National Park Service
U.S. Department of the Interior

Natural Resource Stewardship and Science

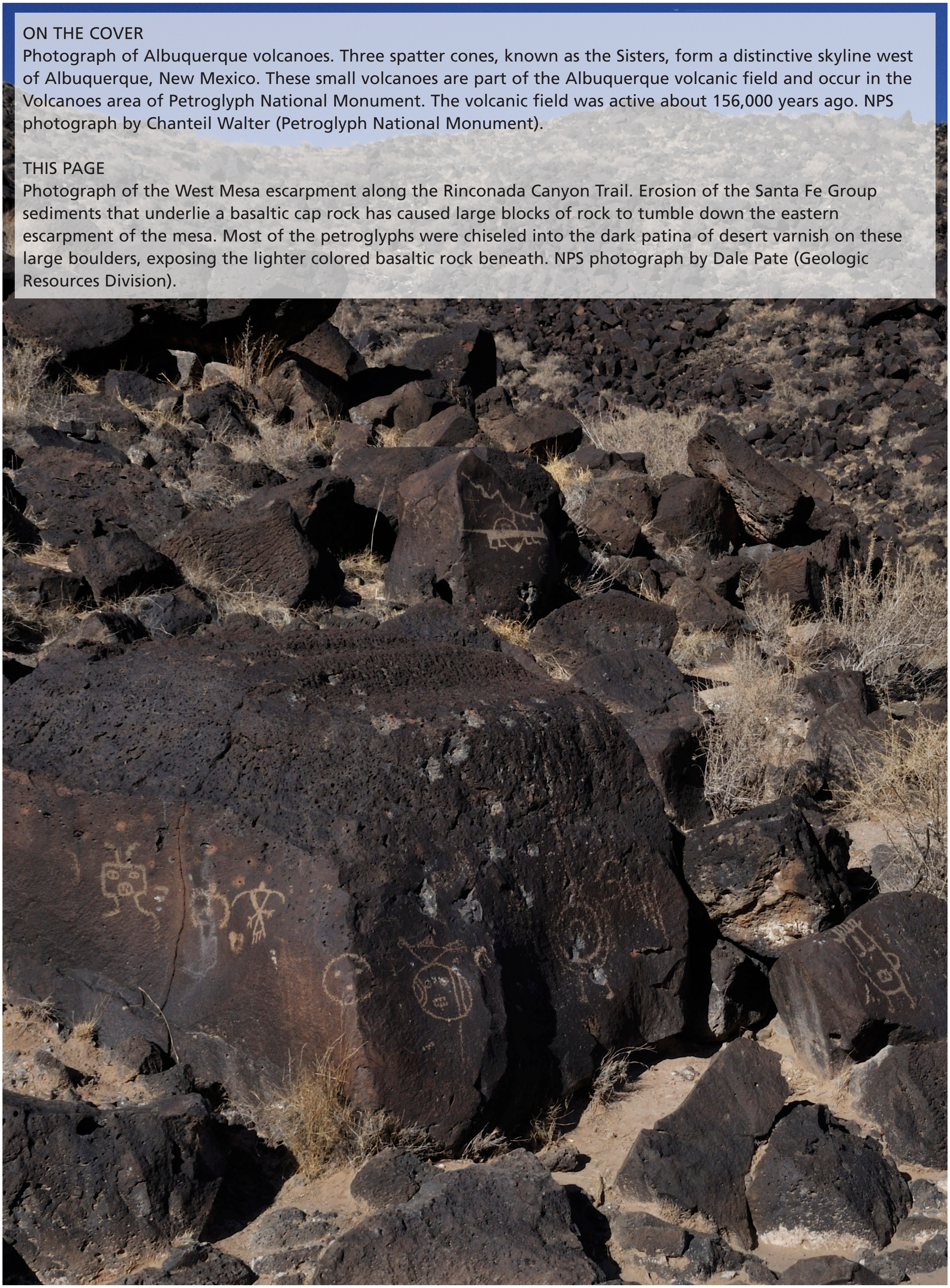
Petroglyph National Monument

Geologic Resources Inventory Report

Natural Resource Report NPS/NRSS/GRD/NRR—2017/1547

ON THE COVER
Photograph of Albuquerque volcanoes. Three spatter cones, known as the Sisters, form a distinctive skyline west of Albuquerque, New Mexico. These small volcanoes are part of the Albuquerque volcanic field and occur in the Volcanoes area of Petroglyph National Monument. The volcanic field was active about 156,000 years ago. NPS photograph by Chanteil Walter (Petroglyph National Monument).

THIS PAGE
Photograph of the West Mesa escarpment along the Rinconada Canyon Trail. Erosion of the Santa Fe Group sediments that underlie a basaltic cap rock has caused large blocks of rock to tumble down the eastern escarpment of the mesa. Most of the petroglyphs were chiseled into the dark patina of desert varnish on these large boulders, exposing the lighter colored basaltic rock beneath. NPS photograph by Dale Pate (Geologic Resources Division).



Petroglyph National Monument

Geologic Resources Inventory Report

Natural Resource Report NPS/NRSS/GRD/NRR—2017/1547

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

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

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

This report is available from the Geologic Resources Inventory website, and the Natural Resource Publications Management website. To receive this report in a format optimized for screen readers, please email irma@nps.gov.

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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 in 2006 and a follow-up conference call in 2017 (see Appendix A). Chapters of this report discuss the monument's geologic setting and significance, including distinctive geologic features and processes within Petroglyph National Monument; describe the geologic history leading to the present-day landscape; highlight geologic issues facing resource managers; and provide information about the previously completed GRI map data.

Although authorized for the protection of more than 20,000 petroglyphs (prehistoric or historic rock carvings), Petroglyph National Monument also contains significant geologic resources. The petroglyphs themselves were etched into a geologic resource—basaltic (characteristically dark volcanic rock rich in iron and magnesium) bounders—that tumbled off the West Mesa escarpment (erosional margin). The monument is located west of downtown Albuquerque within the Albuquerque volcanic field and contains the Albuquerque volcanoes—a line of cinder and spatter cones that developed as a result of a fissure eruption about 156,000 years ago. The monument contains five volcanoes that formed along a fissure near the center of the Rio Grande rift—a tear in the North American continent that is the result of regional stretching of Earth's crust. Three volcanoes—Vulcan, Black, and JA—are accessible from a small parking area off Atrisco Vista Boulevard (formerly known as Paseo del Volcan) on the western side of the monument. The two other volcanoes in the monument—Bond and Butte—are farther north. The monument also contains a series of lava flows and cinder deposits around vents (openings at Earth's surface through which magma erupts and volcanic gases are emitted). The two oldest lava flows form the eastern margin of West Mesa.

This report is supported by two GRI GIS data sets of the bedrock and surficial geology of Petroglyph National Monument. Connell (2006) was the source map used in compiling a GRI GIS data set (petr_geology.mxd) that covers the entire monument at a scale of 1:50,000. Terminology and map units by Connell (2006) are used in this report. Connell (2006) mapped sixteen 7.5-minute quadrangles that make up the Albuquerque–Rio Rancho metropolitan area and vicinity. Four of these quadrangles—Volcano Ranch, Los Griegos, Albuquerque West, and La Mesita Negra SE—are part of the GRI GIS data. In addition, the GRI team converted Shroba et al. (2003) into a GRI GIS data set (mnse_geology.mxd) that covers the southwestern area of the monument at a scale of 1:24,000. Shroba et al. (2003) mapped the La Mesita Negra SE 7.5-minute quadrangle. These two mapping projects—Connell (2006) by the New Mexico Bureau of Geology and Mineral Resources and Shroba et al. (2003) by the US Geological Survey—interpreted the monument's geology slightly differently. Because the map by Connell (2006) covers the entire monument, this report primarily followed that interpretation. Notable differences between the two mapping projects are highlighted in the report, however.

The poster (in pocket) is the primary figure of this GRI report. It displays the GRI GIS data draped over a shaded relief image of the monument and surrounding area. It includes a legend with all the map units within the monument.

This report contains two main tables. One of the main tables (table 1) provides a brief geologic description and setting for each map unit. Table 1 emphasizes geologic time and takes the form of a stratigraphic column where map units are listed from oldest to youngest, bottom to top. Geologic terms used in the map unit descriptions are defined below table 1. The other main table (table 3) summarizes the geologic resource management issues at the monument and connects them to relevant geologic map units. The issues are ordered with respect to management priority and include the following: erosion (resulting chiefly from storm-water runoff); disturbed lands; wind erosion, transport, and deposition; rockfall; volcanic resource inventory, assessment, and protection; earthquakes and faults; abandoned mineral lands; cave resource management; paleontological resource inventory, monitoring, and protection; and volcanic hazards. A discussion of each of these issues follows table 3. Three other tables are included in the report: table 2 provides a comparison of the volcanic map units in the GRI GIS data; tables 4 and 5 highlight the GRI GIS data layers for petr_geology.mxd and mnse_geology.mxd, respectively.

Products and Acknowledgments

The NPS Geologic Resources Division partners with the Colorado State University Department of Geosciences to produce GRI products. The New Mexico Bureau of Geology and Mineral Resources developed one source map and reviewed GRI content. The US Geological Survey also developed one source map. This chapter describes GRI products and acknowledges contributors to this report.

GRI Products

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

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

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

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

Acknowledgments

The GRI team thanks the participants of the 2006 scoping meeting and the 2017 follow-up conference call (see Appendix A) for their cooperation in this inventory. Thanks very much to the New Mexico Bureau of Geology and Mineral Resources and the US Geological Survey for their maps of the area; this report and accompanying GIS data could not have been completed without them. Thanks to **Dale Pate** (NPS Geologic Resources Division) for his input about cave management, clarification on the definition of a cave, and for many of the photographs used in this report. Thanks to **Andy Jochems** (New Mexico Bureau of Geology and Mineral Resources) for his input on the Quaternary faults in the vicinity of the monument. Also, thanks to **Trista Thornberry-Ehrlich** (Colorado State University) and **Michael Barthelmes** (NPS Geologic Resources Division) for their help in creating many of the graphics in this report. Also, **Matt Zimmerer** (New Mexico Bureau of Geology and Mineral Resources), **Chanteil Walter** (Petroglyph National Monument), and **Dale Kissner** (Petroglyph National Monument) provided many photographs, including some taken specifically for this report.

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Geologic Setting, History, 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

Petroglyph National Monument, situated 11 km (7 mi) west of downtown Albuquerque, New Mexico, protects one of the largest petroglyph sites in North America. The monument features more than 20,000 petroglyphs pecked into the dark desert varnish that coats the basaltic boulders along the West Mesa escarpment (fig. 1). Many of the petroglyphs are recognizable as animals, insects, people, and geometric designs (fig. 2). Some petroglyph images may have served both a practical purpose (e.g., marking a location) and have a sacred or spiritual meaning. Different ethnographic groups may interpret the meaning of a particular design differently (see Anschuetz et al. 2002). Some meanings may only ever be known to their carvers.

Although a small percentage of petroglyphs date as far back as 2000 BCE (before common era), the majority (90%) were created by the ancestors of today's Pueblo people, who have lived in the Rio Grande valley since before 500 CE (common era). A population increase around 1300 CE resulted in many new settlements, and the majority of the petroglyphs are thought to have been carved from that time through the late 1680s. This period of settlement ended with the arrival of the first Spanish explorers. Other images date from historic periods, starting in the 1700s with petroglyphs carved by early Spanish settlers.

The monument comprises 2,928 ha (7,236 ac) of land owned by the US government, State of New Mexico, and City of Albuquerque. The monument is managed cooperatively by the National Park Service and City of

Figure 1. Satellite image of West Mesa. Much of West Mesa—a basaltic lava–capped "table land"—and its 23-km- (17-mi-) long escarpment lie within the monument. Lava flows topped by spatter cones and cinders cover the mesa's surface. The mesa is west of the Rio Grande and downtown Albuquerque, New Mexico. Image © 2017 Google. Annotations by Jason Kenworthy (NPS Geologic Resources Division).








Figure 2 (facing page). Photographs of petroglyphs. Prehistoric and historic rock carvings, called "petroglyphs," are a geological–archeological resource connection at the monument. Most were carved between about 1300 and the late 1680s on the basaltic boulders along the West Mesa escarpment. Some of the images seem familiar, such as birds, snakes, humans, stars, and stairways; others, such as spirals, stimulate multiple interpretations. NPS photographs by Dale Pate (Geologic Resources Division).

Albuquerque Open Space Division. This arrangement is distinctive, as is the monument's proximity to a major metropolitan area; few large cities in the United States have young volcanic features in the middle of them. Moreover, the monument protects much of the remaining open space in the Albuquerque region, including important natural resources associated with the Rio Grande rift, Rio Grande (river), and Albuquerque volcanic field (discussed below).

As Albuquerque developed westward across West Mesa, population growth placed a greater and greater burden on the petroglyph-covered basalt escarpment. Vandals desecrated and destroyed many of the petroglyphs, and housing developments on the volcanic cliffs would have made the area off-limits to visitors. In response, citizens worked to establish Indian Petroglyph State Park at Boca Negra Canyon. In addition, a forward-thinking woman, Ruth Eisenberg, was responsible for the preservation of the five volcanoes now in the monument. In the late 1960s, while undertaking a University of New Mexico class project researching the ownership of the volcanoes, Eisenberg discovered that they were privately owned, and for sale. Fearing that they would be subdivided and suburbanized, she established "Save the Volcanoes" and managed to get public and political backing. In 1973 and 1976, the City of Albuquerque bought the cones—the southern three then the northern two, respectively—and created Volcano Park. In 1986, the entire 27-km- (17-mi-) long escarpment—the location of most of the petroglyphs—was placed on the National Register of Historic Places. On 27 June 1990, the petroglyph escarpment and the volcanoes became part of the National Park System with the creation of Petroglyph National Monument.

Geologic Setting and History

The monument's geologic setting consists of four groupings of rock or unconsolidated deposits. The oldest rocks in the monument are sedimentary and originated as basin fill (primarily sand and gravel) in the Rio Grande rift. Another grouping of geologic units in the monument is associated with the development of the Rio Grande (river) and its tributaries. A third grouping is composed of a series of basaltic lava flows and near-vent (an opening at Earth's surface through which magma erupts and volcanic gases are emitted) deposits that make up the Albuquerque volcanic field. A fourth grouping is associated with ongoing geologic processes and the agents of gravity, running water, and wind (table 1).

Rio Grande Rift

Spanning about 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) (fig. 3). It is one of only a few active rifts worldwide that are ripping apart continental crust; others include the East Africa rift, Rhine graben in Germany, and Lake Baikal rift in Russia. In New Mexico, crustal extension progressed from south to north along the Rio Grande rift, starting about 36 million years ago (Eocene Epoch; fig. 4) in the south and initiating about 22 million years ago (Miocene Epoch) in the north (Price 2010). Rio Grande rifting is estimated to have begun about 26 million years ago in the vicinity of the monument (Kelley 2010).

One consequence of extension is faulting where basins drop downward along normal faults (fig. 5) relative to uplifted mountain ranges, called "rift-flank uplifts" or "fault-block mountain ranges." The Sandia Mountains are an example of a rift-flank uplift near the monument (figs. 6 and 7). These mountains are the northernmost of a series of ranges that bound the eastern side of the Rio Grande rift. They extend southward to the Manzanita and Manzano Mountains in the vicinity of Salinas Pueblo Missions National Monument (see GRI report by KellerLynn in preparation). The Sandia Mountains are about 24 km (15 mi) east of the monument visitor center and dominate the eastern Albuquerque skyline (fig. 6). At 3,184 m (10,447 ft) above sea level, North Sandia Peak is the highest point in the range.

Whereas mountain ranges formed on the up-thrown side of the normal faults along the rift, basins (elongated, down-dropped crustal units or blocks bounded on both sides by high-angle normal faults that dip toward each other) formed on the downthrown side. The Rio Grande rift consists of eight major basins

Table 1. Bedrock and surficial deposits at Petroglyph National Monument.

Period	Epoch	Years Ago	Map Unit (symbol)	Geologic Description	Setting
Quaternary	Holocene	11,700 to present day	Active stream-valley alluvium (**Qa**)	Light grayish to yellowish brown sand, silty to clayey sand, and gravel; boulders are common along the western flank of the Sandia Mountains. Very weakly developed soils (stage I carbonate morphology) to nonexistent soils. Thickness: 1–12 m (3–40 ft).	Modern incised tributary stream valleys
Quaternary	Holocene	11,700 to present day	Las Padillas Formation, intermediate channel and floodplain (**Qrpm**)	Pinkish gray to grayish brown sand and pebbly sand with lenses of reddish brown silt and clay; contains paleochannel, point-bar, and overbank levee deposits. Very weak to no soil development. Thickness: 15–34 m (50–112 ft) in wells (base of unit not exposed).	Underlies modern (inner) valley of the Rio Grande
Quaternary	Holocene to Upper Pleistocene	126,000 to present day Radiocarbon dating of detrital charcoal: 1,790 ± 90 and 4,550 ± 140	Younger stream-valley alluvium (**Qay**)	Pale- to light-brown sand, muddy sand, and pebble to cobble gravel; boulders locally present along the front of the Sandia Mountains. Weakly developed soils (stage I and II carbonate morphology). Thickness: as much as 24 m (79 ft).	Rio Grande tributaries; Qay locally contains active stream-valley alluvium (Qa)
Quaternary	Holocene to Upper Pleistocene	126,000 to present day	Eolian sand, undivided (**Qe**)	Pink to light yellowish brown, well-sorted sand. Weakly developed (stage I to II+ carbonate morphology) to nonexistent soils. Thickness: 1–3 m (3–10 ft).	Laterally extensive, active and inactive sand sheets and discontinuous low-relief dunes oriented north to northeast
Quaternary	Holocene to Pleistocene	2.6 million to present day	Colluvium and alluvium, undivided (**Qca**)	Sand and gravel. Weakly to strongly developed calcic soils (stage I to III+ carbonate morphology). Thickness: as much as 5 m (16 ft).	Along hill slopes and margins of mesa-capping lavas
Quaternary	Upper to Middle Pleistocene	781,000 to 11,700	Intermediate stream-valley alluvium (**Qam**)	Yellowish brown to reddish yellow sand, silty clay, and gravel; variable rock types, dominated by chert and volcanic clasts west of the Rio Grande. Variable soil development.	Rio Grande tributaries
Quaternary	Middle Pleistocene	781,000 to 126,000	Los Duranes Formation (**Qrd**)	Pale brown to light reddish brown sand, sandy gravel and sandy clay. Weakly developed soils (stage I carbonate morphology on sand). **Qrd** surface is commonly mantled by eolian sand. Thickness: 40–52 m (130–170 ft).	Rio Grande terrace (former floodplain), 44–48 m (144–157 ft) above the present-day floodplain
Quaternary	Middle Pleistocene	781,000 to 126,000	Albuquerque volcanoes, vents (**Qbv**)	Larger cinder and spatter cones. Smaller vents denoted by an asterisk (*) in GRI GIS data.	Albuquerque volcanic field
Quaternary	Middle Pleistocene	781,000 to 126,000 Whole-rock 238U/230Th dating: 156,000 ± 20,000	Basaltic lavas of the Albuquerque volcanoes Flow 5 (**Qb5**) Flow 4 (**Qb4**) Flow 3 (**Qb3**) Flow 2 (**Qb2**) Flow 1 (**Qb1**)	Vesicular olivine tholeiite (fig. 11) lava flows. Locally divided into five flows (**Qb1**–**Qb5**) based on surface morphology and stratigraphic position.	Albuquerque volcanic field

Table 1, continued. Bedrock and surficial deposits at Petroglyph National Monument.

