National Park Service
U.S. Department of the Interior

Natural Resource Stewardship and Science

Salinas Pueblo Missions National Monument

Geologic Resources Inventory Report

Natural Resource Report NPS/NRSS/GRD/NRR—2018/1706

ON THE COVER
Photograph of the Abó unit. Salinas Pueblo Missions National Monument consists of three noncontiguous units, including the Abó unit (shown on the front cover), which is east of the Manzano Mountains.
NPS photograph courtesy of Marc LeFrancois (Salinas Pueblo Missions National Monument).

THIS PAGE
Photograph of Quarai unit. Red sandstone of the undifferentiated Arroyo de Alamillo and Abo Formations makes up the bedrock at the Quarai unit and provided building stone for the pueblo and mission.
NPS photograph courtesy of Marc LeFrancois (Salinas Pueblo Missions National Monument).

Salinas Pueblo Missions National Monument

Geologic Resources Inventory Report

Natural Resource Report NPS/NRSS/GRD/NRR—2018/1706

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August 2018

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

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Please cite this publication as:

KellerLynn, K. 2018. Salinas Pueblo Missions National Monument: Geologic resources inventory report. Natural Resource Report NPS/NRSS/GRD/NRR—2018/1706. National Park Service, Fort Collins, Colorado.

NPS 313/147851, August 2018

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Executive Summary

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

This report synthesizes discussions from a scoping meeting held in 2006 (see Appendix A). Chapters of this report discuss the significance of the geologic setting, history, and features at Salinas Pueblo Missions National Monument, highlight geologic issues facing resource managers, and provide information about the previously completed GRI map data. A poster (in pocket) illustrates these data.

Salinas Pueblo Missions National Monument consists of three noncontiguous units—Abó, Gran Quivira, and Quarai—with a headquarters and main visitor center in Mountainair, New Mexico. The name Salinas relates to the monument's proximity to salt lakes (las salinas). Salt played an important role in the early settlement and trade of the region. In Spanish colonial times, the area was known as the Salinas Jurisdiction.

Through the centuries, this diverse region has supported prehistoric hunter-gatherers and puebloan groups, Spanish missionaries, and European American settlers. The people, places, and stories of the monument reflect a long tradition of cultural diversity, social interaction, and adaptation to a rich but demanding environment (National Park Service 2014).

The monument preserves ruins of prehistoric Indian pueblos and associated 17th century Spanish missions, as well as 19th and 20th century rancheros. The pueblos and churches were built of local rock: red sandstones (sedimentary rock consisting of sand-sized grains set in a matrix of silt or clay; see table 1) in the Abó and Quarai units and gray limestone (a sedimentary rock consisting chiefly of the mineral calcite, $CaCO_3$) in the Gran Quivira unit.

Although the monument is small, encompassing about 400 ha (990 ac) of federal land, its regional geologic setting is large, incorporating the Rio Grande rift, Manzano Mountains, Estancia basin, and Chupadera Mesa. Permian sedimentary rocks, Tertiary igneous rocks, and unconsolidated Quaternary deposits compose the geology of the monument and represent 299 million years of geologic activity. A geologic time scale (fig. 1) and generalized stratigraphic column (table 1) highlight the timing of geologic events and arrangement of rocks and deposits.

Colorful Permian rocks, called "red beds," make up the bedrock at the monument and contribute to the scenic beauty of the region. In the monument area, the red beds consist of red, orange, and even yellowish to pinkish white sandstones and mudstones, as well as interbedded gray limestone, sandstone, and gypsum. Red sandstones dominate the Abó and Quarai units; gray limestone dominates the Gran Quivira unit.

Red beds in the monument area slope gently toward the Estancia basin (east of the monument) away from the Precambrian crystalline bedrock that composes the core of the Manzano Mountains (west of the monument). Red beds form prominent landscape features such as steep mesas or tilted cuestas at the Abó and Quarai units. At the Gran Quivira unit, the Chupadera Mesa is the primary landform. The mesa—named for the "sucking" or "absorbing" capacity of karst features such as sinkholes—is an elevated "tableland" between the Estancia basin (to the north) and Tularosa basin (to the south).

Tertiary dikes (igneous rock that cuts across preexisting bedding planes), as well as sills (igneous rock that parallels the bedding of a preexisting sedimentary rock or the foliation of preexisting metamorphic rock), intruded the Permian rocks of the Chupadera Mesa, bowing the overlying layers upward into many small anticlinal (arch-like) forms. The Gran Quivira pueblo and mission were built on one of these anticlines. Small exposures of the mafic dike rocks crop out at the Gran Quivira unit.

Quaternary sediments (deposited in the past 2.6 million years) cover much of the land surface of the monument. These deposits consist of a collection of materials representing the expanse of geologic time (fig. 1): Some gravel on broad surfaces above the valley floor is composed of Precambrian (1.43-billion-year-old) clasts shed from the Manzano Mountains, whereas alluvium (poorly sorted sand and gravel) on valley floors and silt on mesa tops may have been deposited during a recent storm.

This GRI report is supported by GIS data (sapu_geology.mxd) from four 1:24,000-scale source maps of the Gran Quivira, Punta de Agua, Abo, and Scholle quadrangles. These maps provided full coverage for all three units in the monument. The GRI GIS data include both bedrock and surficial deposits mapped by geologists from the New Mexico Bureau of Geology and Mineral Resources and Kansas State University. GRI team members compiled the data to conform to the GRI GIS data model. The poster (in pocket) highlights these data draped over a shaded relief image of the monument and surrounding area. Writing of this GRI report was based on these source maps and the resultant GRI GIS data.

The monument's foundation document (National Park Service 2014), which is a primary source of information for resource management within the monument, was used in the preparation of this GRI report. That document lists two "other important resources and values": (1) natural landscapes, which includes cave and karst geology, and (2) paleontological resources. This GRI report contains information applicable to these other important resources and values, which are worthy of consideration in resource management and planning. Also, this report and the accompanying digital map provide data on significant geologic resources at the monument, which the foundation document listed as a medium-priority data need.

In addition to the foundation document, the monument's general management plan/development concept plan (National Park Service 1984) and the monument's water resources management plan (National Park Service 1997) were used in preparing this report. Also, the paleontological resource inventory and monitoring report for the Southern Colorado Plateau Network (Tweet et al. 2009) and the paleontological resource inventory for the monument (Thorpe et al. 2017) were valuable sources of information. Inventory and scientific identification of paleontological resources was a medium-priority data need listed in the foundation document.

This report contains two main tables. Table 1 emphasizes geologic time and takes the form of a stratigraphic column where map units are listed from bottom to top, oldest to youngest. It provides a brief geologic description and setting for each map unit. Notes associated with table 1 define geologic terms used to describe the monument's rocks. Table 3 summarizes the geologic resource management issues at the Abó, Gran Quivira, and Quarai units in the context of relevant geologic map units. Like table 1, table 3 is ordered stratigraphically. Issues within table 3 are listed alphabetically and include abandoned mineral lands; cave and karst resource management; drainage problems and flooding; energy resource development; erosion (water and wind); paleontological resource inventory, monitoring, and preservation; and wetlands. Most issues can be associated with a particular geologic map unit or units and are listed in table 3. Potential resource management actions for these issues are discussed following the table. A few issues—climate change, earthquakes and other ground shaking, and volcanic activity—are broader in scope, encompassing all of the map units and beyond. These are discussed in "Other Resource Management Issues."

Products and Acknowledgments

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

GRI Products

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

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

The compilation and use of natural resource information by park managers is called for in the National Parks Omnibus Management Act of 1998 (§ 204), NPS *Management Policies 2006*, and the Natural Resources Inventory and Monitoring Guideline (NPS-75). “Additional References” and Appendix B in this report 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 (see Appendix A) for their assistance in this inventory. Thanks very much to the **New Mexico Bureau of Geology and Mineral Resources** for its maps of the area; this report and accompanying GIS data could not have been completed without them. Thanks to **Trista Thornberry-Ehrlich** (Colorado State University) for her help in creating many of the graphics in this report. Thanks to **Marc LeFrancois** (Salinas Pueblo Missions National Monument) for providing many photographs from the monument’s collection. Thanks to **Mike Timmons** (New Mexico Bureau of Geology and Mineral Resources) for forwarding a draft of this report to **Charles G. (Jack) Oviatt** (Kansas State University) for review; Jack’s comments, which helped to clarify and improve the final report, were much appreciated.

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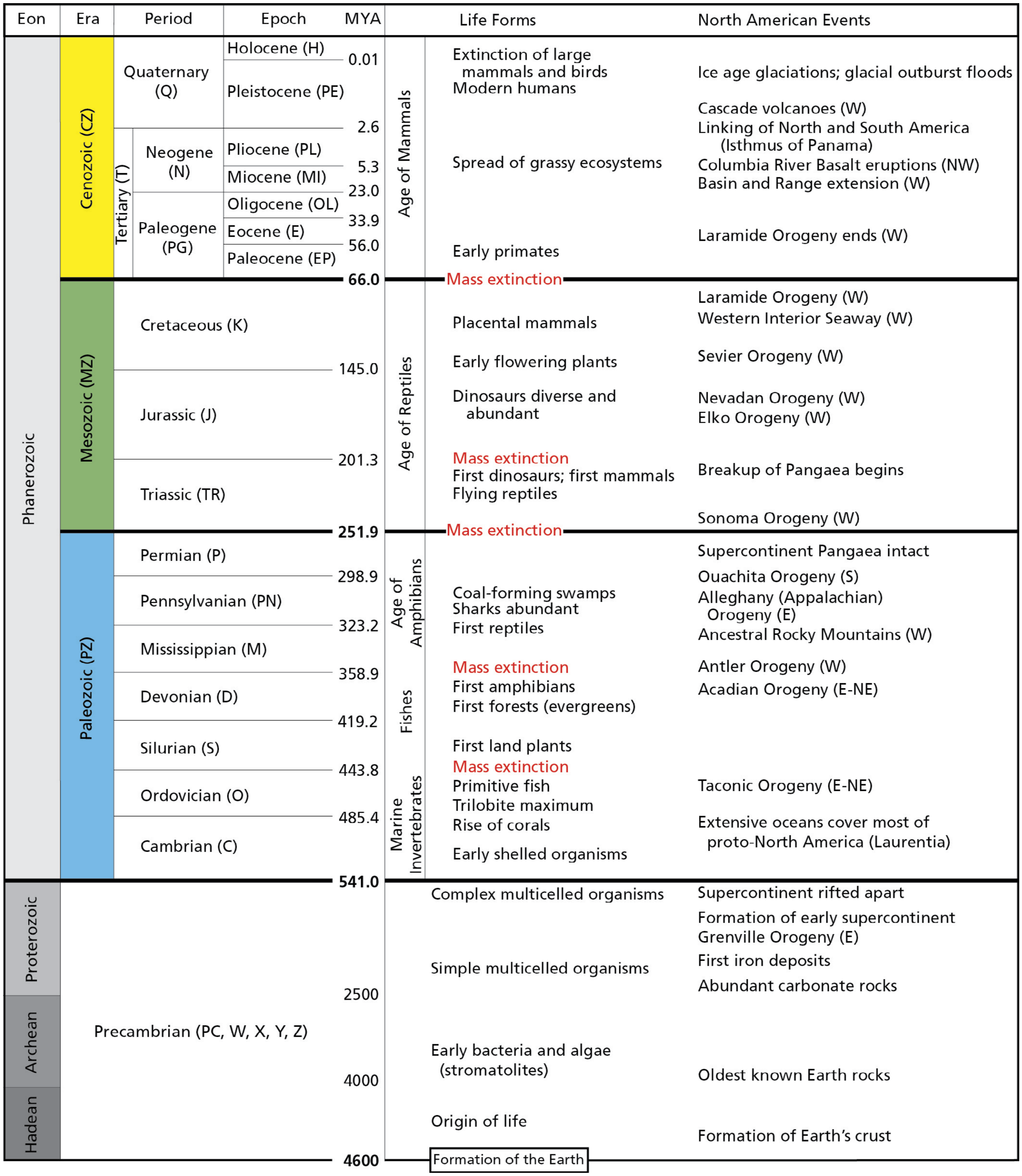


Figure 1. Geologic time scale.
The divisions of the geologic time scale are organized stratigraphically, with the oldest divisions at the bottom and the youngest at the top. GRI map abbreviations for each time division are in parentheses. Geologic events of significance for the monument's geologic story took place during the Permian (P) Period, Tertiary (T) time, and the Quaternary (Q) Period. Rocks or unconsolidated deposits from these time periods were mapped in the monument, though only the Gran Quivira unit contains Tertiary rocks. Compass directions in parentheses indicate regional locations of events. Boundary ages are millions of years ago (MYA). National Park Service graphic using dates from the International Chronostratigraphic Chart (http://www.stratigraphy.org/index/php/ics-chart-timescale; accessed 1 August 2017).

Geologic Setting, History, Features, and Significance

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

Park Establishment

Located in remote, central New Mexico, Salinas Pueblo Missions National Monument consists of three noncontiguous units—Abó, Gran Quivira, and Quarai (fig. 2). The monument headquarters and the main visitor center are in the town of Mountainair (fig. 2). The nearest cities include Belen, about 50 km (30 mi) northwest of Mountainair, and Socorro, about 80 km (50 mi) southwest of Mountainair. Mountainair and the Abó and Quarai units are in southwestern Torrance County. The Gran Quivira unit is in the northeastern Socorro County. Each unit hosts visitor contact stations, picnic areas, interpretive trails, and wayside exhibits.

Together the three units of the monument represent a much larger region of central New Mexico known in Spanish colonial times as the Salinas ("salt") Jurisdiction because of the large salt lakes (las salinas) that formed the basis for settlement and trade in the region (figs. 2, 3, and 4). Since about 1,200 years ago, the eponymous material, along with an abundance of naturally occurring building stone, attracted humans to the area. The monument preserves prehistoric Indian pueblos, historic 17th century Spanish mission churches, and 19th and 20th century rancheros.

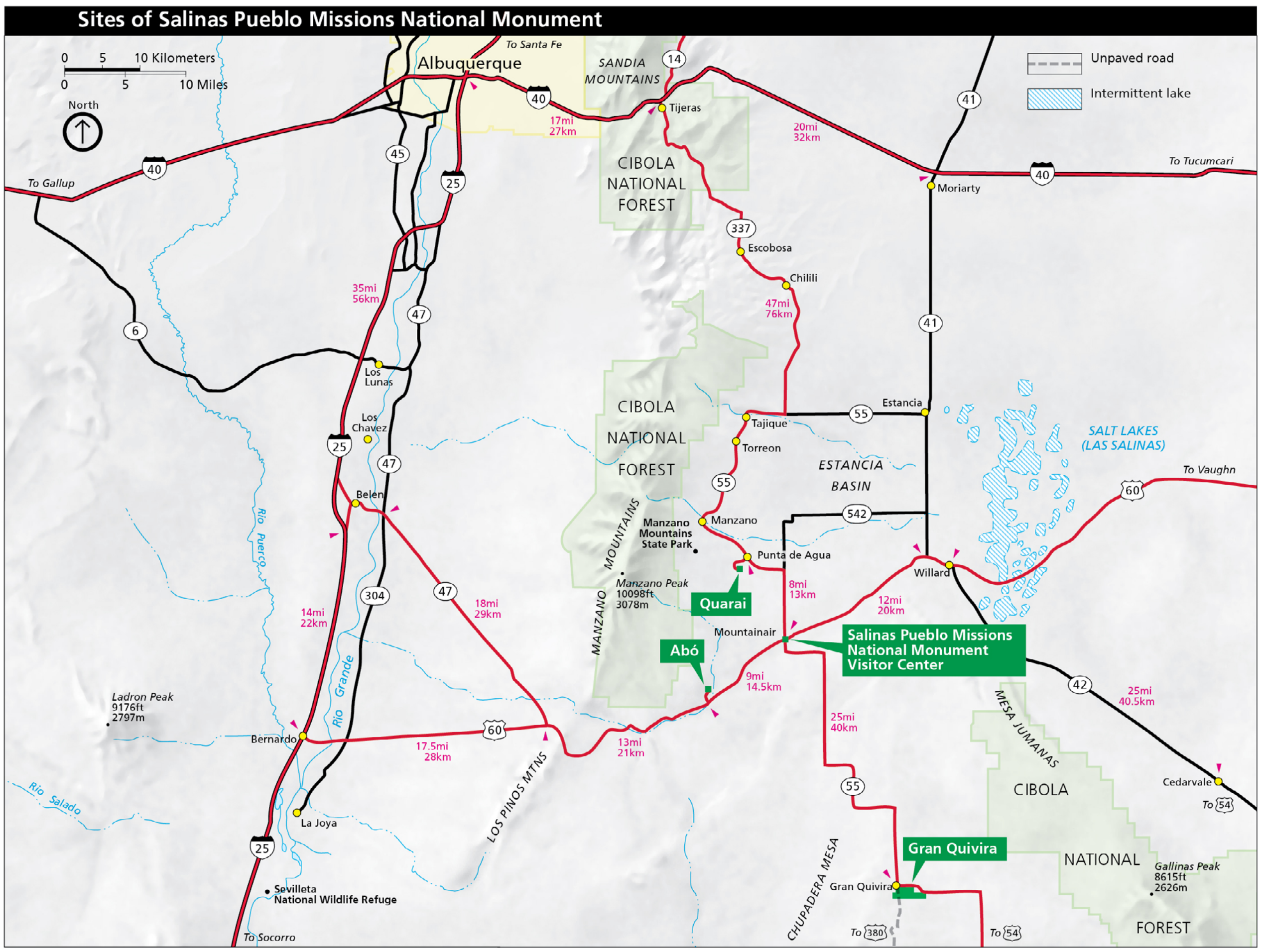


Figure 2. Area map.
Salinas Pueblo Missions National Monument is a collection of three noncontiguous units: Abó, Gran Quivira, and Quarai in central New Mexico. The monument headquarters and visitor center are in Mountainair (population 928). Belen (population 7,269) and Socorro (population 9,051) are the closest cities. The Quarai and Abó units are in the foothills of the Manzano Mountains. The Gran Quivira unit is on Chupadera Mesa. National Park Service graphic.

Figure 3. Photograph of salt lakes.
Ephemeral salt lakes (las salinas, in Spanish) cover the surface of the Estancia basin. This photograph was taken soon after a rain as the sun came out. NPS photograph courtesy of Marc LeFrancois (Salinas Pueblo Missions National Monument).

