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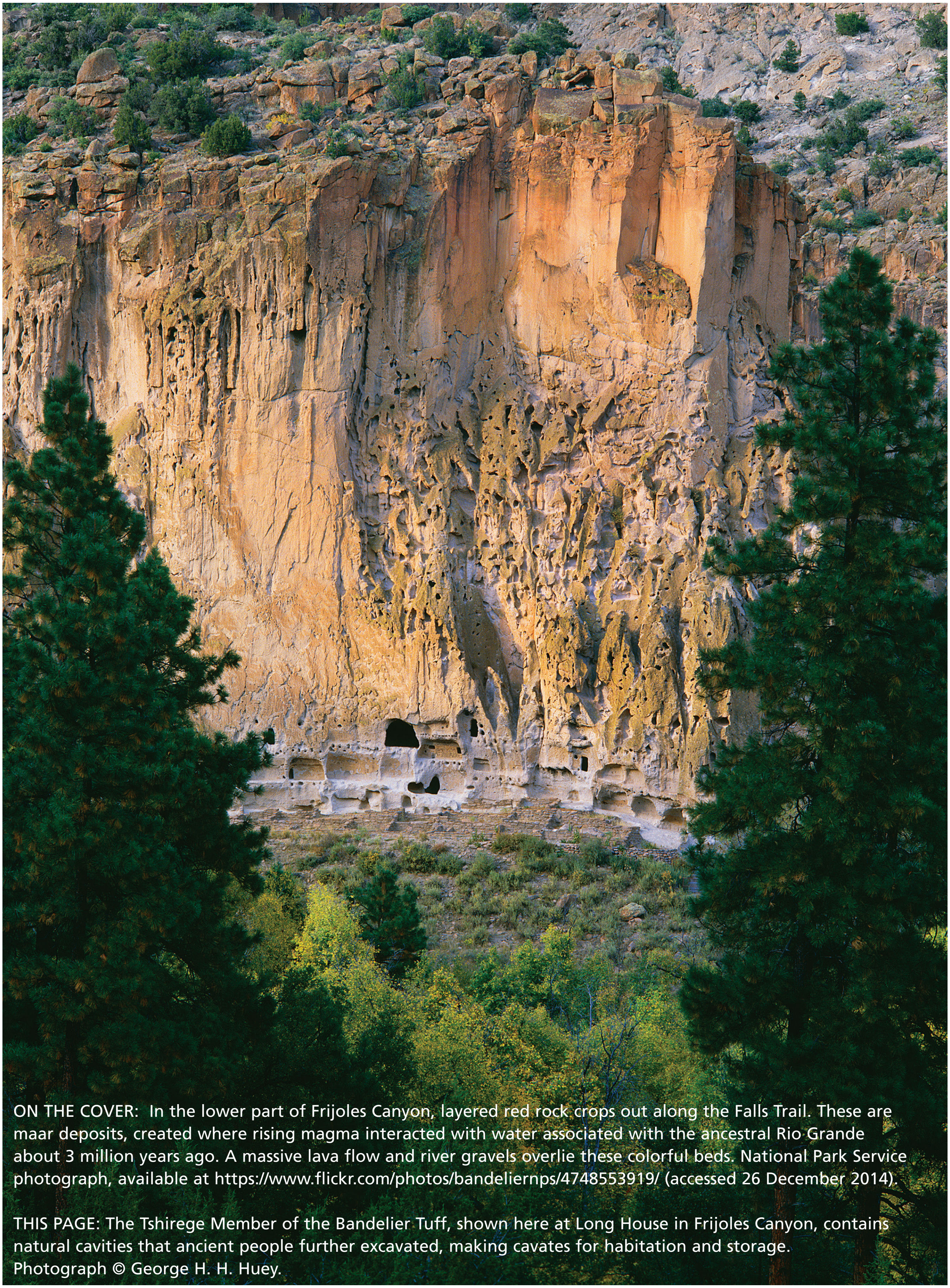
Natural Resource Stewardship and Science

Bandelier National Monument

Geologic Resources Inventory Report

Natural Resource Report NPS/NRSS/GRD/NRR—2015/1036



ON THE COVER: In the lower part of Frijoles Canyon, layered red rock crops out along the Falls Trail. These are maar deposits, created where rising magma interacted with water associated with the ancestral Rio Grande about 3 million years ago. A massive lava flow and river gravels overlie these colorful beds. National Park Service photograph, available at https://www.flickr.com/photos/bandeliernps/4748553919/ (accessed 26 December 2014).

