-studies/north-south-corridor-study); (2) Interstate-11 Corridor, notably between Phoenix and Las Vegas, but with a long-term vision of crossing the state and serving the nation's needs from Mexico to Canada (http://i11study.com/), and (3) high-speed train between Phoenix and Tucson (https://www.azdot.gov/planning/transportation-studies/PassengerRail). These projects, which are in various stages of planning and development, could impact the monument (fig. 8).

Ease of transportation to major metropolitan areas (i.e., Tucson and Phoenix) has the potential to increase urbanization throughout the area. Urbanization can impact surrounding archeological features that are not fully protected by the monument as well as alter the desert environment (National Park Service 2017).

Notably, rapid urban growth will result in future excavations of large river floodplains, thereby creating opportunities to describe, map, and date late Quaternary deposits. Such information would provide important baseline historical data on river behavior and further insight into the relative importance of external factors such as climate versus local geomorphic controls on channel changes, floodplain formation, and archeological site preservation (Huckleberry et al. 2013). Perhaps the Arizona Geological Survey, Arizona Department of Water Resources, and National Park Service could collaborate and develop a plan for mapping river floodplains that incorporates monitoring construction permitting in order to utilize excavation sites for research (see "Geoarchaeology").

Impacts Related to Development

Sonoran Desert Network (2018b) identified the following impacts associated with adjacent residential and commercial development: increase in nonnative plants, trash, and runoff into the monument; decrease in the water quality of runoff due to toxins from vehicles; disruption of animal movement patterns; and increase in mortality of native animals due to free-roaming pets. Of these impacts, runoff is a geologic resource management issue. Developed land has the potential to change the timing and duration of runoff events because roads concentrate water (and concentrate water faster) than natural conditions, thereby increasing peak discharge. Also, future irrigation of lawns in a subdivision could contribute to runoff into the monument or cause unnaturally elevated groundwater levels (see geologic resources evaluation scoping summary for Aztec Ruins National Monument by KellerLynn 2007).

Corridors for transmission lines and buried fiber optic cables are other development-related impacts. These disturbed corridors serve as pathways that concentrate runoff and create "spillways" that have the potential to exacerbate erosion and threaten archeological sites. Arizona Public Service maintains electric transmission lines along the eastern boundary of the monument. The San Carlos Irrigation Project provides electric service to the monument itself (Karl Pierce, Casa Grande Ruins National Monument, superintendent, written communication, 4 September 2018).

Other development-related impacts include construction, which can denude vegetation, creating new sources of windblown dust (see "Windblown Dust"), as well as disrupt biological soil crusts or desert pavement (see "Biological and Physical Soil Crusts, Desert Pavement, and Desert Varnish"). Also, periodic dredging of the Pima Lateral (irrigation canal) results in sediment deposition, which is a potential source of windblown dust along the monument boundary. Sonoran Desert Network (2018b) noted that this sediment likely contains nonnative plant seeds.

Potential Mitigation of Impacts

Boundary expansion is an option for the preservation of resources from future development. Since 2001, stakeholders have shown considerable interest and support for a boundary expansion of the monument to encompass additional archeological resources and to resolve a minor inholding by the Bureau of Land Management (BLM) at the southwest corner of the monument. A boundary expansion that includes the Grewe and Adamsville sites to the east, as well as land swaps with the BLM and Bureau of Indian Affairs, still have the potential to take place (Karl Pierce, Casa Grande Ruins National Monument, superintendent, written and email communication, 26 February 2018).

According to the monument's foundation document (National Park Service 2017, p. 31), questions remain regarding the associated feasibility and management of additional lands. Planning at the monument should begin to develop alternatives of land use. Assessments of feasibility should address the threat of local development and cultural resources related to the purpose and significance of the monument, along with the local economic benefit.

GIS is an important tool for analyzing potential impacts on the landscape and showing these findings to planning boards and during public meetings. The monument's foundation document (National Park Service 2017) noted the need for a GIS layer that shows utility locations, but other layers would be useful as well (e.g., transportation corridors, canals, and land ownership). Notably, the Pima-Maricopa Irrigation Project (Gila River Indian Community) has an online GIS portal (https://www.gilariver.com/#gisportal) that includes land surveys, administrative and geopolitical boundaries, irrigation conveyance (e.g., canals, completed reaches, future rehab reaches, and major conveyance structures), irrigation development plans, groundwater monitoring wells, land use (soils, land class, surface geology), and water gages, which may be of use in the monument's GIS.

Leveraging and sharing data may be an important aspect in working with partners in mitigating impacts to monument resources. The monument's foundation document (National Park Service 2017) identified development of a partnership plan as a need. The plan would establish direction and guidance for new relationships between organizations, energize existing relationships, define roles and responsibilities, and organize and develop special events. Increasing the diversity of partners would be integral to this process.

The developers of *Pinal County Multi-Jurisdictional Hazard Mitigation Plan* (Pinal County 2016)—Pinal County, City of Apache Junction, City of Casa Grande, City of Coolidge, City of Eloy, Town of Florence, Town of Kearny, Town of Mammoth, City of Maricopa, and Town of Superior—are potential partners for mitigation. This plan provides guidance about earth fissures, subsidence, flooding, and severe wind. Notably, the National Park Service was not a contributor to this plan, but because the plan covers potential geologic resource management issues at the monument, it could serve as an impetus for partnering with these stakeholders. The monument's foundation document noted that communications with the City of Coolidge and Pinal County are currently good: "The City of Coolidge is an active partner and good neighbor. The monument considers it very important to maintain interactive relationships with the surrounding community and will continue to work with all stakeholders to determine the kinds of development that would complement the monument setting" (National Park Service 2017, p. 31).

Windblown Dust

Agricultural fields near the monument are likely sources of windblown dust (GRI conference call, 21 February 2018), though no studies specific to the monument have characterized sources of dust or the means of transporting fugitive dust (particulate matter suspended in the air by wind action and human activities but not from a point source such as a smokestack).

The monument seems to be an "accumulation site" for windblown dust (GRI conference call, 21 February 2018), including deposition of silt inside the Great House (National Park Service 2006). Also, scoping participants noted a thin veneer of windblown silt on the river terrace at the monument (National Park Service 2006); Waters and Ravesloot (2001) noted a widespread eolian sand sheet covering this Pleistocene terrace, which they deemed would have been very suitable for plant growth by past irrigation-based agriculturalists. Unit descriptions in the source maps for river terrace and alluvium deposits (**Qi3r**) do not mention an eolian component, however. This is not particularly surprising because loess (windblown dust) is commonly ignored and underrepresented on geologic maps, especially where it is thin (less than 2 m [5 ft] thick) (Madole 1995).

Monument employees have observed biological soils crusts, which may hold loess in place (GRI conference call, 21 February 2018) (see “Biological and Physical Soil Crusts, Desert Pavement, and Desert Varnish”). In addition, desert pavement has been noted in surficial geologic mapping of the area (Huckleberry 1992, 1994b), namely occurring on surfaces the age of those in the monument (**Qi3r**). Desert pavement consists of an interlocking armor of clasts, which stabilizes surfaces. The mechanisms that produce interlocking armor is still debated amongst earth scientists (see “Future Geologic Investigations”).

Sources of information for identifying and quantifying dust emissions include work conducted in the eastern Mojave Desert (Sweeney et al. 2011), along the Interstate 8 corridor of southern California and Arizona (Sweeney and McDonald 2017), and along Interstate 10 between Phoenix and Tucson, which is one of the most dangerous sections of highway in the United States due to the loss of driver visibility as a result of blowing dust (McDonald and Sweeney 2017). Use of the portable in situ wind erosion lab (PI-SWERL) helped these investigations identify and measure the dust emission potential of landforms in both natural and disturbed settings.

Geologic Hazard Assessment

A geologic hazard (“geohazard”) is a natural or human-caused geologic condition or process that may impact monument resources, infrastructure, or visitor safety. Risk is the probability of a hazard to occur combined with the expected degree of damage or loss that may result from exposure to a hazard, or the likelihood of a hazard causing losses (see Holmes et al. 2013). Potential geohazards identified during scoping and discussed in this report include runoff and erosion; dust storms; earth fissures; earthquakes, including induced earthquakes from injection wells; and floods.

An assessment of the greatest hazards to monument resources, especially the Great House and other archaeological resources, is of interest to monument managers in order to better understand what geohazards exist, their prioritization, and recommendations for addressing them (Karl Pierce, Casa Grande Ruins National Monument, superintendent, written communication, 14 July 2018 and 13 August 2018). This interest is in line with the Geologic Resources Division’s preferred approach to work proactively to identify and address geohazards before they result in injury or property loss. GRD staff in the active processes and hazards area (https://www.nps.gov/orgs/1088/contactus.htm) can conduct geologic hazard inventories, risk assessments, mitigation, and incident preparation. Monument staff can formally request assistance via https://irma.nps.gov/Star/.

Climate Change

Because of the potential disruption that climate change may cause to monument resources, including geologic resources, a brief discussion of climate change is included in this GRI report. However, climate change planning is beyond the scope of the GRI program, and monument managers are directed to the NPS Climate Change Response Program to address issues related to climate change (https://www.nps.gov/orgs/ccrp/index.htm).

The monument has both weather and climate change information to support climate change planning. Notably, one of the longest-operating National Oceanic and Atmospheric Administration (NOAA) Cooperative Observer Program (COOP) weather stations in Arizona is located in the monument (Casa Grande Ruins NM, ID#3288778). This weather station was established in 1906 and provides a reliable long–term data set for analyses. The monument also contains two recently established climate stations: a Remote Automated Weather Station, installed in 2014; and a Regional Climate Reference Network station, installed in 2011. The NPS Sonoran Desert Network maintains and operates these stations. In combination with the excellent, long-term, NOAA COOP data set, these stations provide a unique opportunity to study climate and weather patterns in the Sonoran Desert (Filippone and Raymond 2018). Data from these stations are available through The Climate Analyzer (http://www.climateanalyzer.org/).

A climate change summary (Gonzalez 2014) has been prepared for the monument. This document provides climate trends in temperature and precipitation. The summary found that temperature is increasing at a statistically significant rate of 2.1°C (3.8°F) per century. No statistically significant change in precipitation since 1950 was found. Both temperature and aridity are predicted to increase. The summary also lists vulnerabilities; for example, past warming has reduced snowpack widely and rainfall in some areas of Arizona. This may continue to reduce summer streamflow and water supplies.

A climate change resource brief (Monahan and Fisichelli 2014) also was prepared for the monument. Temperature and precipitation were analyzed and "extreme" conditions (exceeding 95% of the historical range) were identified. Six temperature variables were "extreme warm"; no temperature variables were "extreme cold." Thus, temperature at the monument is pushing the limit of the historical range in all except one variable (mean temperature of the wettest month). One precipitation variable was "extreme dry"; no precipitation variables were "extreme wet." Thus, precipitation is pushing the limit of historical range in the driest quarter of the year. In addition, the authors noted that climate change will manifest itself not only as changes in average conditions but also as changes in particular climate events (e.g., more intense storms, floods, or drought).

A park-specific brief (Fisichelli and Ziesler 2015) examined how future warming may alter visitation patterns. Modeling projected decreases in annual visitation, peak-season visitation, and low-season visitation, but an increase in shoulder-season visitation. The overall visitation season will contract by eight to 27 days.

The monument's foundation document (National Park Service 2017) identified extreme weather events due to climate change—e.g., more frequent high winds, more or larger storms during the monsoon season, more or greater dust storms, and more or greater local flooding (the meaning of "local flooding" is not clear with respect to the monument, but may mean "standing water" in topographically low areas as a result of heavy rains)—and its associated influences as having the potential to accelerate exterior surface erosion of the Great House, cause erosion of other archeological features, and impact the shelter over the Great House (National Park Service 2017).

Status of Climate and Water Resources at Casa Grande Ruins National Monument: Water Year 2016 (Filippone and Raymond 2018) combined data collected on climate with an overview of groundwater resources at the monument. According to Filippone and Raymond (2018), detailed analyses of trends will follow in subsequent reports as the period of record, starting in 1906, warrants such assessments.

Earth Fissures

Earth fissures are tension cracks that develop as a result of subsidence due to severe groundwater withdrawal. As the ground settles into the space no longer filled by groundwater, cracks form at depth and propagate upward towards the surface (fig. 9). Earth fissures are dynamic features that constantly change in response to movement in the subsurface (e.g., continuing subsidence) and to activity at the surface (e.g., runoff from precipitation) (Arizona Geological Survey 2008). Damage resulting from earth fissures includes foundation cracks; disrupted highways, canals, and pipelines; arroyo cutting and soil erosion; and vegetation destruction through concentration and removal of overland flow (Jackson 1990).

Enlargement by erosion may be the principal hazard associated with earth fissures because of the potential danger to both animals and people (Jachens and Holzer 1982). Rapid erosion also presents a substantial hazard to infrastructure. In addition, fissures provide a ready conduit to deliver runoff and contaminated waters to groundwater aquifers (Arizona Geological Survey 2015).

Earth fissures are a long-term problem and will continue to form as long as subsidence continues unchecked. In Arizona, fissures were first noted near Eloy in 1929. Today, earth fissures are particularly noteworthy in four counties: Pinal, Maricopa, Cochise, and Pima. Rapid population growth in these counties is increasingly juxtaposing population centers and fissures (Arizona Geological Survey 2015). Likewise, increased groundwater withdrawal for residential and commercial uses increases the potential for earth fissure formation.

The closest mapped earth fissure to the monument is about 10 km (6 mi) to the southwest (fig. 10). At present, Coolidge is not one of the 23 "priority mapping areas" for earth fissures by the Arizona Geological Survey (Arizona Geological Survey 2008). Nevertheless, scoping participants in 2006 identified earth fissures as a resource management issue (National Park Service 2006). Also, Sonoran Desert Network (2018b) identified earth fissures (associated with groundwater depletion) as a key issue; to this end, the Sonoran Desert Network and its partners monitor groundwater levels at the monument (see https://www.nps.gov/im/sodn/groundwater.htm).

If monument managers see a feature that they suspect is a fissure, they can consult the NPS Geological Resources Division and/or the Arizona Geological Survey to review options, including the possibility of consulting a company of qualified, registered geologists and engineers who have experience working with earth fissures. "Additional References" provides a list of online resources about earth fissures.