In 1909, President William Howard Taft used the authority of the Antiquities Act of 1906 to proclaim the ruins of what is now the Gran Quivira unit as "Gran Quivira National Monument." This original monument protected the San Buenaventura Mission and later, through land additions in 1919, the surrounding pueblo mounds. When the National Park Service was created in 1916, Gran Quivira National Monument came under its care.

In 1913, the Museum of New Mexico acquired the Quarai ruins from private ownership, but did not obtain clear title until 1932. In 1937, the ruins of Abó also came under the stewardship of the Museum of New Mexico through purchase and donation by a group of University of New Mexico alumni. Split administration of the three units between the Museum of New Mexico and the National Park Service was simplified in 1980 when all three sites were incorporated into "Salinas National Monument," a single unit of the National Park System. The name was changed to "Salinas Pueblo Missions National Monument" in 1988.

Geologic Setting

Although the monument is small, encompassing about 400 ha (990 ac) of federal land, its regional geologic setting is large, incorporating the Rio Grande rift, Manzano Mountains, Estancia basin, and Chupadera Mesa (fig. 5).

Rio Grande Rift

Spanning 1,000 km (600 mi), from the state of Chihuahua in northern Mexico to central Colorado, the Rio Grande rift is a major feature of crustal extension (pulling apart of Earth's crust) in New Mexico (fig. 5). Crustal extension progressed from south to north along the rift, starting in the Eocene Epoch (about 36 million years ago) in the south and in the Miocene Epoch (about 22 million years ago) in the north (Price 2010).

One consequence of extension is that Earth's crust within the rift has become thinner, allowing higher heat flow from the lower crust and mantle and producing volcanic features along the rift, including the chain of young volcanoes west of Albuquerque at Petroglyph National Monument (see GRI report by KellerLynn in review). In the Gran Quivira unit, mafic dike rocks (**Tim**) (see "Tertiary Rocks") correlate to magmatism associated with crustal extension during the Oligocene Epoch (between about 34 million and 23 million years ago). Another consequence of extension is that faults formed along the margins of the rift and created rift-flank uplifts, also referred to as "fault–block mountain ranges," such as the Manzano Mountains (see "Manzano Mountains"). Mountain ranges formed on the upthrown side of the faults while grabens (elongated, down-dropped basins bounded on both sides by high-angle normal faults that dip toward each other) formed on the downthrown side of the faults. Eight major grabens, also called "basins," formed within the rift (fig. 5). Many National Park System units occur within these basins: Bandelier National Monument is in the Española basin (north of the monument; see GRI report by KellerLynn 2015a). Petroglyph National Monument is in the Albuquerque basin (also north of the monument; see GRI report by KellerLynn in review). White Sands National Monument is in the Tularosa basin (south of the monument; see GRI report by KellerLynn 2012c). Salinas Pueblo Missions National Monument lies outside the rift north of the Tularosa basin.

The Rio Grande rift is manifested on the surface today by the Rio Grande valley, which is about 40 km (25 mi) west of the Abó unit at its nearest. Within the rift, older rocks, some dating from the Precambrian (fig. 1), are covered by Cenozoic sediments that were deposited by the ancestral and modern Rio Grande (rivers). These sediments, along with some volcanic rocks, are filling the rift basins.

Manzano Mountains

The Manzano Mountains are the fault–block mountain range in the vicinity of the monument. They bound the Rio Grande rift, extending northward to the Manzanita and Sandia Mountains and southward to the Los Pinos Mountains (figs. 2 and 5). The Abó and Quarai units are located in the foothills of the Manzano Mountains; each unit is about 16 km (10 mi) from the 3,060-m- (10,039-ft-) high Manzano Peak, the highest peak in the range. The ruins at the Abó and Quarai units are at about

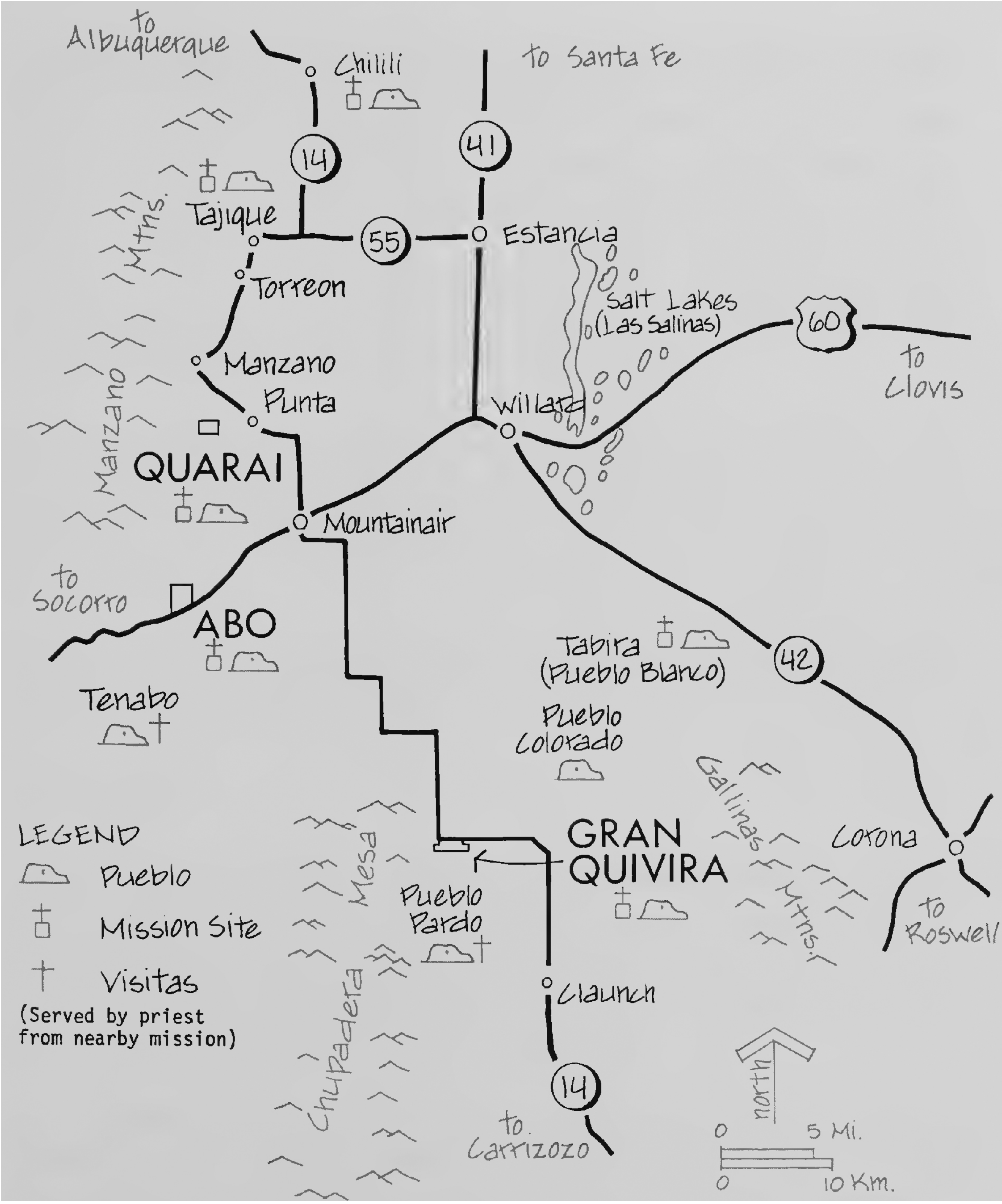
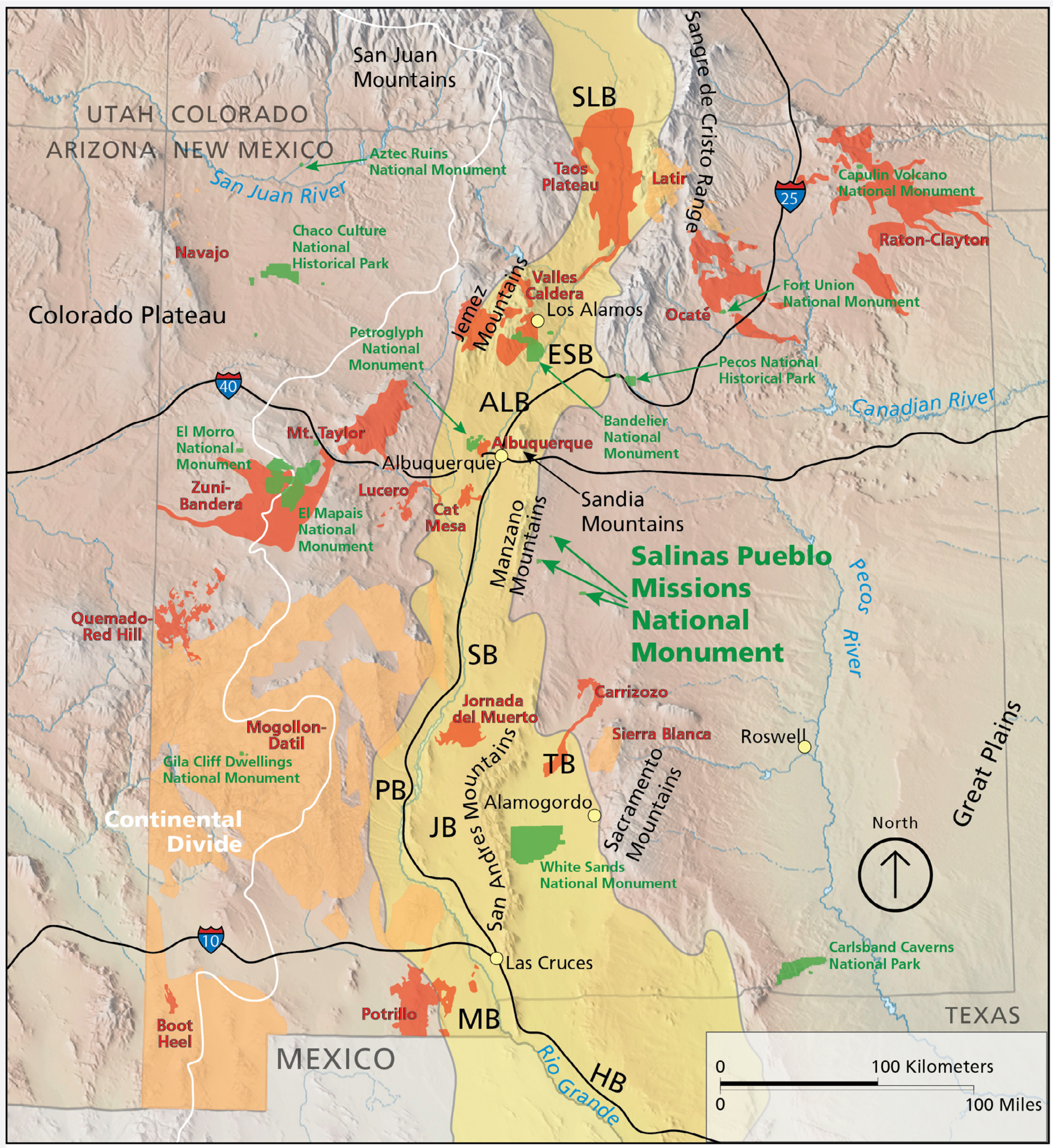


Figure 4. Regional map of Salinas Jurisdiction.
The three units of the monument represent a much larger region of central New Mexico that contained many large pueblos and associated 17th century missions and visitas (churches served by a priest from a nearby mission). Las salinas (salt lakes) formed the basis for settlement and trade in the region. NPS Southwest Regional Office graphic from National Park Service (1984, p. 11).



Rio Grande rift

Late Cenozoic volcanism (15 million years ago to present)

Mid-Tertiary volcanism (40 million–20 million years ago)

Figure 5. Map of major geologic features in New Mexico.
Salinas Pueblo Missions National Monument lies north of the Tularosa basin (TB) but outside the Rio Grande rift. The Tularosa basin and other basins—San Luis (SLB), Española (ESB), Albuquerque (ALB), Socorro (SB), Palomas (PB), Jornada (JB), Mesilla (MB), and Hueco (HB)—dropped down as Earth's crust pulled apart in the rift. The Manzano Mountains are a rift-flank uplift on the eastern side of the rift. The Tertiary dikes at the Gran Quivira unit are part of the Magdalena radial dike swarm, which was first recognized surrounding the Mogollon–Datil volcanic field. Graphic by Trista Thornberry-Ehrlich (Colorado State University) after Connell et al. (2005, figure 1) and Price (2010, p. 13). Base map by Tom Patterson (National Park Service).

1,860 m (6,090 ft) and 2,020 m (6,630 ft) above sea level, respectively. From an elevation of about 2,400 m (8,000 ft), the eastern flank of the mountains slopes gently toward the Estancia basin (see "Estancia Basin").

The word Manzano is derived from the Spanish word "manzanas" meaning apples. The small village of Manzano and the proximal mountains purportedly took their name from ancient orchards there. The orchards were believed to have been planted in the early 1600s by Franciscan priests who established the missions; however, tree-ring dating revealed that the trees were planted no earlier than the 1800s (National Park Service 2015).

The Manzano Mountains consist of a large mass of Precambrian metamorphic and igneous rocks. The Manzano Mountains have been uplifted along mostly concealed north-trending faults to expose the Precambrian core. Uranium-lead (U-Pb) dating of zircons in the igneous Priest Pluton Granite (**Ypp**; see GRI GIS data), which makes up the core of the mountains in the vicinity of the monument, yielded an age of about 1.43 billion years (Bauer et al. 1993). On the eastern flank of the mountains, Precambrian rocks are overlain by east-dipping Paleozoic sedimentary rocks, including the Pennsylvanian limestones ("**PN**" map units such as the Sandia Formation and Madera Group; see GRI GIS data) to the west of the monument and the Permian sandstones, mudstones, and limestones ("**P**" map units) to the west of and within the monument (see the notes associated with table 1 for definitions of rock types). Gravel (**Qgm**) shed from the uplifted mountains consists of fragments of Precambrian, Pennsylvanian, and Permian rocks (see "Quaternary Deposits").

Estancia Basin

The Estancia basin is a closed basin where water escapes only by way of evaporation. It is east of the Manzano Mountains and outside the Rio Grande rift. The original (depositional) basin formed during the Early Pennsylvanian Period (about 320 million years ago). It was the site of accumulating sediments that became the Sandia Formation (**PNs**) and Madera Group (**PNm1–m5**; see GRI GIS data). The present (structural) basin is the site of tectonic activity. It formed as the Manzano, Sandia, Manzanita, and Los Pinos Mountains were uplifted as a result of the development of the Rio Grande rift during the Miocene Epoch (about 20 million to 15 million years ago) (McLemore 2000; Bauer et al. 2003).

All three units of the monument either lie in or on the edge of the Estancia basin. The headquarters in Mountainair and the Quarai unit are within the basin. The Abó unit sits on the southwestern edge of the basin. The Gran Quivira unit sits on the escarpment of Chupadera Mesa, which delineates the southern edge of the Estancia basin.

During the Pleistocene Epoch (2.6 million to 11,700 years ago), the Estancia basin was the site of Lake Estancia—a large pluvial (related to precipitation) lake. The maximum extent of Lake Estancia was about 60 km (40 mi) long by 30 km (20 mi) wide. It would have covered the towns of Estancia and Willard (fig. 2) with nearly 30 m (100 ft) of water (Allen 1994). All three of the monument units would have been near the shores of Lake Estancia (Allen 2005).

Various investigators have studied aspects of Lake Estancia: Meinzer (1911) and Lyons (1969) described the history of Lake Estancia in relation to significant archeological finds in the paleo-lakeshores. Lyons and Ebert (1982) noted that the Estancia basin may have been a refugium where relict populations of species persisted; for example, Holocene mammoth fossils discovered there have been dated to as young as about 6,000 to 4,000 years old. Allen and Anderson (1993, 2000) and Allen (1994, 2005) studied and used Lake Estancia and other ancient lakes in New Mexico as tools for understanding climate change.

The Pleistocene Epoch is known for its ice ages, which corresponded to wetter conditions in New Mexico and the formation of Lake Estancia. That lake, and those that followed, did not have any outlets to the Rio Grande or elsewhere. Thus the water became saline over time, as a result of evaporation. Additionally, underlying Yeso Group evaporites (see "Permian Rocks") contributed to the salinity of the lake.

Shore features, cliffs, terraces, beach ridges, and other lake features preserved in the Estancia basin record a series of changing water levels caused by rapid shifts in climate during the Pleistocene Epoch (from 24,000 to 12,000 years ago). Lake Estancia gradually dried up after about 12,000 years ago, and the floor became exposed (Allen and Anderson 1993, 2000). A return to wetter conditions resulted in the filling of the basin again by a younger lake (called "Lake Willard" by some geologists) at about 10,000 years ago (Bachhuber 1982; Allen and Anderson 2000). Following deflation (removal of sediment by southwesterly wind) of the ancient lake basin since about 8,000 years ago, a playa and surrounding gypsum and clay dunes remain today. This area is known as Las Salinas (figs. 2, 3, and 4).

The geologic evolution of the Estancia basin influenced human occupation in the Salinas Pueblo Missions area. Playa lakes that formed in the basin contained salts, which led to early settlement and mining of the salt (halite) in the basin by Pueblo Indians. These Indians

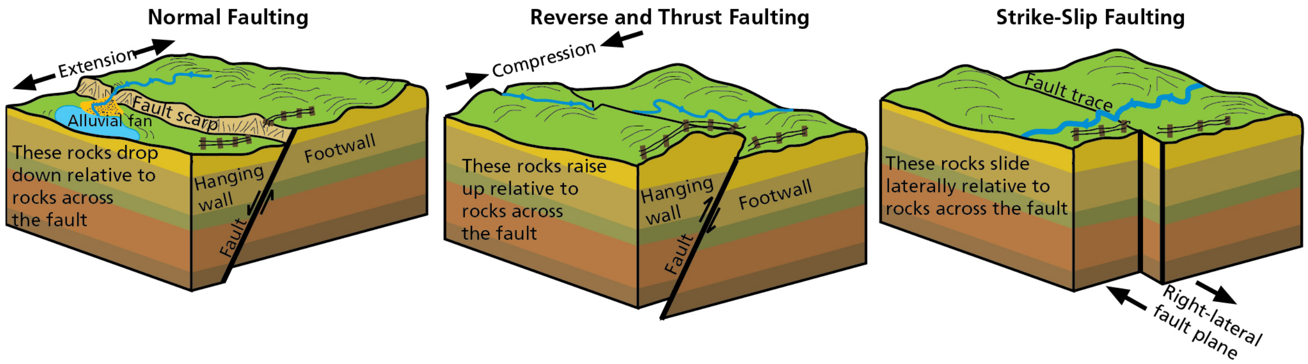


Figure 6. Graphic of fault types.
Movement occurs along a fault plane. Footwalls are below the fault plane, and hanging walls are above. In a normal fault, crustal extension (pulling apart) moves the hanging wall down relative to the footwall. In a reverse fault, crustal compression moves the hanging 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. Faulting in the monument area consists of normal faulting related to the Rio Grande rift and reverse faulting associated with development of the Rocky Mountains. Graphic by Trista Thornberry-Ehrlich (Colorado State University).

established trade routes with the Plains Indians to the east and with other Pueblo Indians along the Rio Grande (McLemore 2000). Both Pueblo Indians and Spanish missionaries obtained salt from these small lakes for domestic use and trading. Some of the salt was transported by humans to Mexico for use in smelting silver (Chronic 1987).