THIS PAGE: The Tshirege Member of the Bandelier Tuff, shown here at Long House in Frijoles Canyon, contains natural cavities that ancient people further excavated, making cavates for habitation and storage. Photograph © George H. H. Huey.

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

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Executive Summary

The Geologic Resources Inventory (GRI) 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 for Bandelier National Monument (New Mexico) on 13–14 July 2005 and a follow-up conference call on 3 July 2014, which were held by the Geologic Resources Division to identify geologic resources of significance and geologic resource management issues, as well as determine the status of geologic mapping. It is a companion document to previously completed GRI GIS data.

Bandelier National Monument is a physiographic meeting place, incorporating major features of the Jemez Mountains volcanic field, Rio Grande rift, Cerros del Rio volcanic field, and Rio Grande (river) in an environment where human beings have acted as a central organism. Bandelier National Monument is situated in the Jemez Mountains volcanic field, where bowl-like Valles caldera takes center stage in location and importance. It is the world's premier example of a resurgent caldera—a giant circular volcano with an uplifted central floor. The name "Valles" reflects the many spectacular valleys within the caldera; Valle Grande is the largest.

The Rio Grande rift is also of physiographic significance for the monument. A series of nine basins, including the Española basin, make up the rift that is characterized by east–west crustal extension, forming grabens (fault-bounded basins) that drop down along normal faults as Earth's crust pulls apart. Bandelier National Monument is on the western side of the Española basin. The Pajarito fault zone, which is composed of normal faults and runs through the monument, bounds the Española basin.

As a consequence of extension, Earth's crust thinned within the Rio Grande rift, allowing heat from Earth's mantle to reach the surface. Volcanism in the monument and vicinity occurred in connection with the development of the rift. For example, basaltic to dacitic lava erupted from vents in the Cerros del Rio volcanic field, which is at the edge of the Española basin. Frijoles and other canyons in the monument preserve evidence of this volcanic activity peripheral to the Jemez Mountains volcanic field.

The monument is east of the 24-km- (15-mi-) wide Valles caldera on the eastward–sloping Pajarito Plateau, which is cut by many canyons. Canyons that cross the monument are—from north to south—Chaquehui, Frijoles, Lummis, Alamo, Capulin, Medio, and Sanchez. These canyons are tributaries to the Rio Grande, which flows through White Rock Canyon along the southwestern edge of the monument. The river cut this steep-walled canyon, though notably, the river itself did not excavate the Rio Grande rift. Rather, the river follows a topographically lowest path within the rift. Its precursor, the ancestral Rio Grande, helped to fill the Española basin with sediment that the modern Rio Grande now erodes.

This GRI report was written for resource managers to support science-informed decision making, but it may also be useful for interpretation. Report preparation used available geologic information, and the NPS Geologic Resources Division did not conduct any new fieldwork in association with this report. Sections of the report discuss distinctive geologic features and processes at Bandelier National Monument, highlight geologic issues facing resource managers, describe the geologic history leading to the present-day landscape, and provide information about the GRI GIS data set. A poster (in pocket) illustrates these data. The Map Unit Properties Table (in pocket) summarizes report content for each geologic map unit within the monument.

The geologic features and processes of primary interest at Bandelier National Monument include the following:

- **Volcanic Rocks and Volcanoes**. Volcanic rocks include basalt, andesite, dacite, and rhyolite, with increasing amounts of silica, from less than 52% to more than 72%. The percentage of silica influences many properties of magma, including viscosity and explosiveness, which in turn influences the type of volcano these magmas produce. The volcano that created the landscape of Bandelier National Monument was rhyolitic, which is generally the most explosive type in the world.