Interesting geological connections exists among earth fissures, pediments, Basin and Range faults, and timing of uplift of the Santan Mountains. Jachens and Holzer (1982) proposed that earth fissures propagate upwards from the buried interface between bedrock and basin

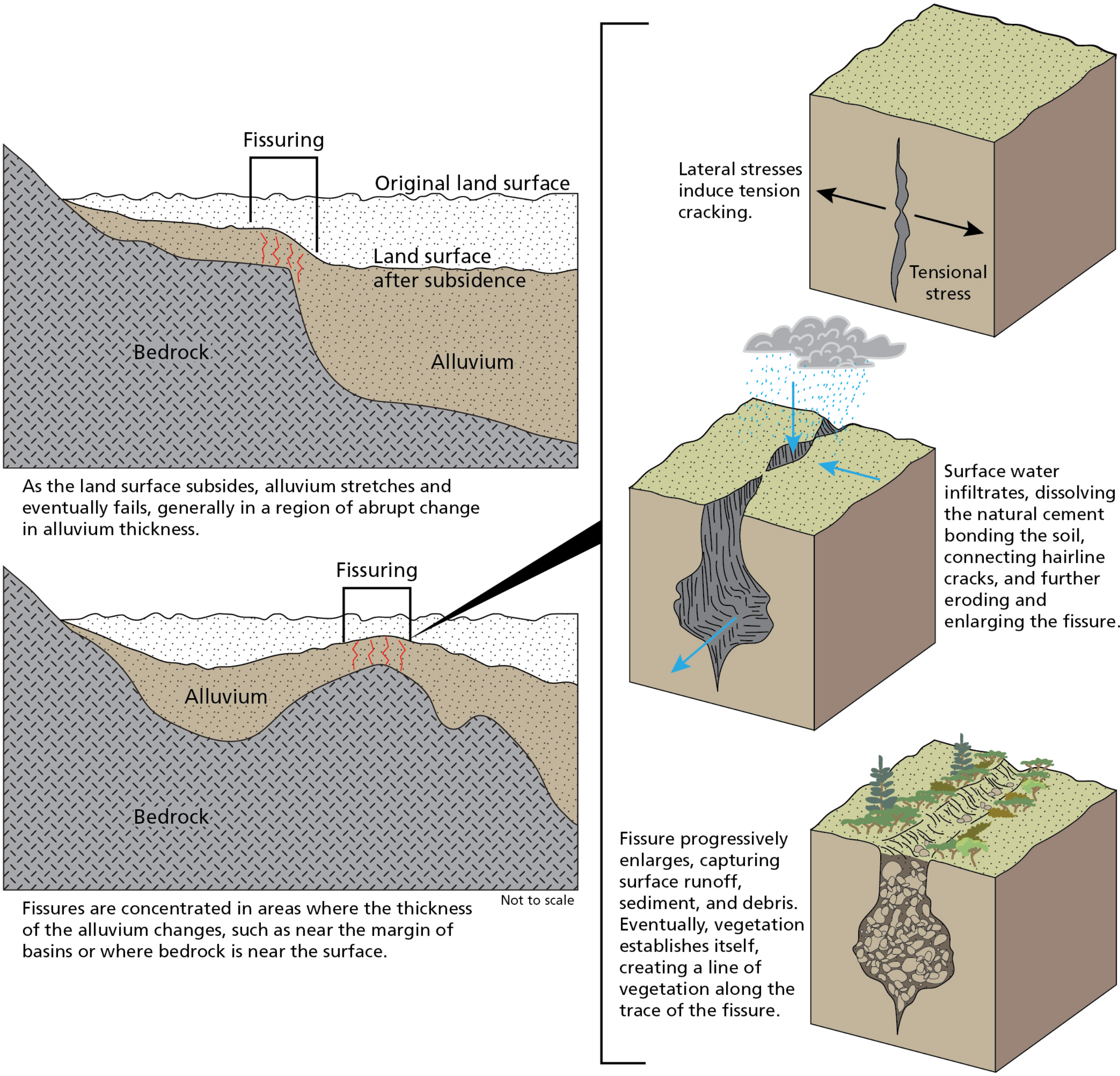

Figure 9. Graphic showing earth fissure development.
Once an earth fissure intersects the surface, a conduit for runoff is created, and the fissure walls become susceptible to rapid erosion during torrential rains. Rapid erosion presents a substantial hazard to people and infrastructure. Moreover, fissures provide a ready conduit to deliver runoff and contaminated waters to groundwater aquifers. Graphic by Trista Thornberry-Ehrlich (Colorado State University) after Pinal County (2016—AZGS graphic in section 4.4.3).

fill (fig. 9). The “interface” may be an escarpment of a buried Basin and Range (range-front) fault. According to Jackson (1990), earth fissures loosely follow the buried range-bounding faults, and the highest potential for fissure development is probably in these areas. Moreover, if earth fissures mark the location of a range-bounding fault, then the width of the pediment can be calculated. For instance, the mountain scarp upslope from Chandler Heights has retreated as much as 8 km (5 mi) (Huckleberry 1994b). Assuming a pedimentation rate of 1 km (0.6 mi) per 1 million years (Damon et al. 1984), this suggests that the Santan Mountains have been tectonically stable for approximately 8 million years (Huckleberry 1994b).

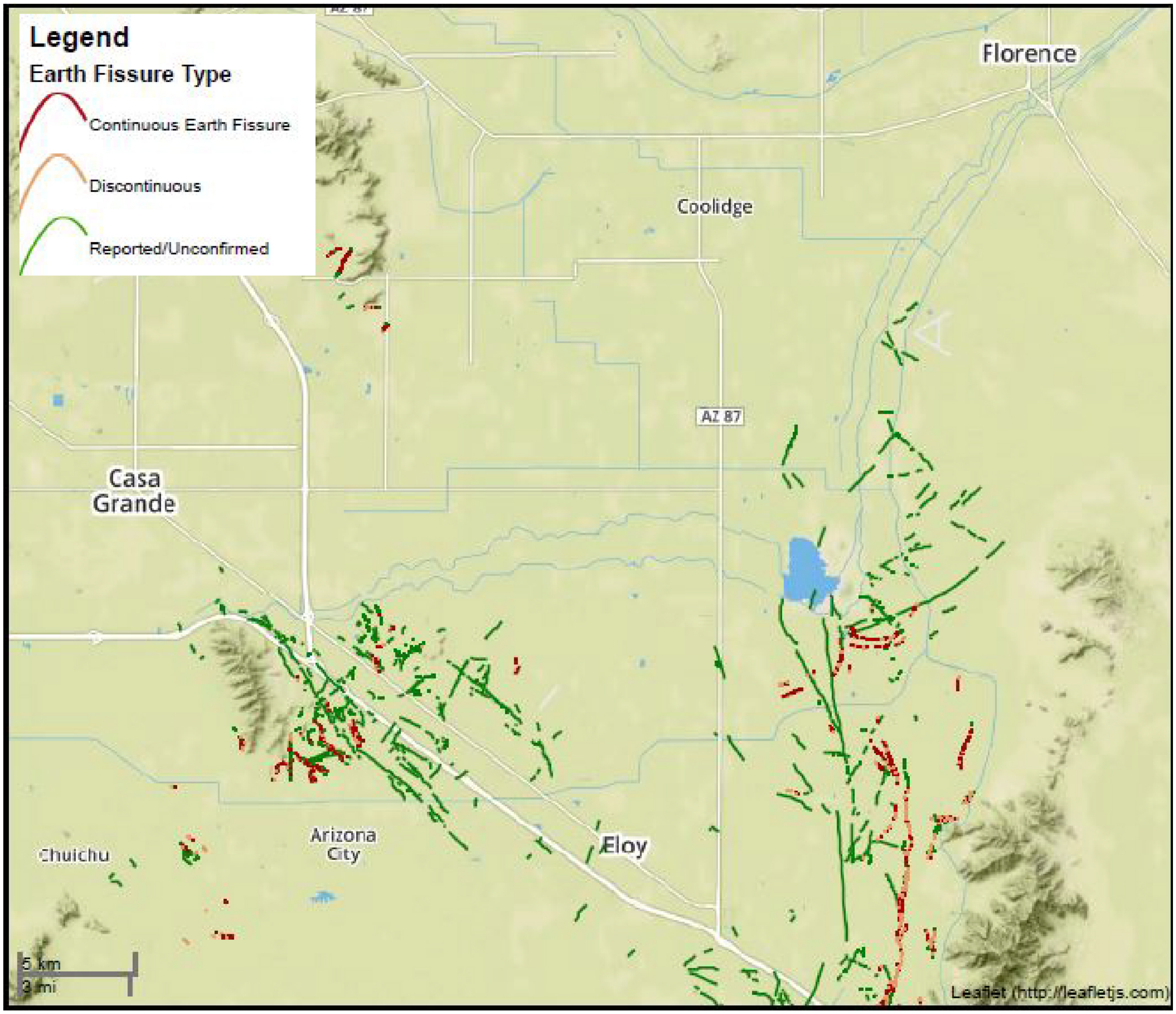

Figure 10. Map of earth fissures.
The map displays the surface trace of earth fissures mapped by AZGS geologists, as well as reported, unconfirmed earth fissures within the study area's boundaries. Continuous earth fissures (red) manifested as open cracks or gullies. Discontinuous earth fissures (yellow) manifested as elongated to circular depressions or as abbreviated or irregular linear depressions. These discontinuous surface features commonly represent an incipient surface expression of an earth fissure. Reported/unconfirmed earth fissures (green) are defined as fissures that could not be confirmed during surface investigations by AZGS geologists, but that have been previously reported by professional geologists in published documents or maps. A blank area on the map does not guarantee earth fissures are not present. Determining the presence or absence of a fissure at any specific site may require additional mapping and/or geotechnical analysis. Graphic generated from AZGS "Natural Hazards in Arizona" map viewer at http://data.azgs.az.gov/hazard-viewer/ (accessed 1 May 2018).

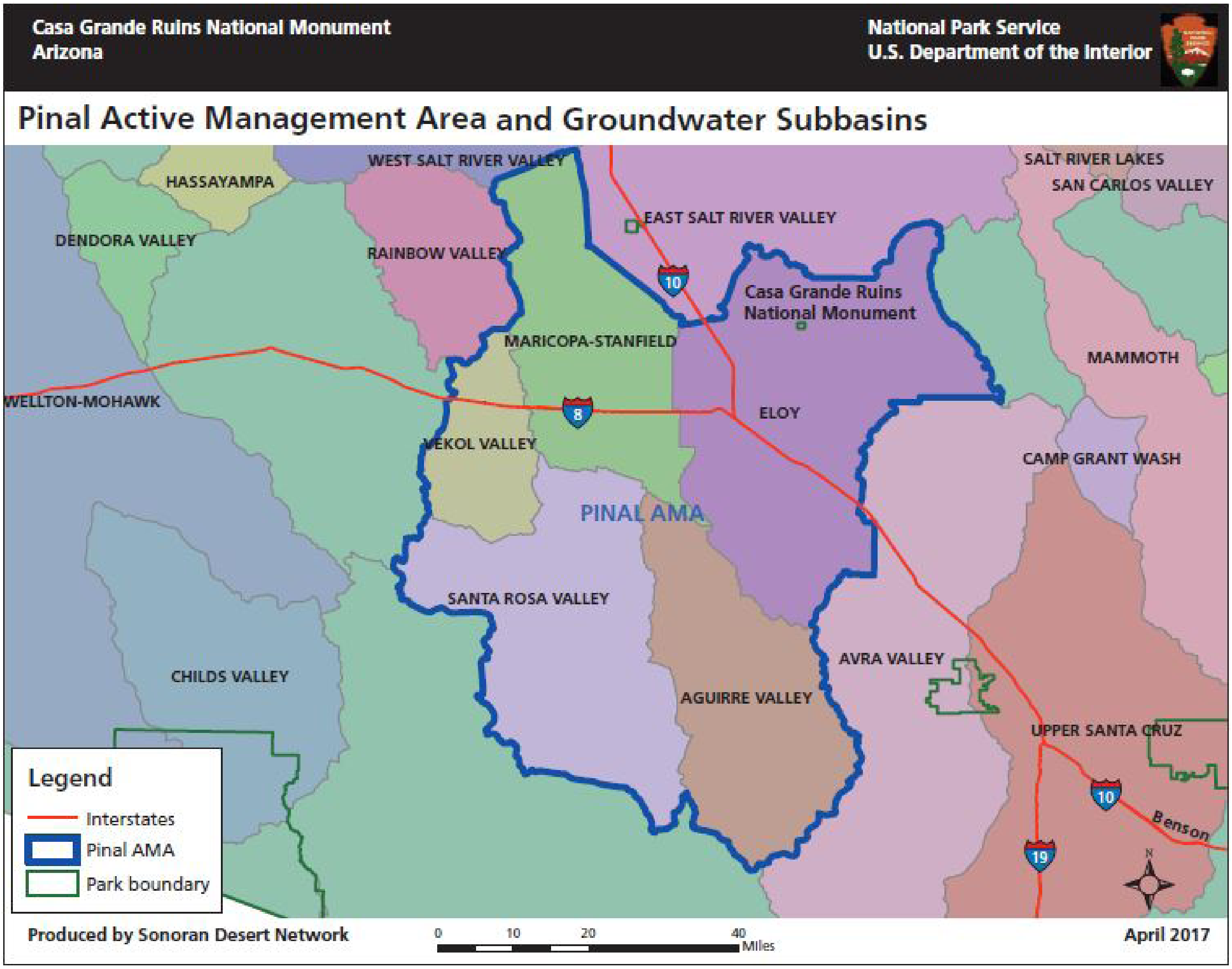

Figure 11. Map of Pinal active management area and groundwater subbasins.
Arizona has seven active management areas (AMAs) or "planning areas." These compose an organizational device that provides a regional perspective on water supply, demand, and resource issues. The area of the Pinal AMA is approximately 11,000 km^2 (4,100 mi^2). The monument is located in the Eloy groundwater subbasin of the Pinal AMA. Sonoran Desert Network graphic from Filippone and Raymond (2018, figure 3-2).

Groundwater Level

Groundwater level, also referred to as "water table level," is a management priority at the monument (Karl Pierce, Casa Grande Ruins National Monument, superintendent, written communication, 14 July 2018).

Natural changes in groundwater levels are a result of climate change (e.g., drought and pluvial episodes), but the main changes are due to human abstraction (meaning to take away or remove). The effects over the past few decades outstrip all those in previous human history (International Union of Geological Sciences 2005).

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

According to Filippone and Raymond (2018), groundwater conditions have significant impacts on the monument and the surrounding area. The monument is located in the north-central section of the Eloy groundwater subbasin of the Pinal active management area (AMA) (fig. 11). Since about 1900, groundwater conditions in the Eloy subbasin have been increasingly dominated by agricultural use. Between 2001 and 2005, 96% of all water pumped in the Pinal AMA went to agricultural use (Arizona Department of Water Resources 2010). Since the early 20th century, the Eloy subbasin has been in groundwater deficit, with more water pumped from the aquifer than was naturally replenished. This has resulted in substantial changes to the natural flow regime, declining water levels, and land subsidence. Groundwater loss has the potential to affect the water supply as well as the stability of built structures through land subsidence (see "Earth Fissures").

Many environmental issues are related to groundwater depletion, including the drainage of wetlands, stability of foundations, and the salinization of soils, but above all is the exhaustion of groundwater reserves (mining). Pollution of groundwater, which is a major problem in urban areas, also reduces the overall groundwater resource (International Union of Geological Sciences 2005).

The Bureau of Reclamation recently informed monument managers that restoring water table levels is an objective of the Central Arizona Project, which is a multipurpose water resource development and management project that delivers Colorado River water, either directly or by exchange, into central and southern Arizona (Bureau of Reclamation 2018). Water table levels can be restored as an indirect result of irrigation or accomplished deliberately by injection pumping (International Union of Geological Sciences 2005). How restoration of water table levels might affect prehistoric structures and/or vegetation within the monument and its management implications for the monument will be of interest (Karl Pierce, Casa Grande Ruins National Monument, superintendent, written communication. 14 July 2018).

In addressing this issue at the monument, the Water Rights Branch of the NPS Water Resources Division would be the lead at the national level and the Sonoran Desert Network would be the lead at the local level. The role of the Water Rights Branch is to secure and protect water rights for the preservation and management of the National Park System through all available local, state, and federal authorities. A basic function of the Water Rights Branch is to measure and analyze groundwater and surface water data. The Water Rights Branch has provided assistance to many parks in the Sonoran Desert Network, though not Casa Grande Ruins National Monument to date (see https://www.nps.gov/orgs/1439/wrb.htm). Staff members have expertise in hydrogeology, groundwater modeling, groundwater sustainability, and water rights (see https://www.nps.gov/orgs/1439/contactus.htm).

Interpretation and Resource Education Relating to the Monument's Geologic Resources

Interpretation and resource education relating to the monument's geologic resources is an additional management priority (Karl Pierce, Casa Grande Ruins National Monument, superintendent, written communication, 14 July 2018). The monument's foundation document (National Park Service 2017) lists the following five interpretive themes; interpretive themes are often described as the key stories or concepts that visitors should understand after visiting a park:

- Diverse oral traditions of the Ancestral Sonoran Desert People and the evocative Casa Grande Ruins provide insight into the ability of humans to thrive within the constraints of challenging natural conditions, which raises questions about the sustainability of modern society that does not live within those constraints.
- The Ancestral Sonoran Desert People applied traditional knowledge of engineering, hydrology, and astronomy, and practiced economic and resource planning that enabled them to live comfortably throughout the region.
- The cultural landscape of the Gila River valley, which includes Casa Grande Ruins and surrounding communities, has been home to the Ancestral Sonoran Desert People and their descendants for thousands of years. This landscape is sacred to the people of six traditionally associated tribes and speaks of ancestral homeland, identity, and tradition.
- The establishment of Casa Grande Ruins as the first archeological reserve in 1892 initiated the beginning of America's archeological preservation movement, from which we all benefit today.
- The physical prominence and sophisticated construction of the Casa Grande [Great House] made it a landmark in early European exploration and western migration and it continues to be a dominant feature on the landscape today.