Chupadera Mesa

The Gran Quivira unit lies on Chupadera Mesa, which forms the southern boundary of the Estancia basin. Bates et al. (1947) and Kelley and Thompson (1964) referred to the mesa as a "tableland"—a broad, elevated region with a nearly level or undulating surface of considerable extent. The mesa covers an area of some 4,400 km^2 (1,700 mi^2). It is about 72 km (45 mi) long and ranges from about 16 km (10 mi) to 24 km (15 mi) across, spanning south from Gran Quivira to the White Sands Missile Range. The high point on the mesa is 2,123 m (6,965 ft) above sea level.

The surface of the mesa is formed by the limestone of the San Andres Formation (**Psa**), which contains gypsum (see "Permian Rocks"). Sinkholes resulting from the dissolution of gypsum and other evaporites (see "Permian Rocks") are common on Chupadera Mesa. The terrain is thought to be the source of the term "chupadera," which is Spanish for "sucker" or "absorbent" (Cather 2009). The sinkholes range in area from a few square yards to several acres (Bates et al. 1947). Drainage (storm and snowmelt runoff and infiltration) of the mesa is into sinkholes. Runoff gathers in small depressions where it either evaporates or disappears into the subsurface (Clebsch 1957).

Drainage of surface water and groundwater on Chupadera Mesa is complex. In addition to surface-water flow from runoff and snowmelt into local closed basins, some surface water from Chupadera Mesa flows to the Tularosa basin (on the southeast side of the mesa), some to the Estancia basin (on the north side of the mesa), and some to the Rio Grande valley (on the west side of the mesa). Groundwater probably flows into the Estancia basin and the Tularosa basin (Charles G. [Jack] Oviatt, Kansas State University, Department of Geology, emeritus, email communication, 1 May 2017).

A distinctive feature of the Chupadera Mesa is the northeast–southwest-trending anticlines that cut across it. These anticlines typically run for lengths of 8 to 16 km (5 to 10 mi) and are generally less than a few hundred feet wide. They formed as a result of Tertiary igneous dikes that intruded Paleozoic strata, arching overlying beds (see "Tertiary Rocks"). The mafic dikes/anticlines are the primary cause of topographic relief in the area.

The faults in the Chupadera Mesa area are another distinctive feature. They have complex movement histories associated with contraction of the Laramide Orogeny and/or extension of the Rio Grande rift (Baer et al. 2004). The Laramide Orogeny was the mountain-building event that resulted in the development of the Rocky Mountains between the Late Cretaceous Period (about 75 million years ago) to the middle Eocene Period (about 40 million years ago). In general, reverse faulting would indicate movement associated with the Laramide Orogeny whereas normal faulting would indicate movement associated with the Rio Grande

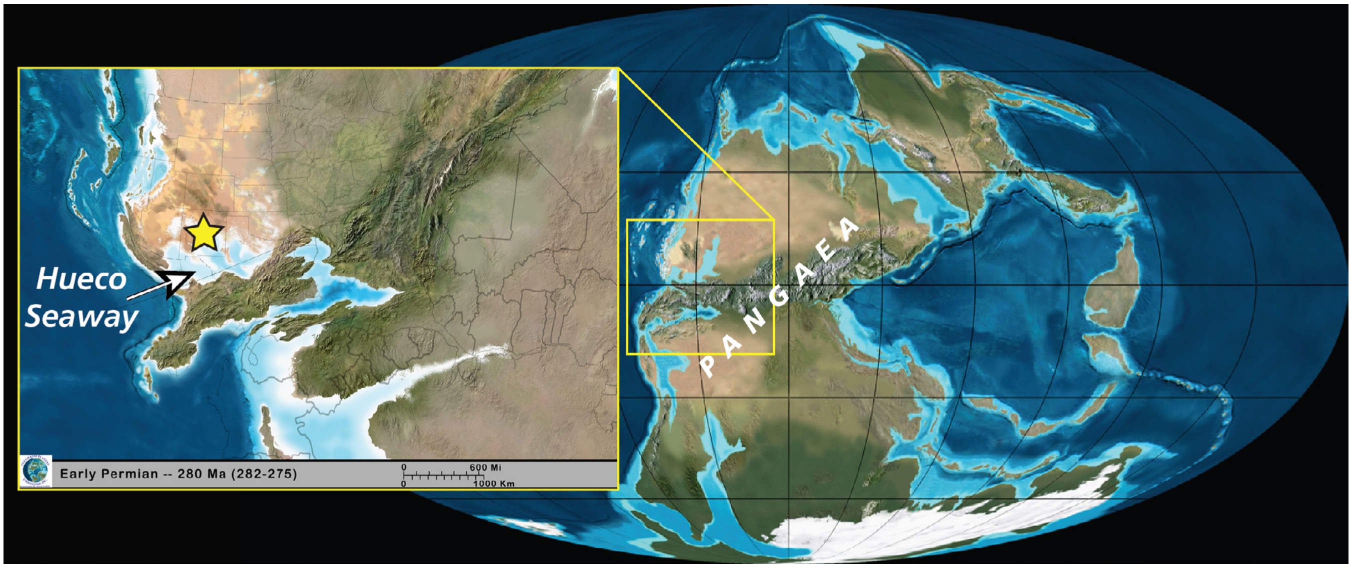


Figure 7. Paleogeographic map of Pangaea.
The Permian bedrock in the monument was deposited between about 299 million and 272 million years ago, when Earth's land masses had come together to form the supercontinent Pangaea. The red-bedded strata exposed in the monument came from near the shore of a shallow tropical sea called the Hueco Seaway. Basemaps are © 2013 Colorado Plateau Geosystems, Inc; used under license.

rift (fig. 6). The closest fault to the Gran Quivira unit is an unnamed fault 2 km (1 mi) to the west; its offset/displacement is unknown (see GRI GIS data).

Geologic History

Permian sedimentary rocks, Tertiary igneous rocks, and unconsolidated Quaternary deposits compose the geology of the monument and represent 299 million years of geologic activity (table 1, on following pages; and fig. 1). The bedrock in the monument preserves a rich record of the early Permian Period, when marine waters inundated the western margin of the proto–North American continent. These rocks represent about 29 million years of geologic time. At that time, Earth's landmasses were configured into a single supercontinent called "Pangaea" (fig. 7) and New Mexico was located near the equator. Rock formations in central New Mexico document the various transgressions (sea level rise/shoreline retreat) and regressions (sea level fall/shoreline advance) of the Hueco Seaway, which was to the south of the supercontinent. Depositional environments included fluvial floodplains, alluvial fans, and avulsing river systems during the late Wolfcampian epoch (approximately 299 to 282 million years ago; see table 1) during a low stand in sea level. As sea levels rose, deposits included eolian dunes and sand sheets, tidal flats, sabkha (flat area where saline minerals crystallize near or at the surface), and shallow marine deposits in the early part of the Leonardian epoch (approximately 282 to 272 million years ago; see table 1). Sea level fluctuations are recorded as limestone lenses and nearshore sands and gypsum in the Los Vallos and Glorieta Formations (table 2). The final period of Permian deposition recorded by the rocks within the monument was the San Andres limestone, representing the last transgression of Permian marine waters.

Mid-Tertiary time in New Mexico is marked by volcanism. Covering about 11 million years of geologic time, the Tertiary rocks at the Gran Quivira unit are representative of this period. Evidence of mid-Tertiary volcanism is best seen in the Mongollon–Datil volcanic field (fig. 5) where 13 supervolcanoes—the largest type of volcanic eruption on Earth—erupted massive amounts of material into the air and onto the surface and then collapsed. The Bursum and Gila Cliff Dwellings calderas, which surround Gila Cliff Dwellings National Monument, are remnants of two of these supervolcanoes (see GRI report about Gila Cliff Dwellings National Monument by KellerLynn 2014). Perhaps the most significant mid-Tertiary event, however, was the inception of the Rio Grande rift (see "Rio Grande Rift").

The Quaternary deposits in the monument represent the past 2.6 million years of geologic time. They represent the ongoing processes responsible for the evolution of the monument's landscape as geologic history continues in the making.

Permian Rocks

The Permian rocks of New Mexico (table 2; fig. 8), including those at the monument, make up a colorful

Table 1. Bedrock and Surficial Deposits at Salinas Pueblo Missions National Monument.

Note: Geologic terms are defined below the table.

Map Unit (symbol)	Period	Epoch	Years Ago	Park Unit	Geologic Description	Setting
Stream alluvium (**Qa**)	Quaternary	Holocene to Upper Pleistocene	126,000 to present day	Abó Quarai	Poorly sorted, sandy to gravelly alluvium. Mostly reddish in color. Clast size: sand to gravel, 1/16 mm (0.0025 in) to more than 256 mm (10 in) in diameter.	Underlies active drainages (intermittent streams) on valley bottoms.
Stream alluvium and eolian sand (**Qae**)	Quaternary	Holocene to Upper Pleistocene	126,000 to present day	Gran Quivira	Poorly sorted, sandy to gravelly alluvium, and eolian sand and silt, mixed with alluvium and colluvium. Clast size: sand to gravel, 1/16 mm (0.0025 in) to more than 256 mm (10 in) in diameter.	Deposited by intermittent streams on valley bottoms and occurs in small dunes and other windblown deposits.
Gravel derived from Manzano Mountains sources (**Qgm**)	Quaternary	Pleistocene	2.6 million to 11,700	Abó Quarai	Poorly sorted alluvial gravel. Clast size: gravel, ranging from pebbles to boulders (2 mm [0.08 in] to more than 256 mm [10 in] in diameter). Broad surfaces capped by Qgm generally slope to the south, overlie rocks of the Los Vallos Formation (**Pyl**), and are mapped as **Qgm/Pyl**. Some surfaces mapped as **Qgm** or **Qgm/Pyl** have a loess (windblown silt) cap that may be 1 m (3 ft) or more thick. Clast size of loess: very fine to coarse silt, 1/16 mm (0.003 in) to 1/256 mm (0.0002 in) in diameter.	Covers broad, rolling, sandstone surfaces. Deposited by streams originating in the Manzano Mountains. Includes fragments of Precambrian (gneiss, schist, and quartzite), Pennsylvanian (limestone), and Permian (sandstone) rocks.
Stream-valley alluvium, intermediate deposits (**Qpm**)	Quaternary	Upper to Middle Pleistocene	781,000 to 11,700	Abó	Poorly sorted, moderately consolidated, sand and gravel. Clast size: gravel, mostly pebbles to cobbles (2 mm [0.08 in] to 256 mm [10 in] in diameter).	Gravels reflect upland drainage composition and are dominated by reddish-brown sandstone. Associated with major tributaries to the Rio Grande.
Mafic dike rocks (**Tim**)	Tertiary	Oligocene	34 million to 23 million	Gran Quivira	Fine- to medium-grained basaltic andesite in poorly exposed dikes and sills.	Igneous intrusions related to Rio Grande rifting arched overlying bedrock, creating the hill on which the Gran Quivira pueblo and mission were built.

Map Unit (symbol)	Period	Epoch	Years Ago	Park Unit	Geologic Description	Setting
San Andres Formation (**Psa**)	Permian	Lower Permian (Leonardian)	~282 million to 272 million (see note)	Gran Quivira	Gray limestone and interbedded gray sandstone and gypsum.	Forms the surface of Chupadera Mesa. Marine transgression and deposition of limestone under shallow, restricted to open marine conditions.
Yeso Group, Arroyo de Alamillo Formation (**Pya**)	Permian	Lower Permian (Leonardian)	~282 million to 272 million (see note)	Abó	Orange to reddish sandstone and minor mudstone; includes some yellowish to pinkish white sandstones near the top of the unit.	Forms one of two cuestas at the Abó unit. Eolian deposition on an arid coastal plain.
Arroyo de Alamillo and Abo Formations, undifferentiated (**Pu**)	Permian	Lower Permian (Leonardian and Wolfcampian)	~299 million to 272 million (see note)	Quarai	Red sandstones.	Consists of red sandstone from two undifferentiated formations in fluvial and coastal settings.
Abo Formation (**Pa**)	Permian	Lower Permian (Leonardian and Wolfcampian)	~299 million to 272 million (see note)	Abó	Red sandstone and mudstone. Weathers to light red and pale reddish brown, with white and green oxidation/reduction spots locally. Contains cross laminae, ripple marks, mud cracks, and interbedded paleosols (buried soils).	Forms one of two cuestas at the Abó unit. Deposited by rivers on an extensive muddy floodplain.

Notes: The source maps used regional names—Wolfcampian, Leonardian, and Guadalupian—for the Permian Period. The Wolfcampian and Leonardian are roughly equivalent to the global Cisuralian Epoch (299 million–272 million years ago; see Henderson et al. 2012; Lucas and Shen 2016; and http://stratigraphy.org/index.php/ics-chart-timescale). The age of the boundary between the Wolfcampian and Leonardian (~282 million years ago) was estimated using Henderson et al. (2012, figure 24.1). The Guadalupian Epoch (272–260 million years ago) is recognized globally (see GRI report about Guadalupe Mountains National Park by KellerLynn 2008). Lucas et al. (2005) elevated the Yeso Formation to group status and divided it into three formations: Arroyo de Alamillo Formation, Los Valles Formation, and Glorieta Sandstone; some older publications and those discussing areas other than central New Mexico may use "Yeso Formation" rather than "Yeso Group." Lueth et al. (2009, p. 89) provided a good description of the contrast between the Arroyo de Alamillo and Abo Formations.

Alluvium (map units Qa, Qae, Qgm, and Qpm)—Stream-deposited sediment.

Basaltic andesite (Tim)—A volcanic rock that is commonly dark gray to black and contains about 53%–57% silica.

Eolian (Qae)—Describes materials formed, eroded, or deposited by the wind.

Gneiss (Qgm)—A foliated metamorphic rock with alternating bands of dark and light minerals. Varieties are distinguished by texture (e.g., augen gneiss), characteristic minerals (e.g., hornblende gneiss), or general composition (e.g., granite gneiss).

Gypsum (Psa)—A sulfate (sulfur + oxygen) mineral of calcium and water ($CaSO_4 \bullet 2H_2O$).

Limestone (Psa)—A sedimentary rock consisting chiefly of the mineral calcite (calcium carbonate, $CaCO_3$).

Mudstone (Pya and Pa)—A fine-grained sedimentary rock with clasts as large as 1/16 mm (0.0025 in) to less than 1/256 mm (0.00015 in). "Claystone" and "siltstone" also can be called "mudstone," or if they break into thin layers "shale." Mudstone is finer grained than sandstone.

Quartzite (Qgm)—Metamorphosed quartz sandstone. A medium-grained, nonfoliated metamorphic rock composed mostly of quartz.

Sandstone (Psa, Pya, Pu, and Pa)—Clastic sedimentary rock composed of predominantly sand-sized grains, 1/16–2 mm (0.0025–0.08 in).

Schist (Qgm)—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.

Table 2. Chart of the Permian stratigraphy in the monument area.

Since the early 1900s, investigators such as Lee (1909), Darton (1922, 1928), Bates et al. (1947), Scott et al. (2005), Oviatt (2010, 2011b, 2012), and Lucas et al. (2016) have recognized and mapped the Permian strata in the Abo Pass area. This table shows the strata as interpreted by Lucas et al. (2016). The rock units with bold text and map unit symbols in parentheses were mapped within the monument and colors correspond to the GRI map poster (in pocket). Table 1 provides details of those map units. Since mapping, a tiny outcrop of Los Vallos Formation was found in the Abó unit. "Fm." = Formation.

Group and/or Formation	Member
San Andres Fm. (Psa)	none
Glorieta Sandstone	none
Yeso Group (Py units), Los Vallos Fm.	Joyita Member
Yeso Group (Py units), Los Vallos Fm.	Cañas Member
Yeso Group (Py units), Los Vallos Fm.	Torres Member
Yeso Group (Py units), Arroyo de Alamillo Fm (Pu)	none
Abo Fm. (Pa and Pal)	Cañon de Espinoso Member
Abo Fm. (Pa and Pal)	Scholle Member
Bursum Fm.	none

sequence of red-bedded strata, known as "red beds," which consist of sandstones (sedimentary rocks with predominantly sand-sized grains) and interbedded carbonate rocks (sedimentary rocks consisting primarily of carbonate minerals, for example, calcium carbonate, $CaCO_3$, also known by its mineral name "calcite") and evaporites (sedimentary rocks composed primarily of minerals produced from a saline solution as a result of extensive or total evaporation of the solvent, usually water). Gypsum (a mineral consisting of hydrous calcium sulfate, $CaSO_4 \cdot 2H_2O$) is the primary constituent of the evaporites at the Gran Quivira unit, which are part of the San Andres Formation (**Psa**). Halite (native salt or table salt) and anhydrite (which readily alters to gypsum) are other minerals that commonly occur in evaporite beds.

Carbonate and evaporite rocks are susceptible to dissolution by water, resulting in a type of topography known as karst, which forms in soluble rocks and is characterized by sinkholes, caves, and underground drainage. Although karst topography is most apparent at Gran Quivira, Land et al. (2013) conducted an evaluation of cave and karst areas at US national parks and concluded that 92.71% of the monument consists of karst (fig. 9).