- **Jemez Mountains Volcanic Field**. Bandelier National Monument is on the eastern flank of the Jemez Mountains, where volcanism began about 14 million years ago. The Valles and Toledo calderas are notable features of the field. The field contains volcanic rocks with a wide range of chemical compositions and eruption styles. The rocks of the Jemez Mountains volcanic field are divided into two major groups—Keres and Tewa. The Keres Group covers the pre-caldera part of the volcanic field and formed about 14 million to 1.8 million years ago. The Tewa Group covers the Toledo and Valles caldera complex, which developed from about 1.85 million to 40,000 years.
- **Bandelier Tuff**. The eruptions that created the Toledo and Valles calderas are the most dramatic volcanic events to have occurred in New Mexico in the recent geologic past (Quaternary Period or the last 2.6 million years of geologic time). These events deposited two members of Bandelier Tuff. The Otowi Member (map unit **Qbo**) formed during collapse of the Toledo caldera about 1.61 million years ago. The Tshirege Member (**Qbt**) formed during the collapse of the Valles caldera about 1.25 million years ago. Before eruption of the Otowi Member, leakage from the Bandelier magma chamber extruded the La Cueva Member about 1.85 million years ago. The La Cueva Member is not included in the GRI GIS data. During each caldera-forming eruption, rhyolitic magma blasted into the air, spreading ash across the landscape. Then, as the eruption column collapsed, pyroclastic flows sped away from the subsiding calderas.
- **Features in Bandelier Tuff**. Layers of Bandelier Tuff are beautifully exposed in the canyon walls of the monument. The tuff hosts many features, some of which have cultural significance, including cavates (hollowed-out chambers by ancestral Puebloans) and an ancient trail system that is still used today. Conical, teepee-shaped landforms, locally called "tent rocks," occur in all three members of Bandelier Tuff.
- **Rio Grande Rift**. In the western part of Bandelier National Monument, the Bandelier Tuff is cut by the Pajarito fault zone, which delineates the active western margin of the Rio Grande rift. In Frijoles Canyon, the 1.25-million-year-old Tshirege Member is displaced about 145 m (480 ft) along the fault zone, creating a notable escarpment. Rocks of the Santa Fe Group fill the rift.
- **Cerros del Rio Volcanic Rocks**. Cerros del Rio volcanic rocks (**QTcrv**), which are mostly basaltic, are well exposed in Bandelier National Monument. Particularly fine examples of a cinder cone, maar volcano (generated from the interaction of rising magma with water near Earth's surface), and resistant lava flows, over which waterfalls now cascade, crop out in Frijoles Canyon. Cerros del Rio lavas erupted between about 2.7 million and 1.1 million years ago. Late-stage volcanism in the Cerros del Rio volcanic field field produced dacite domes and flows, which were sources of lithic resources.
- **Lithic Resources**. The volcanic Jemez Mountains were a source of lithic resources such as obsidian, dacite, and chert, for the people living on the Pajarito Plateau. They used these materials to manufacture tools and projectile points.
- **El Cajete Pyroclastic Beds**. Eruption of the El Cajete vent in the southern part of the Valles caldera about 55,000 years ago produced pyroclastic beds (**Qvec**), which are rich in pumice. Beginning in the 1200s, ancestral Puebloans began to settle on these pumice deposits, which have moisture-trapping capabilities, thus enabling farming on the slopes of the Jemez Mountains for nearly 500 years.
- **Paleontological Resources**. Published reports of Holocene fossils at Bandelier National Monument describe a 3,000-year-old packrat (*Neotoma* spp.) midden, and 8,000-year-old charcoal, wood, and cones of Douglas-fir (*Pseudotsuga menziesii*) in unconsolidated deposits in Frijoles Canyon. Fossils also may occur in unconsolidated Quaternary deposits (**Qp2, 3, 4**; **Qa2, 3, 4**; **Qt**; **Qpa**, **Qa5**; and **Qfa**). Also, ash deposits of Bandelier Tuff (**Qbo** and **Qbt**) may contain fossils. The most likely rock units to contain fossils are the Galisteo Formation (**Tgs**) and Santa Fe Group (Tesuque Formation, **Tstc** and **Tstb**; Chamita Formation **Tscv**; and axial channel facies, **QTsfa**). No fossils from these rock units have been reported from the monument to date, but elsewhere they are known to yield fossils.
- **High-Elevation Features**. Boulder fields (**Qrx**) were mapped at high elevations in Bandelier National Monument. These features have characteristics of rock glaciers, which move by interstitial ice or ice cores. Other high-elevation features are patterned ground (asymmetrical circles, polygons, or stripes created by frost action)

and felsenmeer (German for "sea of rocks," also created by frost action).