Development of interpretive themes is not one of the three GRI program objectives: (1) convene a geologic resources scoping meeting and deliver a summary; (2) compile, develop, and deliver digital map data; and (3) write and deliver a park-specific report. Nevertheless, if an outcome of the GRI process is a desire by monument managers to develop a geologic interpretive theme or connect geologic topics to the existing five themes, GRI materials can be useful in that process.

Topics discussed in this report may be applicable and useful for developing an interpretive theme, for example, the use of geologic material in building (see "Setting and Significance"); the monument's long history, pre-history, and even longer geologic history (see "Geologic Setting and Significance" and "Geologic History"); or the application of archeological methods in geologic studies and vice versa (see "Geoarchaeology").

In an effort to provide some guidance, the "Additional Resources" chapter directs monument managers to sources of information about geologic interpretation and education in the National Park Service. It also provides a list of websites for the Arizona Geological Survey's outreach, education, and social media presence, which may be useful.

Furthermore, the NPS Geologic Resources Division administers the Geoscientists-In-the-Parks (GIP; http://go.nps.gov/gip) and Mosaics in Science (http://go.nps.gov/mosaics) programs. These internship programs place scientists (typically undergraduate students) in parks to complete geoscience-related projects. Participants in these programs give presentations, lead interpretive walks, write site bulletins, and train staff members about the geology of a park. Many interns have used GRI reports in preparing interpretation, education, and training materials. Many of the products created by GIP participants are available at http://go.nps.gov/gip_products; these products will give monument staff an idea of the types of projects that can be accomplished during a GIP or Mosaics in Science internship.

Monument managers are encouraged to contact the Geologic Resources Division about preparing a proposal for acquiring a GIP or Mosaics in Science intern. Proposals could include partnering with other programs such as the Desert Research Learning Center (https://www.nps.gov/im/sodn/drlc.htm) or the Arizona Geological Survey (http://azgs.arizona.edu/).

Paleontological Resource Inventory, Monitoring, and Protection

All paleontological resources are nonrenewable and subject to science-informed inventory, monitoring, protection, and interpretation as outlined by the 2009 Paleontological Resources Preservation Act (see Appendix B). As of Summer 2018, Department of the Interior regulations associated with the act were being finalized.

Tweet et al. (2008) completed a paleontological resource inventory and monitoring report for the Sonoran Desert Network, which includes information about Casa Grande Ruins National Monument. According to Tweet et al. (2008), the potential is low for discovery of in situ fossils in the river terrace and alluvium deposits (**Qi3r**) at the monument. Any fossil discovered would be limited in age to late Pleistocene (130,000–10,000-years-old) or younger. Possible fossils in deposits of this age include testudinids (tortoise), equids (horse), camelids (camel), and proboscideans (mammoths and mastodons) (R. McCord, Arizona Museum of Natural History, paleontologist, personal communication, May 2008, in Tweet et al. 2008, p. 13).

The likelihood of a fossil eroding out of a Pleistocene or older deposit and being transported by floodwaters into the monument is small because the terrace in the monument is 3–6 m (10–20 ft) above the present-day channel of the Gila River and more than 2 km (1 mi) from it. Furthermore, even if the Gila River was undammed and changed course to be flowing near enough to the monument that it might deposit material there, source material (nearby rock formations) lack fossils (Tweet et al. 2008).

Despite this low potential, the collection at the Western Archeological and Conservation Center (WACC) in Tucson contains one fossil specimen (a possible piece of petrified wood) listed from Casa Grande Ruins National Monument and four other fossil specimens (a piece of antler or horn, and three possible teeth) that are associated with the monument (Tweet et al. 2008). Tweet et al. (2008) suggested further study (identification and provenance) on these fossil specimens. The application of photogrammetry (highly detailed 3D images) may be useful in the study of these specimens because the remoteness of the repository and lack of staffing at the WACC facility has created scheduling issues regarding accessing collections by monument staff and researchers. Photogrammetry would facilitate access and research beyond the walls of the WACC facility (see "Highly Detailed Spatial Data").

The antler or horn in the WACC collection is documented as possibly "worked," which could indicate a cultural use (Tweet et al. 2008). Fossils discovered in cultural contexts are both archeological and geological resources. Kenworthy and Santucci (2006) provided an overview and guidance for the discovery of NPS paleontological resources in cultural resource contexts.

Mining Operations

Geographic names such as "Goldmine Mountain" and "Mineral Butte" in the vicinity of the monument are indicative of past mining and underlying geology. Moreover, reddish-brown, iron-stained outcrops are evidence of mineralization (fig. 3). These distinctive outcrops attracted prospectors to the area in the early 1920s. Small mines, pits or quarries, prospect or test pits, and drill holes (see Arizona Bureau of Mines 1963; Wilson and Stubbs 1963) attest to past prospecting. Some gold, silver, and copper ores were mined (Wilson 1969).

The mineralized area north of the monument became known as the Blackwater (or sometimes the Black Rock) mining district. In present-day databases, the Blackwater district is commonly grouped with the Florence mining district. The Blackwater mining district is part of the Gila River Indian Reservation. A study and mapping by Wilson (1969) defined the distribution, geologic character, probable extent, and potential economic importance of the various mineral substances found there.

At present, the mining operation of primary interest to monument managers is the Florence Copper production test facility, which is 12 km (7 mi) northeast of the monument (fig. 3). This facility is presently under construction. The operation is for in situ copper recovery (ISCR), which requires no open pit, no tunneling, no waste dumps, and none of the large equipment typically associated with traditional mining activity (Florence Copper 2014). The extraction process occurs deep in the bedrock. The deposit lies 120 to 370 m (400 to 1,200 ft) below the surface. The production test facility will produce between 500,000,000 and 900,000,000 kg (1 million and 2 million lbs) of copper cathode over 12–18 months of operation (Florence Copper 2014).

Construction and installation of the facility includes drilling of 24 wells (injection, recovery, geochemical sampling, and observation wells) (fig. 12). The well field will occupy about 0.8 ha (2 ac) of a 65-ha (160-ac) state mineral lease. In addition, a 4-ha (10-ac) impoundment will be constructed to store surplus water from operations. Processing facilities and equipment to be built and installed at the facility include tanks for processing and storing ISCR solutions, water treatment tanks and equipment, and storage and off-loading facilities for process chemicals (Florence Copper 2014).

Possible impacts to the monument include vibrations associated with construction and operations such as blasting and drilling (see "Vibration Impact Analysis"). In addition, vehicular traffic has the potential to cause vibrations; Florence Copper (2014) estimated 40 employee vehicles daily as well as trucks (an anticipated one daily) for delivering supplies and another for transporting copper cathode from the facility.

If trucks are bound for Interstate 10, the likely route to use is Highway 87/287, which runs alongside the monument. Even without a completed vibration impact study, the importance of maintaining road surfaces to reduce vibrations is clear (King and King 2003). The National Park Service should work with the Arizona Department of Transportation to identify means such as speed limits, road surface, dust reduction measures, and passing and turning lanes to help minimize environmental and safety impacts on park resources and visitors (Julia Brunner, NPS Geologic Resources Division, Energy and Mineral Branch, policy & regulatory specialist, email communication, 6 April 2018).

Fugitive dust caused by heavy, fast-moving trucks hauling copper cathode is an associated impact. Traffic stirs up the dust, which is made available for transport by wind (see "Surrounding Land Use").

ISCR solution will be injected into a copper-bearing zone below the surface, so injection-induced earthquakes are another potential impact. A combination of many factors is necessary for injection to induce felt earthquakes. These include the injection rate and total volume injected, the presence of faults that are large enough to produce felt earthquakes (notably, no active faults have been mapped at Florence; see "Seismic Hazards"), stresses that are large enough to produce earthquakes, and the presence of pathways for the fluid pressure to travel from the injection point to faults. Seismicity can be induced at distances of 16 km (10 mi) or more away from the injection point and at significantly greater depths than the injection point (US Geological Survey 2018).

The National Park Service works with adjacent land managers and other permitting entities to help ensure that NPS resources and values are not adversely impacted by external mineral exploration and development. The NPS Geologic Resources Division, Energy and Minerals website, http://go.nps.gov/grd_energyminerals, provides additional information. Monument managers are encouraged to contact the

Figure 12. Photograph of drill rigs at Florence Copper.
The Florence Copper production test facility is 12 km (7 mi) northeast of the monument (see fig. 3). The operation, which is presently under construction, is for in situ copper recovery (ISCR). As of March 2018, five drill rigs were working 24/7 to install injection and recovery wells, monitoring wells, and replacement irrigation wells. Florence Copper Inc. photograph available at https://www.florencecopper.com/media/photo-gallery (accessed 7 August 2018). Used by permission.

NPS Geologic Resources Division for technical and policy assistance.

Seismic Hazards

Seismic hazards in Arizona can be considered from two perspectives: (1) the distribution and size of historical earthquakes and (2) the distribution of potentially active faults that might generate large earthquakes. These are considered in turn in the following discussion; connections are made to the monument.

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 (fig. 13), 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 near the Arizona (US)–Sonora (Mexico) border (Arizona Geological Survey 2018). The earthquake predated establishment of the monument, and at that time, only a stage coach route (no town) existed (National Park Service 2006). Nevertheless, this earthquake was felt widely throughout the Southwest, including in Phoenix and Tucson, and would have been felt at the monument (had anyone been there). Shaking during the Sonoran earthquake was estimated by Scarborough and Pearthree (1988) at intensity level VI on the Modified Mercalli Intensity (MMI) Scale (fig. 13). The MMI Scale has 12 levels (I–XII) that quantify shaking and damage

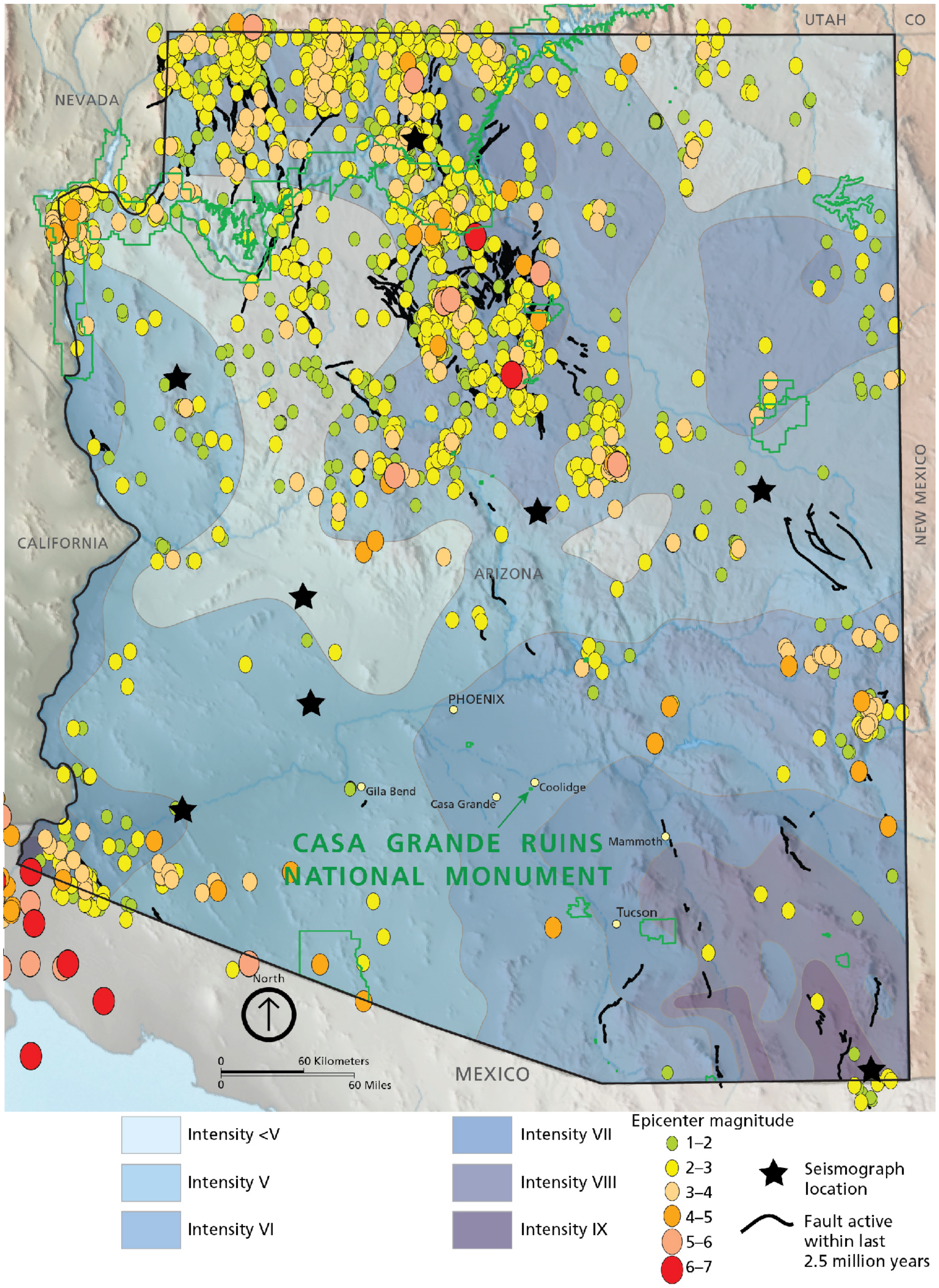

Figure 13. Map of active faults, earthquakes, and seismograph stations in Arizona.
Each year hundreds of unfelt and several felt earthquakes are recorded in Arizona. These earthquakes generally occur within a swath from the north-northwestern to the southeastern part of the state. The Yuma area (southwestern corner of the state) also has earthquakes. Most earthquake activity is located within 8–16 km (5–10 mi) of known faults. The closest active faults to the monument are approximately 100 km (60 mi) to the west (near Gila Bend) and about 90 km (60 mi) to the east (near Mammoth). This map also delineates Modified Mercalli Scale intensities of the 1887 Sonoran earthquake, 1940 Imperial Valley earthquake in southern California (felt in the Yuma area), and three magnitude 6 earthquakes in the early 1900s, which caused damage in the Flagstaff–Grand Canyon region. These show that the state has been subject to intensities of up to IX. Graphic by Trista Thornberry-Ehrlich (Colorado State University) using AZGS graphics and data available at http://azgs.arizona.edu/center-natural-hazards/earthquakes, http://data.azgs.az.gov/hazard-viewer/, and http://www.azgs.az.gov/eq_monitor.shtml (accessed 20 April 2018); and Arizona Earthquake Information Center graphic available at https://www.cefns.nau.edu/Orgs/aeic/ground_shaking.html (accessed 19 April 2018). Base map by Tom Patterson (National Park Service).

based on eyewitness accounts and post-earthquake assessments. 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. To put this in context, 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 (see https://earthquake.usgs.gov/learn/topics/mercalli.php).

The Richter Scale is commonly used to measure the magnitude (energy released) of an earthquake. Using seismograph oscillations, the 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. The Sonoran earthquake was magnitude 7.6 (Arizona Geological Survey 2018). Many earthquakes ranging in magnitude up to about 6 have occurred within Arizona (Beyer and Pearthree 1994).

Active Faults

With respect to the distribution of potentially active faults, geologic investigations indicate that at least 23 faults in Arizona have been active in the past 100,000 years, and thus considered potential sources for future earthquakes. Nearly all of these faults are located within a broad band stretching from northwest to southeast across the state (fig. 13). The Yuma area at the southwestern corner of the state also has active faults; active faults in the Yuma area are associated with the San Andreas Fault system of California and Baja California (Beyer and Pearthree 1994).