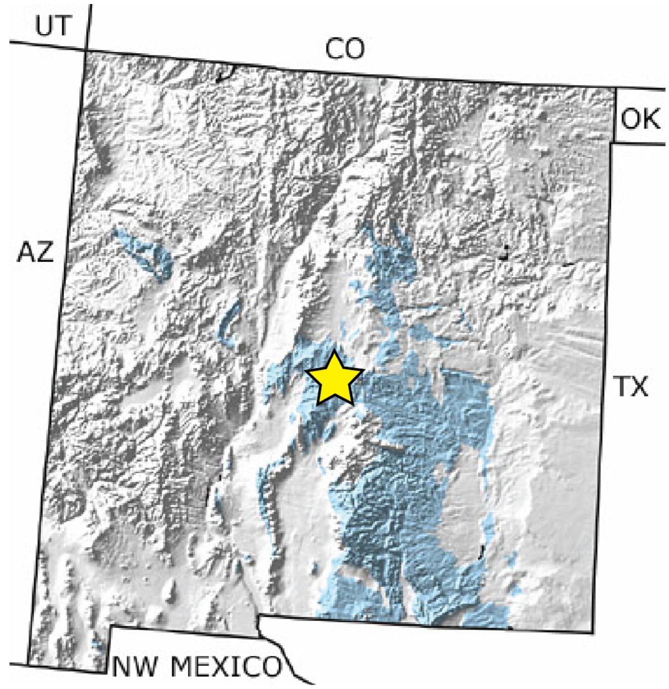


Figure 8. Map of Permian rocks in New Mexico. The bedrock in the monument (star) consists of Permian sedimentary rocks, which form colorful "red beds" in the central and southern parts of the state. Blue on the graphic delineates exposures of these rocks and represents the official color used on USGS maps for the Permian Period. From the Paleontology Portal at http://paleoportal.org/index.php?globalnav=time_space&sectionnav=state&state_id=36&period_id=11 (accessed 1 August 2017).

The Permian sequence of rocks at the monument starts with the continental Abo Formation (**Pa**), which was deposited by rivers that traversed and incised extensive muddy floodplains (table 1). Later deposition gave way to extensive sheetflooding (overland flow not confined to a stream channel) (Lucas et al. 2016). These depositional settings are represented by the sandstone and mudstone that makes up the Abo Formation. At the Abó unit, the Abo Formation (**Pa**) contains fossil plant debris and some bioturbation (the reworking of sediments by organisms, creating distinctive sedimentary features/trace fossils).

The Abo and Arroyo de Alamillo Formations, undifferentiated (**Pu**), follow in stratigraphic order at the monument. These undifferentiated sandstones, which occur in the Quarai unit, were mapped where exposures were not good or where the sandstones occur in steep-walled canyons and could not be separated easily at a scale of 1:24,000. The rocks at the Quarai unit have yielded trace fossils (a fossilized feature such as a

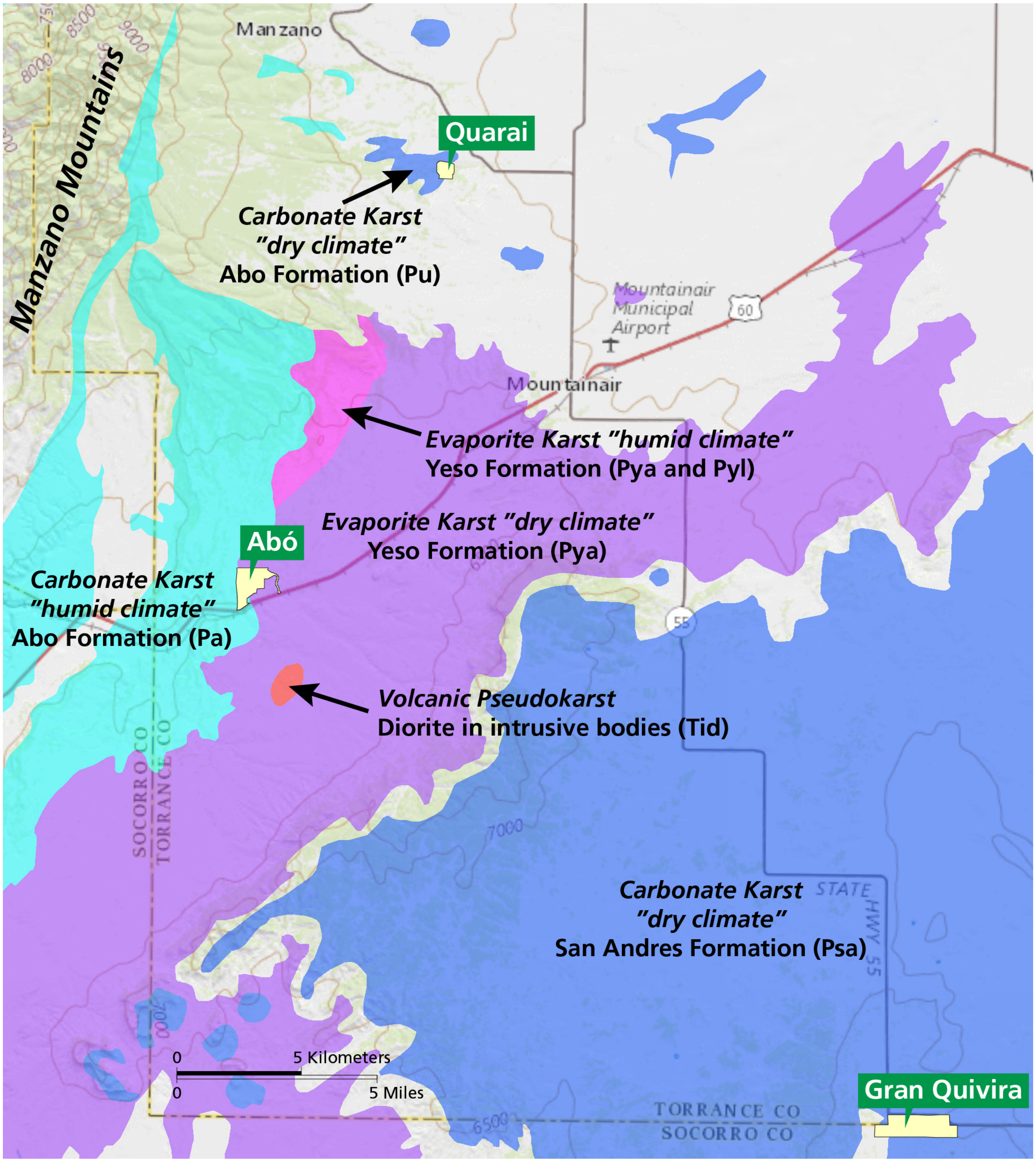


Figure 9. Map of karst areas and types.
According to Land et al. (2013), karst is at or below the surface of 92.71% of the monument. The yellow shapes on the map represent the three units in the monument, from north to south, Quarai, Abó, and Gran Quivira. Karst mapping for the United States was completed by Weary and Doctor (2014). In general New Mexico has a dry climate. Locally, however, Weary and Doctor (2014) classified areas of the Rocky Mountains and the Sierra Nevada as humid regions, with higher effective precipitation amounts mostly caused by orogenic effects (proximity to mountains). Purple on the graphic represents evaporite karst ("evaporite rocks at or near the land surface in a dry climate"). Magenta represents evaporite karst ("evaporite rocks at or near the land surface in a humid climate"). Blue represents carbonate karst ("carbonate rocks at or near the land surface in a dry climate"). Aqua represents carbonate karst ("carbonate rocks at or near the land surface in a humid climate"). Graphic by Jason Kenworthy (NPS Geologic Resources Division) using data from Land et al. (2013) and Weary and Doctor (2014).

track, trail, burrow, or coprolite [dung], that preserves evidence of an organism's life activities, rather than the organism itself) and plant fossils.

The Arroyo de Alamillo Formation is part of the Yeso Group, which records a major northward transgression across Abo red beds, followed by a regression (Harbour 1970; Lucas et al. 2013). A complete section of the Arroyo de Alamillo Formation (**Pya**) is exposed in the Abó unit and consists of 80 m (260 ft) of red beds (Lucas et al. 2016). Many bedding surfaces of the Arroyo de Alamillo Formation are rippled, and some bear trace fossils (tracks and trails). The first vertebrate fossil to be discovered in the Yeso Group was found in the Arroyo de Alamillo Formation at the monument in summer 2016 (see "Paleontological Resource Inventory, Monitoring, and Preservation").

Deposition of the Yeso Group began as dominantly eolian on an arid coastal plain (represented by the Arroyo de Alamillo Formation) followed by deposition within coastal sabkhas, dunes, and restricted marine embayments (represented by the Torres and Cañas Members of the Los Vallos Formation). Yeso Group sedimentation ended with the Los Vallos Formation (Joyita Member), which formed by eolian and fluvial processes during lowered sea level. The Los Vallos Formation was not mapped within the monument; however, since mapping was completed, the base of the Los Vallos Formation (gray dolomite) was discovered at the Abó unit in a tiny outcrop at the northern edge of the gravel-capped hill, south of the visitor center. This outcrop is situated directly above the Arroyo de Alamillo Formation (Charles G. [Jack] Oviatt, Kansas State University, Department of Geology, emeritus, written communication, 1 May 2017).

Interestingly, the Arroyo de Alamillo Formation is stratigraphically equivalent to the De Chelly Sandstone, which in its type area in northeastern Arizona is eolian. The De Chelly Sandstone was named for Canyon de Chelly (see geologic scoping summary about Canyon de Chelly National Monument by KellerLynn 2007). Eolian sandstones in the Arroyo de Alamillo Formation at the Abó and Quarai units are interbedded with fluvial rocks.

The Glorieta Sandstone is also part of the Permian sequence of rocks in the vicinity of the monument (table 2), though it does not crop out within the monument (see GRI GIS data). It is mostly of eolian origin, consisting of primarily sandstone as well as interbedded gypsum and limestone in its upper part where the sandstone transitions to limestones of the San Andres Formation (Charles G. [Jack] Oviatt, Kansas State University, Department of Geology, emeritus, written communication, 1 May 2017).

The sequence of Permian rocks at the monument ends with the deposition of the San Andres Formation (**Psa**). The San Andres Formation is exposed discontinuously across about two-thirds of New Mexico, with sparse outcrops in the central and western parts of the state (Brose et al. 2013; Lucas et al. 2016). The San Andres Formation overlies the Glorieta Sandstone at most outcrops, but at the Gran Quivira unit, it overlies the older Yeso Group. The San Andres Formation is composed primarily of limestone but also contains interbedded gypsum. Gypsum indicates deposition in a coastal sabkha environment; limestone indicates deposition under shallow, restricted (ocean basin with restricted water circulation) to open marine conditions. Chronic (1987) described the San Andres Formation at the Gran Quivira units as composed of marine microfossils.

Tertiary Rocks

The Gran Quivira unit is the only unit in the monument to have Tertiary rocks (indicated by "**T**" map units in the GRI GIS data). These rocks are mafic dike rocks (**Tim**) in poorly exposed dikes and sills. "Mafic" is a term derived from **ma**gnesium + fer**ric** (referring to iron) to describe an igneous rock having abundant dark-colored, magnesium- or iron-rich minerals.

The mafic dikes in the Chupadera Mesa area (see "Chupadera Mesa") are part of the Magdalena radial dike swarm described by Chamberlin et al. (2009). The dikes have an age of 28.88 ± 0.22 million years old (determined using isotopes of argon, $^{40}Ar/^{39}Ar$) and are associated with the crustal extension of the Rio Grande rift (see "Rio Grande Rift"). The radial pattern of these dikes in New Mexico was first recognized by Elston et al. (1976) surrounding the Mogollon–Datil volcanic field in southwestern New Mexico. Thus, mafic dike rocks (**Tim**) provide a connection between Salinas Pueblo Missions National Monument and Gila Cliff Dwellings National Monument, which lies in the Mogollon–Datil volcanic field (see GRI report by KellerLynn 2014).

Bates et al. (1947) and Cather (2009) hypothesized that Tertiary dikes intruded the sedimentary rocks of the Yeso Group (mudstone, sandstone, and gypsum), which are below the surface in the Chupadera Mesa area, and caused the overlying rocks to be bowed upward into anticlinal forms (fig. 10). The hill on which the Gran Quivira pueblo and mission were built is thought to be one of these anticlines (Oviatt 2011a). Mafic dikes that intruded the Permian rocks of the Chupadera Mesa area were largely confined to the Yeso Group because of

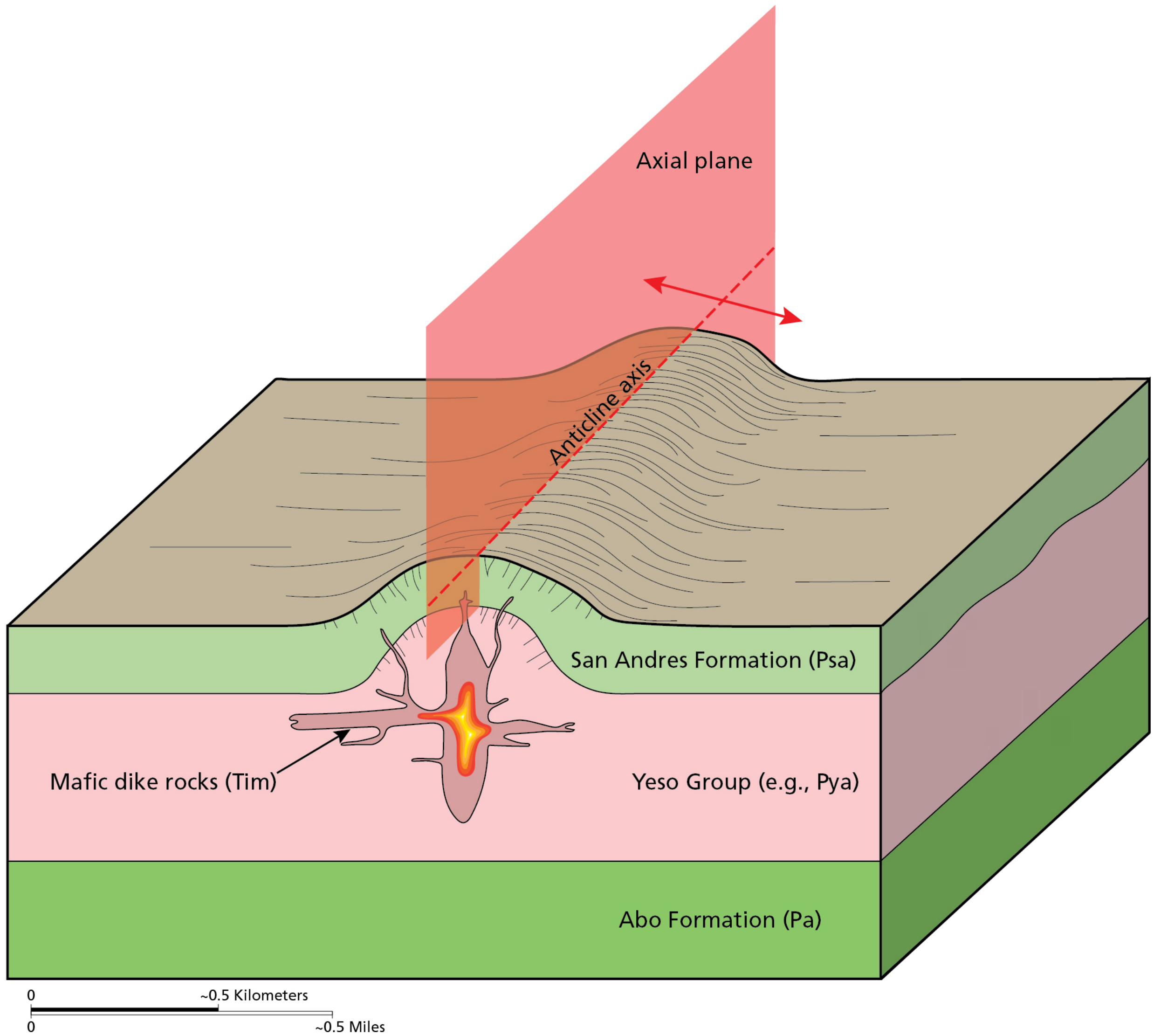


Figure 10. Graphic of Tertiary dikes and Permian strata.
This cross section shows the probable relationship between Tertiary igneous dikes and Permian sedimentary rocks in the Chupadera Mesa area. The dikes originated in the Mogollon–Datil volcanic field (approximately 230 km [140 mi] southwest of the monument) and radiated outward. The dikes were largely confined to the Yeso Group because of the abundance of friable, soft, or readily dissolved rocks such as shale, gypsum, and halite. In the Gran Quivira area, dikes intruded the San Andres Formation (limestone and interbedded sandstone and gypsum), and possibly the underlying Yeso Group and older strata. Anticlines were produced in the overlying sedimentary rocks as dikes intruded the underlying strata. These structures created elongate hills, including the hill upon which the Gran Quivira pueblo and mission were built. Graphic by Trista Thornberry-Ehrlich (Colorado State University) modified from Cather (2009, figure 7).

the abundance of friable, soft, or readily dissolved rocks such as shale, gypsum, and halite (Cather 2009).

In the Gran Quivira area, dikes and sills of igneous rocks intruded the San Andres Formation (limestone and interbedded sandstone and gypsum). Igneous rocks may have intruded the underlying Yeso Group (and possibly other) rocks in the subsurface (as in the model hypothesized by Bates et al. 1945 and Cather 2009), but no Yeso Group rocks are exposed in the Gran Quivira area, so intrusion into these rocks cannot be seen (and confirmed) at the ground surface (Charles G. [Jack] Oviatt, Kansas State University, Department of Geology, emeritus, written communication, 1 May 2017). The intrusions at Gran Quivira probably bowed the sedimentary strata upward to form anticlinal structures (as in the model), but geologic mapping of the Gran Quivira quadrangle did not find outcrops of sedimentary rocks that clearly dip away from presumed anticline axes. Although outcrops of dipping rocks do occur, the dips were found to be chaotic within small areas, and generalizing the dips into consistent patterns (as to show anticlinal forms) was not possible. Thus, the source geologic map (Oviatt 2012) and GRI GIS data do not include anticline symbols for these features. However, field observation, though not based on actual measurements, suggests that the San Andres limestone appears to dip generally parallel to the ground surface down the sides of the linear hills (i.e., on the flanks of presumed anticlines) (Charles G. [Jack] Oviatt, Kansas State University, Department of Geology, emeritus, written communication, 1 May 2017).