Period	Epoch	Years Ago	Map Unit (symbol)	Geologic Description	Setting
Quaternary	Middle Pleistocene	781,000 to 126,000	Older stream-valley alluvium (Qao)	Light reddish brown sand and gravel. Variable soil development; some exhibits stage I to III carbonate morphology with few or no clay films. Thickness: 2–14 m (7–46 ft).	Rio Grande tributaries
Quaternary	Middle Pleistocene	781,000 to 126,000	Lomatas Negras Formation (Qrl)	Pale brown to pink sandy pebble to cobble gravel. Thickness: commonly 3–12 m (10–40 ft) but locally reaches 18 m (59 ft) near the mouth of Arroyo de las Calabacillas.	Oldest inset terrace deposits of the Rio Grande, 65–75 m (213–246 ft) above the present-day floodplain
Tertiary	Lowest Pleistocene (?) to Pliocene	2.6 million to 5.3 million	Ceja Formation, upper sand and gravel member (Tcrg)	Pale brown to yellowish brown cobbly sand and gravel with scattered boulders. Thickness: 20–260 (?) m (66–853 ft); generally less than 100 m (328 ft) thick west of the Rio Grande valley.	Part of the Santa Fe Group; top defined by Llano de Albuquerque surface

Alluvium (map units Qa, Qay, Qca, Qam, and Qao)—stream-deposited sediment.

Basalt (Qbv and Qb1–Qb5)—a volcanic rock that is characteristically dark in color (gray to black), contains approximately 53% silica (silicon dioxide [SiO_2], an essential constituent of many minerals) or less, and is rich in iron and magnesium.

Boulder (Qa, Qay, and Tcrg)—a detached rock fragment, generally somewhat rounded or otherwise distinctively shaped by abrasion during transport, greater than 256 mm (10 in) in diameter; the largest rock fragment recognized by sedimentologists.

Carbonate (soils)—consisting of carbonate minerals (carbon and oxygen plus an element or elements), for example, CaCO3 (calcite) or $CaMg(CO3)_2$ (dolomite).

Chert (Qam)—an extremely hard sedimentary rock, consisting mostly of interlocking crystals of quartz. Chert has conchoidal fracturing, giving the rock a smoothly curved surface that resembles a conch shell.

Clay (Qa, Qrpm, Qam, Qrd, and Qao)—a detrital particle that is less than 0.004 (1/256) mm (0.00015 in) in diameter.

Cobble (Qay, Qrl, and Tcrg)—a rock fragment ranging from 64 to 256 mm (2.5 to 10 in) in diameter, thus larger than a pebble and smaller than a boulder; generally rounded by abrasion.

Colluvium (Qca)—a general term applied to a loose, heterogeneous accumulation of rocks, usually at the foot of a slope or cliff and brought there mainly by gravity.

Eolian (Qe and Qrd)—describes materials formed, eroded, or deposited by the wind.

Gravel (Qa, Qay, Qca, Qam, Qrd, Qao, Qrl, and Tcrg)—an unconsolidated, natural accumulation of rock fragments that are greater than 2 mm (0.08 in) in diameter; deposits may contain boulders, cobbles, and/or pebbles.

Mud (Qay)—a mixture of water with silt or clay.

Overbank levee (Qrpm)—a long, broad, low embankment of sand and coarse silt built by floodwater overflow along both banks of a stream channel.

Paleochannel (Qrpm)—a remnant of a stream channel cut in older rock or sediment and filled by younger rock or sediment; a buried stream channel.

Pebble (Qrpm, Qay, and Qrl)—a rock fragment ranging from approximately 4 to 64 mm (0.16 to 2.5 in) in diameter and generally rounded by abrasion.

Point bar (Qrpm)—a low ridge of sand and gravel deposited in a stream channel on the inside of a meander, where flow velocity slows.

Sand (Qa, Qrpm, Qay, Qe, Qca, Qam, Qrd, Qao, Qrl, and Tcrg)—a detrital particle ranging from 0.06 (1/16) to 2 mm (0.0025 to 0.08 in) in diameter.

Silt (Qa, Qrpm, and Qam)—a detrital particle ranging from 0.004 (1/256) to 0.06 (1/16) mm (0.00015 and 0.0025 in) in diameter, thus smaller than sand.

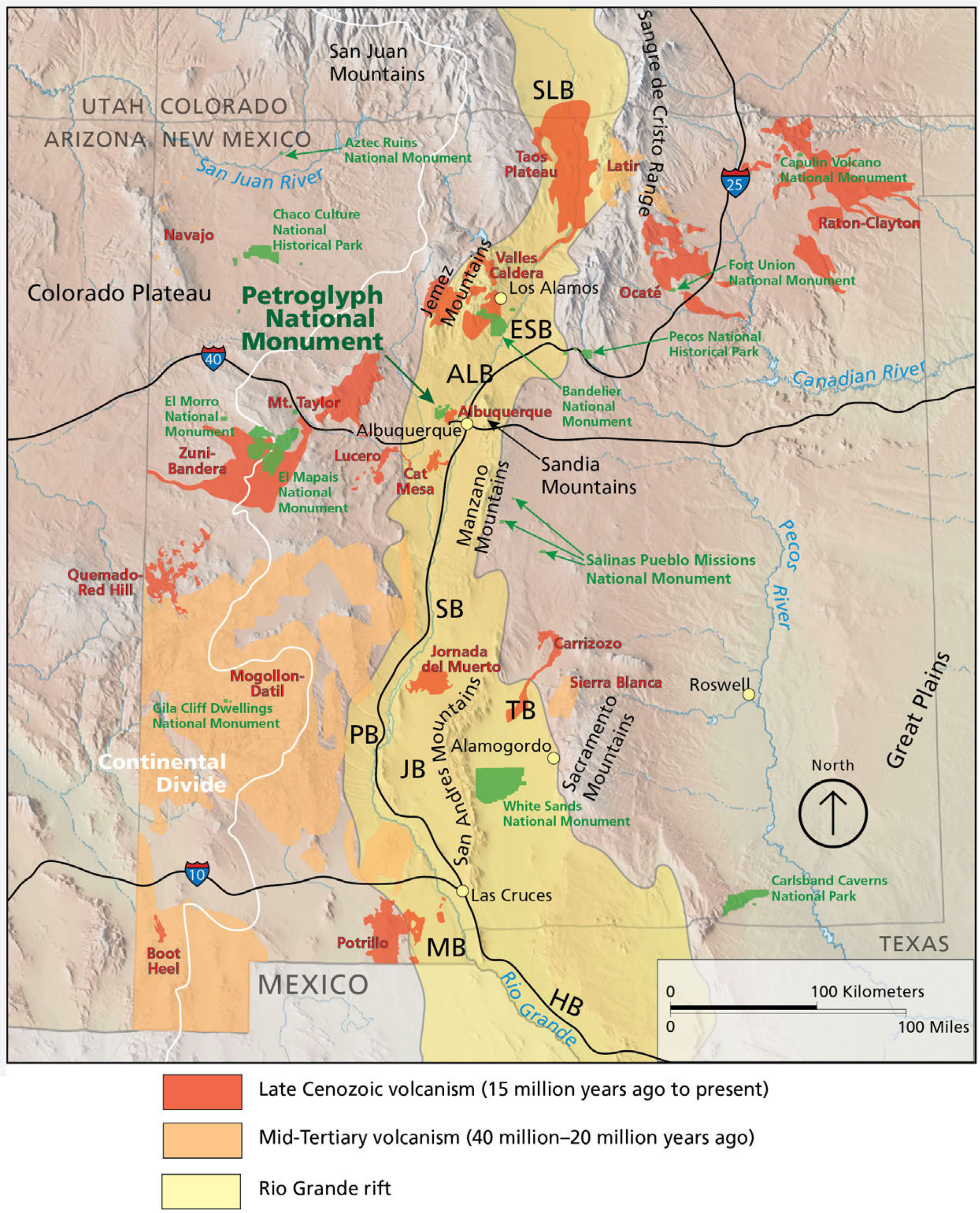

Figure 3. Map of major geologic features in New Mexico. Petroglyph National Monument is within the Albuquerque volcanic field. The field is one of a series of volcanic fields in the Albuquerque basin (ALB) of the Rio Grande rift. The Albuquerque basin and other basins—San Luis (SLB), Española (ESB), Socorro (SB), Palomas (PB), Tularosa (TB), Jornada (JB), Mesilla (MB), and Hueco (HB)—dropped down along normal faults (see figs. 5 and 7) as Earth's crust pulled apart in the rift. Along the margins of the rift, uplift took place. The Sandia Mountains are a rift-flank uplift on the eastern side of the rift. Boundaries of NPS lands are shown in green. 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). GRI reports are available for all of the NPS areas (report for Salinas Pueblo Missions National Monument should be complete late 2017) at the GRI publications page: http://go.nps.gov/gripubs.

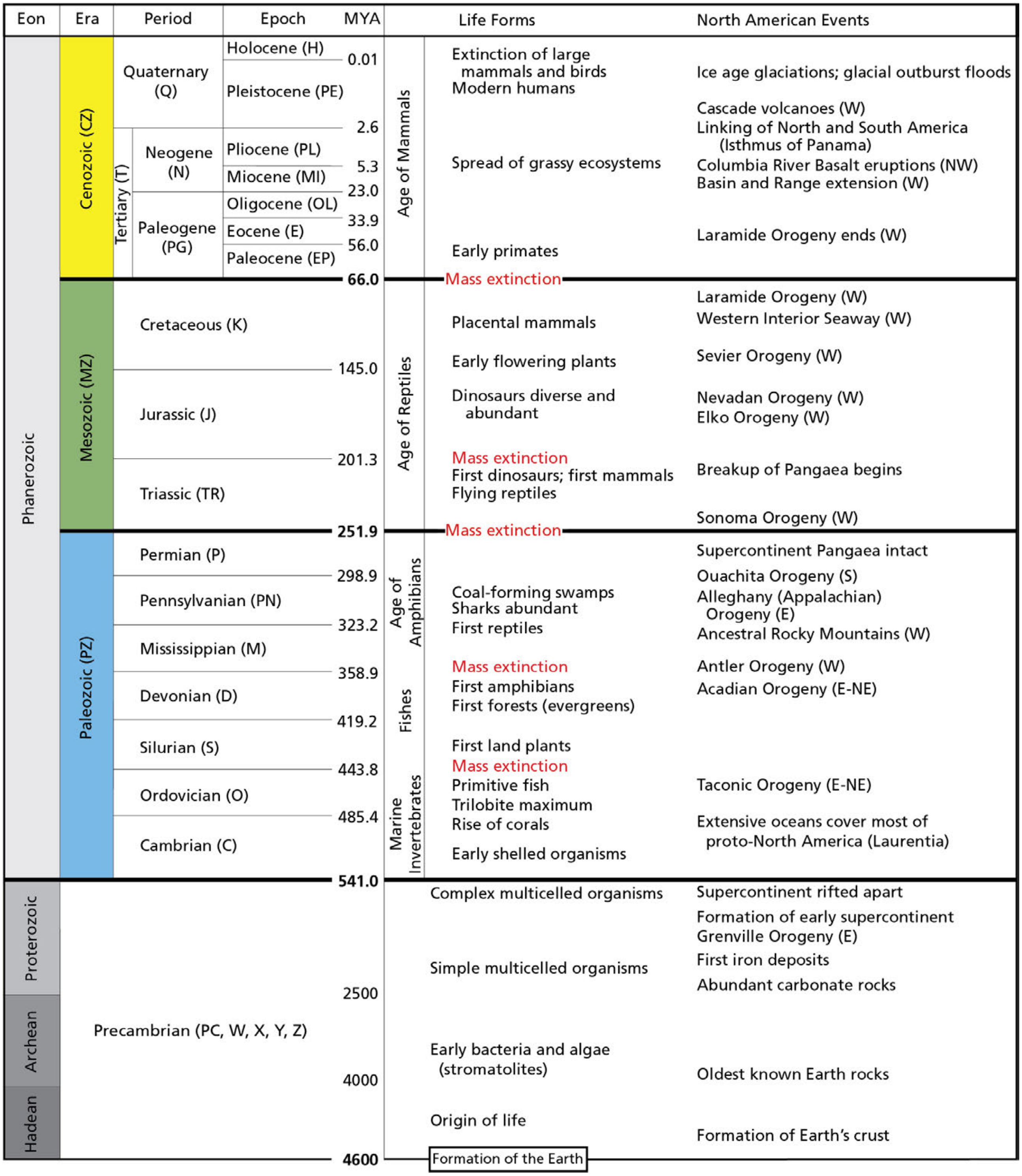

Figure 4. Geologic time scale. The divisions of geologic time are organized stratigraphically, with the oldest divisions at the bottom and the youngest at the top. GRI map abbreviations for each time division are in parentheses. The oldest rocks in the monument are the lowest Pleistocene (?) to Pliocene Ceja Formation (map unit Tcrg). The Albuquerque volcanoes (Qb1–Qb5 and Qbv) erupted during the Middle Pleistocene Epoch (PE). Petroglyphs were etched into basaltic boulders, which are Middle Pleistocene in age. Starting in the Pleistocene Epoch, these boulders were eroded and transported down the West Mesa escarpment; they were mapped as colluvium and alluvium, undivided (Qca). Compass directions in parentheses indicate the regional locations of events. Boundary ages are millions of years ago (MYA). National Park Service graphic using dates from the International Commission on Stratigraphy (http://www.stratigraphy.org/index.php/ics-chart-timescale; version 2017/02, accessed 25 September 2017).

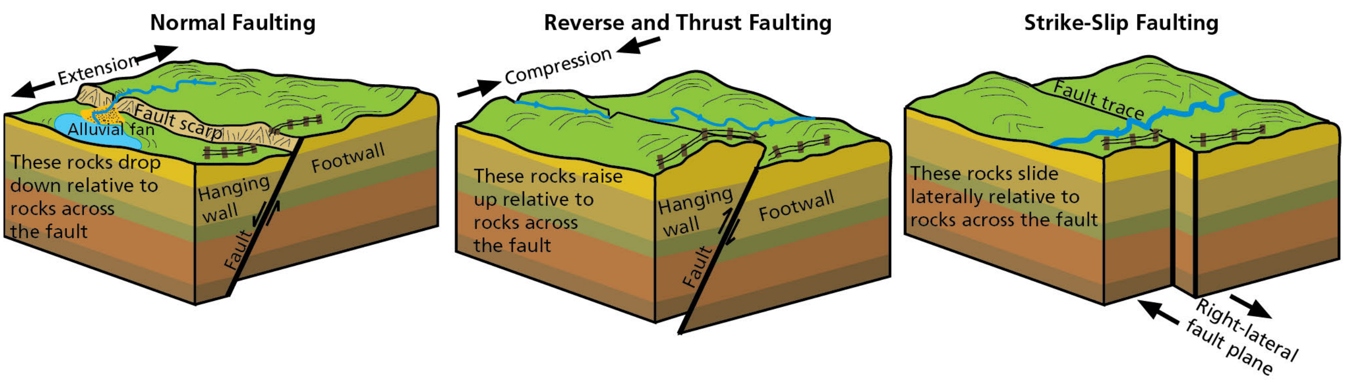

Figure 5. Graphic of fault types. Movement occurs along a fault plane. Footwalls are below the fault plane, and hanging walls are above. In a normal fault, crustal extension (pulling apart) moves the hanging wall down relative to the footwall. In a reverse fault, crustal compression moves the hanging 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. Faults in the monument are normal faults related to extension along the Rio Grande rift. Graphic by Trista Thornberry-Ehrlich (Colorado State University).

Figure 6. Photograph of the Sandia Mountains. The monument offers spectacular views of the Sandia Mountains. These east-tilted, rift-flank mountains on the eastern margin of the Albuquerque basin rise as much as 1,700 m (5,700 ft) above the elevation of the Rio Grande, exposing Precambrian granitic and metamorphic rocks on the west side of the basin. Pennsylvanian limestone and shale cap the mountain block; these rocks are exposed along the eastern slopes of the mountain range. The Sandia Mountains are not part of the GRI GIS data but are clearly within the monument's viewshed. NPS photograph courtesy of Chanteil Walter (Petroglyph National Monument).