The closest active faults to the monument are approximately 100 km (60 mi) to the west (near Gila Bend) and about 90 km (60 mi) to the east (near Mammoth). None of the faults in the GRI GIS data (see poster, in pocket) is considered active. The AZGS "Natural Hazards in Arizona" map viewer (http://data.azgs.az.gov/hazard-viewer/) shows faults that are known to have been active within the last 2.5 million years (Quaternary Period), and thus have some chance to generate an earthquake.

Seismic Monitoring

Earthquake monitoring in Arizona occurs at seismograph stations throughout the state (fig. 13). Most of these stations are maintained by two seismograph networks: the Northern Arizona Seismograph Network (NASN) and the Arizona Broadband Seismograph Network (ABSN). The NASN is supported and maintained by the Arizona Earthquake Information Center at Northern Arizona University in Flagstaff. The ABSN is maintained cooperatively by the Arizona Information Center and the Arizona Geological Survey. Additional support is provided by the Arizona Division of Emergency Management and the three state universities.

The *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. This information may be useful for understanding earthquake-induced ground shaking at the monument (see "Future Geologic Investigations").

Historic Flooding and Flood Potential

Flooding along the middle Gila River is a significant part of the monument's geologic (and human) story (see Huckleberry 1994a). Historical records (e.g., survey plats and anecdotal evidence) indicate that between 1696 and 1891, the middle Gila River was characterized by a single, narrow channel lined by tall trees (Rea 1983). This channel form was maintained despite catastrophic floods in 1833 and 1868 (Dobyns 1981). Obvious bank erosion and channel widening took place in 1891 (Huckleberry 1993b), but it was not until the flood of 1905 that the middle Gila River changed from a single, slightly sinuous, narrow channel to a wide, straight, braided streambed with channels and sand and gravel bars. The flood of 1905 and subsequent floods in 1914 and 1916 resulted in repeated bank cutting and maintenance of this wide, braided channel form.

In 1928 when the Coolidge Dam was constructed upstream from the monument, the channel was still wide, but it began to narrow in the 1950s through 1980s due to reduced flood frequency (Gary Huckleberry, University of Arizona, adjunct researcher and lecturer, written communication, 26 May 2018). The channel widened tremendously again during the floods of January and February 1993, which resulted in the most dramatic channel widening since 1905 (Huckleberry 1994a).

After 1928, drier conditions and the Coolidge Dam effectively decreased the frequency of large floods passing through the drainage, and since that time, the middle Gila River has been mostly dry (Huckleberry 1994a). Only during extreme floods, such as that of October 1983 and January–February 1993, does the river have enough flow to reach the Salt River.

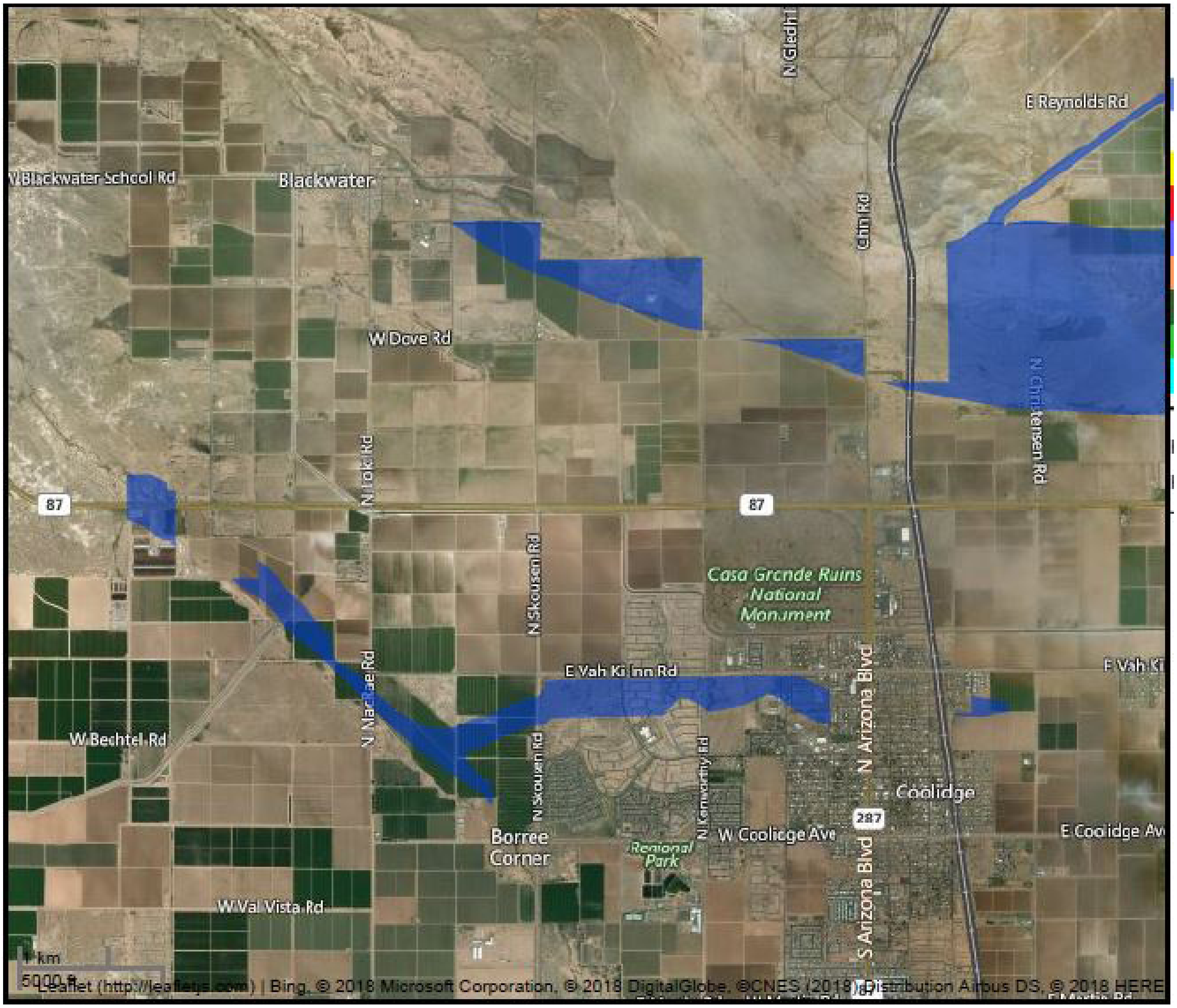

Figure 14. Map of flood potential.
Areas with high flood potential are shown in blue as represented by the 100- and 500-year flood zones determined by the Federal Emergency Management Agency (FEMA) digital flood insurance rate maps (DFIRM) database, dated May 2010. Flood hazard data are currently unavailable for tribal lands in Arizona, which is why the Gila River flood hazard suddenly appears "high" at the boundaries of the Gila River Indian Community, north of the monument. South of the monument, flooding occurs along McClelland Wash. Graphic generated from AZGS "Natural Hazards in Arizona" map viewer at http://data.azgs.az.gov/hazard-viewer/ (accessed 1 May 2018).

At present, the monument sits above the active channel (**Qycr**) and floodplain (**Qyr**) (see poster, in pocket), so the surface of the monument (**Qi3r**) is not inundated during floods. The AZGS "Natural Hazards in Arizona" map viewer (http://data.azgs.az.gov/hazard-viewer/) shows the nearest area to the monument with high flood potential as McClellan Wash or south of East Vah Ki Inn Road, south of the monument (fig. 14). Standing water, however, may accumulate as a result of heavy rains during flash floods (National Park Service 2006).

Future Geologic Investigations

This section provides some suggestions for future geologic studies. This list is primarily an outcome of the discussion during the 2018 conference call. It is not an exhaustive list of research, nor is it a list of the highest priority research to support park management. Some of the suggested studies have clear ties to park management issues; other studies have broader interests and applications.

The NPS Geologic Resources Division administers the Geoscientists-In-the-Parks (GIP; http://go.nps.gov/gip) and Mosaics in Science (http://go.nps.gov/mosaics) programs. These internship programs place scientists (typically undergraduate students) in parks to complete geoscience-related projects; they are potential sources for recruiting assistance for projects listed here and in "Geologic Resources Management Issues."

Geoarchaeology

During the 2018 conference call, Superintendent Karl Pierce requested that information on the river terraces and basins for the Salt, San Pedro, and Santa Cruz Rivers, in addition to the Gila River, be included in the GRI report. Pierce believes this information will be useful to monument managers' understanding and interpretation of the geology of the geographic area inhabited by the Ancestral Sonoran Desert People.

Preliminary research driven by this request suggests a modification to it. That is, river terraces, not basins, are the stratigraphic deposits of interest. Study of basin-fill deposits is unlikely to yield much information about the Ancestral Sonoran Desert People because the basin-filling episode generally predates the Quaternary Period (the past 2.6 million years).

Thoroughly addressing this request is beyond the scope of this GRI report primarily because GRI reports focus on a specific area defined by the GRI GIS data. In the case of Casa Grande Ruins National Monument, these data include only a segment of the middle Gila River (see "Geologic Map Data" and poster, in pocket). Furthermore, this request gets into the realm of geoarchaeology—a multidisciplinary approach that uses the techniques and methods of the earth sciences to examine topics that inform archeological knowledge and thought, and vice versa. Applying archeological methods is beyond GRI objectives. Nevertheless, the following sources of information, which will be useful for future geoarchaeological studies, are provided with this GRI report:

- An index map of geologic maps that intersect the Gila, Salt, Santa Cruz, and San Pedro Rivers (in pocket). Most of these maps are at a scale of 1:24,000, which is a scale useful for resource management and a solid starting point for future geoarchaeological studies.
- A bibliography of these geologic maps (table 4; unless cited elsewhere in this report, these citations are not listed in "Literature Cited").
- A list of selected geoarchaeology references for these river corridors (see below; these are also listed in "Literature Cited").
- Compiled geologic information useful for future geoarchaeological studies (tables 2 and 3).

Of the four rivers of interest (Gila, Salt, San Pedro, and Santa Cruz Rivers), the San Pedro River has 1:24,000-scale mapping of the entire river corridor as well as the river's two tributaries—Aravaipa Creek and Babocomari River (Cook et al. 2009). This mapping effort (Digital Map - River Map 01 DM-RM-01) is not listed on the map index (in pocket), which shows individual 7.5' quadrangle maps. Cook et al. (2009) contains six map sheets, GIS data, and a written report, which can be downloaded from the Arizona Geological Survey's website at http://repository.azgs.az.gov/uri_gin/azgs/dlio/799. In addition, Onken et al. (2014), which builds upon mapping by Cook et al. (2009), completed a geoarchaeological study of the Holocene stream terraces of the San Pedro River. Thus, geoarchaeological information and understanding are quite complete for the San Pedro River. No such mapping or study has been completed for the other three rivers of interest.

Cook et al. (2009) was a component of a much larger geological mapping project conducted by the Arizona Geological Survey (AZGS) for the Arizona Department of Water Resources (ADWR). That project also produced 1:24,000-scale maps for the Verde River (Cook et al. 2010b) and Verde River tributaries (Cook et al. 2010a). Incorporating the Verde River and Verde River tributaries mapping into the GRI GIS data is a possible future ("Inventory 2.0") project for Tuzigoot and Montezuma Castle National Monuments (see GRI reports by KellerLynn in progress). Unfortunately, the Santa Cruz, Salt, and Gila Rivers were not part of this ADWR–AZGS effort. Perhaps the Arizona Department of Water Resources will eventually restart mapping efforts along other major rivers in Arizona, but the Arizona Geological Survey does not have any definitive information about that possibility (Phil Pearthree, AZGS, director, email communication, 21 March 2018).

Other geologic mapping efforts along the Gila River, which began in the 1990s, is ongoing, and by the end of 2019, the Arizona Geological Survey will have "a pretty good picture of the Gila River valley." Once current mapping efforts are completed, Gila River valley maps may be compiled and offered as a larger database for those interested (Joe Cook, AZGS, research geologist, email communication, 21 March 2018). That completed project would be of great value to future geoarchaeological studies related to the monument, particularly if a correlation of map units used by past authors is provided (see table 2).

A considerable amount of geoarchaeological work has been performed along the Santa Cruz River and its tributaries in the Tucson Basin area. Unfortunately, much of that work is in the "gray" literature of cultural resource management reports (Gary Huckleberry, University of Arizona, adjunct researcher and lecturer, written communication, 26 May 2018). Researching gray literature, including checking with local cultural resource management companies for such publications, could be part of a future investigation.

Selected Geoarchaeology References

Reviewing the following articles will provide a more-or-less complete picture of the current geoarchaeological understanding of the Gila River drainage basin; these references are also listed in "Literature Cited." Notably, Waters (2008) provided a geoarchaeological interpretation of the stratigraphic sequences along each of these rivers. Huckleberry et al. (2013) published an updated alluvial chronology for the lower Salt River, including an unexpected discovery of buried late Pleistocene soils and Early Archaic cultural features, which represent the earliest evidence of human activity in the lower Salt River floodplain thus far identified. Onken et al. (2014) utilized archeological site data to provide updated geologic ages of stream terraces along the San Pedro River.

Haynes, C. V., and B. B. Huckell. 1986. Sedimentary successions of the prehistoric Santa Cruz River, Tucson, Arizona. Open-File Report 86-15. Arizona Bureau of Mines and Geology, University of Arizona, Tucson. http://repository.azgs.az.gov/uri_gin/azgs/dlio/453.

Huckleberry, G. A. 1995. Archaeological implications of late-Holocene channel changes on the middle Gila River, Arizona. Geoarchaeology: an international journal 10(3):159–182.

Huckleberry, G., J. Onken, W. M. Graves, and R. Wegener. 2013. Climatic, geomorphic, and archaeological implications of a late Quaternary alluvial chronology for the lower Salt River, Arizona, USA. Geomorphology 185:39–53.

Nials, F., D. Gregory, and J. B. Hill. 2011. The stream reach concept and the macro-scale study of riverine agriculture in arid and semiarid environments. Geoarchaeology 26:724–761.

Onken, J., J. P. Cook, A. Youberg, and P. A. Pearthree. 2014. Geoarchaeological dating of Holocene stream terraces along the San Pedro River, southeastern Arizona, USA. Quaternary International 342:20–32.

Waters, M. R. 1988. Holocene alluvial geology and geoarchaeology of the San Xavier reach of the Santa Cruz River, Arizona. Geological Society of America Bulletin 100:479–491.

Waters, M. R. 2000. Alluvial stratigraphy and geoarchaeology in the American Southwest. Geoarchaeology: an international journal 15(6):537–557.

Waters, M. R. 2008. Alluvial chronologies and archaeology of the Gila River drainage basin, Arizona. Geomorphology 101:332–341.

Waters, M. R., and J. J. Field. 1986. Geomorphic analysis of Hohokam settlement patterns on alluvial fans along the western flack of the Tortolita Mountains [Santa Cruz River area], Arizona. Geoarchaeology: an international journal 1(4):329–345.

Waters, M. R., and J. C. Ravesloot. 2000. Late Quaternary geology of the middle Gila River, Gila River Indian Reservation, Arizona. Quaternary Research 54:49–57.

Waters, M. R., and J. C. Ravesloot. 2001. Landscape change and cultural evolution of the Hohokam along the middle Gila River and other river valleys in south-central Arizona. American Antiquity 66(2):285–299.

Table 4. Bibliography of geologic maps that intersect the Gila, Salt, Santa Cruz, and San Pedro Rivers

*Unless cited elsewhere in this report, these citations are not listed in "Literature Cited."