The Tertiary igneous dikes have an interesting connection to the potential for energy production in the Chupadera Mesa area. The geology of Chupadera Mesa indicates favorable potential for oil and natural gas. The oil and gas source rocks are the Pennsylvanian strata. The oil and gas reservoirs are the continental sandstones of the Abo Formation and the marine and marginal marine sandstones of the Yeso Group. Heating associated with Tertiary igneous activity caused thermal maturation of these oil reservoirs. In addition, the geology of the Chupadera Mesa is favorable to helium generation, migration, and entrapment. The region is underlain by Precambrian granitic rocks in most places, which gamma-ray logs indicate are significantly more radioactive than the overlying sedimentary section. Deep, high-angle faults penetrate the basement in many places. Although many of these faults have a late Paleozoic ancestry, they were reactivated during Laramide tectonism or Rio Grande rifting. The latter event was characterized by extension that would enhance fracture permeability in the Precambrian rocks. In addition, Tertiary igneous activity was apparently accompanied by widespread heating that facilitated the release of helium into the Paleozoic sedimentary sequence (Broadhead 2009).

Quaternary Deposits

Much of the bedrock in the monument is covered by unconsolidated sediments deposited by flowing water (**Qa**) in the Abó and Quarai units and by flowing water and the wind (**Qae**) in the Gran Quivira unit. Stream alluvium, undivided (**Qa**) represents modern activity. The stream alluvium and eolian sand (**Qae**) was deposited starting in the Late Pleistocene Epoch (approximately 126,000 years ago) through the present day.

The stratigraphy and composition of Quaternary deposits at the monument are indicative of the source area, energy needed to transport this material, and the age of the deposit. The cobbles, pebbles, sands, and gravels (table 1) of **Qpm** were derived from mountain-front drainages in the Manzano Mountains. Some of the gravel (**Qgm**) in the Abó and Quarai units is particularly distinctive because it contains Precambrian, Pennsylvanian, and Permian clasts (fragments of source rocks), thereby reflecting bedrock composition of local upland drainage systems and the landscape through which the streams flowed. Larger clasts would have been transported and deposited under high energy conditions (e.g., floods). Stream-valley alluvium (**Qpm**) in the Abó unit, though graded to former and modern levels of the Abo Arroyo, lies above (and predates) active floodplains and channels. As mapped by Scott et al. (2005) in the Scholle quadrangle, including two small deposits on the eastern side of the Abó unit (see poster, in pocket), **Qpm** has moderately developed soils that locally exhibit pedogenic carbonate morphology (development of calcium carbonate, probably related to soil moisture and possibly summer drying events); soil formation is an indication of age (middle to late Pleistocene Epoch), as well as the stability of the deposit.

During excavation and road construction at the Quarai unit in 1939–1940, mammoth bones were discovered. These bones would have been associated with Quaternary deposits. This discovery was cited by Hibben (1941) and Hurt (1990), but neither documentation nor the bones themselves could be found during the paleontological resource inventory by Thorpe et al. (2017). Thus, paleontological resources discovered in Quaternary deposits within monument boundaries are either lost (i.e., the mammoth) or stored at the Western Archaeological Conservation Center (WACC) in Tucson, Arizona (i.e., mammoth tusk fragments).

Local Geologic Features and Connections

The three units of the monument contain archeological and historical structures that were constructed using locally derived building stone. The structures at the Abó and Quarai units are composed of red sandstones. At the Abó unit, these red sandstones are either the Abo Formation (**Pa**) or the Arroyo de Alamillo Formation (**Pya**). At the Quarai unit, the red sandstone is the Arroyo de Alamillo and Abo Formations, undifferentiated (**Pu**). The gray limestone of the San Andres Formation (**Psa**) contrasts these red sandstones.

The builders at Abó and Quarai made full use of natural joints (fractures in rock) that allowed the sandstone to be broken easily into more or less rectangular blocks (Chronic 1987). At Gran Quivira, the limestone was easily pulled out due to veins of gypsum, forming irregular blocks (Marc LeFrancois, Salinas Pueblo

Missions National Monument, exhibit specialist, written communication, 25 May 2017).

The bedrock at all three units hosts petroglyphs (prehistoric rock carvings), and the bedrock at the Abó unit has pictographs (prehistoric rock paintings). Pictographs and petroglyphs at Abó have limited access. Some petroglyphs are readily accessible at Quarai (National Park Service 2014).

Lithic fragments of non-local rocks occur as artifacts. For example, scoping participants identified obsidian (volcanic glass) as stone tools found at the monument. A possible source area of the obsidian is the Jemez Mountains to the north. As reported by Head (1999), the Jemez Mountains yielded lithic resources including obsidian, dacite, and chert (see GRI report about Bandelier National Monument by KellerLynn 2015a).

Abó Unit

The Abó unit contains the oldest pueblo in the monument (fig. 11; next page). It is located about 11 km (7 mi) southwest of Mountainair and encompasses about 110 ha (280 ac) in the foothills of the Manzano Mountains. The Abó pueblo was adjacent to a trade route that led through Abó Pass to the Rio Grande valley. The number and size of unexcavated pueblo mounds at the Abó unit suggest that when the Spanish arrived in 1581 they would have found a thriving community. The Spanish colonial period began in 1621 at Abó. A combination of disease, drought, and famine led to the abandonment of the mission in 1673. In 1815, Spanish sheep herders attempted to return to the area but were displaced by Apaches in 1830. Settlers permanently returned in 1869 (National Park Service 2014).

The landscape of the Abó unit and surrounding area is dominated by gently dipping (<10°) Paleozoic (Pennsylvanian and Permian) sedimentary strata. The pueblo was constructed in a valley between two cuestas. Hard layers of sandstone cap these cuestas, with softer mudstone forming their slopes. East-dipping, red sandstone of the Abo Formation (**Pa**) forms the cuesta west of the ruins. The Yeso Group, Arroyo de Alamillo Formation (**Pya**), forms the cuesta east of the ruins.

Dipping strata of the Abo and Arroyo de Alamillo Formations form extensive slopes that are commonly mantled by a thin layer of Quaternary surficial deposits. At the Abó unit, these deposits consist of a discontinuous cover of stream-valley alluvium (**Qpm**), which predates modern fluvial activity, and range in thickness from 0 to 5 m (16 ft). Scattered archaeological material is associated with these deposits. In addition, the eastern cuesta has gravel derived from Manzano Mountains sources (**Qgm**). Thickness is less than 10 m (30 ft). **Qgm** is associated with scattered archaeological material and architectural remnants.

The largest arroyo cutting through the Abó unit is the Abo Arroyo, which is the main stem draining the 50 km^2 (20 mi^2) Cañon Espinoso watershed. The highest extremity of this arroyo is about 19 km (12 mi) upstream. Arroyos in the southwestern United States are typically ephemeral or intermittent. By contrast, Abo Arroyo exhibits a near permanent, albeit normally small, streamflow. At places the flow seeps into the alluvial fill, flowing underground then reappearing downstream. Stream alluvium (**Qa**) on the valley floor of the Abó unit marks areas of streamflow.

Most of the Abó unit and surrounding area are drained by tributaries of the Abo Arroyo, which flows to the Rio Grande. Even though surface water at the Abó unit flows into the Rio Grande via Abo Arroyo, groundwater that is recharged north and west of the Abó unit—in the same area where the surface water that is generated flows down tributaries of Abo Arroyo—may drain into the Estancia basin because the Paleozoic rocks generally dip in that direction. Sufficient groundwater studies have not been conducted to conclusively determine groundwater flow pathways at the Abó unit (Charles G. [Jack] Oviatt, Kansas State University, Department of Geology, emeritus, email communication, 1 May 2017).

Gran Quivira Unit

The Gran Quivira unit is the largest and southernmost in the monument (fig. 12; next page). It is about 30 km (20 mi) southeast of Mountainair and encompasses about 250 ha (610 ac). In contrast to the other two units, Gran Quivira has no permanent surface water, springs, or distinct arroyos. Also, it is dominated by gray limestone, not red sandstone.

Prior to Spanish contact, Gran Quivira was a vast city with multiple pueblos. First contact with the Spanish probably took place in 1583 with the arrival of Don Antonio de Espejo (National Park Service 2016). The Spanish returned in 1598 with the expedition of Don Juan de Oñate, who became the first Spanish governor of New Mexico. En route to the colonial government in Santa Fe in 1605, Oñate scratched his name into El Morro—“the headland” or prominent sandstone cuesta of El Morro National Monument (see GRI report by KellerLynn 2012b). Oñate’s inscription is the oldest authenticated “signature” at El Morro National Monument. El Morro (the headland) is composed of Middle Jurassic (175 million to 161 million year old) Zuni Sandstone, which is much younger than the sandstones that underlie the Abó and Quarai units.

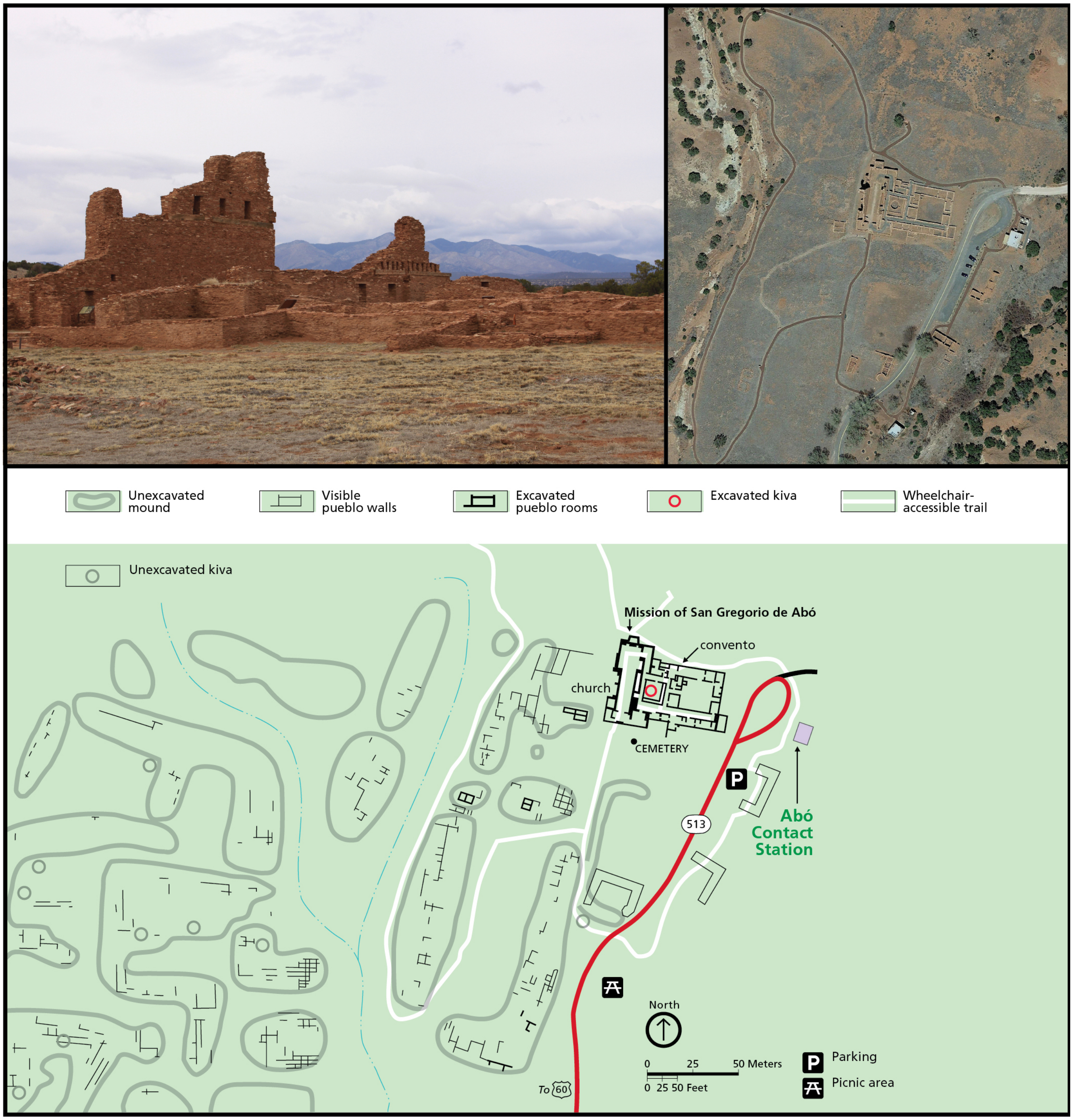


Figure 11. Photographs and map of the Abó unit.
The Abó unit consists of pit houses; jacales (adobe-style housing structures); prehistoric and historic pueblos; 17th century Spanish Franciscan mission structures, including the San Gregorio de Abó church; 19th century ranchero structures; pictographs (prehistoric pictures painted on rock); petroglyphs (prehistoric rock carving); and other associated sites and artifacts (National Park Service 2014). The structures were built using red sandstones of the Abo Formation (Pa) and the Yeso Group, Arroyo de Alamillo Formation (Pya). NPS photograph of ruins courtesy of Marc LeFrancois (Salinas Pueblo Missions National Monument). Aerial imagery from Google Earth (accessed 6 June 2018). NPS map available at https://home.nps.gov/carto/app/#!/parks (accessed 1 August 2017).

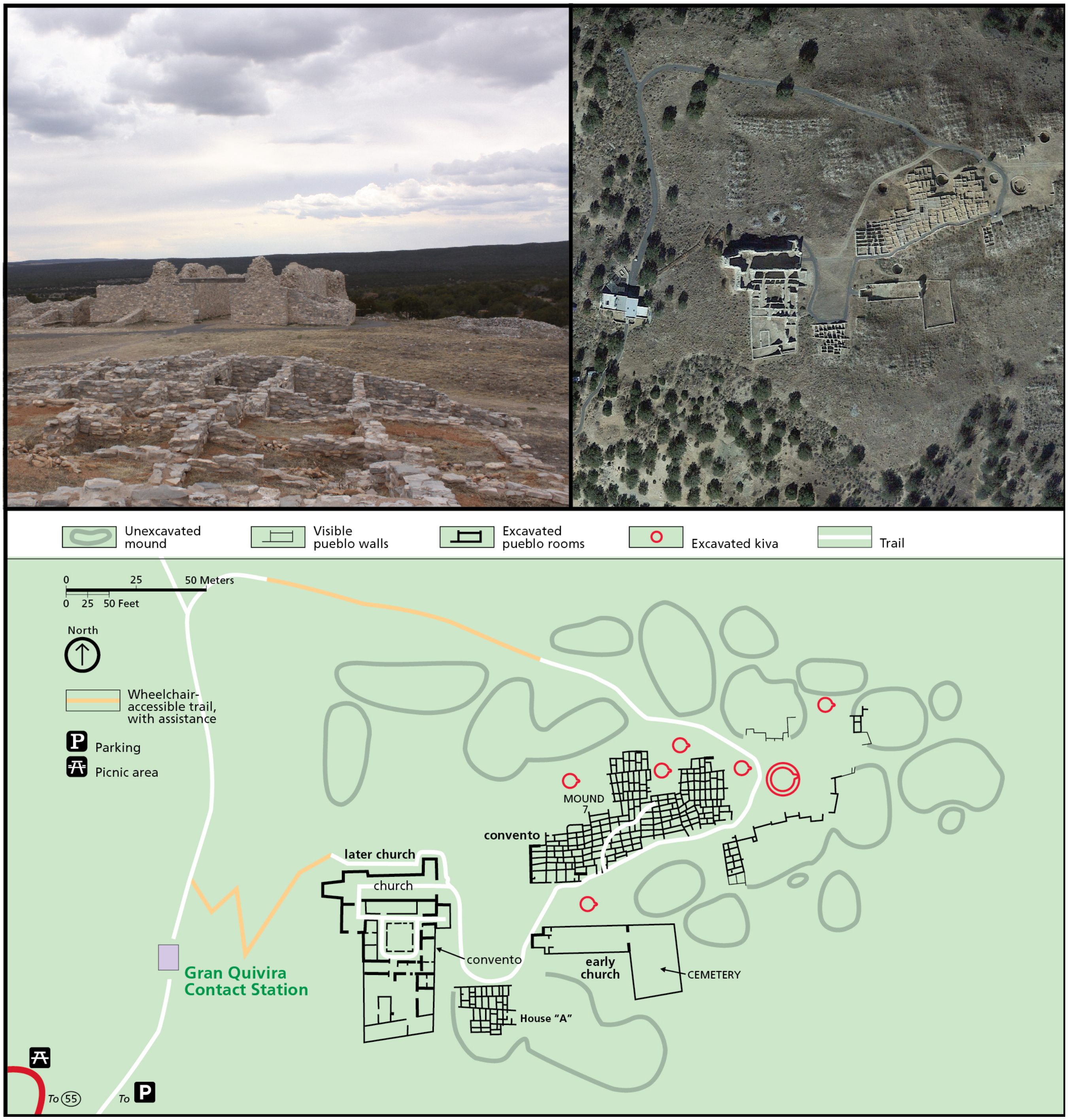


Figure 12. Photographs and map of the Gran Quivira unit.
The Gran Quivira unit consists of pit houses; prehistoric and historic pueblos; 17th century Spanish Franciscan mission structures, including a large church and convento (housing for friars) known as San Buenaventura and a smaller, earlier church, San Isidro; 19th and 20th century homesteads; petroglyphs (prehistoric rock carvings); and other associated sites and artifacts (National Park Service 2014). The structures were built using the gray limestone of the San Andres Formation (Psa). Mound 7 is shown in the foreground of the top left photograph. NPS photograph of ruins courtesy of Marc LeFrancois (Salinas Pueblo Missions National Monument). Aerial imagery from Google Earth (accessed 6 June 2018). NPS map available at https://home.nps.gov/carto/app/#!/parks (accessed 6 June 2018).