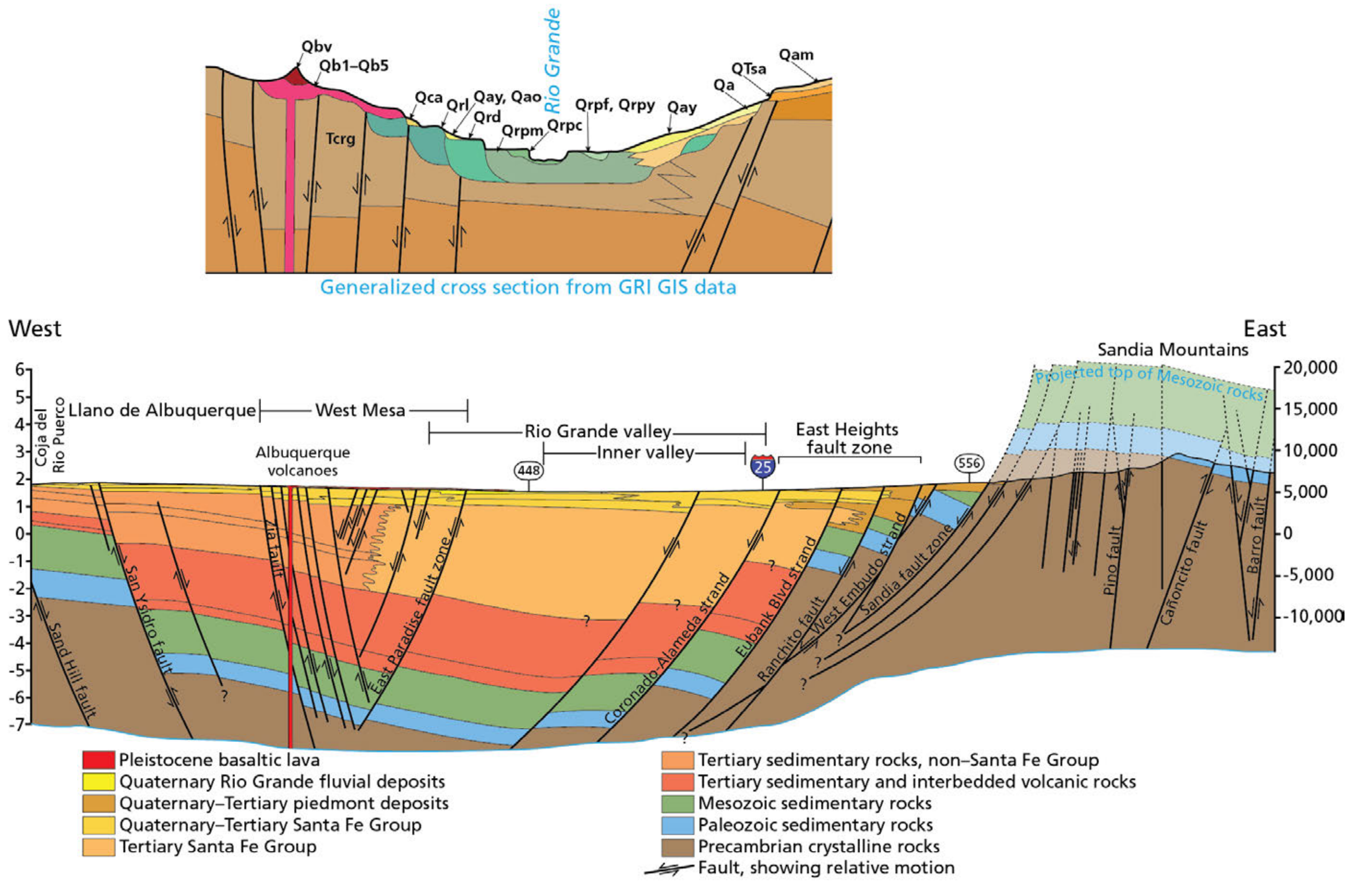

Figure 7. Cross sections of the Albuquerque basin. Normal faults (see fig. 5), which are characteristic of the Rio Grande rift, are a prominent feature in the Albuquerque basin. Faulting began at the margins of the rift and moved basinward. A rift-flank uplift—the Sandia Mountains—was elevated as the basin subsided. Today, the Rio Grande dominates the surface of the rift. Since about 1.2 million to 700,000 years ago, the river has episodically incised into the Santa Fe Group (basin-filling sediments), creating terraces (abandoned floodplains) mapped as the Lomatas Negras (Qrl), Los Duranes (Qrd), and Las Padillas (Qrpm) Formations. Tributaries deposited alluvium. Piedmont surfaces (gravel-covered erosional slopes) occur along the flank of the Sandia Mountains but not within the monument. The basaltic lava of the Albuquerque volcanoes (Qb1–Qb5 and Qbv) erupted about 156,000 years ago atop the Llano de Albuquerque; the Ceja Formation (e.g., Tcrg in the monument) marks the top of the Llano de Albuquerque surface and represents the end of basin filling by the Santa Fe Group. Graphic by Trista Thornberry-Ehrlich (Colorado State University) after cross sections by Connell (2006, B–B') and Bauer et al. (2003, p. 6).

(fig. 3). Four of these have National Park System units in them: Petroglyph National Monument in the Albuquerque basin, Bandelier National Monument (see GRI report by KellerLynn 2015a) and Valles Caldera National Preserve in the Española basin (north of the monument), White Sands National Monument in the Tularosa basin (south of the monument; see GRI report by KellerLynn 2012c), and Great Sand Dunes National Park and Preserve (see GRE report by Graham 2006b) in the San Luis basin (north of the monument in Colorado).

Normal faults in the Albuquerque basin first developed along the margins of the Rio Grande rift during the Miocene Period and progressed basinward (Connell and Wells 1999). The faults are oriented north–south. They are steeply dipping (almost vertical), in some cases tilted more than 70° from horizontal. Eleven fault segments cut across the monument, including portions of the Zia, Star Heights, West Paradise, and East Paradise faults (see poster, in pocket). The vents on the western side of the monument are aligned along a fault, highlighting the connection between rift-related faulting and volcanism (see "Albuquerque Volcanic Field"). The County Dump fault parallels the western boundary, outside the monument.

As the Rio Grande rift began pulling apart and basins such as the Albuquerque basin dropped down relative to the adjacent mountains, sediments (and some lava flows) began filling the rift. In the vicinity of the monument, basin-fill sediments are as much as 2,700 m (8,500 ft) thick (Bauer et al. 2003). Elsewhere in the eastern Albuquerque basin, they are as much as 4,900 m (16,000 ft) thick. These rift-filling sediments, regionally known as the Santa Fe Group, include material deposited by the ancestral Rio Grande, as well as two other ancestral drainages—the Rio San Juan from the west and the Rio Puerco from the northwest. These rivers were broad, braided systems, quite different from the narrow, meandering rivers of today (Bauer et al. 2003).

The ancestral river sediments, together with debris shed from the surrounding uplands, constitute the upper Santa Fe Group. The oldest rocks within the monument, the Ceja Formation (**Tcrg**), represent the last sediments to have been deposited as part of the Santa Fe Group (table 1). Shroba et al. (2003)—the source map for GRI GIS data that covers the southwestern corner of the monument—mapped these rocks as the Pliocene and upper Miocene (fig. 4) Upper Santa Fe Group, undivided (**Ts**). Mapping by Connell (2006)—the source map for GRI GIS data that covers the entire monument—divided the Santa Fe Group into formations, including the Ceja Formation, which is the youngest "member" of the group. According to Connell (2006), the formation was deposited during the Pliocene Epoch (5.3 million–2.6 million years ago) and possibly into the "lowest Pleistocene" Epoch (?). Uncertainty is indicated by a "?" in the GRI GIS data and in the text of this report. Based on the fossils it contains, deposition of the Ceja Formation in the vicinity of the monument ended sometime between 3.6 million and 2.2 million years ago (Morgan and Lucas 2003; Connell 2006).

The Llano de Albuquerque—the surface upon which the monument's volcanic activity took place—is associated with the Santa Fe Group. It marks the top of the Ceja Formation and the maximum level of basin filling by the Santa Fe Group. Modern alluvium and terrace deposits are not included in Santa Fe Group (Spiegel and Baldwin 1963). The Llano de Albuquerque is between 2.5 million and 700,000 years old (Connell and Smith 2005; Shari Kelley, New Mexico Bureau of Geology and Mineral Resources, geophysicist/field geologist, written communication, 31 August 2017) and represents a period of landscape stability. The surface is about 110–215 m (360–705 ft) above the modern Rio Grande floodplain. It serves as a drainage divide, separating the Rio Grande on the east and the Rio Puerco on the west.

Rio Grande

The ancestral Rio Grande developed into the modern Rio Grande as the Albuquerque basin's drainage pattern changed from internal to through-flowing, causing the accumulation of basin-fill sediments (Santa Fe Group) to dramatically decrease and then cease. The first major incision of the Rio Grande valley, which began about 1.2 million to 700,000 years ago (Kelley 2010), marks the end of Santa Fe Group deposition (Lozinsky 1989).

Incision by the Rio Grande and downcutting through the fill was not a continuous process. As the river episodically dissected older fill, it left a distinct record of landforms that represents valley incision; these landforms are called "terraces." Terraces represent former floodplains left "high and dry" as the river cut downward. Four terrace levels occur along the Rio Grande in the Albuquerque area. The western edge of the Rio Grande terraces runs along the eastern edge of the monument; this feature was mapped as a "geologic line feature" in the GRI GIS data (see poster, in pocket). Deposits of three of these four terrace levels are within the monument (table 1). Connell (2006) applied the following terminology to these deposits:

Lomatas Negras Formation (Qrl), oldest and highest terrace. Developed during the Middle Pleistocene Epoch (781,000–126,000 years ago). Volcanic ash from the Yellowstone caldera allowed the Lomatas Negras Formation to be dated to younger than 640,000 years old (Connell et al. 2007). The Lomatas Negras Formation is geochemically indistinguishable from the Lava Creek B ash of Yellowstone. This ash places the youngest age limit on the initiation of incision of the Rio Grande valley in the Albuquerque area.

Los Duranes Formation (Qrd), middle terrace. Developed during the Middle Pleistocene Epoch (781,000–126,000 years ago).

Las Padillas Formation, youngest and lowest terrace. Specifically, the intermediate channel and floodplain deposits (**Qrpm**) of the Las Padillas Formation are in the monument. The Las Padillas Formation underlies the modern Rio Grande valley and floodplain. The base of the Los Padillas Formation was probably cut during the last glacial maximum, which is constrained at approximately 22,000–15,000 years ago in the neighboring Estañcia basin, just east of the Manzano Mountains (Allen and Anderson 2000; see GRI report about Salinas Pueblo Missions National Monument by KellerLynn in preparation).

Following terrace-forming episodes, tributaries to the main river deposited stream-valley alluvium (e.g., **Qoa**, **Qam**, and **Qay**) along the margin of each extant floodplain. Modern stream-valley alluvium (**Qa**) represents present-day aggradation in tributaries (table 1).

Albuquerque Volcanic Field

Another consequence of rifting is volcanism. During extension, Earth's crust becomes thinner, allowing higher heat flow from the mantle, which induces melting and the formation of magma. The weakened, fractured rocks associated with rift-related faults act as pathways for magma ascent, allowing the molten rock to reach the surface where it erupts as lava.

In New Mexico, crustal extension produced many volcanic fields in the Rio Grande rift, including the Albuquerque volcanic field in the Albuquerque basin, as well as the Taos Plateau, Jemez, Cerros del Rio, Santa Ana (San Felipe), Jornada del Muerto, Carrizozo, Elephant Butte, Hillsboro, Potrillo, and Palomas volcanic fields (fig. 3). Some geologists consider the Cerros del Rio and Santa Ana volcanic fields a peripheral part of the Jemez volcanic field (Baldridge 2004; see also the GRI report about Bandelier National Monument by KellerLynn 2015a). As evidenced by lava flows episodically interbedded with the Santa Fe Group strata, volcanism took place throughout much of the history of the Rio Grande rift.

Figure 8. Photograph of Vulcan, Bond, and Butte Volcanoes. The Volcanoes area of the monument offers both panoramic and close-up views of distinctive geologic features. A lava pond with columnar jointing (see fig. 12) lies inside the crater of Vulcan Volcano (middle ground in the photograph). A trail loops through and around the volcano's rim. Bond and Butte Volcanoes are off in the distance to the north. NPS photograph by Chanteil Walter (Petroglyph National Monument).

Figure 9 (facing page). Panoramic photograph of spatter cones. The three southernmost volcanoes in the monument are known as the “Sisters,” shown from left to right: Vulcan Volcano (1,839 m [6,033 ft] above sea level), Black Volcano (2,434 m [7,986 ft] above sea level), and JA Volcano (1,812 m [5,944 ft] above sea level). These volcanoes rise between 150 m (500 ft) and 180 m (600 ft) above the surrounding mesa top. Their formation along an eruptive fissure parallels the north–south-oriented faults in the area. The Sisters make up Albuquerque’s distinctive western skyline. Photograph by Matt Zimmerer (New Mexico Bureau of Geology and Mineral Resources).

The chain of volcanoes in the monument is part of the Albuquerque volcanic field, which is also referred to as the “Albuquerque volcanoes” or “The Volcanoes.” The volcanic field covers an area of 62 km^2 (24 mi^2). The lava erupted from a linear fissure that parallels the orientation (approximately N 2° E) of the general western margin of the Albuquerque basin of the Rio Grande rift. The “fissure line” of the Albuquerque volcanoes is very near the center of the Rio Grande rift. Measured from the farthest north vent (outside the monument) to the farthest south vent, as mapped by Connell (2006), the fissure is approximately 6.5 km (4 mi) long and, in the monument, is marked by the five named volcanoes, from north to south, Butte, Bond (fig. 8) , Vulcan (also known as J), Black, and JA (fig. 9).

Mapping outlined the basic stratigraphic relationships of the volcanic field: the oldest flows are the most widespread and formed the eastern margin of the field. Subsequent flows spread both east and west of the main fissure, but became progressively more restricted. The final erupted material was localized around central vents (fig. 10). Connell (2006) mapped 17 vents in total; 16 of these lie along the north–east-oriented fissure zone; one lies 1,030 m (3,380 ft) to the east (see poster, in pocket). As magma cooled and solidified along the fissure, only a few points continued to erupt. Small cones of cinders, ash, and spatter built up around these centralized points of eruption.

Based on surface morphology and stratigraphic position, Connell (2006) divided the Albuquerque volcanic field into five flows (**Qb1–Qb5**) and five vent deposits (**Qbv**) (see poster, in pocket). Shroba et al. (2003) provided a slightly different mapping scheme and interpretation of lava flows and vents at the monument (table 2; see also GRI GIS data set mnse_geology.mxd).

The Albuquerque volcanic field was active about 156,000 years ago, based on a whole-rock, uranium/thorium ($^{238}U/^{230}Th$), isotopic dating (Peate et al. 1996). Connell (2006) reported this age by Peate et al. (1996), so that is the age used in this report. A range of ages—between 211,000 and 155,000 years ago—commonly have been reported, however (see Kelley 2010). In 2016, the New Mexico Bureau of Geology and Mineral Resources conducted high-precision, argon/argon ($^{40}Ar/^{39}Ar$) isotopic dating of lava-flow samples that yielded ages of 195,000 ± 15,000 and 131,000 ± 11,000 years old (Chan et al. 2016). Additional work to further refine the timing of volcanism in the monument is in progress (Matt Zimmerer, New Mexico Bureau of Geology and Mineral Resources, field geologist, written communication, 29 August 2017). The monument has served as a site for testing various methods useful in dating young lava flows (National Park Service 2006), including $^{238}U/^{230}Th$, potassium/argon ($^{40}K/^{40}Ar$), and now $^{40}Ar/^{39}Ar$.

For comparison, the youngest lava flow in New Mexico is the McCartys flow in El Malpais National Monument (see GRI report by KellerLynn 2012a). Based on cosmogenic chlorine-36 (^{36}Cl) dating, the McCartys flow is 3,900 years old (Dunbar and Phillips (2004). Capulin Volcano erupted 55,000 ± 2,000 years ago and was precisely dated using the $^{40}Ar/^{39}Ar$ method (Zimmerer et al. 2014; see GRI report by KellerLynn 2015b).

Table 2. Comparison of volcanic map units in the GRI GIS data.

Connell (2006)	Shroba et al. (2003)
Qbv (vents)	Qby2c (cinder deposits on lava flow unit 2), Qby5c (cinder deposits on lava flow unit 5)
Qb5 (flow 5)	Qby5 (lava flow unit 5)
Qb4 (flow 4)	Qby4 (lava flow unit 4)
Qb3 (flow 3)	Qby2 (lava flow unit 2), Qby3 (lava flow unit 3)
Qb2 (flow 2)	Qby1 (lava flow unit 1), Qbo (old lava flows)
Qb1 (flow 1)	Qbo (old lava flows)

Note: Both Connell (2006) and Shroba et al. (2003) mapped these units as Middle Pleistocene in age.