- **Galisteo Formation**. The oldest rocks in Bandelier National Monument are 56 million–34 million years old (Eocene Epoch), and comprise the Galisteo Formation (**Tgs**). Unlike other bedrock in the monument, which is volcanic, the Galisteo Formation was deposited by rivers, long before the Jemez Mountains volcanic field came into existence and the Rio Grande flowed across the landscape.

Geologic resource management issues identified during the GRI scoping meeting and follow-up conference call include the following:

- **Fires, Fluvial Geomorphology, and Slope Movements**. Fire has tremendous effects on the landscape at Bandelier National Monument. It is a driving component in an interconnected system that includes streamflow, sediment transport, stream channel morphology, and slope movements. After fires, peak storm-water flow increases, sediment transport increases, stream channel geometry changes, and debris flows occur.
- **Cliff Retreat and Rockfall**. Bandelier Tuff dominates the landscape at Bandelier National Monument. The combination of welded and nonwelded layers promotes differential weathering, resulting in vertical cliffs and talus-covered slopes comprising canyon walls. Cliff retreat occurs by a combination of small rockfalls from cliffs (the most common type of slope movement in the monument); detachment of rocks from slopes; and larger, deep-seated landslides. The cliffs above the headquarters area, Main Loop Trail, and the "big curve" along the monument road are areas of concern with rockfall hazards.
- **Seismic Activity**. The Pajarito fault zone runs through Bandelier National Monument. The most recent surface-rupturing earthquake on the fault zone occurred between 2,200 and 1,400 years ago; no historic surface-rupturing earthquakes have occurred. The most recent relatively large earthquake in the area with strong local effects occurred in 1918. Earthquake magnitude and recurrence intervals along the Pajarito fault zone are poorly constrained, but available data suggest that earthquakes of magnitude 6.5 to 7 may occur at intervals of 10,000 to 60,000 years. The probability of a moderate earthquake (magnitude 5.0 or greater) occurring in the next century and affecting the monument is more than 50%.
- **Cavate Deterioration**. An understanding of the composition of the Bandelier Tuff into which cavates were excavated is important for managing these cultural resources. Preliminary geomorphic assessment of cavates and cliff bases in Frijoles Canyon found that deterioration of the tuff occurs mostly through small-scale spalling and granular erosion and to a lesser degree from rockfall. Discharge of water from the vadose zone at the cliff base, capillary rise of moisture into the tuff, and surface-water flow down cliff faces are the primary processes contributing to deterioration.
- **Volcano Hazards**. Another huge caldera-forming eruption in the Jemez Mountains volcanic field is unlikely. Far more probable are smaller, but still potentially explosive, eruptions similar to those that occurred in Valles caldera 60,000–40,000 years ago. Possible hazards include the construction of a lava dome in the caldera, ash fall, ejection of bombs, and local pyroclastic flows down drainages.
- **Cochiti Dam and Reservoir**. Cochiti Dam is 10 km (7 mi) downstream from Bandelier National Monument. It holds water and sediment from the Rio Grande (river) to form Cochiti Reservoir. Temporary flooding of about 140 ha (350 ac) of NPS lands upstream of the dam during the spring runoff period is allowed under a memorandum of understanding (MOU) between the National Park Service and US Army Corps of Engineers. Flooding has exceeded "temporary" time frames and created problems not anticipated by the MOU signatories, including reactivation of landslides (**Qls**). Another issue is that the reservoir is slowly filling with sediment via a process referred to as "silting." Silting impacts monument resources as a result of burial of riparian areas and providing a favorable medium for pioneer plant succession, including agricultural weeds and riparian exotics.
- **Disturbed Land Restoration**. In 2005, GRI scoping participants identified sites in the amphitheater area in possible need of restoration. A former landfill is immediately south of the amphitheater; a former dump site is west of the landfill. Preliminary assessment and inspection of these sites in 2012 concluded that municipal waste was the primary component, and contaminants, though present, do not exceed background mean concentrations for New Mexico. These sites remain in place.

- **Paleontological Resource Inventory, Monitoring, and Protection**. Tweet et al. (2009) compiled paleontological information for the Southern Colorado Plateau Network, including Bandelier National Monument, but did not conduct a field-based inventory. Managers at Bandelier National Monument are encouraged to contact the NPS Geologic Resources Division for assistance with such an inventory, which would provide detailed, site-specific descriptions and resource management recommendations.