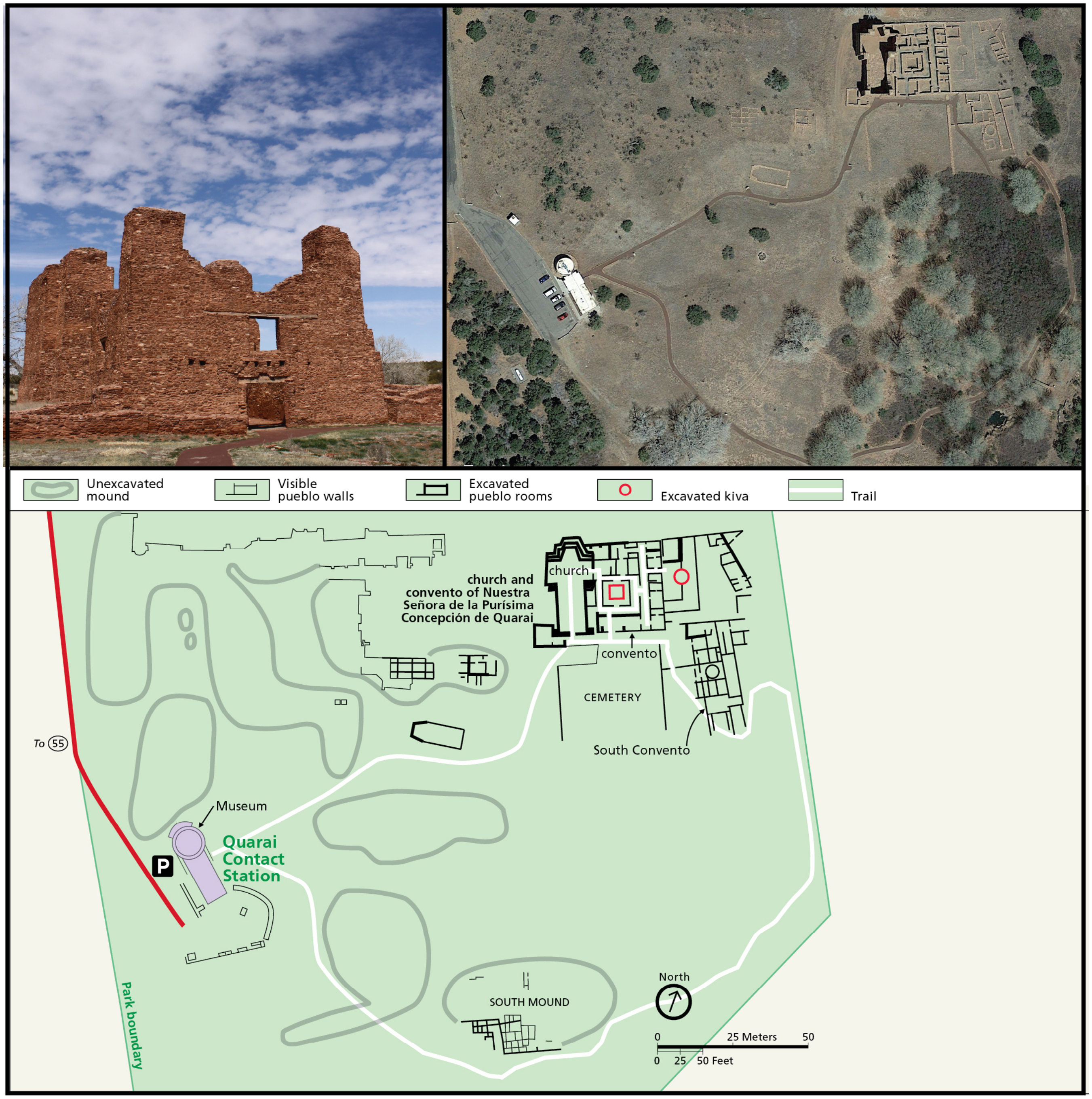


Figure 13. Photographs and map of the Quarai unit.
The Quarai unit consists of a prehistoric settlement; a large 17th century pueblo; a large 17th century Spanish Franciscan mission, including the church of Nuestra Señora de la Purisíma Concepción de Cuarác; a small 19th century church; ranchero compound; petroglyphs (prehistoric rock carvings); and other associated sites and artifacts (National Park Service 2014). The structures were built using the red sandstone of the Arroyo de Alamillo and Abo Formations, undifferentiated (Pu). NPS photograph of ruins courtesy of Marc LeFrancois (Salinas Pueblo Missions National Monument). Aerial imagery from Google Earth (accessed 6 June 2018). NPS map available at https://home.nps.gov/carto/app/#!/parks (accessed 6 June 2018).

The Gran Quivira area is dominated by the San Andres Formation (**Psa**) and associated karst topography composed of rolling hills and broad depressions. Surface exposures are mostly limestone, though some gypsum crops out in hilly areas. Dikes consisting of Tertiary igneous rocks (**Tim**) deformed the San Andres Formation, bowing it upward into anticlines (hills). Six small exposures of mafic dike rocks (**Tim**) were mapped in the Gran Quivira unit (see poster, in pocket). Blocks of mafic dike rocks also are present in colluvium (deposits of fragmented rock transported by gravity on or at the base of slopes) at the surface of the Gran Quivira unit (Oviatt 2011a).

Broad depressions between hills at the Gran Quivira unit contain collapsed areas caused by subsurface dissolution of gypsum and limestone. Sandy alluvium and eolian sand (**Qae**) fills the broad depressions between hills. Eolian sand in poorly developed longitudinal dunes appears on aerial photographs and satellite images as long streaks, having a southwest to northeast orientation, but the dunes are difficult to see on the ground (Oviatt 2011a).

Quarai Unit

The Quarai unit is the smallest and northernmost of the three units in the monument (fig. 13). It encompasses approximately 40 ha (100 ac) and is about 10 km (6 mi) northwest of Mountainair. Like at Gran Quivira, Don Juan de Oñate would have found a thriving city when he arrived in 1598. The Spanish colonial period at Quarai began in 1625. A combination of disease, drought, famine, and Apache raids led to the abandonment of the mission in 1678.

The Quarai pueblo was built where two undifferentiated sandstone formations—Arroyo de Alamillo and Abo (**Pu**)—dip eastward off the Manzano Mountains. These sandstones are an estimated 90 m (300 ft) thick and consist of many alternating layers. The sandstones are red to orange, and these colors dominate road cuts, natural exposures, and younger alluvium derived from these rocks.

A mantle of alluvial gravel from the Manzano Mountains (**Qgm**) covers the broad, rolling, sandstone surfaces (**Pu**) in and around the Quarai unit. **Qgm** is associated with scattered archaeological material and architectural remnants. Stream alluvium, undivided (**Qa**) covers the valley bottom at the Quarai unit. This material has been accumulating since the late Pleistocene Epoch (about 126,000 years ago), and deposition continues to the present day, notably in "Zapato Creek" (an informal name used locally). The creek flows in an arroyo that is about 150 m (500 ft) long and in places more than 6 m (20 ft) deep, cutting into bedrock (National Park Service 1997). Zapato Creek is fed by springs issuing from a shallow aquifer in the Abo Formation (National Park Service 1997). The creek serves as a year-round source of water that supported prehistoric pueblo and colonial mission occupants. The Indians and early explorers knew the site as a refreshing oasis in the midst of dry expanses, and the springs were certainly a key attraction to the Spanish missionaries in the 1600s (National Park Service 1997). An old acequia (irrigation ditch) operated at the Quarai unit until 1972. Today the spring-fed creek nourishes comparatively lush vegetation.

Geologic Resource Management Issues

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

During the 2006 scoping meeting (see National Park Service 2006), participants (see Appendix A) identified many geologic resource management issues, listed below in alphabetical order. Most of the following issues can be associated with a particular geologic map unit or units (see table 3 and "Potential Resource Management Actions").

- Drainage Problems and Flooding
- Water Erosion
- Paleontological Resource Inventory, Monitoring, and Preservation
- Wetlands
- Wind Erosion
- Energy Resource Development
- Cave Resource Management
- Karst Resource Management
- Abandoned Mineral Lands

Some geologic issues are broader in scope or are not associated with a particular map unit; these are discussed in "Other Geologic Resource Management Issues" section and are listed below in alphabetical order.

- Climate Change
- Earthquakes and Other Ground Shaking
- Volcanic Activity

Potential Resource Management Actions

Monument managers are encouraged to contact the NPS Geologic Resources Division (https://www.nps.gov/orgs/1088/contactus.htm) for assistance with the geologic resource management issues listed in table 3 and discussed below. Monument staff can formally request assistance via https://irma.nps.gov/Star/.

The Geologic Resources Division provides technical and policy support for geologic resource management issues in three emphasis areas: (1) geologic heritage, including cave, karst, and paleontological resources; (2) active processes and hazards; and (3) energy and minerals management (see http://go.nps.gov/geology).

Resource managers may find *Geological Monitoring* (Young and Norby 2009) useful for addressing geologic resource management issues. The manual provides guidance for monitoring vital signs—measurable parameters of the overall condition of natural resources. Each chapter of *Geological Monitoring* covers a different geologic resource and includes detailed recommendations for resource managers, suggested methods of monitoring, and case studies. Resource managers may contact the GRI team for PDF files of chapters (see https://www.nps.gov/subjects/geology/geological-monitoring.htm).

If funding allows, resource managers could consider obtaining quantitative information via photogrammetry (the science of making measurements from photographs). Traditionally, photogrammetry is associated with aerial images taken by a camera that is mounted in an aircraft. Multiple overlapping photos of the ground are taken as the aircraft flies along a flight path. These photos are processed in a stereo-plotter (an instrument that lets an operator see two photos at once in a stereo view) and used to create maps or digital elevation models. The Geologic Resources Division has the equipment and software to conduct close-range photogrammetry where the camera is close to the subject and typically hand-held or on a tripod, but also may be attached to a low altitude unmanned vehicle. The result is a 3D model. The NPS Geologic Resources Division Photogrammetry website (http://go.nps.gov/grd_photogrammetry) provides more information and examples of a variety of applications for resource management. Photogrammetry could provide a tool for monitoring erosion, fossils, building stability, and subsidence/collapse at the monument.

Abandoned Mineral Lands

Small-scale quarrying of the Yeso Group, Arroyo de Alamillo Formation (**Pya**) took place at the Abó unit prior to NPS acquisition. According to the scoping summary (National Park Service 2006), reclamation was underway. If managers require assistance with AML issues, they are encouraged to contact the NPS Geologic Resources Division.

Notably, the quarries at the monument are not included in the servicewide Abandoned Mineral Lands (AML) database (see Burghardt et al. 2014). All AML features should be recorded because an accurate inventory identifies human safety hazards and contamination issues, and facilitates closure, reclamation, and restoration of AML features. When appropriate for resource management and visitor safety, AML features

Table 3. Geologic Resource Management Issues at Salinas Pueblo Missions National Monument.

Table continues on next 2 pages.

Map Unit (symbol)	Park Unit	Issues
Stream alluvium (**Qa**)	Abó Quarai	**Drainage Problems and Flooding** **Qa** is associated with drainage problems along the trail and throughout the Quarai unit. A shallow diversion dike and a berm keep moisture away from the church, but the berm will not withstand substantial flooding. The diversion (ditch) needs to be regularly cleared of sediment to avoid overflowing during storms. Flood risks at the Abó unit do not appear extreme because the ruins and other buildings are above the 100-year flood line (National Park Service 1997). In addition, the principal arroyo at the Abó unit has some characteristics that are favorable from a flooding perspective: (1) the ruins lie on the inside of a curve in the main arroyo, and cutting normally does not occur on the inside of stream curves; and (2) the arroyo appears to now flow mainly along sandstone bedrock (no longer in erodible materials) in the area east of the ruins. A small arroyo feeds into the northwest corner of the Quarai unit and at times flows around the northern edges of the mission ruins. This small arroyo drains about 3 km^2 (1 mi^2) and can produce brief periods of localized flooding next to the mission ruins. During a 100-year storm, water is predicted at about 15 cm (6 in) deep around the perimeter of the ruins and in the parking lot area. **Water Erosion** At the Abó unit, **Qa** is associated with small, intermittent streams that cause considerable erosion, resulting in prehistoric and historic material washing out of the deposits. At the Quarai unit, **Qa** is associated with a spring-fed creek and arroyo. Except for some minor bank sloughing, the arroyo is stable and contains old trees and well-established vegetation. Further downward cutting is unlikely because the channel has reached bedrock (**Pu**); however, some minor bank sloughing is expected to continue, especially as a result of severe storms. **Paleontological Resource Inventory, Monitoring, and Preservation** **Qa** yielded the remains of a mammoth discovered during road building in 1939–1940 at the Quarai unit (see Hurt 1990). Neither documentation nor the bones themselves could be found during the paleontological resource inventory by Thorpe et al. (2017). Paleontological resources are generally in good and stable condition. Vandalism, looting, and erosion pose threats to their continued stable condition. **Wetlands** The spring-fed creek at the Quarai unit has a small but dependable flow that supports an estimated 2 ha (5 ac) of critical riparian or wetland vegetation within the unit as well as another estimated 0.8 ha (2 ac) on private land downstream from the unit's boundary. These wetlands serve as critical habitat for birds and wildlife (National Park Service 1997).
Stream alluvium and eolian sand (**Qae**)	Gran Quivira	**Water and Wind Erosion** Eolian erosion and deposition of sediment have implications for cultural resources through repeated cycles of burial and exposure. **Qae** is subject to erosion from dry winds and the occasional pounding by thunderstorms, so small rills and gullies appear throughout the unit.
Gravel derived from Manzano Mountains sources (**Qgm**)	Abó Quarai	**Wind Erosion** The surfaces mapped as **Qgm** have a loess (windblown silt) cap that may be 1 m (3 ft) or more thick, which may be subject to eolian erosion. Eolian erosion and deposition of sediment have implications for cultural resources through repeated cycles of burial and exposure.
Stream-valley alluvium, intermediate deposits (**Qpm**)	Abó	**Water and Wind Erosion** **Qpm** sits higher than active drainages, about 6–12 m (20–40 ft) above local base level, thus the material is probably not subject to intermittent-stream erosion but may be subject to wind erosion and occasionally water erosion during thunderstorms. As mapped by Scott et al. (2005) in the Scholle quadrangle, **Qpm** has moderately developed soils, which is indicative of age (middle to late Pleistocene Epoch) and the stability of the deposit.

Table 3, continued. Geologic Resource Management Issues at Salinas Pueblo Missions National Monument.

Map Unit (symbol)	Park Unit	Issues
Mafic dike rocks (**Tim**)	Gran Quivira	**Energy Resource Development** Heating associated with **Tim** caused thermal maturation of oil reservoirs. Tertiary dikes were accompanied by widespread heating that facilitated the release of helium from Precambrian rocks into the Paleozoic sedimentary strata.
San Andres Formation (**Psa**)	Gran Quivira	**Cave Resource Management** Historic NPS records suggest that both natural caves and artificial tunnels may be present at Gran Quivira. The reburial design of the pueblo (for the purpose of preservation and protection of cultural resources) needs to consider the location of natural cave systems (for the purpose of preservation and protection of natural resources). **Karst Resource Management** The Gran Quivira unit receives as much precipitation as the other two units, but contains no surface water because of the karst landscape. Summer precipitation not lost to high evapotranspiration becomes groundwater recharge and percolates down into sinkholes, crevices, and solution channels. Sinkholes in the vicinity of the Gran Quivira unit are the result of the dissolution of Permian evaporite rocks. Collapse related to subsurface dissolution of limestone and gypsum causes cracks at the surface, which is a concern for the integrity of the ruins. **Energy Resource Development** **Psa** is a petroleum reservoir rock; however, it crops out or is present only at shallow depths or has been eroded from most of the Chupadera Mesa area and is therefore of minor interest for oil and gas development there. Organic hydrocarbon material commonly seeps out of **Psa**, including from building stone in the Gran Quivira ruins (see "Research Topics"). Karstic dissolution has rendered the San Andres Formation highly permeable in some areas; nevertheless, it is too shallow or crops out in too many places to form a significant reservoir for oil and gas in the Estancia basin. **Paleontological Resource Inventory, Monitoring, and Preservation** Bedrock consists of marine microfossils. Building stone contains (macro)fossils (e.g., gastropod and coquina bed). Paleontological resources are generally in good and stable condition. Vandalism, looting, and erosion pose threats to their continued stable condition.
Yeso Group, Arroyo de Alamillo Formation (**Pya**)	Abó	**Abandoned Mineral Lands** Small-scale quarry operations took place prior to NPS acquisition; reclamation is underway. **Energy Resource Development** Exploratory wells show the presence of oil and gas in the Estancia basin. In the Chupadera Mesa area, the marine and marginal marine sandstones are favorable oil and gas reservoirs; also, anhydrite beds make good seals for helium. **Water and Wind Erosion** Erosion threatens a significant pictograph (prehistoric picture painted on rock) site that is situated underneath an outcrop of Pya. This overhanging rock shelf, and the pictographs painted on it, will fall one day. The Abó unit also has petroglyphs, which are not known to be threatened by erosion. **Karst Resource Management** Dissolution of gypsum in bedrock is occurring. Evidence of dissolution is provided by locally variable dips in the sandstones and limestones that overlie gypsum beds. **Paleontological Resource Inventory, Monitoring, and Preservation** The first known vertebrate fossil in the Yeso Group, specifically the Arroyo de Alamillo Formation (**Pya),** was discovered in the Abó unit in 2016. **Pya** also contains trace fossils, including tracks. Paleontological resources are generally in good and stable condition. Vandalism, looting, and erosion pose threats to their continued stable condition.

Table 3, continued. Geologic Resource Management Issues at Salinas Pueblo Missions National Monument.

Map Unit (symbol)	Park Unit	Issues
Arroyo de Alamillo and Abo Formations, undifferentiated (**Pu**)	Quarai	**Karst Resource Management** Local collapse of bedrock related to subsurface gypsum dissolution is occurring. Dissolution causes anomalous dips in some outcrops. **Energy Resource Development** Exploratory wells show the presence of oil and gas in the Estancia basin. In the Chupadera Mesa area, the marine and marginal marine sandstones are favorable oil and gas reservoirs; also, anhydrite beds make good seals for helium. **Paleontological Resource Inventory, Monitoring, and Preservation** The bedrock at the Quarai unit contains trace fossils and plant fossils. Paleontological resources are generally in good and stable condition. Vandalism, looting, and erosion pose threats to their continued stable condition.
Abo Formation (**Pa**)	Abó	**Energy Resource Development** Exploratory wells in the Estancia basin show the presence of gas, though whether it is hydrocarbon, nitrogen, CO_2, or another compound is unknown. The continental sandstone is a favorable oil and gas reservoir in the Chupadera Mesa area; also, thick shales make good seals for helium. **Paleontological Resource Inventory, Monitoring, and Preservation** Bedrock at the Abó unit contains plant fossils. Paleontological resources are generally in good and stable condition. Vandalism, looting, and erosion pose threats to their continued stable condition.

can also present opportunities for interpretation as cultural resources. AML features also may provide habitat for bats and other animals, some of which are protected under the Endangered Species Act or state species listings. The Geologic Resources Division can provide assistance in adding information to the servicewide database. The NPS AML website, http://go.nps.gov/aml, provides further information.