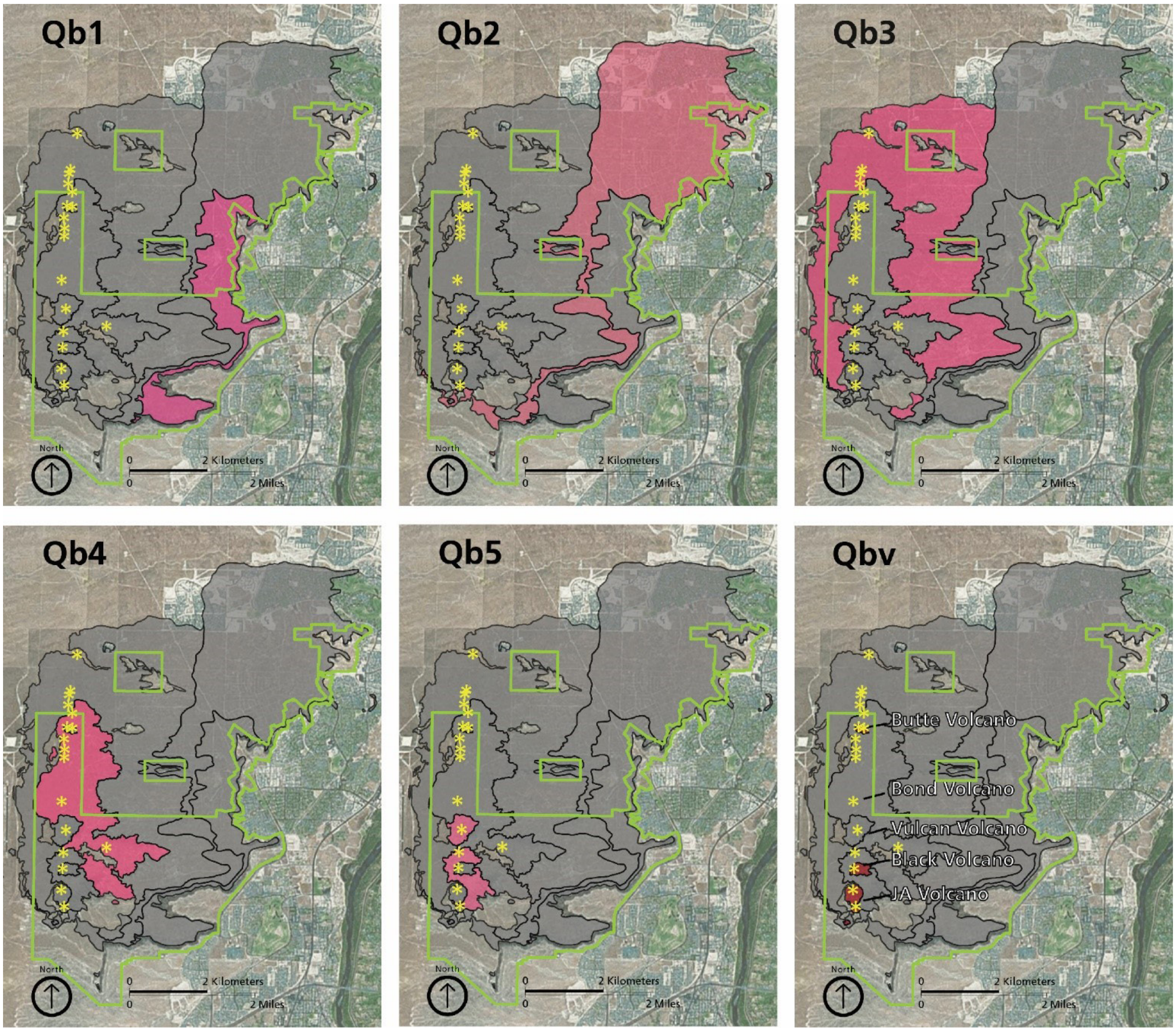

Figure 10. Graphic of the sequence of lava flows and eruptions at the monument and vicinity. Connell (2006) mapped six eruptive phases in the Albuquerque volcanic field. The earliest eruptions (Qb1 and Qb2) were low viscosity and spread to the east from a fissure, which is marked by a vertical line of vents (*) on the figure. Subsequent flows covered earlier flows; lava would have covered the landscape between the vents (line of yellow asterisks) and the edges of flows. During the third eruptive phase (Qb3), lava spread from the fissure to both the east and the west. Later eruptions (Qb4 and Qb5) were thicker and less expansive and became more and more restricted to central vents; they culminated with the formation of cones (Qbv). Graphic by Michael Barthelmes (NPS Geologic Resources Division) using GRI GIS data (petr_geology.mxd) compiled from the source map by Connell (2006).

Dating of the lava flows in the Albuquerque volcanic field by any one study (e.g., Bachman and Mehnert 1978; Champion et al. 1988; Geissman et al. 1990; Peate et al. 1996; Singer et al. 2008) and examination of physical features (e.g., overlapping deposits from various vents) indicate that all of the vents were active simultaneously. Furthermore, all of the flows were erupted within a relatively short period of time—on the scale of months to a few years—as evidenced by the lack of paleosols (buried soil layers) or windblown deposits between consecutive flows.

Volcanic Features and Terminology

Connell (2006) identified the rock that makes up the Albuquerque volcanic field as basaltic lava, specifically vesicular olivine tholeiite (fig. 11). Almost all the volcanic features in the monument are composed of this rock. The abundant vesicles in the rock are the remnants of volcanic gases (mostly carbon dioxide and water vapor) that are inherent in magma and ultimately cause eruptions. Tholeiite is one of two principal types of basaltic lava in the US Southwest; the other is alkali basalt. These basaltic lavas are defined on the basis of the relative abundance of sodium and potassium. The Albuquerque volcanoes are made of tholeiite, which is low in sodium and especially low in potassium.

White caliche (a layer of cemented calcium carbonate) and green, yellow, or orange lichen (a composite organism made up of a fungus and alga) create crusts on the surfaces of the basaltic boulders. A black, metallic-looking patina called "desert varnish" coats the boulders (see "Petroglyphs").

Because small-scale volcanic features are generally of interest to visitors, and an understanding of them is useful for interpretation as well as resource management, descriptions of these features are commonly included in GRI reports. Connell (2006), however, only provided basic information about the age, composition, and dimensions of the lava flows in the monument. Thereby, the following list of features was compiled using terms mentioned

Figure 11 (left). Photographs of basalt. The upper photograph is a hand sample collected from the monument for research purposes by the New Mexico Bureau of Geology and Mineral Resources. It is approximately 10 cm (4 in) wide. The lower photograph shows native rock near Vulcan Volcano. The volcanic rock in the monument is basaltic lava, specifically vesicular olivine tholeiite. "Vesicular" describes the texture of the rock, which is characterized by abundant vesicles (cavities) formed by the expansion of gases during the solidification of the rock. "Olivine," which is commonly olive-green, is a silicate (silicon + oxygen) mineral of magnesium and iron, $(Mg,Fe)_2SiO_4$; it is an essential mineral in igneous rocks such as basalt. "Tholeiite" is a type of basalt whose classification is based on the amount of sodium (Na) and its oxidation state (which is reduced). New Mexico Bureau of Geology and Mineral Resources photograph courtesy of Matt Zimmerer. NPS photograph by Chanteil Walter (Petroglyph National Monument).

by Crumpler (1999), Bauer et al. (2003), Shroba et al. (2003), and Kelley (2010) as occurring in the Albuquerque volcanic field. No compiled database or map of these small-scale features within the monument is known, however (see "Volcanic Resource Inventory, Assessment, and Protection"). Where available, descriptions of the following features were adapted from the aforementioned publications, but in many cases, no description was provided and the following descriptions were written using the USGS Volcano Hazard Program's online glossary (https://volcanoes.usgs.gov/vsc/glossary/) and GRI reports for other volcanic parks, including El Malpais National Monument (KellerLynn 2012a), Capulin Volcano National Monument (KellerLynn 2015b), and Craters of the Moon National Monument (KellerLynn in review).

- **A'a** is a Hawaiian word used to describe the physical appearance of the surface of a basaltic lava flow that is rough, jagged, or clinker-like (see "pahoehoe" below).
- **Agglutinate** is a welded pyroclastic deposit. The term is commonly used for deposits of bombs fused while hot and viscous. Agglutinate typically occurs in spatter cones (see associated definitions).
- **Agglomerate** consists of consolidated pyroclastic rock made primarily of bombs.
- **Ash** consists of fine fragments (less than 2–4 mm [0.08–0.16 in] in diameter) of volcanic rock formed by a volcanic explosion or ejection from a volcanic vent.
- **Bombs** form when globs of molten rock are ejected into the air and shaped while in flight.
- **Break-outs** occur where continued feeding of channeled lava forces new lobes to develop and flow laterally around the preceding flow fronts.
- **Channels**, also called "gutters," are open-topped conduits for flowing lava. A channel is commonly lined by lava levees, which serve as a retaining wall of hardened lava along the sides. Accumulation of layers in the upper walls of the channel may evolve into a closed lava tube as an eruption progresses and the walls build up and solidify into a roof.
- **Cinders** are volcanic fragments, commonly glassy and containing vesicles (cavities formed by volcanic gases), ranging in size from 4 to 32 mm (0.16 to 1.3 in) in diameter that fall to the ground as solid material. Young lava flow unit 5 (**Qby5**) of Shroba et al. (2003) has cinders associated with fire fountain eruptions from Vulcan (J) and Black Volcanoes.
- **Kipukas** are areas of older rock surrounded by younger lava flows. The term "kipuka" is Hawaiian meaning "opening." These features also are referred to as "geologic windows," and indeed, the Northern Geologic Window and Southern Geologic Window areas in the monument were mapped as older rock (i.e., Ceja Formation [**Tcrg**]) surrounded by younger lava flows (i.e., **Qb2** and **Qb3**) (see poster, in pocket). In reality, the Ceja Formation is poorly exposed in the windows, but pebbles and cobbles of granite, quartzite, and chert are evidence of its occurrence.
- **Lapilli** are pyroclastic materials ranging between 2 and 64 mm (0.08 and 2.5 in) in diameter with no characteristic shape. They may be either solidified or viscous upon landing.
- **Lava flows** are masses of molten rock that pour onto Earth's surface during an effusive eruption. Both moving lava and the resulting solidified deposit are referred to as "lava flows." Flows at the monument are relatively thin, ranging in thickness between 1 and 7 m (3 and 23 ft) (Shroba et al. 2003). Total thickness of flows is generally less than 15 m (50 ft) (Connell 2006).
- **Lava ponds** are ponded areas of lava with little surface relief. They form where basaltic magma wells up in a pit or crater, and may also form on pahoehoe surfaces when flows are ponded by an obstacle. A solidified lava pond that consists of massive gray basalt with weakly developed columnar jointing (parallel, prismatic columns, polygonal in cross section, that form as a result of contraction during cooling) occupies the crater of Vulcan Volcano (fig. 12).
- **Lava tubes** are the principal means by which pahoehoe lava spreads widely and thinly during an eruption. Lava tubes form by the crusting over of lava channels (fig. 13). The lava tubes in the monument are relatively small in diameter, between about 20–50 cm (8–20 in) across, and discontinuous.
- **Pahoehoe** is a Hawaiian word used to describe the physical appearance of the surface of a basaltic lava flow that is smooth, ropy, or billowy (fig. 14). Young lava flow units 1 (**Qby1**) and 2 (**Qby2**) of Shroba et al. (2003) are characterized by transitional surface forms from pahoehoe to a'a.

Figure 12. Photograph of columnar jointing. The relatively smooth surface of a lava pond occurs in the crater of Vulcan Volcano in the monument. As the lava cooled, columnar joints formed in the ponded lava. NPS photograph by Chanteil Walter (Petroglyph National Monument).

Figure 14. Photograph of pahoehoe. Pahoehoe is a type of lava commonly found in effusive, basaltic lava flows. The Hawaiian term, “pahoehoe,” describes the ropy appearance of the lava. As shown here, the lava flows around Vulcan Volcano contain pahoehoe. NPS photograph by Chanteil Walter (Petroglyph National Monument).

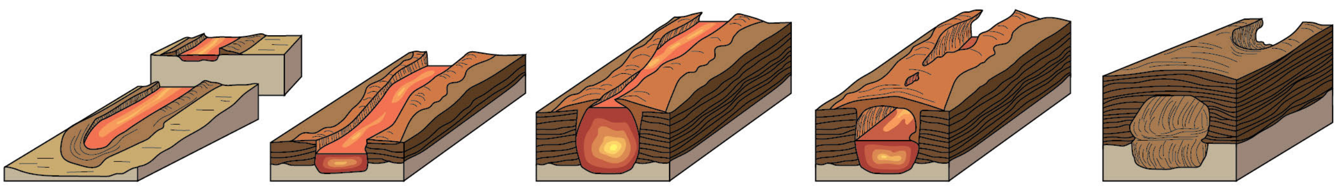

Figure 13. Graphic of lava-tube formation. The graphic shows the progression of lava-tube formation. In step 4, a crust may develop along the edges of a channel and merge like a zipper in the center, or separate crustal plates may form, tear loose, and drift along until they fuse to one another and the channel sides. In a turbulent lava flow, splashing and overflow along the channel create levees that may arch over the channel and join. A crust may thicken via repeated overflows onto its surface and/or accretion of cooled lava on its underside. Lava also can erode downward, deepening the tube and leaving empty space above the flowing lava. Graphic by Trista Thornberry-Ehrlich (Colorado State University) after USGS graphic by Bruce Rogers.

- **Push-ups**. Shroba et al. (2003) identified push-ups as occurring in young lava flow unit 3 (**Qby3**) and unit 5 (**Qby5**). The term "push-up" is atypical in reference to volcanic features, however, and is listed in neither the USGS Volcano Hazard Program's online glossary nor the Glossary of Geology (Neuendorf et al. 2005). Whether Shroba et al. (2003) were referring to lava that pushed up an overlying, solidified crust (see "tumuli" below) or features referred to as "squeeze-ups" (lava that squeezes out onto the solidified surface of a lava flow) is unknown.
- **Pyroclast** is a general term applied to volcanic products that resulted from explosive ejection and fragmentation of erupting material. The term literally means "fire broken."
- **Rafted** is a term typically used to describe pieces of a crater wall that were carried off like icebergs by a lava flow. Shroba et al. (2003) noted "rafted pyroclastic deposits" in young lava flow unit 3 (**Qby3**) but did not describe the "pre-rafted" location.
- **Ramps**. Shroba et al. (2003) identified "ramp structures" as occurring on young lava flow unit 5 (**Qby5**). Presumably, these are inclined surfaces on a lava flow, but the use of the term is atypical in reference to volcanic features, and whether the structures were built upward by the accumulation of pyroclastic material or the pushing upward by a lava flow or underlying lava below a solidified crust is unknown. The aprons of lava at the bases of the cones may also be referred to as "ramps."
- **Scoria** is vesicular volcanic ejecta, essentially magma that has been frothed up by escaping gases. Young lava flow unit 5 (**Qby5**) of Shroba et al. (2003) has scoria associated with fire fountain eruptions (fountains of glowing lava and ash that may have reached heights of 9 m [30 ft] or more) from Vulcan (J) and Black Volcanoes.
- **Spatter** consists of fluid globs of lava welded together. Spatter (and cinders) on the cones in the monument are among the last volcanic material to have erupted from the fissure.
- **Spatter cones**. The volcanoes in the monument are small spatter cones, measuring between 30 and 150 m (100 and 490 ft) at the base and 6 to 50 m (20 to 160 ft) high. At 1,838 m (6,030 ft) above sea level, Vulcan Volcano is the largest. It formed primarily by fire fountains that were active in a centralized vent and in smaller vents on the flanks of the cone. Spatter accumulated around the vent and welded together. The spatter material is thickest on the southeastern side of Vulcan Volcano, indicating that it was blown by the wind toward the south and east during the fountaining eruption. Young lava flow unit 5 (**Qby5**) of Shroba et al. (2003) has spatter associated with fire fountain eruptions from Vulcan (J) and Black Volcanoes.
- **Tumuli** are created when the upward pressure of slow-moving, still-molten lava within a flow swells or pushes the overlying solidified crust upward.

West Mesa

The monument is located in an area locally known as West Mesa, which stretches across Albuquerque's western landscape (fig. 1). The West Mesa landscape is extremely significant to a diverse assemblage of ethnographic communities that maintain association with the monument and West Mesa. The location of the mesa allowed people to observe the entire region from one point, and it is connected in many stories with the much higher Sandia Mountains to the east. The ethnographic landscape report by Anschuetz et al. (2002) identified many ties between the living, the physical, and the spiritual world of West Mesa.

The mesa consists of basaltic lava resting on the basin-filling sediments of the Santa Fe Group, namely the Ceja Formation (**Tcrg**). The first two lava flows (**Qb1** and **Qb2**) that erupted in the Albuquerque volcanic field traveled the farthest east and are exposed along the eastern margin of the mesa (fig. 10).

In the time since the eruption of the volcanic field, the erosive power of the wind and water, including lateral erosion by the Rio Grande, abraded and carried away the softer underlying sedimentary rocks of the Santa Fe Group. With the loss of underlying support, the basalt cap rock broke and collapsed at the edge of the mesa, creating today's West Mesa escarpment. The cliffs that make up the escarpment range in height from about 9 m (30 ft) at the northern end to about 90 m (300 ft) at the southern end. Connell (2006) mapped the material that has accumulated on the slope and at the base of the escarpment as colluvium and alluvium, undivided (**Qca**). Mapping the material as both colluvium and alluvium is indicative of the gravity-driven (colluvium) and stream-deposited (alluvium) processes responsible for its formation.

Widespread layers of eolian sand and silt, too thin to be mapped, cover the mesa. At the southern end of the monument and southward, Connell (2006) mapped active and inactive sand sheets and discontinuous dunes. These features were mapped as modern windblown sand (**Qe**).

Petroglyphs

Colluvium and alluvium, undivided (**Qca**), occur along the entire length of the escarpment (see poster, in pocket). This is the place where American Indians and settlers of Spanish, Mexican, and American Indian descent chose to carve petroglyphs. The petroglyphs lend cultural significance to geologic features such as colluvial boulders, lava flows, and the escarpment. Many of the petroglyphs clearly illustrate the connection of the people who created them to the monument's landscape and its underlying geologic foundation (see Anschuetz et al. 2002).

Figure 15. Photograph of the trail in Boca Negra Canyon. The most heavily visited and easily accessible petroglyphs in the monument are found in Boca Negra Canyon. The Boca Negra unit of the monument was originally established in 1973 as Indian Petroglyph State Park. Paved trails in Boca Negra Canyon provide opportunities for viewing petroglyphs, along with wayside signs that interpret images and their context. Photograph by user khlnmusa available at https://commons.wikimedia.org/wiki/File:Boca_Negra_Canyon_in_the_Petroglyp_National_Monument.jpg (Creative Commons Attribution-ShareAlike 3.0 [CC BY-SA 3.0] Unported License).

Most of the petroglyphs are on large basaltic boulders, for example, along trails in Rinconada Canyon south of the visitor center and Boca Negra Canyon north of the visitor center (fig. 15), as well as in Piedras Marcadas Canyon. The boulders are coated with desert varnish, also called "rock varnish." This very dark-brown to black stain occurs on rock surfaces in arid regions throughout the world. It commonly forms "water stripes" on steep rock faces where storm runoff flows down the face of a cliff (fig. 16). It is also noted on gravel surfaces called "desert pavement" or blackened boulders lying on sloped surfaces such as alluvial fans.