River	Index map ID	Citation*	Quadrangle
Gila	G1	Youberg, A., J. E. Spencer, and P. A. Pearthree. 2011. Geologic map of the Yuma East 7.5' quadrangle, Yuma County, Arizona (scale 1:24,000). Digital Geologic Map DGM-86. Arizona Geological Survey, Tucson, Arizona. http://repository.azgs.az.gov/uri_gin/azgs/dlio/1361.	Yuma East
Gila	G2	Shipman, T. C., S. M. Richard, and J. E. Spencer. 2006. Geologic Map of the Fortuna 7.5' quadrangle, Yuma County, Arizona (scale 1:24,000). Digital Geologic Map DGM-55. Arizona Geological Survey, Tucson, Arizona. http://repository.azgs.az.gov/uri_gin/azgs/dlio/592.	Fortuna
Gila	G3	Olmsted, F. H. 1972. Geologic map of the Laguna Dam 7.5' quadrangle, Arizona and California (scale 1:24,000). Geologic Quadrangle Map GQ-1014. US Geological Survey, Reston, Virginia. https://pubs.er.usgs.gov/publication/gq1014.	Laguna Dam
Gila	G4	Richard, S. M. 1992. Geologic map of the Imperial Reservoir quadrangle, Yuma County, Arizona and Imperial County, California (scale 1:24,000). Open-File Report OFR-92-11. Arizona Geological Survey, Tucson, Arizona. http://repository.azgs.az.gov/uri_gin/azgs/dlio/916.	Imperial Reservoir
Gila	G5	Gilbert, W. G. 1991. Bedrock geology of the eastern Gila Bend Mountains, Maricopa County, Arizona (scale 1:24,000). Open-File Report OFR-91-05. Arizona Geological Survey, Tucson, Arizona. http://repository.azgs.az.gov/uri_gin/azgs/dlio/903.	Spring Mountain; Cotton Center; Cotton Center NW; Citrus Valley East
Gila	G6	Pearthree, P. A., C. A. Ferguson, R. C. Harris, and J. P. Cook. 2015. Geologic map of the Wintersburg 7.5' quadrangle and parts of the Arlington, Gillespie, and Tonopah quadrangles, Maricopa County, Arizona (scale 1:24,000). Digital Geologic Map DGM-77. Arizona Geological Survey, Tucson, Arizona. http://repository.azgs.az.gov/uri_gin/azgs/dlio/1645.	Arlington
Gila	G7	Skotnicki, S. J. 2002. Geologic map and report for the Buckeye 7.5' quadrangle, Maricopa County, Arizona (scale 1:24,000). Digital Geologic Map DGM-15. Arizona Geological Survey, Tucson, Arizona. http://repository.azgs.az.gov/uri_gin/azgs/dlio/484.	Buckeye
Gila	G8	Skotnicki, S. J. 2002. Geologic map and report for the Avondale SW 7.5' quadrangle, Maricopa County, Arizona (scale 1:24,000). Digital Geologic Map DGM-16. Arizona Geological Survey, Tucson, Arizona. http://repository.azgs.az.gov/uri_gin/azgs/dlio/487.	Avondale SW
Gila	G9	Field, J. J., and P. A. Pearthree. 1991. Surficial geology around the White Tank Mountains, central Arizona (scale 1:24,000). Open-File Report OFR-91-08. Arizona Geological Survey, Tucson, Arizona. http://repository.azgs.az.gov/uri_gin/azgs/dlio/906.	Perryville
Gila	G10	Huckleberry, G. 1992 (maps revised June 1994). Surficial geology of the eastern Gila River Indian Community Area, western Pinal County, Arizona (scale 1:24,000). Open-File Report OFR-92-07. Arizona Geological Survey, Tucson, Arizona. http://repository.azgs.az.gov/uri_gin/azgs/dlio/914.	Blackwater; Gila Butte; Gila Butte SW; Gila Butte NW; Sacaton; Sacaton Butte
Gila	G11	Huckleberry, G. 1993. Surficial geology of the middle Gila River area, north-central Pinal County, Arizona (scale 1:24,000). Open-File Report OFR-93-03. Arizona Geological Survey, Tucson, Arizona. http://repository.azgs.az.gov/uri_gin/azgs/dlio/447.	Florence; Florence SE; Grayback; North Butte
Gila	G12	Cornwall, H. R., and M. H. Kreiger. 1975. Geologic map of the Kearny quadrangle, Pinal County, Arizona (scale 1:24,000). Geologic Quadrangle Map GQ-1188. US Geological Survey, Reston, Virginia. https://pubs.er.usgs.gov/publication/gq1188.	Kearny
Gila	G13	Banks, N. G., and M. H. Krieger. 1977. Geologic map of the Hayden quadrangle, Pinal and Gila Counties, Arizona (scale 1:24,000). Geologic Quadrangle Map GQ-1391. US Geological Survey, Reston, Virginia. https://pubs.er.usgs.gov/publication/gq1391.	Hayden
Gila	G14	Willden, R. 1964. Geology of the Christmas quadrangle, Gila and Pinal Counties, Arizona (scale 1:62,500). Bulletin B-1161-E. US Geological Survey, Reston, Virginia. https://pubs.er.usgs.gov/publication/b1161E.	Mescal Warm Spring; Christmas; Coolidge Dam

River	Index map ID	Citation*	Quadrangle
Gila	G15	Youberg, A. M., and J. P. Cook. 2017. Geologic map of the Pima and southern half of the Markham Creek 7.5′ quadrangles, Graham County, Arizona, v. 1.0 (scale 1:24,000). Digital Geologic Map DGM-120. Arizona Geological Survey, Tucson, Arizona. http://repository.azgs.az.gov/uri_gin/azgs/dlio/1738.	Pima
Gila	G16	Youberg, A. 2013. Geologic map of the Thatcher 7.5′ quadrangle, Graham County, Arizona (scale 1:24,000). Digital Geologic Map DGM-105. Arizona Geological Survey, Tucson, Arizona. http://repository.azgs.az.gov/uri_gin/azgs/dlio/1550.	Thatcher
Gila	G17	Cook, J. P., and A. Youberg. 2013. Geologic map of the Safford 7.5′ quadrangle, Graham County, Arizona (scale 1:24,000). Digital Geologic Map DGM-104. Arizona Geological Survey, Tucson, Arizona. http://repository.azgs.az.gov/uri_gin/azgs/dlio/1551.	Safford
Gila	G18	Richter, D. H., B. B. Houser, and P. E. Damon. 1983. Geologic map of the Guthrie quadrangle, Graham and Greenlee Counties, Arizona (scale 1:48,000). Miscellaneous Investigations Series Map I-1455. US Geological Survey, Reston, Virginia. https://pubs.er.usgs.gov/publication/i1455.	Gila Box; Guthrie
Gila	G19	Morrison, R. B. 1965. Geologic map of the Duncan and Canador Peak quadrangles, Arizona and New Mexico (scale 1:48,000). Miscellaneous Geologic Investigations Map I-442. US Geological Survey, Reston, Virginia. https://pubs.er.usgs.gov/publication/i442.	Duncan; Canador Peak
Gila	G20	Hedlund, D. C. 1980. Geologic map of the Redrock NW quadrangle, Grant County, New Mexico (scale 1:24,000). Miscellaneous Field Studies Map MF-1263. US Geological Survey, Reston, Virginia. https://pubs.er.usgs.gov/publication/mf1263.	Redrock
Gila	G21	McLemore, V. T. 2005. Geologic map of the Wild Horse Mesa area, Grant County, New Mexico (scale 1:48,000). Open-File Report OFR-486. New Mexico Bureau of Geology and Mineral Resources, Socorro, New Mexico. https://geoinfo.nmt.edu/publications/openfile/details.cfml?Volume=486.	Mangas Springs
Gila	G22	Ratté, J. C., and D. L. Gaskill. 1975 (reprinted 2002). Reconnaissance geologic map of the Gila Wilderness study area, southwestern New Mexico (scale 1:62,500). Geologic Investigations Series Map I-886. US Geological Survey, Washington, DC. http://pubs.er.usgs.gov/publication/i886. Note: GRI GIS data are available for this map (see GRI report about Gila Cliff Dwelling National Monument by KellerLynn 2014).	Canteen Canyon; Canyon Hill; Granny Mountain
Gila	G23	Ratté, J. C., D. L. Gaskill, and J. R. Chappell. 2014. Geologic map of the Gila Hot Springs 7.5′ quadrangle, and the Gila Cliff Dwellings National Monument, Catron and Grant Counties, New Mexico (scale 1:24,000). Open-File Report OFR-2014-1036. US Geological Survey, Reston, Virginia. https://pubs.er.usgs.gov/publication/ofr20141036. Note: GRI GIS data are available for this map (see GRI report about Gila Cliff Dwelling National Monument by KellerLynn 2014).	Gila Hot Springs; Little Turkey Park
Salt	S1	Péwé, T. L., C. S. Wellendorf, and J. T. Bales. 1986. Geology, Tempe quadrangle, Maricopa County, Arizona (scale 1:24,000). Geologic Investigations Maps GI-2-A. Arizona Bureau of Geology and Mineral Technology, Tucson, Arizona. http://repository.azgs.az.gov/uri_gin/azgs/dlio/1413.	Tempe
Salt	S2	Skotnicki, S. J., and C. A. Ferguson. 1996. Bedrock geologic map of the Apache Junction and Buckhorn quadrangles, Maricopa and Pinal Counties, Arizona (scale 1:24,000). Open-File Report OFR-96-08. Arizona Geological Survey, Tucson, Arizona. http://repository.azgs.az.gov/uri_gin/azgs/dlio/244.	Buckhorn
Salt	S3	Scarborough, R. B. 1981. Reconnaissance geology, Salt River—from Roosevelt Dam to Granite Reef Dam, central Arizona (scale 1:50,000). Open-File Report OFR-81-30. Arizona Bureau of Geology and Mineral Technology, Tucson, Arizona. http://repository.azgs.az.gov/uri_gin/azgs/dlio/1323.	Granite Reef Dam
Salt	S4	Skotnicki, S. J., and R. S. Leighty. 1997. Geologic map of the Stewart Mountain quadrangle, Maricopa Counties, Arizona (scale 1:24,000). Open-File Report OFR-97-12. Arizona Geological Survey, Tucson, Arizona. http://repository.azgs.az.gov/uri_gin/azgs/dlio/816.	Stewart Mountain

River	Index map ID	Citation*	Quadrangle
Salt	S5	Ferguson, C. A., and W. G. Gilbert. 1997. Geology of the Mormon Flat Dam quadrangle, Maricopa County, Arizona (scale 1:24,000). Open-File Report OFR-97-14. Arizona Geological Survey, Tucson, Arizona. http://repository.azgs.az.gov/uri_gin/azgs/dlio/239.	Mormon Flat Dam
Salt	S6	Gilbert, W. G., and C. A. Ferguson. 1997. Geology of the Horse Mesa Dam quadrangle, Maricopa County, Arizona (scale 1:24,000). Open-File Report OFR-97-15. Arizona Geological Survey, Tucson, Arizona. http://repository.azgs.az.gov/uri_gin/azgs/dlio/238.	Horse Mesa Dam
Salt	S7	Spencer, J. E., S. M. Richard, C. A. Ferguson, and W. G. Gilbert. 1999. Preliminary bedrock geologic map and cross sections of the Windy Hill 7.5′ quadrangle, Gila County, Arizona (scale 1:24,000). Open-File Report OFR-99-12. Arizona Geological Survey, Tucson, Arizona. http://repository.azgs.az.gov/uri_gin/azgs/dlio/1045.	Windy Hill
Salt	S8	Faulds, J. E. 1989. Geologic map of the Salt River region, Rockinstraw Mountain quadrangle, Gila County, Arizona (scale 1:24,000). Contributed Map CM-89-B. Arizona Geological Survey, Tucson, Arizona. http://repository.azgs.az.gov/uri_gin/azgs/dlio/728.	Dagger Peak; Meddler Wash
Santa Cruz	SC1	Pearthree, P. A., C. A. Ferguson, and M. K. Mahan. 2008. Geologic map of the Antelope Peak NE 7.5′ quadrangle and the southern 2/3 of the Maricopa 7.5′ quadrangle, Pinal County, Arizona (scale 1:24,000). Digital Geologic Map DGM-63. Arizona Geological Survey, Tucson, Arizona. http://repository.azgs.az.gov/uri_gin/azgs/dlio/615.	Maricopa
Santa Cruz	SC2	Klawon, J. E., P. A. Pearthree, S. J. Skotnicki, and C. A. Ferguson. 1998. Geology and geologic hazards of the Casa Grande area, Pinal County, Arizona (scale 1:24,000). Open-File Report OFR-98-23. Arizona Geological Survey, Tucson, Arizona. http://repository.azgs.az.gov/uri_gin/azgs/dlio/381.	Casa Grande West; Chuichu; Stanfield
Santa Cruz	SC3	Jackson, G. 1990. Surficial geologic maps of the Picacho Basin (scale 1:24,000). Open-File Report OFR-90-02. Arizona Geological Survey, Tucson, Arizona. http://repository.azgs.az.gov/uri_gin/azgs/dlio/321.	Casa Grande Mountains; Eloy South
Santa Cruz	SC4	Ferguson, C. A., W. G. Gilbert, J. E. Klawon, P. A. Pearthree, and L. Peters. 1999. Geologic map of the Sawtooth Mountains and the north end of the West Silver Bell Mountains, Pinal and Pima Counties, Arizona (scale 1:24,000). Open-File Report OFR-99-16. Arizona Geological Survey, Tucson, Arizona. http://repository.azgs.az.gov/uri_gin/azgs/dlio/1048.	Arizona City
Santa Cruz	SC5	Ferguson, C. A., W. G. Gilbert, T. R. Orr, J. E. Spencer, S. M. Richard, and P. A. Pearthree. 1999 (revised September 2000). Geologic map of the Samaniego Hills, Pinal and Pima Counties, southern Arizona (scale 1:24,000). Open-File Report OFR-99-17. Arizona Geological Survey, Tucson, Arizona. http://repository.azgs.az.gov/uri_gin/azgs/dlio/1049.	Friendly Corners; Samaniego Hills
Santa Cruz	SC6	Field, J. J., and P. A. Pearthree. 1993. Surficial geologic maps of the northern Avra Valley—Desert Peak area, Pinal and Pima Counties, southern Arizona (scale 1:24,000). Open-File Report OFR-93-13. Arizona Geological Survey, Tucson, Arizona. http://repository.azgs.az.gov/facets/results/OFR-93-13.	Red Rock; West of Marana
Santa Cruz	SC7	McKittrick, M. A. 1988. Surficial geologic maps of the Tucson metropolitan area (scale 1:24,000). Open-File Report OFR-88-18. Arizona Geological Survey, Tucson, Arizona. http://repository.azgs.az.gov/uri_gin/azgs/dlio/346.	Tucson; Tucson North; Jaynes; Ruelas Canyon; Marana
Santa Cruz	SC8	Jackson, G. W. 1989. Surficial geologic maps of the northeastern, southeastern, and southwestern portions of the Tucson metropolitan area (scale 1:24,000). Open-File Report OFR-89-02. Arizona Geological Survey, Tucson, Arizona. http://repository.azgs.az.gov/uri_gin/azgs/dlio/324.	Tucson SW
Santa Cruz	SC9	Pearthree, P. A., and A. Youberg. 2000. Surficial geologic maps and geologic hazards of the Green Valley—Sahuarita area, Pima County, Arizona, v. 1.0 (scale 1:24,000). Digital Geologic Map DGM-03. Arizona Geological Survey, Tucson, Arizona. http://repository.azgs.az.gov/uri_gin/azgs/dlio/463.	Esperanza Mill; Sahuarita