Cave Resource Management

The Federal Cave Resources Protection Act of 1988 requires the identification of "significant caves" in NPS areas, the regulation or restriction of use as needed to protect cave resources, and inclusion of significant caves in land management planning. The act also imposes penalties for harming a cave or cave resources and exempts park managers from releasing specific location information for significant caves in response to a FOIA request (see also Appendix B).

Historic NPS records suggest that both natural caves and artificial tunnels may be present beneath and adjacent to Mound 7—a large excavated and partially reconstructed Native American pueblo—at Gran Quivira. The results of a study by Ball et al. (2005) were inconclusive, however, and further refined karst radar data are needed to identify caves.

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

If a cave is present, Quaternary fossils also may be present (Thorpe et al. 2017). Caves may preserve dung and/or the bones of Pleistocene mammals such as ground sloth and camelids. Another potential fossil resource for caves at the monument is packrat (*Neotoma* spp.) middens (Tweet et al. 2012). These rodent nests can date back tens of thousands of years, and may yield fossils of plants, arthropods, and microvertebrates. Packrat middens are known in the vicinity of the Sevilleta Long Term Ecological Research site in Socorro County, 40 km (25 mi) southwest of the Abó unit (Pendall et al. 1999). Santucci et al. (2001) presented an overview and cited selected examples of National Park Service fossils found in caves.

In the *Geological Monitoring* chapter about caves and associated landscapes, Toomey (2009) described methods for inventorying and monitoring cave-related vital signs, including the following: (1) cave meteorology, such as microclimate and air composition; (2) airborne sedimentation, including dust and lint; (3) direct visitor impacts, such as breakage of cave formations, trail use in caves, graffiti, and artificial cave lighting; (4) permanent or seasonal ice; (5) cave drip and pool water, including drip locations, rate, volume, and water chemistry, pool microbiology, and temperature; (6) cave microbiology; (7) stability issues associated with breakdown, rockfall, and partings; (8) mineral growth of speleothems, such as stalagmites and stalactites; (9) surface expressions and processes that link the surface and the cave environment, including springs, sinkholes, and cracks; (10) regional groundwater levels and quantity; and (11) fluvial processes, including underground streams and rivers.

Karst Resource Management

Karst is a landscape that forms through the dissolution of soluble rock, most commonly carbonates such as limestone or dolomite (Toomey 2009). Caves, sinkholes, losing streams, springs, and internal drainage are characteristic features of karst landscapes. The majority of the monument (92.71%) is made up of karst (Land et al. 2013).

A variety of laws, regulations, and policies guide the management of karst resources (see Appendix B and https://www.nps.gov/subjects/caves/cave-karst-protection.htm). The National Park Service manages karst terrain to maintain the inherent integrity of its water quality, spring flow, drainage patterns, and caves. The NPS Cave and Karst website, https://www.nps.gov/subjects/caves/index.htm, provides more information. Monument managers are encouraged to contact the NPS Geologic Resources Division with questions and concerns about resource management and park planning with respect to karst. The aforementioned Geological Monitoring chapter by Toomey (2009) is applicable for karst as well as caves.

Energy Resource Development

The geologic setting of the monument, including the Estancia basin and Chupadera Mesa, is favorable for energy resource development. Broadhead (1997) reported on the oil and gas potential of the Estancia basin. Broadhead (2009) reported on the oil, natural gas, and helium potential of the Chupadera Mesa area.

No oil or hydrocarbon gas production has been established in the Estancia basin, but 43 exploratory wells have been drilled. In addition, two exploratory wells near Mountainair showed the potential for oil (Broadhead 1997). No oil and gas production has been established in the Chupadera Mesa area, but 47 exploratory wells have been drilled (Broadhead 2009). The only commercial gas production in the Salinas Pueblo Missions area took place in two small fields west of the town of Estancia in the 1930s and 1940s; carbon dioxide (CO_2) was produced from Lower Pennsylvanian sandstones in those fields. Moreover, three pipelines pass through Torrance County; two of these also pass through Socorro County (Broadhead 1997).

The Salinas Pueblo Missions area has a climate and landscape that is highly desirable to wind and solar energy development. Conservative estimates predict that upwards of 500 more wind turbines will be installed near the monument in the next few years (fig. 14), in addition to large fields collecting solar energy, associated transmission lines, and a CO_2 pipeline running tangential to monument boundaries (fig. 15). Many of these developments are implemented without monument staff being aware of the proposals or given the opportunity to comment (National Park Service 2014).

Monument managers seek to coordinate with neighboring communities for a cohesive, locally led effort to protect the historic properties and cultural landscapes of the monument (National Park Service 2014). These efforts could be through engagement in planning processes for proposed developments or through the furthering of a proposal for the designation of a national heritage area (NHA) of the Salinas province, including other nearby national register properties. A NHA designation would provide some protection to the area, the guidance of a board of directors, and the completion of a comprehensive plan for management. Also, managers seek to work with the NPS Intermountain Region regarding development of a position paper or guidance for commenting and interfacing with regard to development proposals. This guidance would help park managers speak with one voice regarding where the National Park Service stands on these issues and how to best communicate in order to protect NPS resources (National Park Service 2014).

The NPS Geologic Resources Division is available to provide monument staff with policy and technical assistance regarding energy issues. The NPS Energy and Minerals Management website, https://www.nps.gov/subjects/energyminerals/index.htm, provides additional information.

Paleontological Resource Inventory, Monitoring, and Preservation

According to the paleontological resources inventory for the monument (Thorpe et al. 2017), most fossil localities are within the Abó unit, with the exception of the now-lost mammoth discovered at the Quarai unit and a few fossil localities at the Gran Quivira unit. Two NPS publications provide specific information about the paleontological resources at the monument: Tweet et al. (2009) and Thorpe et al. (2017). These publications addressed medium-priority needs listed in the monument's foundation document (National Park Service 2014). Both provided recommendations for resource management of paleontological resources at

Figure 14. Photograph of wind turbines. The Salinas Pueblo Missions area has a climate and landscape that is highly desirable to wind development. Conservative estimates predict that upwards of 500 more wind turbines will be installed near the monument in the next few years. The figure shows High Lonesome Wind Farm immediately south of Willard on the Jumano Mesa (a finger of the Chupadera Mesa). Photograph from National Park Service (2014, p. 29).

Figure 15. Photograph of energy infrastructure. Corridors for transmission lines and buried pipelines create pathways that concentrate runoff, which can exacerbate erosion and threaten archeological sites. This photograph was taken along Highway 55, north of the Gran Quivira unit. Photograph from National Park Service (2014, p. 29).

the monument, and Thorpe et al. (2017) recommended interpretive themes.

Following a field inventory conducted in summer 2016, which was documented by Thorpe et al. (2017), the Permian rocks at the monument are known to contain trace fossils (*Skolithos*, *Taenidium*, and possible *Cruziana*/*Rusophycus*), trace fossil burrows (*Planolites*), bioturbation, an arthropod trackway (*Diplichnites*), tracks (*Dromopus* and *Batrachichnus*), tracks and toe impressions (*Dromopus*), plant impressions (*Walchia*), plant fossils (*Walchia piniformis* and *Dicranophyllum*), fossil plant debris (stems and sticks), nautiloid/bellerophontid gastropod specimens, and two counterparts of the lower half of an early Permian synapsid reptile.

The articulated vertebrate skeletal impression was discovered within the Abó unit in summer 2016 (fig. 16). This specimen is significant not only because vertebrates are rare, but also because it consists of two counterparts. This specimen is the first vertebrate body fossil discovered in the Yeso Group and more specifically in the Arroyo de Alamillo Formation (Thorpe et al. 2017).

NPS management policies (see Appendix B) for paleontological resource management generally focus on in situ occurrences of fossils. Monument managers may find the *Geological Monitoring* chapter about in situ paleontological resources by Santucci et al. (2009) of interest and use for monitoring fossils at the monument. That chapter described five methods and vital signs for monitoring in situ paleontological resources: (1) erosion (geologic factors), (2) erosion (climatic factors), (3) catastrophic geohazards, (4) hydrology/bathymetry, and (5) human access/public use.

Fossils are also found in cultural resource contexts. Kenworthy and Santucci (2006) provided an overview of NPS paleontological resources in cultural resource contexts. Such fossils may be subject to the legislative protection and management/preservation guidance found in the 1979 Archeological Resources Protection Act (ARPA), 1990 Native American Graves Protection and Repatriation Act (NAGPRA), NPS *Management Policies 2006* section 5.3, and NPS Directors Orders (DO) 28 (Cultural Resources Management) and DO 29 (Ethnography Program [in development]). Tweet et al. (2009) identified artifacts from the Quarai unit made of bone, shell, chert, and other potentially fossiliferous stones; many artifacts are chalcedony, for example, which is one of the mineral types that petrified wood can take. The WACC database lists at least three pieces of petrified wood from the Gran Quivira unit among its collection (Tweet et al. 2009). Thorpe et al. (2017)

Figure 16. Photograph of Permian vertebrate skeleton.
In summer 2016, Ron Fields (Salinas Pueblo Missions National Monument, integrated resource specialist) and Emily Thorpe (GIP intern) discovered an articulated skeleton of a Permian reptile, in two counterparts (see Thorpe 2017). The fossil consists of hind limb bones (some broken), posterior vertebrae, and hand and finger bones. This is the first vertebrate fossil to be discovered in the Yeso Group, specifically the Arroyo de Alamillo Formation. NPS photograph by Emily Thorpe (cover image of Thorpe et al. 2017)

documented a cast of an unidentified gastropod in a block of San Andres limestone used for building in the church at Gran Quivira, as well as a block of coquina, consisting mostly of unidentified brachiopod shells and possibly bivalve shells, used in construction of the church at Gran Quivira. Whether this block is a part of the San Andres Formation is unknown; more study might determine its provenience. A coquina bed composed mostly of brachiopods in the Gran Quivira unit is the source of the coquina block used in construction of the church at Gran Quivira. In addition, the Abó unit contains landscaping rock (limestone) from a quarry at Abo Pass (west of the ruins); it contains an abundance and variety of marine fossil hash, likely from the Bursum Formation (table 3).

The NPS Geologic Resources Division is available to provide monument staff with policy and technical assistance regarding paleontological resource issues. The NPS Fossils and Paleontology website, https://www.nps.gov/subjects/fossils/index.htm, provides additional information.

Water Resource Issues

As listed in table 3, water resource issues at the monument include drainage problems and flooding, [water] erosion, and wetlands. The water resources management plan (National Park Service 1997) addressed water-related issues at the monument and provided recommendations and a project statement for technical assistance that would design and help initiate the collection of some basic, low-technology measurements of watershed and hydrologic data to help generally quantify erosion, any pollution, major precipitation events, average stream and spring discharges, and the extremes in flows for these two units.

In addition to "revisiting" the 1997 water resources management plan, monument managers also may find the *Geological Monitoring* chapter about fluvial geomorphology by Lord et al. (2009) of interest and use for understanding stream dynamics and monitoring stream systems at the Abó and Quarai units. Lord et al. (2009) described methods for monitoring the following vital signs: (1) watershed landscape (vegetation, land use, surficial geology, slopes, and hydrology), (2) hydrology (frequency, magnitude, and duration of streamflow rates), (3) sediment transport (rates, modes, sources, and types of sediment), (4) channel cross section, (5) channel planform, and (6) channel longitudinal profile.

Some locals would like to see the old acequia at the Quarai unit rehabilitated (National Park Service 1997). The water rights for this ancient water use are complex, however, and would require legal analysis. Furthermore, rehabilitation of the acequia potentially could affect the wetlands in the area, raising an issue for wetland protection (see Appendix B). Monument managers are encouraged to contact the NPS Water Resources Division for assistance with issues concerning wetlands and water rights.

Wind Erosion

Eolian—also spelled "aeolian," for example by Lancaster (2009)—processes refer to windblown erosion, transportation, and deposition of sediments. Erosion by wind involves two linked processes: abrasion (mechanical wearing of coherent materials, including playa crusts and clods created by tillage) and deflation (removal of loose material). Quaternary deposits (**Qae**, **Qgm**, and **Qpm**) may be susceptible to wind erosion. An effect of wind erosion may be the transport of fine sediment, causing dust storms (events in which visibility is reduced to less than 1 km [0.6 mi] by blowing dust). Dust storms impact air quality in their immediate vicinity as well as in areas downwind. Deposition of dust may have a significant effect on the composition and nature of soils in arid regions and beyond. Far-traveled dust from distant sources may have a significant effect on soil chemistry and nutrient status (Farmer 1993). In addition, the ruins may be affected by abrasion ("sand blasting"), particularly the petroglyphs and pictographs (Marc LeFrancois, Salinas Pueblo Missions National Monument, exhibit specialist, written communication, 24 May 2017).

In the *Geological Monitoring* chapter about aeolian features and processes, Lancaster (2009) described the following methods and vital signs for monitoring aeolian resources: (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. The NPS Geological Monitoring website, http://go.nps.gov/geomonitoring, provides additional information.

Other Geologic Resource Management Issues

The following geologic resource management issues are large in scope, encompassing the monument's geologic landscape (and all of its map units) and beyond.

Climate Change

The monument's foundation document (National Park Service 2014) identified a climate change vulnerability assessment and climate change scenario planning as needs. A climate change summary (Gonzalez 2014) and a climate change resource brief (Monahan and Fisichelli 2014) provide information about the historical range of variability and trends in temperature and precipitation, which may be applicable to these data and planning needs. A climate change vulnerability assessment and scenario planning could be completed in cooperation with the NPS Climate Change Response Program (see https://www.nps.gov/orgs/ccrp/index.htm).

The primary identified threat from climate change at the monument is drought. Results by Cook et al. (2015) point to a remarkably drier future that falls far outside the contemporary experience of natural and human systems in western North America, conditions that may present a substantial challenge to adaptation. Drought will continue to reduce water availability and increase wildfire frequency and magnitude, and therefore, threaten to alter the vegetation composition and structure of the cultural landscape of the monument and accelerate weathering, deterioration, and loss of archeological and cultural resources (National Park Service 2014). Drought–related geologic impacts are a result of a complex interplay among fire frequency and magnitude, vegetation composition and structure, winter snowpack and summer runoff, streamflow, stream-channel morphology, sediment transport, erosion of surficial deposits (e.g., **Qa** and **Qae**), and mass wasting (gravity-driven processes such as landslides). Studies on the interconnected system that includes fire, streamflow, stream-channel morphology, and landslides at Bandelier National Monument may be useful in climate change scenario planning at the monument (see GRI report by KellerLynn 2015a and references therein).

Earthquakes and Other Ground Shaking

Small earthquakes with a magnitude greater than 1.3 commonly occur in New Mexico. Earthquakes with a magnitude of 5.0 or greater, which can cause significant property damage, are relatively rare events, but earthquakes larger than magnitude 6.0 have taken place in the historical past and will probably occur again (Kelley 2016). A magnitude 5.0 earthquake has a 0.5 to 0.6 probability (50%–60% "chance") of occurring within 50 km (30 mi) of Mountainair in the next 100 years. A magnitude 6.0 earthquake has a 0.10–0.12 probability (10%–12% "chance") of occurring (fig. 17) (US Geological Survey 2017).

Knowledge of past earthquake activity can help monument managers anticipate what to expect from future earthquakes. In 1997–1998, the "Willard Swarm" of earthquakes was widely felt throughout central New Mexico, including all three units of the monument (National Park Service 2006). During the swarm, approximately 150 earthquakes were recorded in the region of Willard, Mountainair, and Estancia. The strongest magnitude quake was 3.8 and occurred on 4 January 1998. The epicenter was approximately 10 km (6 mi) northeast of Mountainair (Lupo 1998).

Monument managers many find various vital signs of interest and use for planning at the monument. The *Geological Monitoring* chapter about earthquakes and seismic activity by 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.

In addition to earthquakes, other types of ground shaking could damage the ruins at the monument. Energy development and production, including blasting, mining, and transportation; heavy vehicular traffic, especially on rough roads near sensitive sites; railroad traffic; and road construction can all result in shaking. Notably, the nearby rail line has recently been expanded to add a second parallel track (fig. 18). Also, military activities may cause felt vibrations at the monument (National Park Service 2006). The monument's proximity to the White Sands Missile Range and Holloman Air Force Base in Alamogordo has resulted in incidents from low-flying aircraft traveling throughout the region, with potential impacts from low-flying aircraft and sonic booms intruding on soundscapes and the acoustic environment and potentially damaging historic structures (National Park Service 2014). No seismic study has been conducted at the monument, but studies by King et al. (1985, 1991) conducted at Chaco Culture National Historical Park may be applicable (see GRI report by KellerLynn 2015c).

Volcanic Activity

New Mexico has experienced more than 700 volcanic events (single eruption from a vent or a series of associated eruptions from a vent) over the past 5 million years (Limburg 1990). The eruptive styles of these events ranged from dangerously explosive to passive. National Park System units within the state illustrate these styles; for the most to least explosive events, see the following GRI reports: Gila Cliff Dwellings National Monument (KellerLynn 2014), Bandelier National Monument (KellerLynn 2015a), Capulin Volcano National Monument (KellerLynn 2015b), Petroglyph National Monument (KellerLynn in review), and El Malpais National Monument (KellerLynn 2012a).