Products and Acknowledgments

The NPS Geologic Resources Division partners with institutions such as Colorado State University, the US Geological Survey, state geological surveys, local museums, and universities to develop GRI products. This chapter describes those products and acknowledges contributors to this report.

GRI Products

The objective of the Geologic Resources Inventory is to provide 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. To realize this objective, the GRI team undertakes three tasks for each natural resource park: (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 digital geologic map 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 compilation and use of natural resource information by park managers is called for in the 1998 National Parks Omnibus Management Act (section 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 would like to thank the participants of the 2005 scoping meeting and 2014 conference call (see Appendix A) for their assistance with this inventory. Thanks very much to **Fraser Goff** (New Mexico Bureau of Geology and Mineral Resources) for his expertise and technical review of this report, which greatly improved its accuracy and content. In addition, thanks to **Brian Jacobs** and **Barbara Judy** (Bandelier National Monument), who provided references and answered questions during the report-writing process. **Trista Thornberry-Ehrlich** (Colorado State University) created many graphics for this report, in particular, the modified resurgent-caldera model (fig. 8) and updated Bandelier Tuff stratigraphy (fig. 10). **Elaine Jacobs** (Los Alamos National Laboratory) gave us a much-needed photograph of obsidian (fig. 24). We thank **Kay Beeley** (Bandelier National Monument) for her help during the review process: she followed up with park staff and researchers, provided photographs, received permission to use photographs, and supplied review comments. Thanks to **Jamie Civitello** (Valles Caldera National Preserve) for furnishing information about lithic resources, and for knowing that basalt and dacite are different rocks. We thank **Shari Kelley** (New Mexico Bureau of Geology and Mineral Resources) for her clarification of the rocks in the Keres Group. Thanks to **Gina D'Ambrosio** (New Mexico Bureau of Geology and Mineral Resources) for providing photographs from bureau publications. **Eric Bilderback** (NPS Geologic Resources Division) reviewed the "Fires, Fluvial Geomorphology, and Slope Movements" section. Thanks very much to **Stephen Monroe** (NPS Southern Colorado Plateau Network) for his input on the effects of the Las Chonchas Fire in the monument. And, finally, thanks to **George H. H. Huey** and **Lauren Blauert** (George H. H. Huey Photography, Inc.) for licensing use of the inside cover image.

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Geologic Setting and Significance

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

Bandelier National Monument is a volcanology mecca—a "must see" destination for geologists, volcanologists, and volcano aficionados. The monument hosts a premier example of an ash-flow tuff, which is quite possibly the world's most famous (see "Bandelier Tuff" section). The tuff, which dominates the monument's landscape, represents caldera-forming eruptions that are of a scale never witnessed by humans (Dunbar 2005). Researchers and educators come to the monument to see the Bandelier Tuff because of its extensive exposures and the volcanic features it preserves.

Many of the seminal papers and maps published in the 1960s about volcanism feature Bandelier National Monument and vicinity. These publications include work by US Geological Survey (USGS) geologists, in particular, R. L. Smith and R. A. Bailey, along with their colleague C. S. Ross. Smith, Bailey, and Ross began mapping the Valles caldera in 1938, finishing in 1970 (see "Valles Caldera" section).

Although remapped since that time (see "Geologic Map Data" chapter), the Smith et al. (1970) map serves as a benchmark for the study of volcanism around the globe. Moreover, the famous paper "Resurgent Cauldrons" by Smith and Bailey (1968) presented a seven-stage model for caldera formation. This model, hypothesized at the monument and vicinity, has stood the test of time and is still taught in classrooms today (see "Valles Caldera" section).

Over the years, geologists have combined and subdivided the rocks of the Jemez Mountains volcanic field into various formations and groups. It is now divided into two major groups of rocks—Keres and Tewa. The Keres Group represents the pre-caldera portion of the Jemez Mountains volcanic field and consists of domes, flows, tuffs, and associated sediments that started erupting onto the landscape about 14 million years ago (Gardner et al. 2010; Goff et al. 2011; Kelley et al. 2013). The Tewa Group represents the Valles–Toledo caldera complex that produced the Bandelier Tuff, starting about 1.85 million years ago (Quaternary Period, Pleistocene Epoch; fig. 1). The Tewa Group includes rhyolite domes and lava flows, small- and large-volume pyroclastic flows, ash fall, and a variety of volcaniclastic deposits. The last of the Tewa Group was deposited 45,000–34,000 years ago as the Banco Bonito flows in Valles caldera.