River	Index map ID	Citation*	Quadrangle
Santa Cruz	SC10	Youberg, A., and W. R. Helmick. 2001. Surficial geology and geologic hazards of the Amado-Tubac area, Santa Cruz and Pima Counties, Arizona (scale 1:24,000). Digital Geologic Map DGM-13. Arizona Geological Survey, Tucson, Arizona. http://repository.azgs.az.gov/uri_gin/azgs/dlio/480. Note: GRI GIS data are available for this map (see GRI report about Tumacácori National Historical Park by Graham 2011b).	Amado; Tubac
Santa Cruz	SC11	Page, W. R., C. M. Menges, F. Gray, M. E. Berry, M.W. Bultman, M. A. Cosca, and D. P. VanSistine. 2016. Geologic map of the Rio Rico and Nogales 7.5′ quadrangles, Santa Cruz County, Arizona (scale 1:24,000). Scientific Investigations Map SIM-3354. US Geological Survey, Reston, Virginia. https://pubs.er.usgs.gov/publication/sim3354.	Rio Rico
Gila-San Pedro	SP1	Krieger, M. H. 1974. Geologic map of the Winkelman quadrangle, Pinal and Gila Counties, Arizona (scale 1:24,000). Geologic Quadrangle Map GQ-1106. US Geological Survey, Reston, Virginia. https://pubs.er.usgs.gov/publication/gq1106.	Winkelman
San Pedro	SP2	Young, J. J., J. E. Spencer, B. J. MacFarlane, and S. M. Richard. 2009. Geologic map of the Lookout Mountain 7.5′ quadrangle, Pinal County, Arizona (scale 1:24,000). Digital Geologic Map DGM-66. Arizona Geological Survey, Tucson, Arizona. http://repository.azgs.az.gov/uri_gin/azgs/dlio/621.	Lookout Mountain
San Pedro	SP3	Spencer, J. E., B. F. Gootee, S. M. Richard, and J. P. Cook. 2009. Geologic map of the Mammoth 7.5′ quadrangle, Pinal County, Arizona (scale 1:24,000). Digital Geologic Map DGM-67. Arizona Geological Survey, Tucson, Arizona. http://repository.azgs.az.gov/uri_gin/azgs/dlio/624.	Mammoth
San Pedro	SP4	Gootee, B. F., J. E. Spencer, C. A. Ferguson, S. M. Richard, J. P. Cook, and B. J. MacFarlane. 2009. Geologic map of the Clark Ranch 7.5′ quadrangle and the west half of the Rhodes Peak 7.5′ quadrangle, Pinal and Graham Counties, Arizona (scale 1:24,000). Digital Geologic Map DGM-68. Arizona Geological Survey, Tucson, Arizona. http://repository.azgs.az.gov/uri_gin/azgs/dlio/626.	Clark Ranch
San Pedro	SP5	Pearthree, P. A., J. P. Cook, S. J. Skotnicki, and J. E. Spencer. 2009. Geologic map of the Peppersauce Wash 7.5′ quadrangle and part of the Kielberg Canyon 7.5′ quadrangle, Pinal and Pima Counties, Arizona (scale 1:24,000). Digital Geologic Map DGM-69. Arizona Geological Survey, Tucson, Arizona. http://repository.azgs.az.gov/uri_gin/azgs/dlio/629.	Kielberg Canyon
San Pedro	SP6	Cook, J. P., and J. E. Spencer. 2008. Geologic map of the Redington 7.5′ quadrangle, Cochise, Graham, and Pima Counties, Arizona (scale 1:24,000). Digital Geologic Map DGM-60. Arizona Geological Survey, Tucson, Arizona. http://repository.azgs.az.gov/uri_gin/azgs/dlio/609.	Redington
San Pedro	SP7	Spencer, J. E., S. M. Richard, J. P. Cook, W. R. Dickinson, S. H. Lingrey, and J. H. Guynn. 2008. Geologic map of the Soza Canyon 7.5′ quadrangle, Cochise and Pima Counties, Arizona (scale 1:24,000). Digital Geologic Map DGM-61. Arizona Geological Survey, Tucson, Arizona. http://repository.azgs.az.gov/uri_gin/azgs/dlio/611.	Soza Canyon
San Pedro	SP8	Spencer, J. E., J. P. Cook, S. H. Lingrey, S. M. Richard, C. A. Ferguson, and J. H. Guynn. 2008. Geologic map of the Wildhorse Mountain 7.5′ quadrangle, Cochise County, Arizona (scale 1:24,000). Digital Geologic Map DGM-62. Arizona Geological Survey, Tucson, Arizona. http://repository.azgs.az.gov/uri_gin/azgs/dlio/613.	Wildhorse Mountain
San Pedro	SP9	Youberg, A., S. M. Richard, and J. E. Spencer. 2006. Geologic map of the Galleta Flat East 7.5′ quadrangle, Cochise County, Arizona (scale 1:24,000). Digital Geologic Map DGM-56. Arizona Geological Survey, Tucson, Arizona. http://repository.azgs.az.gov/uri_gin/azgs/dlio/594.	Galleta Flat East
San Pedro	SP10	Youberg, A., S. J. Skotnicki, T. C. Shipman, and C. A. Ferguson. 2004. Geologic map of the Benson 7.5′ quadrangle, Cochise County, Arizona (scale 1:24,000). Digital Geologic Map DGM-34. Arizona Geological Survey, Tucson, Arizona. http://repository.azgs.az.gov/uri_gin/azgs/dlio/565.	Benson

River	Index map ID	Citation*	Quadrangle
San Pedro	SP11	Youberg, A. 2006. Geologic map of the Saint David 7.5′ quadrangle, Cochise County, Arizona (scale 1:24,000). Digital Geologic Map DGM-48. Arizona Geological Survey, Tucson, Arizona. http://repository.azgs.az.gov/uri_gin/azgs/dlio/635.	Saint David
San Pedro	SP12	Ferguson, C. A., T. C. Shipman, E. C. Moore, S. M. Richard, and J. E. Spencer. 2006. Geologic map of the Fairbank 7.5′ quadrangle, Cochise County, Arizona (scale 1:24,000). Digital Geologic Map DGM-50. Arizona Geological Survey, Tucson, Arizona. http://repository.azgs.az.gov/uri_gin/azgs/dlio/639.	Fairbank
San Pedro	SP13	Pearthree, P. A., C. A. Ferguson, and K. A. Demsey. 2006. Geologic map of the Lewis Springs 7.5′ quadrangle, Cochise County, Arizona (scale 1:24,000). Digital Geologic Map DGM-51. Arizona Geological Survey, Tucson, Arizona. http://repository.azgs.az.gov/uri_gin/azgs/dlio/640.	Lewis Springs
Gila	SP14	Hon, K. A., F. Gray, K. S. Bolm, K. A. Dempsey, and P. A. Pearthree, 2007. A digital geologic map of the Miller Peak, Nicksville, Bob Thompson Peak, and Montezuma Pass quadrangles, Arizona (scale 1:24,000). Unpublished Scientific Investigations Map. US Geological Survey, Reston, Virginia. https://irma.nps.gov/DataStore/Reference/Profile/2171321. Note: GRI GIS data are available for this map (see GRI report about Coronado National Memorial by Graham 2011a).	Nicksville; Bob Thompson Peak
San Pedro	SP15	Ferguson, C. A., B. J. Johnson, J. Cook, T. C. Shipman, and P. A. Pearthree. 2006. Geologic map of the Hereford 7.5′ quadrangle and the northern part of the Stark 7.5′ quadrangle, Cochise County, Arizona (scale 1:24,000). Digital Geologic Map DGM-57. Arizona Geological Survey, Tucson, Arizona. http://repository.azgs.az.gov/uri_gin/azgs/dlio/605.	Stark; Hereford

Vibration Impact Analysis

The monument's foundation document (National Park Service 2017) identified a "vibration impact analysis" as a data need. As urban traffic and large transport vehicles increase, low-flying aircraft continues, and development of Tucson–Phoenix transportation strategies move forward (fig. 8) (see "Surrounding Land Use"), vibration impacts on the Great House and other archeological sites seem possible but are not fully understood. Identifying potential impacts would help determine adaptive management strategies to mitigate future and contemporary damage. The vibration impact analysis should identify mitigation measures (Julia Brunner, NPS Geologic Resources Division, Energy and Mineral Branch, policy & regulatory specialist, email communication, 6 April 2018).

The foundation document highlighted low-flying aircraft as a potential source of vibrations. Repeated passes of low-flying aircraft may induce vibrations within the Great House and other structures, potentially accelerating erosion and cracking. Other sources of human-caused vibrations include heavy traffic (meaning the amount of traffic as well as the weight of vehicles) and construction (see "Surrounding Land Use").

Natural sources of vibrations include earthquakes (see "Seismic Hazards"). In addition, winds impose a considerable force on exposed walls of archeological structures, initiating vibrations and swaying (King et al. 1985).

During the 2018 conference call, participants posed a potential research question: What magnitude earthquake can the Great House withstand? This question could possibly be investigated as part of a vibration impact study.

Earthquake magnitude is not the only factor of importance, however. King and King (1998) noted the significance of induced vibrations that are in phase or are the same frequency as the natural frequencies of a structure. "When an induced vibration from any source is 'in tune' with that structure, that structure will amplify the induced vibrations—many times to and beyond the point of structure failure" (King and King 1998, p. 1).

Some data about vibrations are currently available, for example, King and King (1998) conducted a "vibration investigation" at the monument. Unlike studies that these investigators conducted elsewhere, however, the 1998 report for the monument provided no guidance for "safe distances" of human activities and did not provide a map that delineated zones within which various vibration-causing sources should be excluded. King and King (1998) did provide a few notable conclusions, however: The original, collective structure of the Great House was robust and could, and probably did, withstand the induced motions from earthquakes without appreciable damage. Now, however, the Great House has been divided into a series of weaker, individual walls, separated by junctions referred to as "vibration hinge-lines." As a result, the structure is no longer acting as a unit, and some of the separate walls are working against each other. Thus, the Great House today is more sensitive to regional earthquakes than the original structure. King and King (1998) noted that the structure is very robust to "local induced vibrations" (presumably those induced during testing, though the meaning is unclear).

Monument managers may find the following vibration studies from other parks of interest and use for planning: King et al. (1985, 1991a) at Chaco Culture National Historical Park (New Mexico), King and Algermissen (1987) at Hovenweep National Monument (Utah and Colorado), King et al. (1988) at White Sands National Monument (New Mexico), and King et al. (1991b) at Pueblo Grande (Phoenix, Arizona).

Researchers at the University of Utah, Department of Geology & Geophysics (see http://geohazards.earth.utah.edu/team.html), are studying and monitoring arches, which are dynamic natural features that bend, sag, sway, and shake in response to a variety of environmental forces (see http://geohazards.earth.utah.edu/arch.html). Findings by Jeffrey Moore (assistant professor) and his colleagues, including PhD candidate Riley Finnegan, whose thesis topic is anthropogenic induced resonance of rock arches, may be applicable to the Great House for understanding its ambient vibrations and deformation. Monument managers are encouraged to contact the NPS Geologic Resources Division (https://www.nps.gov/orgs/1088/contactus.htm) for assistance in finding researchers who have the expertise to conduct a vibration impact study. Monument staff can formally request assistance via https://irma.nps.gov/Star/.

Highly Detailed Spatial Data

The National Park Service has invested time, energy, and money in the collection of highly detailed spatial data for the monument (table 5).

Conference call participants identified two projects for which these data would be useful: a vibration impact study (see "Vibration Impact Analysis") and an inventory of prehistoric borrow pits. Borrow pits, which were mined for caliche by the Ancestral Sonoran Desert People, are significant archeological features (see "Geologic Setting and Significance"). Systematically studying borrow pits has long been on the list of potential research projects at the monument (Casa Grande Ruins National Monument, staff, communication during conference call, 21 February 2018). Wilcox and Shenk (1977) identified this need and concluded that many questions will remain unanswered until a detailed, systematic study of borrow pits is conducted. Lidar may help jumpstart such a study.

Monument staff has observed that mesquite seems to grow in borrow pits because these features collect water (Casa Grande Ruins National Monument, staff, communication during conference call, 21 February 2018). During field verification of borrow pits revealed by lidar, this observation and associated hypothesis (i.e., mesquite marks borrow-pit locations) could be tested.

Monument staff needs assistance with analysis of existing spatial data (see table 5). The monument's foundation document (National Park Service 2017) listed this as a medium-priority need. Analysis of lidar data has the power to discover previously undocumented features such as walls or canals, which may reveal additional human compounds at the monument (Casa Grande Ruins National Monument, staff, communication during conference call, 21 February 2018). Analyzed lidar imagery can be used for park planning, decision making, and preservation (National Park Service 2017).

In analyzing spatial data, having an understanding of geology and geomorphology is important, including when looking for archeological features. For example, certain types of bedrock, such as flagstone, have a tabular form in rock outcrops, which may be misinterpreted as a human construction. Also, linear traces may be windblown features or the result of glacial ice moving across a landscape, not the result of human activity (e.g., clay mining or agricultural furrows).

Both the NPS Southern Arizona Office and Geologic Resources Division have staff with expertise to help process highly detailed spatial data, which can be very unwieldy. Staff members at the Southern Arizona Office have the ability to convert these data into different formats or subsample as needed (Jake DeGayner, NPS Southern Arizona Office, geographer, email communication, 7 August 2018). The Geologic Resources Division also has equipment and software to conduct close-range photogrammetry to create 3D models (e.g., of the Great House). The NPS Geologic Resources Division Photogrammetry website (http://go.nps.gov/grd_photogrammetry) provides more information and examples of a variety of photogrammetry applications for resource management. Monument managers may contact the NPS Geologic Resources Division (https://www.nps.

gov/orgs/1088/contactus.htm) or formally request assistance via https://irma.nps.gov/Star/.

During consultations and meetings during the last four years, the Gila River Indian Community Tribal Historic Preservation Office expressed opposition to use of lidar, as well as ground penetrating radar, at the monument due to concerns of “disturbing the ancestors” (Karl Pierce, Casa Grande Ruins National Monument, superintendent, written communication, 14 July 2018). The use of existing lidar and other highly detailed spatial data needs to be balanced with tribal wishes. The Intermountain Region has a tribal affairs office, which may be able to provide guidance on this matter.

Table 5. Existing spatial data for Casa Grande Ruins National Monument

Data type	Description	Area/feature covered	Provider	Year	Data retained by
Terrestrial laser scanning	3D point clouds of the Great House and compounds A and B. in .xyz text file format. 1-cm topographic map of compound A fill levels, and detailed mapping of Great House levels. Orthophotographic images of Compound A wall face lidar models textured with digital photographs. Some highly decimated polygonal models.	Great House Compound A Compound B	Western Mapping Company	2008–2010	Southern Arizona Office
Aerial photogrammetry	Detailed planimetric map	Compound A Compound B Administrative area	Western Mapping Company	2008–2010	Southern Arizona Office
Aerial lidar and orthophotography	15-cm digital elevation model of the monument. 7.5 cm 4-band orthoimagery. LAS multiple discrete return classified point cloud data.	Monument area	Aerometric/Quantum Geospatial	2013	Southern Arizona Office
Ground penetrating radar	See Doolittle and Carr (2007).	Compound A	Natural Resources Conservation Service (Newton Square, Pennsylvania, and Phoenix, Arizona); National Park Service (Casa Grande Ruins National Monument, Intermountain Regional Office, and Western Archeological Conservation Center); University of Arizona; Arizona State Historic Preservation Office; Statistical Research, Inc. (Tucson, Arizona)	2007	Unknown (Rebecca Carr Wong, Bureau of Land Management, Berryessa Snow Mountain National Monument, national monument manager, email communication to Karl Pierce, 10 September 2018).

Biological and Physical Soil Crusts, Desert Pavement, and Desert Varnish

The monument contains a plethora of surface "crusts." For example, Sonoran Desert Network (2018b) identified biological soils crusts as a "key resources" at the monument. Conference call participants noted that biological soil crusts hold down dust (see "Wind Erosion"). In addition, surficial geologic mapping (e.g., Huckleberry 1992, 1994b) showed that desert pavement (a residual surface of wind erosion, typically composed of gravel and commonly cemented by caliche) is present on geomorphic surfaces (e.g., terraces and alluvial fans) in the Casa Grande Ruins area, and may be present in the monument. Additionally, desert varnish (also called "rock varnish") is present on many geomorphic surfaces in the area. Salt crusts also may be present (National Park Service 2006).

Thus an investigation and inventory of the types of "crusts" (biological, physical, and combinations thereof) and other surface coatings at the monument is likely warranted because of their association with ecosystem health and stability, as well as the possible contribution such an investigation would provide to the ongoing debate about the genesis of desert varnish (see Dickerson 2011).