Based on the past occurrence of volcanism, Limburg (1990) estimated a roughly 1% chance that some type of volcanic eruption could occur somewhere in New Mexico in the next 100 years, and a 10% chance that an eruption will occur in the next 1,000 years. Intersections of the Rio Grande rift with crosscutting lineaments (zones of crustal weakness) are likely prospects for future volcanic activity because the deeply penetrating mosaic of intersecting fractures aids the ascent, storage, and differentiation of magmas (Chapin et al. 2004). Among other areas, including the Jemez volcanic field at the intersection of the Jemez lineament and Rio Grande rift, which is significant for

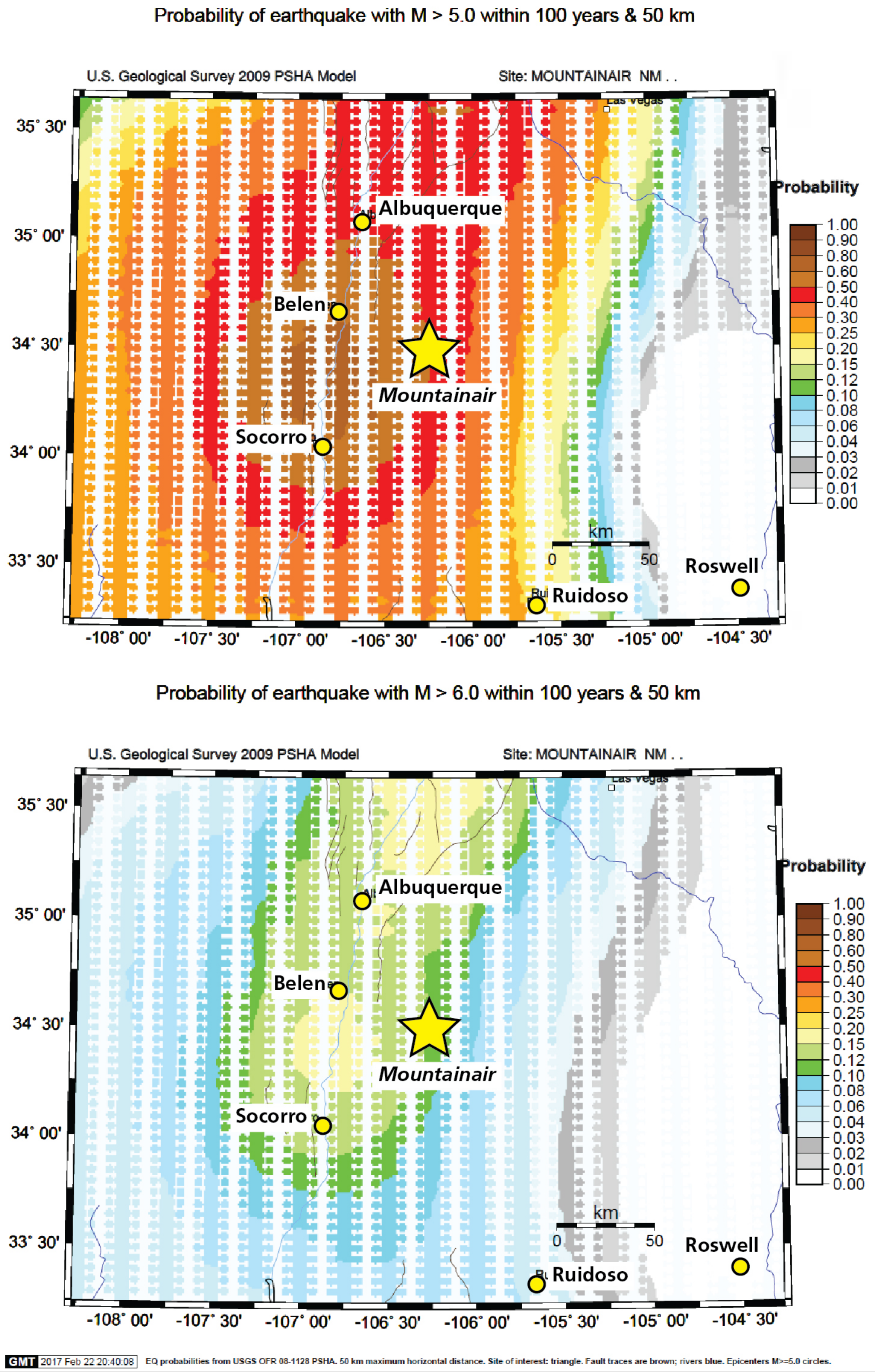


Figure 17. Maps of earthquake probability.
These maps show the probability of earthquakes with magnitude 5.0 (top) and 6.0 (bottom) occurring in the next 100 years within 50 km (30 mi) of Mountainair, New Mexico (yellow star; other cities labelled with yellow dots). Maps were developed using the USGS 2009 Earthquake Probability Mapping tool (as of 2017, this tool is no longer available online). The "puzzle piece" appearance is an artifact from processing the model data.

Figure 18. Photograph of train over Abo Arroyo.
In 1995, the Atchison, Topeka & Santa Fe Railroad (AT&SF) merged with the Burlington Northern to become the BNSF Railway. BNSF Railway owns the line and constructed a second track adjacent to the southern boundary of the Abó unit. Vibrations associated with rail construction and the frequent passing of trains is a concern for the stability of archeological resources. Photograph from National Park Service (2014, p. 28).

Bandelier National Monument, Carrizozo Malpais is a prospective area for future volcanism in the Tularosa basin (fig. 5). North–trending rift faults cut the Capitan lineament at Carrizozo, and volcanism occurred at this intersection about 5,200 years ago (Dunbar 1999) from a vent at Little Black Peak (Weber 1964; Renault 1970). The Gran Quivira unit is 43 km (27 mi) north of the Carrizozo Malpais lava flows. If volcanism reinitiates at Carrizozo Malpais, proximity could result in seismic activity at the Gran Quivira unit. Injection of magma below the surface would result in ground shaking or faulting at the surface. The similarity between Carrizozo and the Hawaiian Kupaianaha flow in Hawaii Volcanoes National Park (see GRI report by Thornberry-Ehrlich 2009) suggests that the Carrizozo flows were emplaced at a steady, slow eruption rate. The duration of the eruption may have been as long as two or three decades (Keszthelyi and Pieri 1993).

The *Geological Monitoring* chapter about volcanoes (Smith et al. 2009) described six vital signs and methodologies for understanding and monitoring volcanoes: (1) earthquake activity, (2) ground deformation, (3) gas emission at ground level, (4) emission of gas plumes and ash clouds, (5) hydrologic activity, and (6) slope instability. Resource managers many find these vital signs of interest and use at the monument.

Research Topics

The NPS Geologic Resources Division administers the Geoscientists-in-the-Park (GIP) and Mosaics in Science programs. These internship programs place scientists (typically undergraduate students) in parks to complete geoscience-related projects, which may address resource management issues. To date, the monument has had one GIP, Emily Thorpe, who conducted a paleontological inventory at the monument in summer 2016 (fig. 16). Other resource-management needs (see table 3), as well as intriguing research topics, could be addressed by a GIP or Mosaics in Science intern. More information is available at the programs' websites (http://go.nps.gov/gip and http://go.nps.gov/mosaics).

The monument's water resources management plan (National Park Service 1997) posed two research questions with the potential to be addressed by a GIP or Mosaics in Science intern. First, the Gran Quivira unit has no surface water, so an intriguing question is what was the water supply during prehistoric and Spanish colonial times? Today, the Gran Quivira unit has a deep well that supplies dependable and safe, albeit mineralized, water. Second, what is the origin and history of the acequia (irrigation ditch) at the Quarai unit? These questions have archaeological, hydrological, and geological aspects, and could benefit from geologic analysis, including geomorphology, sedimentology, and stratigraphy.

Another research question, discussed during GRI scoping in 2006, is the origin of the organic hydrocarbon material that commonly seeps out of the San Andres Formation (**Psa**), including from building stone in the ruins. The cause is unknown. This question also has the potential to be addressed by a GIP or Mosaics in Science intern.

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 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). Colors and symbols on geologic maps correspond to geologic map units. The unit symbols consist of an uppercase letter indicating the age (fig. 1) and lowercase letters indicating the formation's name. Other symbols depict structures such as faults or folds, locations of past geologic hazards that may be susceptible to future activity, and other geologic features. Anthropogenic features such as mines or quarries, as well as observation or collection locations, may be indicated on geologic maps. The American Geosciences Institute website, http://www.americangeosciences.org/environment/publications/mapping, provides more information about geologic maps and their uses.

Geologic maps are typically one of two types: surficial or bedrock. Surficial geologic maps typically encompass deposits that are unconsolidated and formed during the Quaternary Period (the past 2.6 million years). Surficial map units are differentiated by geologic process or depositional environment. 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 GRI produced a geologic map for Salinas Pueblo Missions National Monument that shows both bedrock and surficial deposits.

Source Maps

The GRI team does not conduct original geologic mapping. The team digitizes paper maps and compiles and converts digital data to conform to the GRI GIS data model. The GRI GIS data set includes essential elements of the 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 sapu_geology.pdf.

Four 1:24,000-scale source maps provided geologic data for the three units of the monument:

- Gran Quivira unit: Preliminary geologic map of the Gran Quivira 7.5-minute quadrangle by Oviatt (2012).
- Quarai unit: Preliminary geologic map of the Punta de Agua 7.5-minute quadrangle by Oviatt (2011b).
- Abó unit (eastern side): Preliminary geologic map of the Abo 7.5-minute quadrangle by Oviatt (2010).
- Abó unit (western side): Preliminary geologic map of the Scholle 7.5-minute quadrangle by Scott et al. (2005).

GRI GIS Data

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

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

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

- A GIS readme file (sapu_gis_readme.pdf) that describes the GRI data formats, naming conventions, extraction instructions, use constraints, and contact information;
- Data in ESRI geodatabase GIS format;
- Layer files with feature symbology (table 4);
- Federal Geographic Data Committee (FGDC)–compliant metadata;
- An ancillary map information document (sapu_geology.pdf) that contains information captured from source maps such as map unit descriptions, geologic unit correlation tables, legends, cross sections, and figures;

- An ESRI map document (sapu_geology.mxd) that displays the GRI GIS data; and
- A version of the data viewable in Google Earth (sapu_geology.kmz) (table 4).

Table 4. GRI GIS data layers for Salinas Pueblo Missions National Monument.

Data Layer	On Poster?	Google Earth Layer?
Geologic Cross Section Lines	No	No
Geologic Attitude and Observation Localities	No	No
Map Symbology	Yes	No
Point Geologic Units (mafic dike rocks, unit Tim)	Yes	No
Geologic Observation Localities	No	No
Folds	Yes	Yes
Faults	Yes	Yes
Geologic Contacts	Yes	Yes
Geologic Units	Yes	Yes

GRI Map Poster

A poster of the GRI GIS 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 (table 3). 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 GRI for assistance locating these data.

Use Constraints

Graphic and written information provided in this report is not a substitute for site-specific investigations. Ground-disturbing activities should neither be permitted nor denied based 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 or on the poster. Based on the source map scale (1:24,000) and US National Map Accuracy Standards, geologic features represented in the geologic map data are expected to be horizontally within 12 m (40 ft) of their true locations.

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Additional References

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

Geology of National Park Service Areas

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

NPS Resource Management Guidance and Documents

- Management Policies 2006 (Chapter 4: Natural Resource Management): http://www.nps.gov/policy/mp/policies.html
- National Parks Omnibus Management Act of 1998: https://www.nps.gov/gis/data_standards/omnibus_management_act.html
- NPS-75, Natural Resource Inventory and Monitoring Guideline: https://www.nps.gov/applications/npspolicy/DOrders.cfm (Note: This link is listed below Director's Order 77)
- NPS Natural Resource Management Reference Manual #77: http://www.nature.nps.gov/Rm77/
- Geologic Monitoring manual: http://go.nps.gov/geomonitoring
- NPS Technical Information Center (TIC) (Denver, Colorado; repository for technical documents): http://etic.nps.gov/

Climate Change Resources

- NPS Climate Change Response Program: http://www.nps.gov/subjects/climatechange/resources.htm
- US Global Change Research Program: http://www.globalchange.gov/home
- Intergovernmental Panel on Climate Change: http://www.ipcc.ch/

Geological Surveys and Societies

- New Mexico Bureau of Geology and Mineral Resources: https://geoinfo.nmt.edu/
- New Mexico Geological Society: https://nmgs.nmt.edu/
- US Geological Survey: http://www.usgs.gov/
- Geological Society of America: http://www.geosociety.org/
- American Geophysical Union: http://sites.agu.org/
- American Geosciences Institute: http://www.americangeosciences.org/
- Association of American State Geologists: http://www.stategeologists.org/

US Geological Survey Reference Tools

- National Geologic Map Database (NGMDB): http://ngmdb.usgs.gov/ngmdb/ngmdb_home.html
- 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 (many 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 29 March 2006. 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.

Name	Affiliation	Position
Tim Connors	NPS Geologic Resources Division	Geologist
Bruce Heise	NPS Geologic Resources Division	Geologist
Katie KellerLynn	Colorado State University	Geologist/research associate
Ron Kerbo	NPS Geologic Resources Division	Cave specialist
Marc LeFrançois	Salinas Pueblo Missions National Monument	Exhibit specialist
Mike Medrano	Petroglyph National Monument	Natural resource specialist
Michael Quijano	Petroglyph National Monument	Chief ranger
Tobin Roop	Salinas Pueblo Missions National Monument	Archeologist
Ren Thompson	US Geological Survey	Geologist
Mike Timmons	New Mexico Bureau of Geology and Mineral Resources	Geologist
Andrew Waggener	Salinas Pueblo Missions National Monument	GIS specialist
Gretchen Ward	Petroglyph National Monument	Archeologist

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 January 2018. Contact the NPS Geologic Resources Division for detailed guidance.

Resource	Resource-specific Laws	Resource-specific Regulations	2006 Management Policies
Caves and Karst Systems	**Federal Cave Resources Protection Act of 1988, 16 USC §§ 4301– 4309** requires Interior/Agriculture to identify "significant caves" on Federal lands, regulate/restrict use of those caves as appropriate, and include significant caves in land management planning efforts. Imposes civil and criminal penalties for harming a cave or cave resources. Authorizes Secretaries to withhold information about specific location of a significant cave from a Freedom of Information Act (FOIA) requester. **National Parks Omnibus Management Act of 1998, 54 USC § 100701** protects the confidentiality of the nature and specific location of cave and karst resources. **Lechuguilla Cave Protection Act of 1993, Public Law 103-169** created a cave protection zone (CPZ) around Lechuguilla Cave in Carlsbad Caverns National Park. Within the CPZ, access and the removal of cave resources may be limited or prohibited; existing leases may be canceled 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. Regulations in association with **2009 PRPA** are being finalized (December 2017).	**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
Rocks and Minerals	**NPS Organic Act, 54 USC. § 100101 et seq**. directs the NPS to conserve all resources in parks (which includes rock and mineral resources) unless other-wise 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 re-sources…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	**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 are-as. **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; re-quires 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.) **The Oil Pollution Act of 1990** requires responsible parties to compensate the public for the natural resources damage caused by the Deepwater Horizon oil spill.	**36 CFR Part 6** regulates solid waste disposal sites in park units. **36 CFR Part 9, Subpart B ("9B")** requires the owners/operators of nonfederally owned oil and gas rights 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 ● 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 and Gas, Salable Minerals, and Non-locatable 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. **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 re-sources and/or administration. **Exceptions**: Native American 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 USC §§ 2101-2108)**, all minerals are subject to lease and apply to Native American trust lands within NPS units. **Federal Coal Leasing Amendments Act of 1975, 30 USC § 201** does not authorize the BLM to issue leases for coal mining on any area of the national park system.	**36 CFR § 5.14** states prospecting, mining, and…leasing under the mineral leasing laws [is] prohibited in park areas except as authorized by law. **43 CFR Part 3160** governs onshore oil and gas operations, which are overseen by the BLM. BLM regulations at **43 CFR Parts 3100, 3400, and 3500** govern Federal mineral leasing. Regulations re: Native American Lands within NPS Units: **25 CFR Part 211** governs leasing of tribal lands for mineral development. **25 CFR Part 212** governs leasing of allotted lands for mineral development. **25 CFR Part 216** governs surface exploration, mining, and reclamation of lands during mineral development. **25 CFR Part 224** governs tribal energy resource agreements. **25 CFR Part 225** governs mineral agreements for the development of Indian-owned minerals entered into pursuant to the **Indian Mineral Development Act of 1982, Pub. L. No. 97-382, 96 Stat. 1938** (codified at **25 USC §§ 2101-2108**). **30 CFR §§ 1202.100-1202.101** governs royalties on oil produced from Indian leases. **30 CFR §§ 1202.550-1202.558** governs royalties on gas production from Indian leases. **30 CFR §§ 1206.50-1206.62 and §§ 1206.170-1206.176** governs product valuation for mineral resources produced from Indian oil and gas leases. **30 CFR § 1206.450** governs the valuation coal from Indian Tribal and Allotted leases.	**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** **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.	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**. **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.	**Section 8.7.3** states that operators exercising rights in a park unit must comply with **36 CFR Parts 1 and 5**.
Park Use of Sand and Gravel	**Materials Act of 1947, 30 USC § 601** does not authorize the NPS to dispose of mineral materials outside of park units. **Exception:** **16 USC §90c 1(b)** the non-wilderness portion of Lake Chelan National Recreation Area, where sand, rock and gravel may be made available for sale to the residents of Stehekin for local use as long as such 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 ● 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. **Coastal Wetlands Planning, Protection and Restoration Act ("Breaux Act", Public Law 101-646, Title III CWPPRA) (1990)** identifies, prepares, and funds construction of coastal wetlands restoration projects. **Coastal Barriers Resource Act 16 USC §§ 3501-3510 (2003)** restricts Federal expenditures that encourage development of coastal barriers and considers long-term conservation of natural resources. **Executive Order 11644 (use of off-road vehicles on public lands) (1972)** establishes policies to control and direct ORV use on public lands so as to protect land resources, promote safety of land users, and to minimize conflicts among land uses. **Executive Order 11989 (off-road vehicles on public lands) (1974)** closes off-road areas to ORV use that will impact soil, vegetation, wildlife, wildlife habitat, or cultural or historic resources until adverse effects have been eliminated and measures have been implemented to prevent future recurrence. Also includes authority to close public lands to ORVs where their use is not specifically authorized. *continued in Regulations column*	**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 low-lands. **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. **36 CFR §4.10** prohibits motor vehicle use except on park roads, in parking areas and on routes and areas designated for off-road motor vehicle use; and requires that designated ORV routes and areas be promulgated as special regulations, with designations complying with Executive Order 11644. *Laws, continued:* **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 listing*	**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 ● Avoid putting new developments in areas subject to natural shoreline processes unless certain factors are present. *See also Climate Change listing*

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 in-corporate 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). **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. **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). *Guidance, continued:* **NPS Climate Change Response Strategy (2010)** describes goals and objectives to guide NPS actions under four integrated components: science, adaptation, mitigation, and communication. **Revisiting Leopold: Resource Stewardship in the National Parks (2012)** will guide US National Park natural and cultural re-source 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. *continued from 2006 Management Policies column:* **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 land-scape 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 ● develop/follow written prescriptions (instructions).

NPS 313/147851, August 2018

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