Desert varnish is a natural rock coating composed of clays, organic compounds, and manganese and iron oxides. About 70% of the total mass of a desert varnish deposit is composed of clay minerals. Notably, this clay component is an eolian deposit, not an alteration product of the surface of the stained rock. Many researchers have proposed that microbial activity is critical to the formation of desert varnish; others have invoked an inorganic origin, in particular, silica coatings composed of opal. Despite the extensive literature related to desert varnish, many uncertainties and controversies regarding its composition and formation remain (Dickerson 2011). The GRI report about Petrified Forest National Park discusses desert varnish in depth (see KellerLynn 2010).

The petroglyphs within the monument were created by pecking into or chipping away at desert varnish to expose the lighter colored rock beneath. The final rock carvings display a stunning gray-on-black contrast. With the ongoing growth of desert varnish, many older petroglyphs have begun to darken over the centuries (National Park Service 2012).

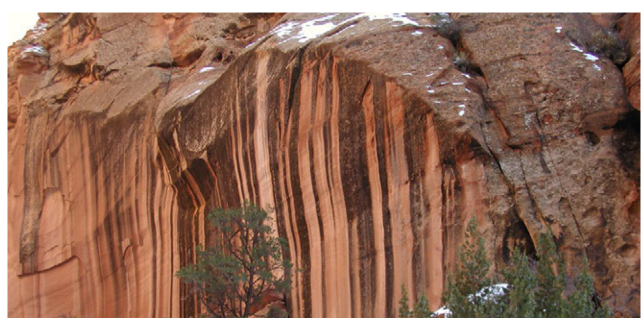

Figure 16. Photograph of desert varnish. Streaks of desert varnish coat a sandstone cliff face in Capitol Reef National Park, south central Utah (see GRE report by Graham 2006a). Photograph by Katie KellerLynn (Colorado State University).

Geologic Resource Management Issues

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

During the 2006 scoping meeting and 2017 conference call, participants (see Appendix A) identified geologic resource management issues, which are summarized in table 3. The issues are ordered based on management priority. A discussion of potential resource management actions for each issue follows table 3.

The Geologic Resources Division can provide technical and policy support for each of these issues (see http://go.nps.gov/geology). GRD programs and staff focus on three areas of emphasis: (1) geologic heritage, including cave and paleontological resources; (2) active processes and hazards, including erosion; and (3) energy and minerals management, including abandoned mineral lands (AML). Monument managers are encouraged to contact the NPS Geologic Resources Division (https://www.nps.gov/orgs/1088/contactus.htm). Monument staff can formally request assistance via https://irma.nps.gov/Star/.

In addition, the NPS Geologic Resources Division administers the Geoscientists-In-the-Parks (GIP) and Mosaics in Science programs. These internship programs place scientists (typically undergraduate students) in parks to complete geoscience-related projects. Some potential projects are highlighted in the following discussion of issues. More information is available at the programs' websites (http://go.nps.gov/gip and http://go.nps.gov/mosaics).

Resource managers may find *Geological Monitoring* (Young and Norby 2009; http://go.nps.gov/geomonitoring) 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. Where applicable, those chapters are highlighted in the following discussion.

Table 3. Geologic resource management issues at Petroglyph National Monument. Table continues on next page.

Issue	Summary	Potential Needs	Associated Map Unit/ Geologic Feature
Erosion	Erosion is caused chiefly by storm-water runoff but is exacerbated by adjacent development and past disturbances (e.g., roads and social trails; see "Disturbed Lands").	Inventory and monitor previously established gully observation sites (see "Monitoring Erosion") in order to assess whether changes in management practices are needed to preserve petroglyphs or maintain natural rates of erosion. Prepare for land exchange with the City of Albuquerque.	Quaternary alluvium, colluvium, and eolian sand (**Qa, Qrpm, Qay, Qam, Qrd, Qca, Qe**) of Connell (2006) Sheetwash deposits (**Qsw**) of Shroba et al. (2003) Surficial deposits atop lava flows (too thin to have been mapped)
Disturbed Lands	Disturbed lands at the monument include old roads (some of which are currently used as "administrative roads" by NPS staff and some of which will be part of a future, established trail network), two abandoned motor-cross tracks, and an estimated 240 km (150 mi) of social trails.	Assessment of these disturbances in order to determine which require restoration and which can be used as part of a designated trail system.	Quaternary alluvium, colluvium, and eolian sand (**Qa, Qrpm, Qay, Qam, Qrd, Qca, Qe**) of Connell (2006) Sheetwash deposits (**Qsw**) of Shroba et al. (2003) Surficial deposits atop lava flows (too thin to have been mapped)

Table 3, continued. Geologic resource management issues at Petroglyph National Monument.

Issue	Summary	Potential Needs	Associated Map Unit/ Geologic Feature
Wind Erosion, Transport, and Deposition	Windblown dust is accumulating on the ground surface along the West Mesa, changing the color of the landscape from black to tan. Where dust buildup is substantial, it has the potential to obscure petroglyphs. The wind is also causing mass accumulations of tumbleweeds, which are likely covering petroglyphs as they can get very deep within the canyons of the escarpment.	Identifying sources of dust. Potential mitigation includes techniques associated with oil and gas operations.	Eolian sand (**Qe**) Sheetwash deposits (**Qsw**) Colluvium and alluvium, undivided (**Qca**)
Rockfall	Unstable tumbling boulders along the West Mesa escarpment and rockfall off the mesa have the potential to destroy petroglyphs or create safety hazards for visitors.	Inventory and monitor rockfall areas. Minimize visitor use infrastructure in rockfall areas as part of the visitor use management plan.	Colluvium and alluvium, undivided (**Qca**)
Volcanic Resource Inventory, Assessment, and Protection	Geologic mapping has not occurred at a scale that identifies individual volcanic features, which are at risk from human activities (e.g., trampling, vandalism, and theft).	Field-based inventory of individual features, including GPS locations and photographs, and a condition assessment of individual features.	Albuquerque volcanoes, vents (**Qbv**) Albuquerque volcanoes, flows 1–5 (**Qb1–Qb5**)
Earthquakes	Twenty-seven Quaternary-age faults have been identified within 20 km (12 mi) of downtown Albuquerque (Personius et al. 1999). The faults are associated with the Rio Grande rift and are responsible for 10 earthquakes of MMI (Modified Mercalli Intensity) V ("moderate" shaking) or greater since 1849. Earthquakes capable of MMI VIII ("severe" shaking) have occurred in the past tens of thousands of years. Segments of 11 faults cross the monument.	Earthquake hazard assessment, including areas with the potential for earthquake-induced rockfall, and a response plan.	Faults (see poster, in pocket; and GRI GIS data)
Abandoned Mineral Lands	The NPS AML database and Burghardt et al. (2014) identified three AML features at three sites within the monument. Two of these sites have been reclaimed.	Reclamation of remaining site.	Albuquerque volcanoes, vents (**Qbv**) Albuquerque volcanoes, flow 5 (**Qb5**)
Cave Resource Management	Caves formed in welded spatter at the monument. Commonly lava tubes are cave resources, but the lava tubes in the monument are too small to enter. Lava tubes may contain archeological and paleontological resources in need of protection, however.	Cave management plan that addresses visitor use and the potential for vandalism, as well as the location of trails and roads with respect lava tubes for the purpose of visitor safety (i.e., lava-tube collapse) and resource protection.	Albuquerque volcanoes, vents (**Qbv**) Albuquerque volcanoes, flows 1–5 (**Qb1–Qb5**)
Paleontological Resource Inventory, Monitoring, and Protection	In situ fossils are not common in the rocks at the monument. "Reworked" petrified wood has been found in the Ceja Formation. The monument's museum collections contain fossil specimens. Elsewhere in central New Mexico, Quaternary deposits have yielded fossils (e.g., "Ice Age" mammals), and lava tubes may contain packrat middens.	Field-based paleontological survey to identify in situ paleontological resources and document fossils in the museum collection.	Ceja Formation, upper sand and gravel member (**Tcrg**) Potential for fossil discovery in Quaternary alluvium, terrace deposits, and eolian sand (**Qrpm, Qay, Qe, Qca, Qam, Qrd, Qao**, and **Qrl**) Potential for fossil discovery and packrat middens in lava tubes (**Qb1–Qb5**)
Volcano Hazards	The vents at the monument are unlikely to erupt again, but a future eruption within the Rio Grande rift, including the Albuquerque basin, is likely.	Volcanic hazard assessment and response plan.	Albuquerque volcanoes, vents (**Qbv**) Albuquerque volcanoes, flows 1–5 (**Qb1–Qb5**)

Erosion

Erosion is a major resource management challenge at the monument. It has the potential to impact the monument's petroglyphs and landscape, including volcanic features (see "Inventory of Volcanic Features"). Storm-water runoff is the primary agent of erosion, but wind erosion, transport, and deposition of dust is another management concern with respect to the preservation of petroglyphs (see "Wind Erosion, Transport, and Deposition").

Map Units Indicative of Erosion

Showing areas of erosion was not the purpose of mapping by Connell (2006; scale 1:50,000) and Shroba et al. (2003; scale 1:24,000). However, certain map units such as modern stream-valley alluvium (**Qa**) and eolian sand (**Qe**) are indicative of and have the potential for erosion. Also, sheetwash deposits (**Qsw**) (sand and silt chiefly deposited by non-channelized surface-water flow, referred to as "sheet flow") are indicative of erosion. Shroba et al. (2003) mapped sheetwash deposits in the southwestern part of the monument. Sheet flow can grade into channelized flow as water flow becomes progressively more concentrated in particular downslope routes. Low-lying areas of sheetwash deposits (**Qsw**) are susceptible to sheet and stream flooding and to gullying. Disturbed areas of **Qsw** probably are susceptible to wind erosion and deposition.

Gullying

High-intensity storms and the development of gullies during summer 1991 prompted the first study of gully formation within the monument (Gellis 1995, 1996). Findings of that study indicated that gullying took place during moderate storms having a recurrence interval of two years or less. Thus, unusually high intensity rainfall or high runoff events are not required for gullying to take place. In addition, the study found that disturbed lands such as roads and trails appeared to be a significant factor in gullying. Most of the 50 gullies identified by Gellis (1995) were along the northern part of the West Mesa escarpment. At the time of that study, the northern part of the mesa was more developed than the southern part and contained many dirt roads and unpaved foot and bicycle paths. Thirty of the 50 identified gullies were connected to runoff from dirt roads. In short, human-created dirt roads and paths channeled surface runoff and increased erosion (fig. 17).

Figure 17. Photograph of gullying. Because of its erodible soils and scant vegetative cover, the monument is sensitive to natural and human activities that may accelerate erosion. Disturbances such as roads and social trails, which channel surface-water flow, exacerbate gullying. This figure shows photographs of a road near Badger Pass in the monument. NPS photographs courtesy of Chanteil Walter (Petroglyph National Monument).

Another interesting finding by Gellis (1995) was that the erosion caused by the gullies may not be a direct threat to the petroglyphs. Most of the petroglyphs occur on basaltic outcroppings or loose boulders, whereas most of the gullies are in areas of loamy-sandy soils. Gellis (1995) did not correlate petroglyphs sites with gullies, but suggested that this would be a worthwhile project because a gully could undercut the soil below a boulder and cause it to roll and damage petroglyphs. A GIP or Mosaics in Science intern could conduct such a project. Additionally, increases in surface runoff over petroglyphs could increase erosion on the boulder surface and deteriorate the petroglyphs. Gellis (1995), however, did not test or determine the relationship between surface runoff and boulder erosion. This is another potential study by a GIP or Mosaics in Science intern. Methods by Bass Rivera and Meyer (2006, 2009) in studies of cavate deterioration in the Bandelier Tuff at Bandelier National Monument may be applicable (see GRI report about Bandelier National Monument by KellerLynn 2015a).

Arroyos

The monument is cut by five primary arroyo systems, from north to south: (1) Piedras Marcadas, (2) Boca Negra, (3) San Antonio, (4) Rinconada, and (5) Ladera (see poster, in pocket). The arroyos in the monument span a total of 34.6 km (21.5 mi) (National Park Service 2017c). These arroyos drain eastward from the Albuquerque volcanic field to the Rio Grande, carrying ephemeral surface-water flow across the top of West Mesa and down the escarpment.

Arroyos tend to respond quickly to precipitation and have flashy flows (streamflow that rises to flood stage and wanes quickly). Because of their denuded appearance, arroyos commonly evoke negative reactions and are seen as a symptom that something is wrong. The natural function of arroyos is complicated, however, and ongoing phases alternating between aggradation and degradation may represent normal behavior of this type of fluvial system.

Resource management at the monument requires an appreciation of arroyos along with an awareness of the complexity of these drainages and their response to change. An article by Love and Gellis (2001), "What Decision Makers Should Know about Arroyos in New Mexico," may be useful. Also, consideration of the long history of erosion control efforts of Chaco Arroyo at Chaco Culture National Historical Park (see GRI report by KellerLynn 2015c), for example, may provide perspective on management of these features. A variety of papers about arroyos are available (see "Resources"), and various NPS management policies provide guidance (see Appendix B).

Monitoring Erosion

Gellis (1995) initiated a qualitative monitoring protocol for more than 100 gully "observation sites" in the monument. The data collected by Gellis (1995) and this protocol provide an obvious starting place in the development of a monitoring program at the monument. Also, the NPS Soil Resources Inventory suggested the use of Upland Soil Erosion Monitoring and Assessment: An Overview by Ypsilantis (2011).

The draft natural resource condition assessment for the monument (National Park Service 2016b) suggested a variety of monitoring options including photogrammetry. In 2014, the Geologic Resources Division produced quantitative photogrammetry images at the eastern boundary of the monument, along Lava Bluff Drive Northwest, where "erosion trenches" have developed between a storm-water retention basin and the West Mesa escarpment. These high-resolution images (visualization at the centimeter scale) and resultant 3D digital elevation model can be used to help resource managers assess whether documented changes are within a normal range of variation, or if the observed changes dictate a corrective action in management practices. The NPS Geologic Resources Division Photogrammetry website (http://go.nps.gov/grd_photogrammetry) provides more information.

Lord et al. (2009), the *Geological Monitoring* chapter about fluvial geomorphology, described methods for inventorying and monitoring geomorphology-related vital signs, including (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. That chapter provides an overview of river and stream dynamics, describes possible stressors that may lead to channel instability, and provides guidelines and methods for monitoring (from low-budget methods where minimal expertise in fluvial geomorphology is required to higher-level methodologies requiring greater expertise, a larger budget, and more time). Consideration of these vital signs and methods may be useful in the development of a monitoring program at the monument.

The draft foundation document for the monument (National Park Service 2016a) suggested partnering with the Albuquerque Arroyo Flood Control Authority and the City of Albuquerque on hydrologic monitoring, and continuing to cooperate with the Southern Colorado Plateau Network on photogrammetry and arroyo profiling. The network is currently photo-monitoring points at Lava Bluffs and Boca Negra (Chanteil Walter, Petroglyph National Monument, environmental protection specialist, written communication, 1 September 2017).

Interpretation and Outreach

Erosion is a topic ripe for interpretation at the monument, as well as for public education and outreach, because local users are likely familiar with its effects, particularly in light of the 2013 storms and flooding in Albuquerque. The draft foundation document for the monument (National Park Service 2016a) suggested many opportunities for public engagement with respect to recreation, which also are applicable to the prevention of erosion.

The GRD report by Bilderback (2013) provided many examples of how human modifications to surface-water flow can exacerbate erosional processes. These examples, which could be used in presentations or on field trips, could help to engage the public on how to prevent impacts. Bilderback (2013) also provided recommendations regarding the Santa Fe Village neighborhood (fig. 18), which is adjacent to the monument and located at the mouth of the San Antonio Arroyo drainage system.

Park Planning

Park planning with respect to erosion is ongoing. As discussed by Bilderback (2013), Santa Fe Village, an adjacent suburban development/neighborhood, is an area of concern. The National Park Service in collaboration with the City of Albuquerque proposed to exchange 2 ha (5 ac) of NPS-owned lands behind homes in Santa Fe Village for 4 ha (9 ac) of lands currently owned by the City of Albuquerque adjacent to the Volcanoes Day Use Area. In addition, the City of Albuquerque proposed to construct a permanent

Figure 18. Photograph of the Santa Fe Village. The Santa Fe Village neighborhood is located between Middle San Antonio Arroyo and South San Antonio Arroyo adjacent to (immediately east of) the monument. The neighborhood abuts the West Mesa escarpment. The National Park Service and the City of Albuquerque are preparing for a land exchange of 2 ha (5 ac) of NPS-owned lands behind the homes in Santa Fe Village for 4 ha (9 ac) of city–owned lands currently adjacent to the Volcanoes Day Use Area. The land exchange will allow the City of Albuquerque to manage runoff between the West Mesa escarpment and the Santa Fe Village neighborhood. NPS photograph courtesy of Dale Kissner (Petroglyph National Monument).

erosion control concrete storm channel on the 2 ha (5 ac) of exchanged land in Santa Fe Village. The City of Albuquerque anticipates the project to happen in the next one to four years (Chanteil Walter, Petroglyph National Monument, environmental protection specialist, written communication, 31 August 2017).

Originally, an environmental assessment (EA) for the land exchange and construction of concrete storm channel was to have been prepared in compliance with the National Environmental Policy Act (NEPA) in order to (1) analyze a reasonable range of alternatives to meet project objectives, (2) evaluate potential issues and impacts to park resources and values, and (3) identify mitigation measures to lessen the degree or extent of these impacts (National Park Service 2017a). However, after further consideration—including analysis of the proposed action and associated impacts and consideration of public scoping and tribal comments—monument managers determined that the proposed action fits within a categorical exclusion, and no extraordinary circumstances apply; therefore, an EA is no longer required. The National Park Service prepared a categorical exclusion, which was signed by the superintendent on 20 April 2017.