The terms "Keres" and "Tewa" have geological, geographical, and cultural significance. Keres rocks were named by Bailey et al. (1969) for the Keresan Range—an old name for this part of the Jemez Mountains. Keres is also the name of a Pueblo language. Around the area today, Keres speakers, like the rocks of the same name, are to the south, which was also likely true in the past (Leahy 1999). Another Pueblo language is Tewa, with speakers in the north. Tradition holds that Frijoles Canyon—a notable canyon for its geological and archeological resources in the monument—was the dividing line between Keres and Tewa language groups. Some native speakers say that the name "Tyuonyi" (for the pueblo in Frijoles Canyon) means a "place of meeting" or "place of treaty" (Leahy 1999). Griggs (1964) chose the name "Tewa" for the rocks that cover this area of the Jemez Mountains.

Bandelier Tuff is divided into three members—La Cueva, Otowi, and Tshirege. The Tshirege Member dominates the landscape of the monument, making up the mesas and canyon walls (fig. 2). Weathering and erosion of the softer layers of this member led to the Swiss-cheese appearance of some of the cliffs (fig. 3). Ancestral Puebloans (ancestors of today's Pueblo and Hopi people, and commonly called Anasazi in earlier literature) enlarged many of these holes for living and storage. Frijoles Canyon is a notable locale for these particular cliff dwellings, called "cavates," which are inexorably tied to the Bandelier Tuff.

Frijoles Canyon is a small part of an extensive area once inhabited by ancestral Puebloans. Villages were scattered throughout the surrounding Pajarito Plateau and Rio Grande valley. At times, members of this far-flung culture inhabited parts of Colorado, Utah, Arizona, and New Mexico. Their ancient homes can be seen in places such as Mesa Verde National Park (see GRI report by Graham 2006), Canyon de Chelly

National Monument (see GRI scoping summary by KellerLynn 2007), and Chaco Culture National Historical Park (see GRI report by KellerLynn 2015).

In 1880, people from the Cochiti Pueblo brought anthropologist Adolph Bandelier to Frijoles Canyon to see the place they consider their ancestral home. Bandelier was impressed and in 1890 wrote his classic novel, *The Delight Makers*, which is set in Frijoles Canyon among the ancestral people who lived there. Bandelier returned four times to the place that would become named in his honor (Barey 1990).

In 1916, Bandelier National Monument was established by presidential proclamation to protect and preserve for public enjoyment and education the large Pueblo settlements and spectacular cliff dwellings of the southern Pajarito Plateau. At that time, the monument and its archeological resources enjoyed considerable national prominence both in the public eye and within the discipline of archeology, largely as a result of the pioneering explorations of Adolph Bandelier and the later excavations and preservation efforts of Edgar L. Hewett (Toll 1995).

Bandelier National Monument consists of two noncontiguous units, a main unit and Tsankawi Section (fig. 4). Both units of the monument are amidst vast areas of open space. The northeastern boundary of the main unit is adjacent to Los Alamos National Laboratory, which covers 10,700 ha (26,500 ac); public access is restricted on these Department of Energy lands. To the northwest is Valles Caldera National Preserve—a multiuse nature preserve that incorporates most of the caldera and consists of 36,000 ha (88,900 ac) of grasslands and forests. In December 2014, the preserve was authorized as a unit of the National Park System. In addition, more than 405,000 ha (1 million ac) of the Santa Fe National Forest surround the main unit, including the Dome Wilderness, which is administered by the US Forest Service and is adjacent to the Bandelier Wilderness within Bandelier National Monument. About 70% of the monument is designated wilderness. The southern boundary of the monument is contiguous with lands owned by the New Mexico State Lands Office. NPS lands adjacent to the Rio Grande include an easement granted to the US Army Corps of Engineers for the operation of Cochiti Dam and Reservoir.

Tsankawi takes its name from Tsankawi Pueblo, a major archeological pueblo or village, containing about 275 ground-floor rooms. Tsankawi encompasses approximately 300 ha (800 ac) northeast of the main unit. Tsankawi sits atop a mesa formed by Sandia Canyon on the south and Los Alamos Canyon on the north and has a commanding view in all directions. Tsankawi is nearly surrounded by Los Alamos National Laboratory with tribal lands of the San Ildefonso Pueblo adjoining on the south and east.