Various GRI reports provide information about surface crusts, which may be of use to monument managers. The report about Canyonlands National Monument (KellerLynn 2005) and White Sands National Park (KellerLynn 2012) discussed the significance of biological soil crusts in two very different ecosystems. The Canyonlands GRI report addressed impacts from off-trail hiking and the importance of monitoring biological soil crusts. The White Sands GRI report highlighted biological soil crusts as indicators of ecosystem stability, health, and climate change; recovery rates following disturbances; and the use of biological soil crusts in groundwater modeling and interpreting satellite imagery. In addition, the GRI reports about Petrified Forest National Park (KellerLynn 2010) and Petroglyph National Monument (KellerLynn 2017) discussed the significance and genesis of desert varnish.

Geologic Map Data

A geologic map in GIS format is the principal deliverable of the GRI program. GRI GIS data produced for the monument follows the source maps listed here and includes components described in this chapter. A poster (in pocket) displays the data draped over imagery of the monument and surrounding area. Complete GIS data are available at the GRI publications website: http://go.nps.gov/gripubs.

Geologic Maps

A geologic map is the fundamental tool for depicting the geology of an area. Geologic maps are two-dimensional representations of the three-dimensional geometry of rock and sediment at or beneath the land surface (Evans 2016). The colors on a geologic map indicate the rock types or deposits and ages present in an area. On the geologic map for the monument, the browns are the oldest rocks, and the yellows are the youngest deposits. In addition to color, rocks and deposits are delineated as map units, and each map unit is labeled by a symbol. Usually, the map unit symbol consists of an uppercase letter indicating the age (e.g., **Q** for Quaternary or **K** for Cretaceous) and lowercase letters indicating the rock formation's name or the type of deposit (see table 1). Other symbols on geologic maps depict the contacts between map units, structures such as faults or folds, and linear features such as dikes. Some map units, such as landslide deposits, delineate locations of past geologic hazards, which may be susceptible to future activity. Anthropogenic features such as mines or quarries, as well as observation or collection locations, may be indicated on geologic maps. The American Geosciences Institute website, http://www.americangeosciences.org/environment/publications/mapping, provides more information about geologic maps and their uses.

Geologic maps are generally one of two types: surficial or bedrock. Surficial geologic maps typically encompass deposits that are unconsolidated and formed during the past 2.6 million years (Quaternary Period). Surficial map units are differentiated by geologic process or depositional environment. Reports and text that accompany the source maps (discussed below) provide map unit descriptions for the 13 surficial deposits and one artificial deposit that are shown in the GRI GIS data (see table 1 and cagr_geology.pdf). The map unit symbols for these units begin with "**Q**" for the Quaternary Period.

Bedrock geologic maps encompass older, typically more consolidated sedimentary, metamorphic, and/or igneous rocks. Bedrock map units are differentiated based on age and/or rock type. The 16 bedrock map units in the GRI GIS data for the monument consist of Proterozoic ("**X**" and "**Y**" units), Cretaceous ("**K**"), Tertiary and Cretaceous ("**TK**"), and Tertiary ("**T**") rocks exposed in the Santan Mountains north of the monument (see table 1). Richard et al. (2006) mapped these units but only provided descriptions for two of these units. Map unit descriptions for the other 14 map units are provided as part of this report in table 1. These map unit descriptions are from Peterson (1969; geologic map of the Superior quadrangle, Pinal County), Wilson (1969; mapping of mineral deposits of the Gila River Indian Reservation), Ferguson and Skotnicki (1996; bedrock geologic map of the Santan Mountains), and Skotnicki and Ferguson (1996; bedrock geologic map of the Sacaton Mountains), as indicated in table 1.

Source Maps

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

The GRI team used the following three source maps to produce the GRI GIS data for the monument and surrounding area (fig. 15). The data cover the Blackwater and Coolidge quadrangles. Information provided in this report is based on these source maps.

- Northern part of the Blackwater quadrangle, including parts of the middle Gila River channel and Santan Mountains: Richard et al. (2006).
- Southern part of the Blackwater quadrangle, including parts of the middle Gila River and McClellan Wash: Huckleberry (1992).
- Entire Coolidge quadrangle: Klawon et al. (1998).

GRI GIS data include essential elements of source maps such as map unit descriptions, a correlation chart of units, a map legend, map notes, cross sections, figures, and references. These items are included in a GRI ancillary map information document, which for the monument is cagr_geology.pdf.

GRI GIS Data

The GRI team standardizes map deliverables by implementing a data model that is based on an ESRI geodatabase to ensure data quality, product consistency, and that a digital map is user friendly and well communicated. The GRI GIS data model is the architectural blueprint or schema for the GIS data; it includes defining data layers based on spatial representation (i.e., polygon, line, or point) and geologic theme (e.g., faults, folds, and contacts). Feature attribution (how feature information is stored) and geodatabase topology (spatial relationship rules that ensure spatial integrity) are also components of the data model. The GRI GIS data for the monument was compiled using data model version 2.0, which is available at http://go.nps.gov/gridatamodel.

GRI GIS data are available on the GRI publications website http://go.nps.gov/gripubs and through the NPS Integrated Resource Management Applications (IRMA) portal https://irma.nps.gov/App/Portal/Home; enter "GRI" as the search text and select a park from the unit list. The GRI Geologic Maps website, http://go.nps.gov/geomaps, provides more information about the program's map products.

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

- A GIS readme file (readme.txt) that describes the GRI data formats, naming conventions, extraction instructions, use constraints, and contact information;
- Data in ESRI geodatabase GIS format;
- An ESRI map document (cagr_geology.mxd) that displays the GRI GIS data and allows for user interaction and analysis;
- Layer files that contain symbology for each data layer (see table 6);
- Federal Geographic Data Committee (FGDC)–compliant metadata, which are organized in a user-friendly, frequently asked questions (FAQ) format; and
- An ancillary map information document (cagr_geology.pdf) that contains information captured from source maps such as map unit descriptions, geologic unit correlation tables, legends, cross sections, and figures.

Table 6. GRI GIS data layers for Casa Grande Ruins National Monument.

Data Layer	On Poster?	On Google Earth Layer?
Geologic Attitude and Observation Localities	No	No
Mine Point Features (gravel pit and sand pit)	No	No
Faults	Yes	Yes
Linear Dikes	Yes	Yes
Geologic Contacts	Yes	Yes
Geologic Units	Yes	Yes

GRI Map Poster

A poster of the GRI GIS data draped over a shaded relief image of the monument and surrounding area is included with this report. Not all GIS feature classes are included on the poster (see table 6). Geographic information and selected park features have been added to the poster. Digital elevation data and added geographic information are not included in the GRI GIS data, but are available online from a variety of sources. Contact the GRI team for assistance locating these data.

Use Constraints

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

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

The GRI GIS data are a compilation of three source maps (see "Source Maps" and fig. 15). The GRI team strives to remain true to the individual sources, thus in the compilation process, polygons are neither merged across quadrangle boundaries nor adjusted between mapping projects. As a result, discontinuities (commonly called "boundary faults" or "internal map boundaries") may occur. This is the case for the GRI GIS data for the monument (cagr_geology.mxd). Feature discontinuities occur in the Blackwater quadrangle between mapping by Richard et al. (2006) and Huckleberry (1992) as well as along the boundary between the Blackwater and Coolidge quadrangles, which separates mapping by Huckleberry (1992) and Klawon et al. (1998) (fig. 15).

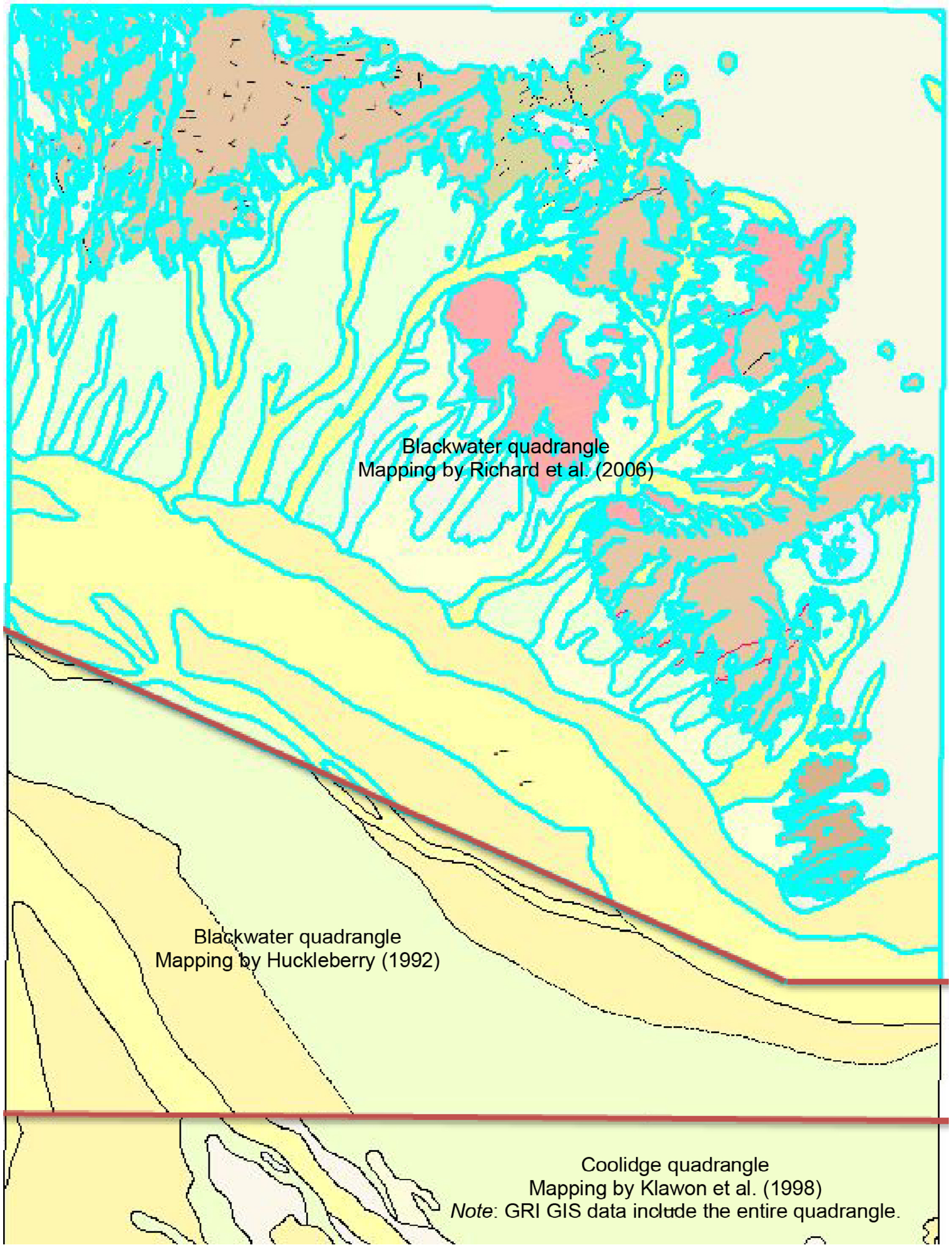

Figure 15. GRI GIS index map.
The GRI team used three source maps to produce the GRI GIS data for the monument and surrounding area. Mapping by Richard et al. (2006) covers the northern part of the Blackwater quadrangle. Mapping by Huckleberry (1992) covers the southern part of the Blackwater quadrangle. Note: The "boundary" between these two mapping projects is not a straight line. Mapping by Klawon et al. (1998) covers the Coolidge quadrangle. Discontinuities ("boundary faults") of adjacent map units are the result of these different mapping projects. Graphic by Stephanie O'Meara (Colorado State University) with annotations by Katie KellerLynn (Colorado State University).

Future Mapping Projects

GRI GIS data for Casa Grande Ruins National Monument encompasses the Blackwater and Coolidge quadrangles. During scoping in 2006, monument staff expressed an interest in obtaining geologic map data for the Florence and Valley Farms quadrangles, east of the monument (fig. 16); the Adamsville site, which is owned by the State of Arizona but of interest for a future boundary expansion, is at the boundary of these two quadrangles (see "Potential Mitigation of Impacts"). At the time of scoping, GRI practice was to only provide data for quadrangles that included portions of the NPS boundary, so the Florence and Valley Farms quadrangles were not included. Should monument staff members still be interested in acquiring geologic data for these quadrangles, they can consultthe Geologic Resources Division and Inventory and Monitoring Division. Such expanded map coverages may be supported under the next generation of NPS inventories, termed "Inventory 2.0," to be initiated in about 2020.

Notably, the information in the scoping summary still appears to hold true (see table 2 in National Park Service 2006); that is, at a scale of 1:24,000, only surficial mapping for the Florence quadrangle is available. Huckleberry (1993a)—which comprises five map sheets (scale 1:24,000), including the Florence quadrangle (sheet 1 of 5)—would serve as the source for these data.

During scoping in 2006, monument staff also expressed an interest in obtaining geologic map data for the Gila Butte NW quadrangle (fig. 16). During the 2018 conference call, monument staff stated that this is still of interest because Hohokam Pima National Monument is within that quadrangle. Hohokam Pima National Monument contains the prehistoric village of Snaketown, which was designated a national historic landmark in 1964. The area was further protected by declaring it a national monument in 1972. It was listed on the National Register of Historic Places in 1974. This site is owned by the Gila River Indian Community; it has no facilities and is not open to the public. Staff members at Casa Grande Ruins National Monument serve as the NPS contact for Hohokam Pima National Monument.

Surficial geologic data at a scale of 1:24,000 for the Gila Butte NW quadrangle could be provided by Huckleberry (1992). That surficial geologic map is sheet 1 in Arizona Geological Survey Open-File Report 92-7. Sheet 6 of that report, which covers the Blackwater quadrangle, was a source map for the current GRI GIS data. Conversion of sheet 1 of Huckleberry (1992) into the GRI GIS data model should be proposed as part of "Inventory 2.0."

Ideally, geologic map coverage for any NPS area includes both surficial and bedrock geologic data. However, 1:24,000-scale, bedrock geologic maps are not available for the Florence, Valley Farms, or Gila River NW quadrangles. Spencer et al. (1996) provided surficial and bedrock geologic mapping for the Mesa 30' × 60' quadrangle (scale 1:100,000), which includes these three quadrangles. That publication does not include detailed map unit descriptions, however. Conversion of the Florence, Valley Farms, or Gila River NW quadrangle areas from the Mesa 30' × 60' quadrangle into the GRI data model and collaboration with the Arizona Geological Survey to develop detailed map unit descriptions should be proposed as part of "Inventory 2.0."

A correlation of Quaternary deposits (table 2) and field verification along the middle Gila River are needed. While in the field, it may be prudent to address the "boundary faults" that were created as result of the juxtaposition of different map units by source map authors (see fig. 15; and poster, in pocket). This may be a project that could be completed by a Geoscientists-In-the-Parks (GIP; http://go.nps.gov/gip) or Mosaics in Science (http://go.nps.gov/mosaics) intern, particularly if it was done under the supervision of the Arizona Geological Survey. The Sonoran Desert Network also may be able to provide assistance (Karl Pierce, Casa Grande Ruins National Monument, superintendent, written communication, 14 July 2018).