Another area of concern is the "Painted Pony" or Staghorn Drive area of the monument (near Boca Negra). A scoping meeting is scheduled for the end of September 2017 (Chanteil Walter, Petroglyph National Monument, environmental protection specialist, written communication, 1 September 2017).

Disturbed Lands

In the GRI GIS data, artificial fill (af) indicates some areas of disturbed lands (see poster, in pocket). Disturbed lands at the monument (not mapped in GRI GIS data) include old roads, two abandoned motor-cross tracks, and an estimated 240 km (150 mi) of social trails. Such disturbances create preferred pathways for storm-water runoff, exacerbating erosion (see "Gullying"). Old roads (some of which are part of the NPS administrative road system), social trails, and accompanying evidence of illegal access and use are especially evident along the monument's western border in the Volcanoes area of the monument. The proliferation of social trails is due to the lack of defined trails and specific trailheads (National Park Service 2016a).

The National Park Service is developing a visitor use management plan for the monument in order to formalize a trail system and manage public use. Planning will include an assessment of old roads and social trails to determine which require restoration and which could be incorporated into a system of about 60–80 km (40–50 mi) of designated trails (GRI conference call, 25 April 2017). The plan will identify the primary administrative roads and address the management and maintenance of a trail system, access points, associated infrastructure, and allowable uses. It will include expectations for long-term monitoring and analysis of visitor capacity (National Park Service 2017b).

In 2015, Suzanna Doak, a Mosaics in Science intern, examined the sustainability of the existing trails within the monument with respect to NPS standards (Doak 2015). These findings will be useful in determining which access points and trails to close to the public in order to limit human-induced erosion. The project developed a digital elevation model (DEM) from 2010 LiDAR and a surface–water flow model, showing direction and accumulation, which may be useful for park planning.

With respect to restoration of social trails, monument managers may find strategies at other parks worthy of consideration. For example, researchers have commended managers at Little Bighorn Battlefield National Monument in southeastern Montana for "the re-working of visitor movement patterns and the excellent trail relocation, along with appropriate enforcement to keep visitors on the trails" (Bock and Bock 2006, p. 28; see GRI report about Little Bighorn Battlefield National Monument by KellerLynn 2011). Recent improvements to the trail system at Deep Ravine in Little Bighorn Battlefield National Monument indicate a correlation between improved trails and a decrease in the formation of social trails. Since the new trail system at Deep Ravine opened, the proliferation of social trails has "decreased dramatically" (National Park Service 2007). Short of improving all trail systems, however, park managers at Little Bighorn Battlefield National Monument are addressing the problem by developing revegetation projects to reintroduce native "prickly" species such as yucca and cactus, in accordance with the national monument's resources management plan. These methods will help to minimize both shortcutting and the continued use of unauthorized trails (National Park Service 2007).

Monument managers are encouraged to contact the NPS Geologic Resources Division for assistance. The NPS Geologic Resources Division Disturbed Land Restoration website, http://go.nps.gov/grd_dlr, provides more information.

Wind Erosion, Transport, and Deposition

Along the West Mesa escarpment in areas that are adjacent to disturbed lands or developments, the naturally black, basaltic boulders and the ground surface surrounding these boulders now appear tan as a result of windblown-dust accumulation (fig. 19). The accumulation of windblown dust is, thereby, changing the landscape visually. Moreover, dust accumulation has the potential to mask petroglyphs in areas of substantial dust buildup. The wind is also causing mass accumulations of tumbleweeds, which are likely covering petroglyphs deep within the canyons of the escarpment.

Dust is primarily attributed to wind erosion of disturbed lands within the monument and developed areas adjacent to the monument. However, no studies specific to the monument have characterized actual sources of dust or means of transporting fugitive dust (particulate matter suspended in the air by wind action and human activities but not from a point source such as a smokestack).

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

Figure 19. Photograph of dust accumulation. In areas along the West Mesa escarpment that are adjacent to disturbed lands or developments, dust accumulation is visibly altering the naturally dark-brown or black color of the landscape. NPS photograph courtesy of Dale Kissner (Petroglyph National Monument).

If the sources and transport mechanisms of the windblown dust in the monument can be identified, mitigation may be possible. Techniques to mitigate windblown dust associated with oil and gas operations, for example at Lake Meredith National Recreation Area and Alibates Flint Quarries National Monument in the Texas Panhandle (see GRI report by KellerLynn 2015d), may be applicable to the monument. Moreover, preservation techniques applied to the "signatures" at El Morro National Monument may be applicable (see GRI report by KellerLynn 2012b).

Lancaster (2009), the *Geological Monitoring* chapter about eolian (spelled "aeolian" in Lancaster 2009) features and processes, described the following methods and vital signs: (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. Many of these vital signs are applicable to the windblown processes operating at the monument.

Rockfall

Unstable tumbling boulders along the West Mesa escarpment and rockfall (free falling of a newly detached segment of bedrock) from the mesa have the potential to destroy petroglyphs or create safety hazards for visitors (National Park Service 2016a) (fig. 20). A map unit closely associated with rockfall is colluvium. Connell (2006) mapped colluvium and alluvium, undivided (**Qca**), along the length of the escarpment, adjacent to spatter cones and vents, and as deposits of sand and gravel from nearby hill slopes within the lava flows (see poster, in pocket). According to Shroba et al. (2003), "colluvium" refers to surficial material transported on slopes chiefly by mass-wasting (gravity-driven) processes—such as creep, debris flow, and rockfall—aided by running water not confined to channels (sheetwash). At the southwest corner of the monument, Shroba et al. (2003) mapped alluvium and colluvium, undivided (**Qac**).

Figure 20. Photograph of rockfall. Rockfalls occurs naturally along the West Mesa escarpment and have the potential to destroy petroglyphs or create safety hazards for visitors. In early 2005, a visitor mishap in the Boca Negra area of the monument caused the large boulder shown in the photograph to tumble down onto the steps. A pickup truck was stranded about 8 m (25 ft) up the escarpment; the boulder was dislodged when the truck was removed. NPS photograph courtesy of Dale Kissner (Petroglyph National Monument).

Rockfall is a type of slope movement that may require monitoring for the protection of resources and visitor safety. In the *Geological Monitoring* chapter about slope movements, Wieczorek and Snyder (2009) described five vital signs for understanding and monitoring slope movements: (1) types of landslide, (2) landslide causes and triggers, (3) geologic materials in landslides, (4) measurement of landslide movement, and (5) assessment of landslide hazards and risks. In addition, Highland and Bobrowsky (2008), the US Geological Survey Landslides website (http://landslides.usgs.gov/), and the NPS Geologic Resources Division Geohazards (http://go.nps.gov/geohazards) and Slope Movement Monitoring (http://go.nps.gov/monitor_slopes) websites provide detailed information regarding slope movements, monitoring, and mitigation options.

Volcanic Resource Inventory, Assessment, and Protection

The GRI GIS data show the locations of larger scale volcanic features such as lava flows and cinder deposits surrounding vents. Connell (2006; scale 1:50,000) divided the basaltic lavas of the Albuquerque volcanoes into vents (**Qbv**) and five flows (**Qb1–Qb5**). In the southwestern part of the monument, Shroba et al. (2003; scale 1:24,000) mapped flows (**Qby1–Qby5**) and cinder deposits (**Qby2c** and **Qby5c**). Individual volcanic features such as those listed in "Volcanic Features and Terminology," however, have not been mapped or otherwise inventoried within the monument. GRI report reviewers suggested a possible partnership between the New Mexico Bureau of Geology and Mineral Resources (NMBGMR) and the monument where NMBGMR staff (in particular, Matt Zimmerer, who is a field geologist and accomplished photographer) could go out with monument staff to identify and photograph small-scale, individual features (Shari Kelley, New Mexico Bureau of Geology and Mineral Resources, geophysicist/field geologist, written communication, 31 August 2017). Features could be recorded with GPS at the same time as photographing. These photographs could be used as part of a condition assessment.

According to the draft natural resource condition assessment for the monument, "additional surveys of geologic features should be conducted at finer scales than prior surveys in an effort to obtain current conditions of individual features" (National Park Service 2016b, section 4.4.6, "Data Gaps/Research Needs/Management Recommendations"). Mapping by Richman (2010; scale 1:24,000), a GIP intern at Capulin Volcano National Monument, may serve as a model for detailed mapping of the volcanic features at the monument. The map by Richman (2010) included the following volcanic features: two boca ramparts, 16 lava cascades, 19 lava lakes, 15 lava levees, 18 lava ridges, one pooled lava flow, one push-up, two rafted cinder cones, 24 spatter deposits, one spatter flow, 23 squeeze-ups, and 18 tumuli (see GRI GIS report by KellerLynn 2015b). A similar project by a GIP or Mosaics in Science intern at Petroglyph National Monument may be possible. The list of volcanic features provided in this report could serve as a guide for individual features to be mapped (see "Volcanic Features and Terminology"). Also, a forthcoming map by the US Geological Survey, with dating by the New Mexico Bureau of Geology and Mineral Resources, will likely provide useful information and potentially an updated base map (see "Future Geologic Map").

According to the draft natural resource condition assessment for the monument, "nearly all of the park has been surveyed so the location of nearly all volcanic features is known, but confidence in the current conditions of most features is only moderate" (National Park Service 2016b, section 4.4.5, "Level of Confidence"). The draft natural resource condition assessment for the monument also states that "various maps and sources of information regarding the volcanic landscape are available, but need to be gathered, analyzed and annotated for use by park management" (National Park Service 2016b, section 4.4.6, "Data Gaps/Research Needs/Management Recommendations"). This research and data need could be accomplished as part of the aforementioned mapping project by a GIP or Mosaics in Science intern.

According to the draft natural resource condition assessment (National Park Service 2016b), volcanic resources are largely protected from landscape or climate-level (e.g., increasing intensity of storms due to climate change) impacts, however, they are at risk at very local scales from human impacts (e.g., trampling, vandalism, and theft). Along these same lines, the draft foundation document (National Park Service 2016a) noted that social trails and off-trail hiking have created visual impacts and damage to the volcanoes in the monument. Thus, similar to erosion (see "Erosion" and "Disturbed Lands"), the proliferation of social trails also is a concern for the preservation of volcanic features. Consequently, the visitor use management plan should consider volcanic features with respect to the placement of designated trails, either leading visitors to interesting features worthy of interpretation or avoiding sensitive features.

Implementation of the visitor use management plan could include a stay-on-the-trail program, using various methods to keep people on trails. Managers at the monument currently use post-and-cable fencing to delineate the edges of trails. Other methods include posting signs that inform monument visitors, building cairns with posts and reflective tape to mark trails across rocky areas, and providing literature that reminds visitors to tread lightly and informs them of the damage they can do to the surrounding rocks by going off trail (see GRI report for Craters of the Moon National Monument and Preserve by KellerLynn in review). Additionally, rangers could give resource protection messages during ranger-led walks and talks, and all visitors at the visitor center could receive a handout about staying on the trails. A stay-on-the-trail program would also be useful for erosion control (see "Erosion" and "Disturbed Lands").

Earthquakes and Faults

An earthquake is a sudden motion or trembling in the earth caused by the abrupt release of slowly accumulated strain. Earthquakes take place where rocks suddenly move along a fault. The US Geological Survey monitors earthquake activity in Albuquerque.

The Richter scale is commonly used to measure earthquake magnitude (strength of an earthquake/the strain energy released by it). Using seismograph oscillations, the scale provides a numeric expression. Destructive earthquakes typically have magnitudes between about 5.5 and 8.9. The scale is logarithmic and a difference of one represents an approximate thirtyfold difference in magnitude. Earthquake intensity is measured using the Modified Mercalli Intensity (MMI) scale—from MMI I (not felt/imperceptible by humans) to MMI XII (total damage/total destruction of developed areas and alteration of the landscape). The intensities are further described on the US Geological Survey website: https://earthquake.usgs.gov/learn/topics/mercalli.php. Earthquakes can directly damage park infrastructure or trigger other hazards such as rockfall, which may impact park resources, infrastructure, or visitor safety (see "Rockfall"). Earthquakes also may be a precursor to volcanic activity (see "Volcanic Hazards").

The rate of earthquake activity in New Mexico is characterized as moderate (Wong 2009). For example, 15 earthquakes of magnitude 4.0 and larger have occurred in the state since 1980 when seismographic coverage of the southwestern United States became uniform. This compares with 25 and 47 earthquakes in the neighboring states of Arizona and Utah, respectively. In contrast, 950 magnitude 4.0 and larger earthquakes have occurred in southern California since 1980 (Wong 2009).

An examination of the distribution of active faults in New Mexico shows them concentrated within the Rio Grande rift, particularly along its boundaries. According to Wong (2009), because of the large number of active faults in the Rio Grande rift, the probability of a future large earthquake (magnitude 6.5 or greater; capable of creating surface rupture and significant shaking and damage) in the rift is significant. Such events have occurred repeatedly over the past ~1 million years in the Albuquerque basin.

The GRI GIS data show 11 mapped fault segments within the monument (see poster, in pocket). These faults correspond to the USGS Quaternary fault and fold database (US Geological Survey 2017). The Zia fault zone crosses the northwestern corner of the monument. That fault zone and the County Dump fault, and East Paradise faults are the youngest in the monument with movement less than 128,000 years ago. All other fault segments in the monument are interpreted as having moved during the Middle Pleistocene Epoch, less than 750,000 years ago (Connell 2006). Because all of these faults moved during the Quaternary Period (the past 2.6 million years), they are considered likely sources of future earthquakes. All the faults in the monument and vicinity are normal faults that are oriented generally north–south.

Given that both the hazard (large earthquakes are possible) and risk (highly populated area) for earthquakes are relatively high in the Albuquerque area, the County Dump and East Paradise faults have been field studied and detailed reports were prepared (McCalpin et al. 2006; Personius and Mahan 2000). The most recent three earthquakes along the County Dump fault occurred about 30,000 years ago, between 40,000 and 45,000 years ago, and between 75,000 and 80,000 years ago (McCalpin et al. 2006). Vertical displacement during those earthquakes measured between 0.35 m (1.1 ft) and <3.5 m (11.5 ft) (McCalpin et al. 2006). There have been as many as 14 earthquakes in the past ~800,000 to 1.5 million years with average displacement of 1.2 m (3.9 ft) and estimated magnitudes are between 6.5 and 6.9 (McCalpin et al. 2006). Of the three most recent significant earthquakes on the East Paradise fault, two occurred within the past 75,000 years and the third quake about 200,000 years ago (Personius and Mahan 2000). Surface ruptures during those quakes measured between 0.5 m and 1.25 m (1.6 ft and 4.1 ft) with estimated magnitudes between 6.8 and 7.0 (Personius and Mahan 2000).

Earthquake hazards can be classified into two categories: (1) primary hazards include ground shaking, surface fault rupture (movement on a fault deep within the earth breaks through to the surface), and uplift or subsidence; (2) secondary hazards include liquefaction (a phenomenon in which the strength and stiffness of sediment or soil is reduced by earthquake shaking; liquefaction occurs in loosely packed, water-logged sediments at or near the ground surface), landslides (downslope movement of soil and rock material), and water waves such as tsunamis; these are either caused by strong ground shaking or, in the case of tsunamis, sudden uplift or subsidence.

In New Mexico, ground shaking, surface fault rupture, liquefaction, and earthquake-induced landslides are the most important hazards. Wong (2009) provided much of the following information:

- **Ground Shaking**. Strong ground shaking can take place throughout the state but will be concentrated within the Rio Grande rift because of the proximity to active faults and because of the amplifying effects of the alluvial sediments in the basins (e.g., Albuquerque basin) that make up the rift. Ground shaking from any large earthquake within the rift could be quite severe because of the presence of alluvial sediments that blanket the Rio Grande valley. These sediments can amplify the ground motions to very damaging levels. A large earthquake in the Rio Grande valley could result in significant damage and casualties, particularly as a result of the extensive use of unreinforced masonry (adobe) construction and the existence of many older structures. Movement along any fault in the Albuquerque basin would shake the monument. Projected shaking from a magnitude 6.9 on the County Dump fault (or other similar faults) would produce MMI VIII intensity within the monument and Albuquerque (fig. 21). This corresponds to "severe" shaking with the following description of damage: "Damage slight in specially designed structures; considerable damage in ordinary substantial buildings with partial collapse. Damage great in poorly built structures. Fall of chimneys, factory stacks, columns, monuments, walls. Heavy furniture overturned."
- **Surface Fault Rupture**. Surface faulting occurs when an earthquake ruptures the fault to Earth's surface. As a result, movement generated at depth along the fault is propagated upward, resulting in displacement of the ground surface. Any structure situated along an active fault is subject to damage not just from regional shaking but from direct rupture and movement of the ground upon which the structure is situated. Infrastructure on the eastern side of the monument, including the monument's visitor center, headquarters building, maintenance building, and entrance station, does not appear to have been built on faults (see poster, in pocket). The restroom at the Volcanoes area on the western side of the monument is in proximity of the County Dump and Zia faults; its exact location and the potential of an impact from surface rupture would need to be verified by a geologist in the field. With respect to the Star Heights fault zone, as mapped by Connell (2006) and shown in the GRI GIS data, it appears that the fault does not extend into the monument. However, based on US National Map Accuracy Standards and the source map scale of 1:50,000, geologic features represented in the GRI GIS data are expected to be horizontally within 25 m (82 ft) of their true locations. Thus, field verification by a geologist is recommended prior to significant infrastructure development. As noted above, surface ruptures have occurred repeatedly in the past along faults mapped near the monument. Displacements on the County Dump and East Paradise faults ranged from 0.35 m (1.1 ft) to <3.5 m (11.5 ft) (McCalpin et al. 2006; Personius and Mahan 2000).
- **Liquefaction**. The areas of most concern in New Mexico with respect to liquefaction are concentrated along the Rio Grande (river) due to the presence of a high water table and liquefiable soils.

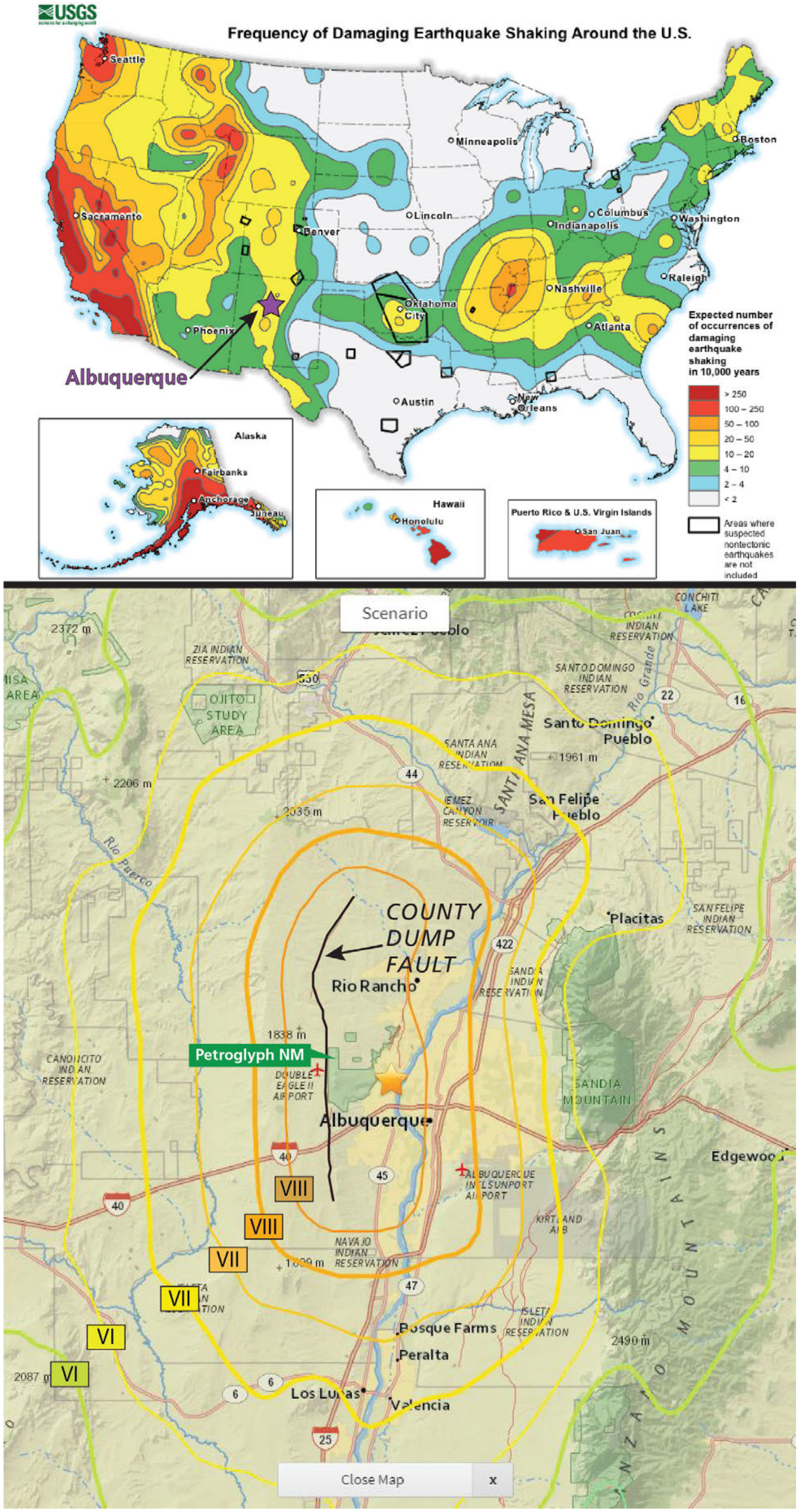

Figure 21. National earthquake probability map and local intensity map. The top map provides national context for the relative probability of earthquakes in the Rio Grande rift area of New Mexico. The yellow area, which surrounds Albuquerque corresponds to an expected 10 to 20 earthquakes with "damaging shaking" (MMI VI) over a 10,000 year period. This corresponds to between "1 in a thousand" and "1 in 500" probability of a damaging earthquake in any year. The bottom map shows projected shaking intensity using the Modified Mercalli Index (MMI) for a magnitude 6.9 earthquake on the County Dump fault. MMI values for Albuquerque and the monument could reach MMI VIII, or "severe" shaking. Earthquakes of those magnitude have occurred in the past along the County Dump and other local faults. National Seismic Hazard Map produced by the US Geological Survey in 2014, available at https://earthquake.usgs.gov/hazards/learn/. Local map is a screenshot of shaking intensity scenario map produced by the US Geological Survey, available at https://earthquake.usgs.gov/scenarios/eventpage/bssc20142038_m6p89_se#executive.

- **Earthquake-Induced Landslides.** Earthquake-induced landslides are triggered by strong ground shaking. The rugged topography with steep mountain slopes and canyon walls in the Rio Grande rift are conducive to landslides and rockfalls as evidenced by the non-earthquake-related failures documented throughout the state.

In the *Geological Monitoring* chapter about earthquakes and seismic activity, Braile (2009) described the following methods and vital signs: (1) monitoring earthquakes, (2) analysis and statistics of earthquake activity, (3) analysis of historical and prehistoric earthquake activity, (4) earthquake risk estimation, (5) geodetic monitoring and ground deformation, and (6) geomorphic and geologic indications of active tectonics. Refer to the USGS Earthquake Hazards website for information and planning tools (https://earthquake.usgs.gov/). Also contact the New Mexico Bureau of Geology and Mineral Resources for local concerns. With respect to earthquake-induced landslides, Wieczorek and Snyder (2009), Highland and Bobrowsky (2008), the USGS Landslide Hazard Program website (http://landslides.usgs.gov/), and the NPS Geologic Resources Division Geohazards (http://go.nps.gov/geohazards) and Slope Movement Monitoring (http://go.nps.gov/monitor_slopes) websites provide detailed information regarding slope movements, monitoring, and mitigation options.

Abandoned Mineral Lands

Abandoned mineral lands (AML) are lands, waters, and surrounding watersheds that contain facilities, structures, improvements, and disturbances associated with past mineral exploration, extraction, processing, and transportation, including oil and gas features and operations, for which the National Park Service takes action under various authorities to mitigate, reclaim, or restore in order to reduce hazards and impacts to resources.

Before establishment in 1990, mining took place in what is now Petroglyph National Monument. One of the cones, named Cinder Volcano, which was south of JA Volcano and had been part of the prominent "Sisters" segment of cones, was mined out of existence. Cinders from this cone and three other quarries in the monument—one on the flank of Vulcan Volcano, one of the flank of Black Volcano, and one in a lava flow south of JA Volcano—were mined for railroad bed material, cinder blocks, and landscaping material (Kelley 2010).

The three abandoned cinder quarries visually impacted the cultural landscape of the monument and presented visitor safety hazards (Greco 2004). These quarries were mined as recently as the mid-1980s.

The NPS Abandoned Mineral Lands (AML) database and Burghardt et al. (2014) list the three quarries in the monument. The AML database includes data points and a location map of these quarries. Two of these sites were mitigated in 2002 by the US Army Corps of Engineers Rapid Response Group in collaboration with the National Park Service, using funding provided by the NPS AML Program. According to Greco (2004), one of the reclaimed sites is on the southeastern corner of Vulcan Volcano; the other is immediately south of the volcano (on the flank of Black Volcano, as described above). The larger of the two quarries (the one on the flank of Black Volcano), which contained a 18-m- (60-ft-) high headwall, posed the greatest safety hazard, and was the most aesthetically displeasing; it received the bulk of the efforts during the week-long "rapid response" reclamation period.

One, high-priority site still requires mitigation (Burghardt et al. 2014). This site is in a lava flow south of JA Volcano. Monument managers are encouraged to contact the Geologic Resources Division for further assistance. The NPS AML website, http://go.nps.gov/aml, provides information for understanding AML, reclamation, and restoration. An online AML handbook is available at https://www.nps.gov/subjects/abandonedminerallands/aml-handbook.htm.

Cave Resource Management

The nature of volcanism at the monument was not conducive for the creation of large lava tubes like those at Lava Beds National Monument (see GRI report by KellerLynn 2014b) or Craters of the Moon National Monument (see GRI report by KellerLynn in review), but small ones (too small to enter; see Kelley 2010) are known to occur within the monument's boundaries. The Federal Cave Resources Protection Act of 1988, defines a cave as "any naturally occurring void, cavity, recess, or system of interconnected passageways beneath the surface of the earth…and which is large enough to permit an individual to enter."

Although the lava tubes in the monument are too small to fit the definition of a cave, other caves, for example some formed in welded spatter, do occur within the monument. The Federal Cave Resources Protection Act of 1988 (FCRPA) and its subsequent regulations published in 1991 provides guidance for the Departments of Interior and Agriculture concerning the identification and planning efforts for "significant caves." For the National Park Service, the regulations stipulate that all caves on NPS properties are "significant." This act requires that caves be considered in any land management planning and their use be regulated or restricted as needed to protect cave resources. The act also imposes penalties for harming a cave or cave resources and exempts park managers from releasing specific location information for significant caves in response to a FOIA request (see also Appendix B). Other laws, such as the Archeological Resources Protection Act, also provide managers with tools to protect specific resources found within caves (and on the surface) by exempting their nature and location from FOIA requests.

Managers have documentation, including physical surveys and maps and an inventory of in-cave resources, on all the caves in the monument. Additionally, an archeological inventory has been completed for approximately 95% of the monument. During that inventory, no new caves were discovered. With this information available, monument managers feel that they have all the information they need to adequately manage the monument's caves. However, monument managers could use some assistance with planning the locations of roads and trails with respect to cave resources. Monument managers need information identifying areas of potential collapse or areas that need to be avoided in order to protect cave resources (National Park Service 2006).

The NPS Cave and Karst Program provides assistance with (1) protection for natural processes in cave ecosystems and karst landscapes, (2) scientific studies and research in or about cave and karst resources and systems, (3) cartographic surveys and inventories of cave systems, (4) educational and recreational opportunities, (5) development of guidelines to maximize cave protection and management, (6) monitoring of natural environmental conditions and visitor use impact, and (7) methods for sustainable use of cave resources. In addition, consideration of the vital signs outlined in the *Geological Monitoring* chapter about caves and associated landscapes (Toomey 2009) may be useful for monument managers in developing a cave management plan.

Paleontological Resource Inventory, Monitoring, and Protection

Elsewhere in New Mexico, the Santa Fe Group has yielded a remarkable faunal assemblage of terrestrial vertebrate fossils, including camels, horses, antelopes, rhinoceroses, elephants, and rodents (Bauer et al. 2003). Fossils specific to the Ceja Formation include petrified wood, invertebrate trace fossils (such as tracks, trails, or burrows that preserves evidence of an organism's life, rather than the organism itself), turtles, birds, rodents, rabbits, equids, camelids, and deer.

Within the monument, pieces of Triassic petrified wood have been discovered within the Ceja Formation (**Tcrg**). The discovery of these much-older fossils in Pliocene–Pleistocene river deposits suggests that the pieces of petrified wood were "reworked," meaning they were eroded out of Triassic sediments by Pliocene–Pleistocene streams, transported, and subsequently deposited along with the Ceja Formation sediments (Tweet et al. 2009).

Fossils have yet to be documented from the following rock units within the monument, but they are known to preserve fossils elsewhere. Thus, future field investigations within the monument may recover fossils from one or more of these units.

- **Lomatas Negras Formation** (**Qrl**), Middle Pleistocene, may yield mammal fossils younger than about 640,000 years old, including ground sloths, equids, camels, and llamas.
- **Lava tubes may contain Quaternary flora** (e.g., twigs, charcoal, and wood) and fauna (e.g., bones of bats, bighorn sheep, and deer), as well as packrat middens ("dens" containing collections of plant material, food waste, coprolites [dung], bones, and other biological materials) that document the environment within the builder's foraging range. Middens can be well-preserved in arid, protected settings such as caves, rock shelters, and lava tubes. They are important tools for reconstructing the paleoecology and climate of the Late Pleistocene and Holocene Epochs of western North America (Santucci et al. 2001).
- **Los Duranes Formation** (**Qrd**), Middle Pleistocene, may yield mammal fossils between about 156,000 and 98,000 years old, including ground sloths, bears, equids, camels, llamas, bison, and mastodons.

- **Quaternary sedimentary rocks and deposits** (**Qam, Qca, Qe, Qay,** and **Qrpm**), Middle Pleistocene–Holocene, may yield similar, though younger, fossils to the Lomatas Negras and Los Duranes Formations.

The monument's museum collections also contain fossils, primarily petrified wood. Prehistoric people probably brought these pieces from elsewhere, though petrified wood is commonly found in the arroyos in the area. Artifacts may also be paleontological resources, for example, those consisting of petrified wood, chert, and chalcedony. Kenworthy and Santucci (2006) presented an overview and cited selected examples of NPS fossils found in cultural resource contexts.

A paleontological resource inventory and monitoring report for the Southern Colorado Plateau Network (Tweet et al. 2009) provided recommendations for resource management of paleontological resources at the monument. In the *Geological Monitoring* chapter about paleontological resources, Santucci et al. (2009) 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.

Volcanic Hazards

Limburg (1990) estimated that New Mexico has had more than 700 volcanic events (single eruption or a series of associated eruptions from a vent) during the past 5 million years. The eruptive styles ranged from dangerously explosive (e.g., Valles Caldera) to passive (e.g., Albuquerque volcanoes). Many National Park System units (and associated GRI reports) in New Mexico highlight volcanic eruptions, from most to least explosive: Gila Cliff Dwellings National Monument (KellerLynn 2014a), Bandelier National Monument (KellerLynn 2015a), Capulin Volcano National Monument (KellerLynn 2015b), 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.

The area around Albuquerque has the potential for future volcanic activity because of its location in the Rio Grande rift. Small volcanoes (e.g., cinder cones and spatter cones), such as those in the Albuquerque volcanic field, do not typically reactivate like big volcanoes (e.g., stratovolcanoes), so renewed activity in the Albuquerque volcanic field would likely take place at a new vent somewhere in the Rio Grande rift (New Mexico Museum of Natural History and Science 2017). Determining the exact location of a future vent is virtually impossible, however (Matt Zimmerer, New Mexico Bureau of Geology and Mineral Resources, field geologist, written communication, 30 August 2017).

A draft NPS volcanic resources/hazard inventory by Walkup (2013) identified the following volcanic hazards for the monument:

- **Ash and Tephra Fall**. Small, basaltic eruptions are likely to have relatively small amounts of ash associated with them, but even minor volumes of airborne ash can create hazards with respect to air quality and air travel. If a future eruption were to produce ash, it would likely cause major disruptions to air traffic in the immediate area and possibly for larger regions throughout the southwestern United States. The weight of ash may cause buildings and power lines to collapse. Ash is abrasive; also, it is very slippery when wet. Fine ash can cause respiratory issues and is extremely irritating to the eyes. Tephra (a collective term used for all pyroclastic material, regardless of size, shape, or origin, ejected into the air during a volcanic eruption) fall is a significant threat to human safety and infrastructure adjacent to an erupting vent (see Volcanic Projectiles [bullet point] below).
- **Earthquakes**. In the event of an eruption, localized earthquakes would be expected to take place as a result of magma moving through the subsurface. New Mexico Museum of Natural History and Science (2017) noted that one of the larger earthquake swarms in New Mexico occurred in 1972 beneath the Albuquerque volcanoes; however, evidence does not indicate that new magma was moving upward. Instead, the earthquake swarm may have been caused by readjustment of dikes (former sites of magma intrusion) and faults at great depth as the deeper portions of the dikes continued to cool and contract.
- **Gas**. Magmatic events are often preempted by outgassing, as a result of a decrease in confining pressure when rising magma nears the surface. Volatiles (substances given off as gas when heated)

are lighter than the magma and can travel through porous rocks and thus reach the surface prior to eruption. Because carbon dioxide (CO_2) is heavier than air, it can pool in surface depressions, which can kill animals or humans in the area. Excess CO_2 gas in soils can kill trees and other plants, producing dead zones. Other gases, such as sulfur dioxide (SO_2), hydrogen sulfide (H_2S), and water vapor, also may be present and can affect air quality.

- **Lava Eruptions**. The Albuquerque volcanic field has erupted basaltic lava in the past and could do so again. Lava flows will threaten roads, buildings, and other infrastructure in their path. Also, lava could ignite structural fires and wildfires. Because basalt is fluid and gas-poor, basalt flows are commonly considered to be "slow moving" (i.e., humans can outrun them); however, some flows, especially where they are channelized, can reach speeds of 100 kph (60 mph).
- **Volcanic Projectiles**. Volcanic projectiles ranging from lapilli to large volcanic bombs (up to several meters in diameters) would be a significant hazard in areas adjacent to a vent. They are a localized hazard, but very large rocks can be thrown out if the eruption has sufficient power. Even small rock fragments can be lethal and cause injury within about 5 km (3 mi) of the erupting vent.

Resource managers many find the following *Geological Monitoring* vital signs of interest and use at the monument: (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 (Smith et al. 2009). See also the "Resources" at the end of this report. No active volcano monitoring is occurring within the monument, but seismometers are in the vicinity. The Yellowstone Volcano Observatory monitors volcanic activity in New Mexico (see https://volcanoes.usgs.gov/observatories/yvo/).

Geologic Map Data

A geologic map in GIS format is the principal deliverable of the GRI. 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 1:50,000-scale data (from the source map by Connell 2006) 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. Map unit symbols consist of an uppercase letter indicating the age (fig. 4) and lowercase letters indicating the formation's name. Other map 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 generally one of two types: surficial or bedrock. Surficial geologic maps typically depict deposits that are unconsolidated and formed during the past 2.6 million years (Quaternary Period). Surficial map units are differentiated by geologic process or depositional environment. Bedrock geologic maps show older, typically more consolidated sedimentary, metamorphic, and/or igneous rocks. Bedrock map units are differentiated based on age and/or rock type. The GRI GIS data for the monument consist of two data sets, both of which contain surficial and bedrock map units.