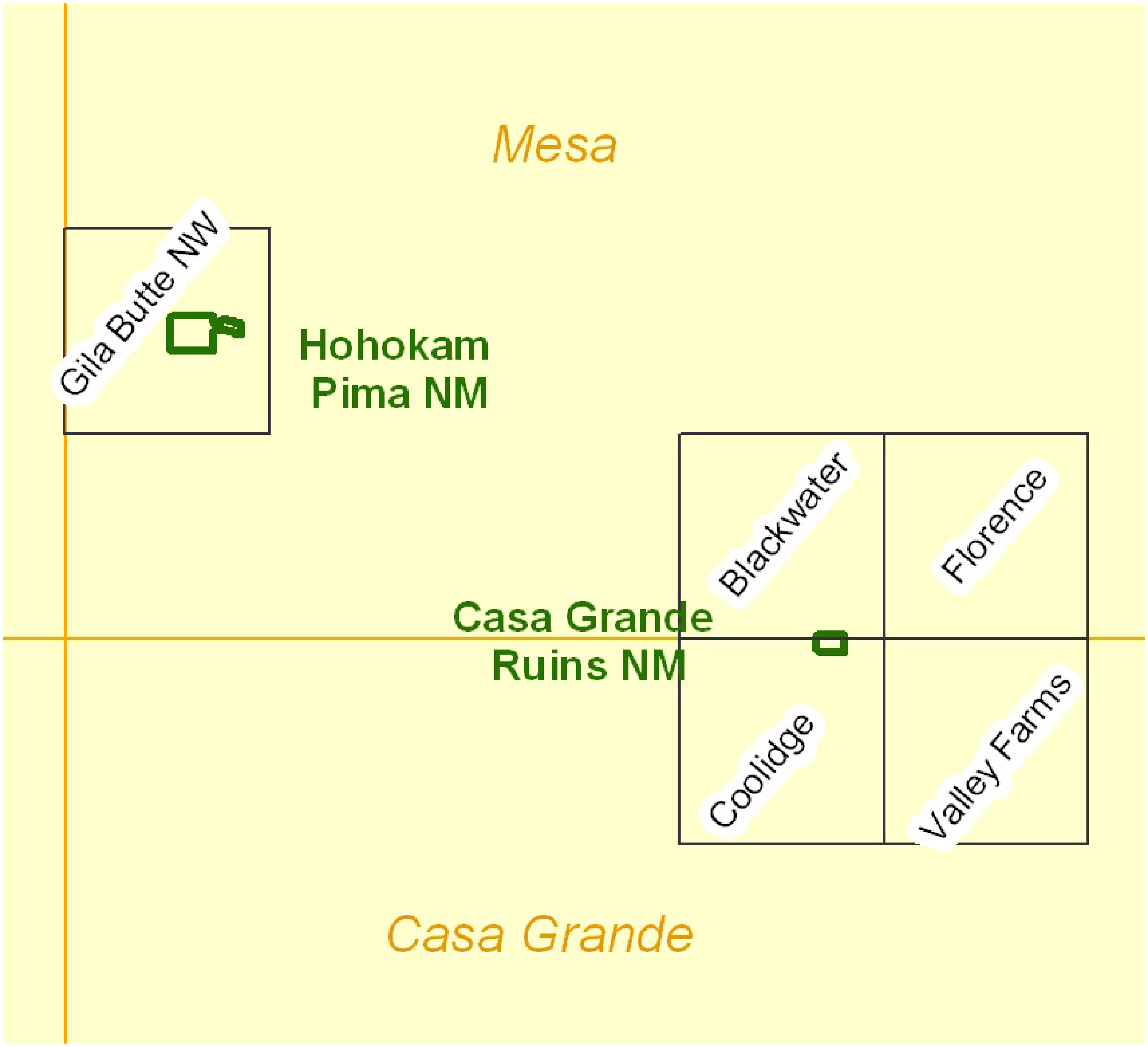

Figure 16. Quadrangles of interest for Casa Grande Ruins National Monument.
The 7.5' quadrangles (scale 1:24,000) are labeled in black. Names in yellow (i.e., “Mesa” and “Casa Grande”) indicate 30' × 60' quadrangles (scale 1:100,000). Green outlines indicate monument boundaries. Currently, GRI map data for the monument cover the Blackwater and Coolidge 7.5' quadrangles. A potential project for “Inventory 2.0” is adding geologic map data for the Gila Butte NW, Florence, and Valley Farms quadrangles. NPS graphic by Tim Connors (NPS Geologic Resources Division).

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Additional Resources

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

Arizona Geological Survey (AZGS) Outreach and Education

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

Arizona Mine Data

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

Climate Change

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

Earth Fissures

- Arizona's Earth Fissure Center: http://www.azgs.az.gov/EFC.shtml
- Arizona Land Subsidence Group (including a white paper on effective risk management): http://www.azlandsubsidence.org/
- AZGS earth fissure brochure (2008): http://www.azgs.az.gov/efresources.shtml
- AZGS earth fissure study area maps: http://www.azgs.az.gov/efresources.shtml
- AZGS tips for reducing the occurrence of earth fissures and their associated effects: http://data.azgs.az.gov/hazard-viewer/mitigation/fissures.html

Geological Surveys and Societies

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

Groundwater Level

- Arizona Department of Water Resources (ADWR): http://www.azwater.gov/azdwr/
- ADWR groundwater site inventory data: http://gisweb.azwater.gov/waterresourcedata/
- Bureau of Reclamation, Central Arizona Project (includes general information, a history of irrigation in the area, details of project construction, and details (and changes) of the authorized plan): https://www.usbr.gov/projects/index.php?id=504
- Gila River Indian Community, Pima-Maricopa Irrigation Project: https://www.gilariver.com/#top
- Groundwater Depletion in the United States (1900–2008) by L. F. Konikow. Published in 2013 by the US Geological Survey as Scientific Investigations Report 2013-5079. http://pubs.usgs.gov/sir/2013/5079.
- "Indicators in the Groundwater Environment of Rapid Environmental Change" by W. M. Edmunds. Pages 121–136 in A. R. Berger and W. J. Iams, editors. Geoindicators: Assessing Rapid Environmental Changes in Earth Systems. Published in 1996 by A. A. Balkema, Rotterdam, The Netherlands.

- International Groundwater Resources Assessment Centre: https://www.un-igrac.org/
- International Union of Geological Sciences (IUGS), Geoindicators—groundwater level: http://www.lgt.lt/geoin/doc.php?did=cl_groundwaterlevel
- Sonoran Desert Network (information about groundwater): https://www.nps.gov/im/sodn/groundwater.htm
- USGS groundwater information pages: https://water.usgs.gov/ogw/

Natural Hazards in Arizona

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

NPS Geologic Interpretation and Education

- America's Geologic Heritage: An Invitation to Leadership by the NPS Geologic Resources Division and American Geosciences Institute (AGI). Published in 2015 by AGI.
- Desert Research Learning Center (works with park managers to develop resource education products relating to natural resources in parks): https://www.nps.gov/im/sodn/drlc.htm
- NPS Geologic Resources Division Education website: http://go.nps.gov/geoeducation
- NPS Geoscientist-In-the-Parks (GIP) internship and guest scientist program: http://go.nps.gov/gip
- NPS Views (geology-themed modules are available for Geologic Time, Paleontology, Glaciers, Caves and Karst, Coastal Geology, Volcanoes, and a variety of geologic parks): http://go.nps.gov/views
- Parks and Plates: The Geology of Our National Parks, Monuments, and Seashores by Robert J. Lillie (Oregon State University). Published in 2005 by W. W. Norton and Company, New York.

NPS Resource Management Guidance and Documents

- 1998 National parks omnibus management act: http://www.gpo.gov/fdsys/pkg/PLAW-105publ391/pdf/PLAW-105publ391.pdf
- Appendix B of the GRI report.
- Geological Monitoring by Rob Young and Lisa Norby. Published in 2009 by the Geological Society of America. Available online at http://go.nps.gov/geomonitoring
- Management Policies 2006 (Chapter 4: Natural resource management): http://www.nps.gov/policy/mp/policies.html
- NPS-75: Natural resource inventory and monitoring guideline: http://www.nature.nps.gov/nps75/nps75.pdf
- NPS Natural resource management reference manual #77: http://www.nature.nps.gov/Rm77/
- NPS Technical Information Center (TIC) (Denver, Colorado; repository for technical documents): https://www.nps.gov/dsc/technicalinfocenter.htm

US Geological Survey (USGS) Reference Tools

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

Appendix A: Scoping Participants

The following people attended the GRI scoping meeting, held on 8 May 2006, or the follow-up report writing conference call, held on 21 February 2018. Discussions during these meetings supplied a foundation for this GRI report. The scoping summary document is available on the GRI publications website: http://go.nps.gov/gripubs.

2006 Scoping Meeting Participants

Name	Affiliation	Position
Lee Allison	Arizona Geological Survey	State geologist
Debbie Angell	NPS Sonoran Desert Network	GIS specialist
Rebecca Carr	Casa Grande Ruins National Monument	Archaeologist
Katie KellerLynn	Colorado State University	Geologist, research associate
Lisa Norby	NPS Geologic Resources Division	Geologist
Phil Pearthree	Arizona Geological Survey	Geologist
Melanie Ransmeier	NPS Geologic Resources Division	GIS specialist
Carol West	Casa Grande Ruins National Monument	Acting superintendent

2018 Conference Call Participants

Name	Affiliation	Position
Mike Conway	Arizona Geological Survey	Geologist
Alycia Hayes	Casa Grande Ruins National Monument	Archaeologist, chief of Facilities Management and Resource Stewardship
Katie KellerLynn	Colorado State University	Geologist, research associate
Jason Kenworthy	NPS Geologic Resources Division	Geologist, GRI reports coordinator
Karl Pierce	Casa Grande Ruins National Monument	Superintendent
Katherine Shaum	Casa Grande Ruins National Monument	Archaeological technician

Appendix B: Geologic Resource Laws, Regulations, and Policies

The NPS Geologic Resources Division developed this table to summarize laws, regulations, and policies that specifically apply to NPS minerals and geologic resources. The table does not include laws of general application (e.g., Endangered Species Act, Clean Water Act, Wilderness Act, National Environmental Policy Act, or National Historic Preservation Act). The table does include the NPS Organic Act when it serves as the main authority for protection of a particular resource or when other, more specific laws are not available. Information is current as of December 2017. Contact the NPS Geologic Resources Division for detailed guidance.

Resource	Resource-specific Laws	Resource-specific Regulations	2006 Management Policies
Caves and Karst Systems	**Federal Cave Resources Protection Act of 1988, 16 USC §§ 4301 – 4309** requires Interior/Agriculture to identify "significant caves" on Federal lands, regulate/restrict use of those caves as appropriate, and include significant caves in land management planning efforts. Imposes civil and criminal penalties for harming a cave or cave resources. Authorizes Secretaries to withhold information about specific location of a significant cave from a Freedom of Information Act (FOIA) requester. **National Parks Omnibus Management Act of 1998, 54 USC § 100701** protects the confidentiality of the nature and specific location of cave and karst resources. **Lechuguilla Cave Protection Act of 1993, Public Law 103-169** created a cave protection zone (CPZ) around Lechuguilla Cave in Carlsbad Caverns National Park. Within the CPZ, access and the removal of cave resources may be limited or prohibited; existing leases may be cancelled with appropriate compensation; and lands are withdrawn from mineral entry.	**36 CFR § 2.1** prohibits possessing/destroying/disturbing…cave resources…in park units. **43 CFR Part 37** states that all NPS caves are "significant" and sets forth procedures for determining/releasing confidential information about specific cave locations to a FOIA requester.	**Section 4.8.1.2** requires NPS to maintain karst integrity, minimize impacts. **Section 4.8.2** requires NPS to protect geologic features from adverse effects of human activity. **Section 4.8.2.2** requires NPS to protect caves, allow new development in or on caves if it will not impact cave environment, and to remove existing developments if they impair caves. **Section 6.3.11.2** explains how to manage caves in/adjacent to wilderness.
Paleontology	**National Parks Omnibus Management Act of 1998, 54 USC § 100701** protects the confidentiality of the nature and specific location of paleontological resources and objects. **Paleontological Resources Preservation Act of 2009, 16 USC § 470aaa et seq.** provides for the management and protection of paleontological resources on federal lands.	**36 CFR § 2.1(a)(1)(iii)** prohibits destroying, injuring, defacing, removing, digging or disturbing paleontological specimens or parts thereof. **Prohibition in 36 CFR § 13.35** applies even in Alaska parks, where the surface collection of other geologic resources is permitted. **43 CFR Part 49** (in development) will contain the DOI regulations implementing the Paleontological Resources Preservation Act.	**Section 4.8.2** requires NPS to protect geologic features from adverse effects of human activity. **Section 4.8.2.1** emphasizes Inventory and Monitoring, encourages scientific research, directs parks to maintain confidentiality of paleontological information, and allows parks to buy fossils only in accordance with certain criteria.

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

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

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

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

Resource	Resource-specific Laws	Resource-specific Regulations	2006 Management Policies
Coastal Features and Processes	**NPS Organic Act, 54 USC § 100751 et. seq.** authorizes the NPS to promulgate regulations to protect park resources and values (from, for example, the exercise of mining and mineral rights). **Coastal Zone Management Act, 16 USC § 1451 et. seq**. requires Federal agencies to prepare a consistency determination for every Federal agency activity in or outside of the coastal zone that affects land or water use of the coastal zone. **Clean Water Act, 33 USC § 1342/ Rivers and Harbors Act, 33 USC 403** require that dredge and fill actions comply with a Corps of Engineers Section 404 permit. **Executive Order 13089** (coral reefs) (1998) calls for reduction of impacts to coral reefs. **Executive Order 13158** (marine protected areas) (2000) requires every federal agency, to the extent permitted by law and the maximum extent practicable, to avoid harming marine protected areas. *See also "Climate Change"*	**36 CFR § 1.2(a)(3)** applies NPS regulations to activities occurring within waters subject to the jurisdiction of the US located within the boundaries of a unit, including navigable water and areas within their ordinary reach, below the mean high water mark (or OHW line) without regard to ownership of submerged lands, tidelands, or lowlands. **36 CFR § 5.7** requires NPS authorization prior to constructing a building or other structure (including boat docks) upon, across, over, through, or under any park area. *See also "Climate Change"*	**Section 4.1.5** directs the NPS to re-establish natural functions and processes in human-disturbed components of natural systems in parks unless directed otherwise by Congress. **Section 4.4.2.4** directs the NPS to allow natural recovery of landscapes disturbed by natural phenomena, unless manipulation of the landscape is necessary to protect park development or human safety. **Section 4.8.1** requires NPS to allow natural geologic processes to proceed unimpeded. NPS can intervene in these processes only when required by Congress, when necessary for saving human lives, or when there is no other feasible way to protect other natural resources/ park facilities/historic properties. **Section 4.8.1.1** requires NPS to: ● Allow natural processes to continue without interference, ● Investigate alternatives for mitigating the effects of human alterations of natural processes and restoring natural conditions, ● Study impacts of cultural resource protection proposals on natural resources, ● Use the most effective and natural-looking erosion control methods available, and avoid new developments in areas subject to natural shoreline processes unless certain factors are present. *See also "Climate Change"*

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

Resource	Resource-specific Laws	Resource-specific Regulations	2006 Management Policies
Upland and Fluvial Processes	**Rivers and Harbors Appropriation Act of 1899, 33 USC § 403** prohibits the construction of any obstruction on the waters of the United States not authorized by congress or approved by the USACE. **Clean Water Act 33 USC § 1342** requires a permit from the USACE prior to any discharge of dredged or fill material into navigable waters (waters of the US [including streams]). **Executive Order 11988** requires federal agencies to avoid adverse impacts to floodplains. (see also **D.O. 77-2**) **Executive Order 11990** requires plans for potentially affected wetlands (including riparian wetlands). (see also **D.O. 77-1**)	None applicable. *2006 Management Policies, continued:* **Section 4.6.6** directs the NPS to manage watersheds as complete hydrologic systems and minimize human-caused disturbance to the natural upland processes that deliver water, sediment, and woody debris to streams. **Section 4.8.1** directs the NPS to allow natural geologic processes to proceed unimpeded. Geologic processes…include…erosion and sedimentation…processes. **Section 4.8.2** directs the NPS to protect geologic features from the unacceptable impacts of human activity while allowing natural processes to continue.	**Section 4.1** requires NPS to manage natural resources to preserve fundamental physical and biological processes, as well as individual species, features, and plant and animal communities; maintain all components and processes of naturally evolving park ecosystems. **Section 4.1.5** directs the NPS to re-establish natural functions and processes in human-disturbed components of natural systems in parks, unless directed otherwise by Congress. **Section 4.4.2.4** directs the NPS to allow natural recovery of landscapes disturbed by natural phenomena, unless manipulation of the landscape is necessary to protect park development or human safety. **Section 4.6.4** directs the NPS to (1) manage for the preservation of floodplain values; [and] (2) minimize potentially hazardous conditions associated with flooding. *continued in Regulations column*

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

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

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