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. GRI GIS data include 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 the petr_geology.hlp file.

The GRI team used two source maps to produce the GRI GIS data for the monument:

- Connell (2006; scale 1:50,000) was compiled into the GRI GIS data set petr_geology.mxd. This data set includes the Volcano Ranch, Los Griegos, Albuquerque West, and La Mesita Negra SE quadrangles, and covers the entire monument.
- Shroba et al. (2003; scale 1:24,000) was compiled into the GRI GIS data set mnse_geology.mxd. This data set covers the southwest area of the monument within the La Mesita Negra SE quadrangle.

These source maps provided information for this report. Because it covers the entire monument, the primary source map used in writing this report was Connell (2006).

GRI GIS Data

The GRI team standardizes map deliverables by using a data model. The GRI GIS data for the monument was compiled using data model version 1.4, which is available at http://go.nps.gov/gridatamodel. This data model dictates GIS data structure, including layer architecture, feature attribution, and relationships within ESRI ArcGIS software. The GRI Geologic Maps website, http://go.nps.gov/geomaps, provides more information about the program's map products.

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

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

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

Table 4. GRI GIS data layers for petr_geology.mxd (Connell 2006; scale 1:50,000).

Data Layer	On Poster?
Cross Section Lines	No
Geologic Attitude and Observation Points	No
Geologic Sample Localities	No
Mine Point Features	No
Volcanic Point Features	Yes
Geologic Line Features	Yes
Fault and Fold Symbology	Yes
Folds	Yes
Faults	Yes
Buried Igneous Body Boundaries	No
Buried Igneous Bodies	No
Surficial Contacts	No
Surficial Geologic Units	No
Geologic Contacts	Yes
Geologic Units	Yes

Table 5. GRI GIS data layers for mnse_geology.mxd (Shroba et al. 2003; scale 1:24,000).

Data Layer	On Poster?
Geologic Attitude and Observation Points	No
Geologic Measurement Localities	No
Mine Point Features	No
Fault Symbology	No
Faults	No
Surficial Contacts	No
Surficial Units	No
Geologic Contacts	No
Geologic Units	No

GRI Map Posters

PA poster of the GRI GIS data set (petr_geology.mxd) draped over a shaded relief image of the monument and surrounding area is included with this report. Not all GIS feature classes are included on the poster (see table 4). 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. Monument managers may contact the GRI team for assistance locating these data.

Use Constraints

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

Minor inaccuracies may exist with respect to the locations of geologic features relative to other geologic or geographic features in the GRI GIS data and on the poster. Based on US National Map Accuracy Standards and the source map scales of 1:50,000 (petr_geology.mxd) and 1:24,000 (mnse_geology.mxd), geologic features represented in the geologic map data and poster are expected to be horizontally within 25 m (82 ft) or 12 m (40 ft) of their true locations, respectively.

Future Geologic Map

The US Geological Survey is working on a new geologic map that will cover the monument boundary plus a buffer zone that includes all of the volcanic deposits and possibly as far east as the Rio Grande. The New Mexico Bureau of Geology conducted isotopic dating of the lava flows for this forthcoming map. A preliminary version of the map was presented at the Geological Society of America's Annual Meeting in 2016 (see Chan et al. 2016). The map will probably be produced at a scale of 1:24,000, thus providing greater detail than Connell (2006; scale 1:50,000). The map is based on new LiDAR data, so the geologic line work has been significantly revised from previous maps. The intention is that the map will serve as a planning tool for monument staff. The map unit descriptions will be intentionally brief, however (Ren Thompson, US Geological Survey, geologist, email communication to Tim Connors, NPS Geologic Resources Division, 25 April 2017). Contact GRI to submit this map as a potential "inventories 2.0" project.

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Resources

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

Arroyos in New Mexico

"What Decision Makers Should Know about Arroyos in New Mexico": https://geoinfo.nmt.edu/geoscience/hazards/erosion/home.html.

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Climate Change

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/

Earthquakes in New Mexico

New Mexico Bureau of Geology and Mineral Resources, earthquake education and resources: http://tremor.nmt.edu

US Geological Survey, earthquake information about New Mexico: https://earthquake.usgs.gov/earthquakes/byregion/newmexico.php

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Geology of National Park Service Areas

NPS Geologic Resources Division—Energy and Minerals, Active Processes and Hazards, and Geologic Heritage: http://go.nps.gov/geology

NPS Geologic Resources Division Education website: http://go.nps.gov/geoeducation

NPS Geologic Resources Inventory: http://go.nps.gov/gri

NPS Geoscientists-In-the-Parks (GIP) internship and guest scientist program: http://go.nps.gov/gip

NPS Views (geology-themed modules for Geologic Time, Paleontology, Glaciers, Caves and Karst, Coastal Geology, Volcanoes, and a variety of geologic parks): http://go.nps.gov/views

USGS geology online books index (categorized by park name): https://www.nps.gov/parkhistory/online_books/geology/books-geology.htm

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Geological Surveys and Societies

New Mexico Bureau of Geology and Mineral Resources: https://geoinfo.nmt.edu/

New Mexico Geological Society, Fall Field Conference Guidebooks: https://nmgs.nmt.edu/publications/guidebooks/home.cfml?ListBy=Number

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/

NPS Resource Management Guidance and Documents

Management Policies 2006 (Chapter 4: natural resource management): http://www.nps.gov/policy/mp/policies.html

1998 National Parks Omnibus Management Act: http://www.gpo.gov/fdsys/pkg/PLAW-105publ391/pdf/PLAW-105publ391.pdf

NPS-75 (natural resource inventory and monitoring guideline): http://www.nature.nps.gov/nps75/nps75.pdf

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NPS Technical Information Center (TIC) (Denver, Colorado; repository for technical documents): http://etic.nps.gov/

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

USGS 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 (downloadable PDFs of any topographic map in the United States): http://store.usgs.gov (click on "Find Map")

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/

Volcanic Hazards in New Mexico

New Mexico Bureau of Geology and Mineral Resources, FAQ page about volcanism: https://geoinfo.nmt.edu/faq/volcanoes/home.html.

New Mexico Museum of Natural History and Science, information about the Albuquerque Volcanoes: http://www.nmnaturalhistory.org/volcanoes/albuquerque-basin-volcanic-field.

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Appendix A: Scoping Participants

The following people attended the GRI scoping meeting, held on 29 March 2006, or participated in a follow-up conference call, held on 25 April 2017. Discussions during this meeting and call supplied a foundation for this GRI report. The scoping summary document is available on the GRI publications website: http://go.nps.gov/gripubs.

2006 Scoping Meeting Participants

Name	Affiliation	Position
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

2017 Conference Call Participants

Name	Affiliation	Position
Tim Connors	NPS Geologic Resources Division	Geologist
Katie KellerLynn	Colorado State University	Geologist/research associate
Shari Kelley	New Mexico Bureau of Geology and Mineral Resources	Geologist
Jason Kenworthy	NPS Geologic Resources Division	Geologist/GRI reports coordinator
Dale Kissner	Petroglyph National Monument	Chief ranger/chief of resources
Dale Pate	NPS Geologic Resources Division	Cave and Karst Program lead
Chanteil Walter	Petroglyph National Monument	Environmental protection specialist
Matt Zimmerer	New Mexico Bureau of Geology and Mineral Resources	Geologist

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 July 2017. Contact the NPS Geologic Resources Division for detailed guidance.

Resource	Resource-specific Laws	Resource-specific Regulations	2006 Management Policies
Paleontology	**National Parks Omnibus Management Act of 1998, 16 USC § 5937** 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. DOI regulations in association with 2009 PRPA are being finalized (July 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.
Rocks and Minerals	**NPS Organic Act, 16 USC § 1 et seq.** directs the NPS to conserve all resources in parks (including rock and mineral resources), unless otherwise authorized by law.	**36 CFR § 2.1** prohibits possessing, destroying, disturbing mineral resources… in park units. **Exception: 36 CFR § 13.35** allows some surface collection of rocks and minerals in some Alaska parks (not Klondike Gold Rush, Sitka, Denali, Glacier Bay, or 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.
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.	None applicable.	**Section 9.1.3.3** clarifies that only the NPS or its agent can extract park-owned common variety minerals (e.g., sand and gravel), and: -only for park administrative uses; -after compliance with NEPA and other federal, state, and local laws, and a finding of non-impairment; -after finding the use is park's most reasonable alternative based on environment and economics; -parks should use existing pits and create new pits only in accordance with park-wide borrow management plan; -spoil areas must comply with Part 6 standards; and -NPS must evaluate use of external quarries. Any deviation from this policy requires a written waiver from the Secretary, Assistant Secretary, or Director.

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

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

Resource	Resource-specific Laws	Resource-specific Regulations	2006 Management Policies
Caves and Karst Systems	**Federal Cave Resources Protection Act of 1988, 16 USC §§ 4301 – 4309** requires Interior/Agriculture to identify "significant caves" on Federal lands, regulate/ restrict use of those caves as appropriate, and include significant caves in land management planning efforts. Imposes civil and criminal penalties for harming a cave or cave resources. Authorizes Secretaries to withhold information about specific location of a significant cave from a Freedom of Information Act (FOIA) requester. **National Parks Omnibus Management Act of 1998, 54 USC § 100701** protects the confidentiality of the nature and specific location of cave and karst resources. **Lechuguilla Cave Protection Act of 1993, Public Law 103-169** created a cave protection zone (CPZ) around Lechuguilla Cave in Carlsbad Caverns National Park. Within the CPZ, access and the removal of cave resources may be limited or prohibited; existing leases may be cancelled with appropriate compensation; and lands are withdrawn from mineral entry.	**36 CFR § 2.1** prohibits possessing/ destroying/disturbing…cave resources…in park units. **43 CFR Part 37** states that all NPS caves are "significant" and sets forth procedures for determining/releasing confidential information about specific cave locations to a FOIA requester.	**Section 4.8.1.2** requires NPS to maintain karst integrity, minimize impacts. **Section 4.8.2** requires NPS to protect geologic features from adverse effects of human activity. **Section 4.8.2.2** requires NPS to protect caves, allow new development in or on caves if it will not impact cave environment, and to remove existing developments if they impair caves. **Section 6.3.11.2** explains how to manage caves in/adjacent to wilderness.

NPS 354/140570, November 2017

National Park Service
U.S. Department of the Interior

Natural Resource Stewardship and Science
1201 Oak Ridge Drive, Suite 150
Fort Collins, Colorado 80525

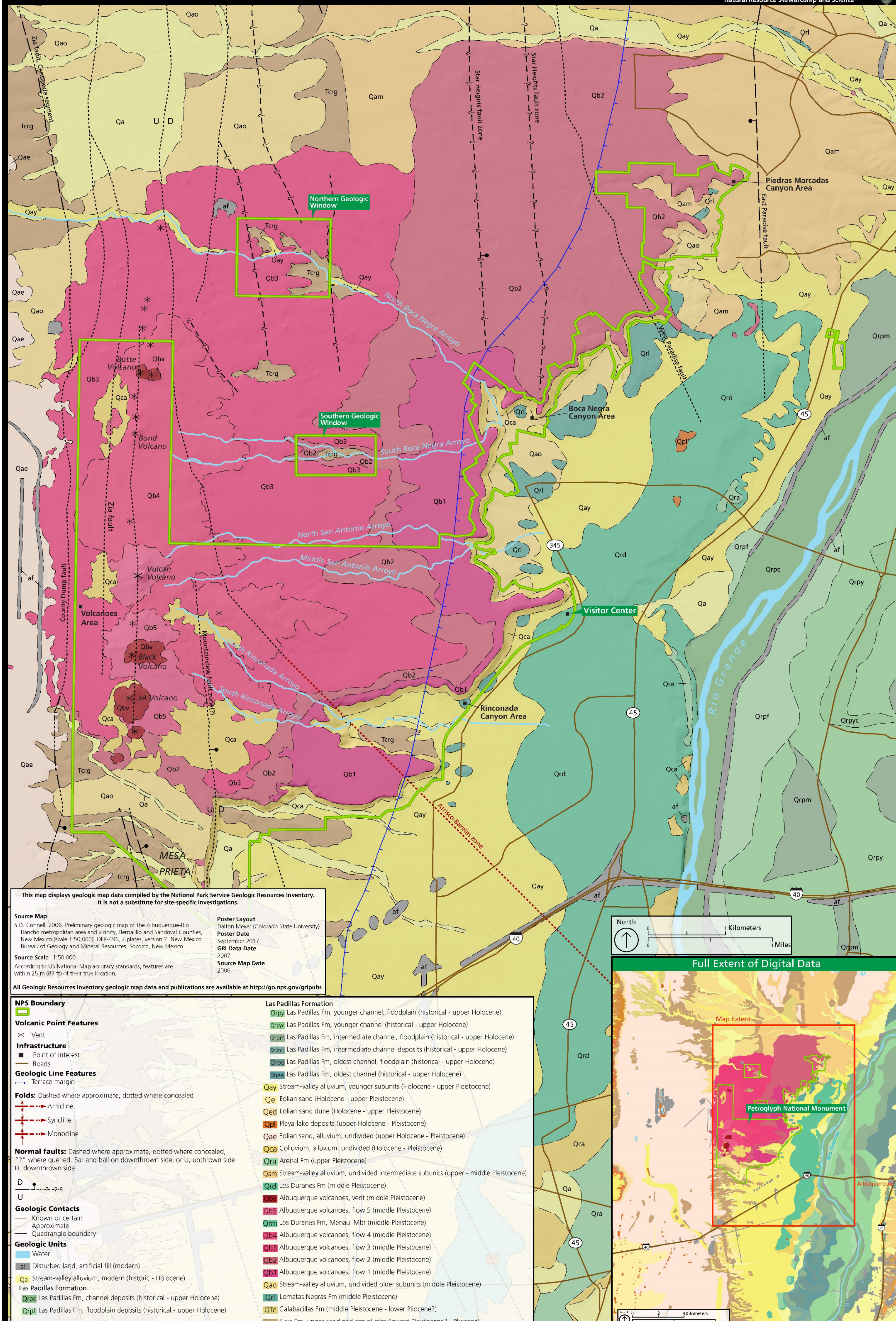
www.nature.nps.gov

Geologic Map of Petroglyph National Monument

New Mexico

National Park Service
U.S. Department of the Interior

Geologic Resources Inventory
Natural Resource Stewardship and Science



This map displays geologic map data compiled by the National Park Service Geologic Resources Inventory. It is not a substitute for site-specific investigations.

Source Map

S.D. Connell. 2006. Preliminary geologic map of the Albuquerque-Rio Rancho metropolitan area and vicinity, Bernalillo and Sandoval Counties, New Mexico (scale 1:50,000). OFR-496, 2 plates, version 2. New Mexico Bureau of Geology and Mineral Resources, Socorro, New Mexico.

Source Scale 1:50,000

According to US National Map accuracy standards, features are within 25 m (83 ft) of their true location.

Poster Layout
Dalton Meyer (Colorado State University)
Poster Date
September 2017
GRI Data Date
2007
Source Map Date
2006

All Geologic Resources Inventory geologic map data and publications are available at http://go.nps.gov/gripubs

NPS Boundary

Volcanic Point Features
- Vent

Infrastructure
- Point of interest
- Roads

Geologic Line Features
- Terrace margin

Folds: Dashed where approximate, dotted where concealed
- Anticline
- Syncline
- Monocline

Normal faults: Dashed where approximate, dotted where concealed, "?" where queried. Bar and ball on downthrown side, or U, upthrown side D, downthrown side.

D
U

Geologic Contacts
- Known or certain
- Approximate
- Quadrangle boundary

Geologic Units
- Water
- af Disturbed land, artificial fill (modern)
- Qa Stream-valley alluvium, modern (historic - Holocene)

Las Padillas Formation
- Qrpc Las Padillas Fm, channel deposits (historical - upper Holocene)
- Qrpf Las Padillas Fm, floodplain deposits (historical - upper Holocene)

Las Padillas Formation
- Qrpy Las Padillas Fm, younger channel, floodplain (historical - upper Holocene)
- Qrpyc Las Padillas Fm, younger channel (historical - upper Holocene)
- Qrpm Las Padillas Fm, intermediate channel, floodplain (historical - upper Holocene)
- Qrpmc Las Padillas Fm, intermediate channel deposits (historical - upper Holocene)
- Qrpo Las Padillas Fm, oldest channel, floodplain (historical - upper Holocene)
- Qrpoc Las Padillas Fm, oldest channel (historical - upper Holocene)

- Qay Stream-valley alluvium, younger subunits (Holocene - upper Pleistocene)
- Qe Eolian sand (Holocene - upper Pleistocene)
- Qed Eolian sand dune (Holocene - upper Pleistocene)
- Qpl Playa-lake deposits (upper Holocene - Pleistocene)
- Qae Eolian sand, alluvium, undivided (upper Holocene - Pleistocene)
- Qca Colluvium, alluvium, undivided (Holocene - Pleistocene)
- Qra Arenal Fm (upper Pleistocene)
- Qam Stream-valley alluvium, undivided intermediate subunits (upper - middle Pleistocene)
- Qrd Los Duranes Fm (middle Pleistocene)
- Qbv Albuquerque volcanoes, vent (middle Pleistocene)
- Qb5 Albuquerque volcanoes, flow 5 (middle Pleistocene)
- Qrm Los Duranes Fm, Menaul Mbr (middle Pleistocene)
- Qb4 Albuquerque volcanoes, flow 4 (middle Pleistocene)
- Qb3 Albuquerque volcanoes, flow 3 (middle Pleistocene)
- Qb2 Albuquerque volcanoes, flow 2 (middle Pleistocene)
- Qb1 Albuquerque volcanoes, flow 1 (middle Pleistocene)
- Qao Stream-valley alluvium, undivided older subunits (middle Pleistocene)
- Qrl Lomatas Negras Fm (middle Pleistocene)
- QTc Calabacillas Fm (middle Pleistocene - lower Pliocene?)
- Tcrg Ceja Fm, upper sand and gravel mbr (lowest Pleistocene? - Pliocene)