Figure 1 (facing page). Geologic time scale. The divisions of the geologic time scale are organized stratigraphically, with the oldest divisions at the bottom and the youngest at the top. GRI GIS map abbreviations for each time division are in parentheses. Compass directions in parentheses indicate the regional locations of events. Boundary ages are millions of years ago (MYA). Time periods with orange text are represented in the GRI GIS map data for Bandelier National Monument. The oldest rocks exposed in the monument are from the Eocene Epoch (E). Volcanic activity in the Jemez Mountains volcanic field has been ongoing since the Miocene Epoch (MI). Pliocene (PL) Cerros del Rio volcanic rocks in the monument host notable features such as a cinder cone and maar volcano. Bandelier Tuff erupted as ash fall and pyroclastic flows during the Pleistocene Epoch (PE). National Park Service graphic using dates from the International Commission on Stratigraphy (http://www.stratigraphy.org/index.php/ics-chart-timescale; accessed 6 April 2015).

Eon	Era	Period	Epoch	MYA		Life Forms	North American Events
Phanerozoic	Cenozoic (CZ)	Quaternary (Q)	Holocene (H)	0.01	Age of Mammals	Extinction of large mammals and birds Modern humans	Ice age glaciations; glacial outburst floods Cascade volcanoes (W)
			Pleistocene (PE)	2.6			
		Tertiary (T): Neogene (N)	Pliocene (PL)	5.3			Linking of North and South America (Isthmus of Panama)
			Miocene (MI)	23.0		Spread of grassy ecosystems	Columbia River Basalt eruptions (NW) Basin and Range extension (W)
		Tertiary (T): Paleogene (PG)	Oligocene (OL)	33.9			
			Eocene (E)	56.0			Laramide Orogeny ends (W)
			Paleocene (EP)	**66.0**		Early primates Mass extinction	
	Mesozoic (MZ)	Cretaceous (K)		145.0	Age of Reptiles	Placental mammals Early flowering plants	Laramide Orogeny (W) Western Interior Seaway (W) Sevier Orogeny (W)
		Jurassic (J)		201.3		Dinosaurs diverse and abundant	Nevadan Orogeny (W) Elko Orogeny (W)
		Triassic (TR)		**252.2**		Mass extinction First dinosaurs; first mammals Flying reptiles Mass extinction	Breakup of Pangaea begins Sonoma Orogeny (W)
	Paleozoic (PZ)	Permian (P)		298.9	Age of Amphibians		Supercontinent Pangaea intact
		Pennsylvanian (PN)		323.2		Coal-forming swamps Sharks abundant	Ouachita Orogeny (S) Alleghany (Appalachian) Orogeny (E)
		Mississippian (M)		358.9		First reptiles	Ancestral Rocky Mountains (W)
		Devonian (D)		419.2	Fishes	Mass extinction First amphibians First forests (evergreens)	Antler Orogeny (W) Acadian Orogeny (E-NE)
		Silurian (S)		443.8		First land plants Mass extinction	
		Ordovician (O)		485.4	Marine Invertebrates	Primitive fish Trilobite maximum	Taconic Orogeny (E-NE)
		Cambrian (C)		**541.0**		Rise of corals Early shelled organisms	Extensive oceans cover most of proto-North America (Laurentia)
Proterozoic		Precambrian (PC, X, Y, Z)		2500		Complex multicelled organisms Simple multicelled organisms	Supercontinent rifted apart Formation of early supercontinent Grenville Orogeny (E) First iron deposits Abundant carbonate rocks
Archean				4000		Early bacteria and algae (stromatolites)	Oldest known Earth rocks
Hadean				**4600**		Origin of life Formation of the Earth	Formation of Earth's crust

Figure 2. Photograph of Bandelier Tuff. The walls of Frijoles Canyon display colorful Bandelier Tuff, which consists of extensive ash falls and pyroclastic flows. The Tshirege Member makes up most of the canyon walls. National Park Service photograph.

Figure 3. Photograph of Tshirege Member cliff face. In Frijoles Canyon, the Tshirege Member forms cliff faces that resemble Swiss cheese. Ancestral Puebloans took advantage of the relatively soft nature of the tuff and its preexisting cavities to excavate cavates, which they inhabited between 1150 and 1550 CE (common era). Photograph by Katie KellerLynn (Colorado State University).

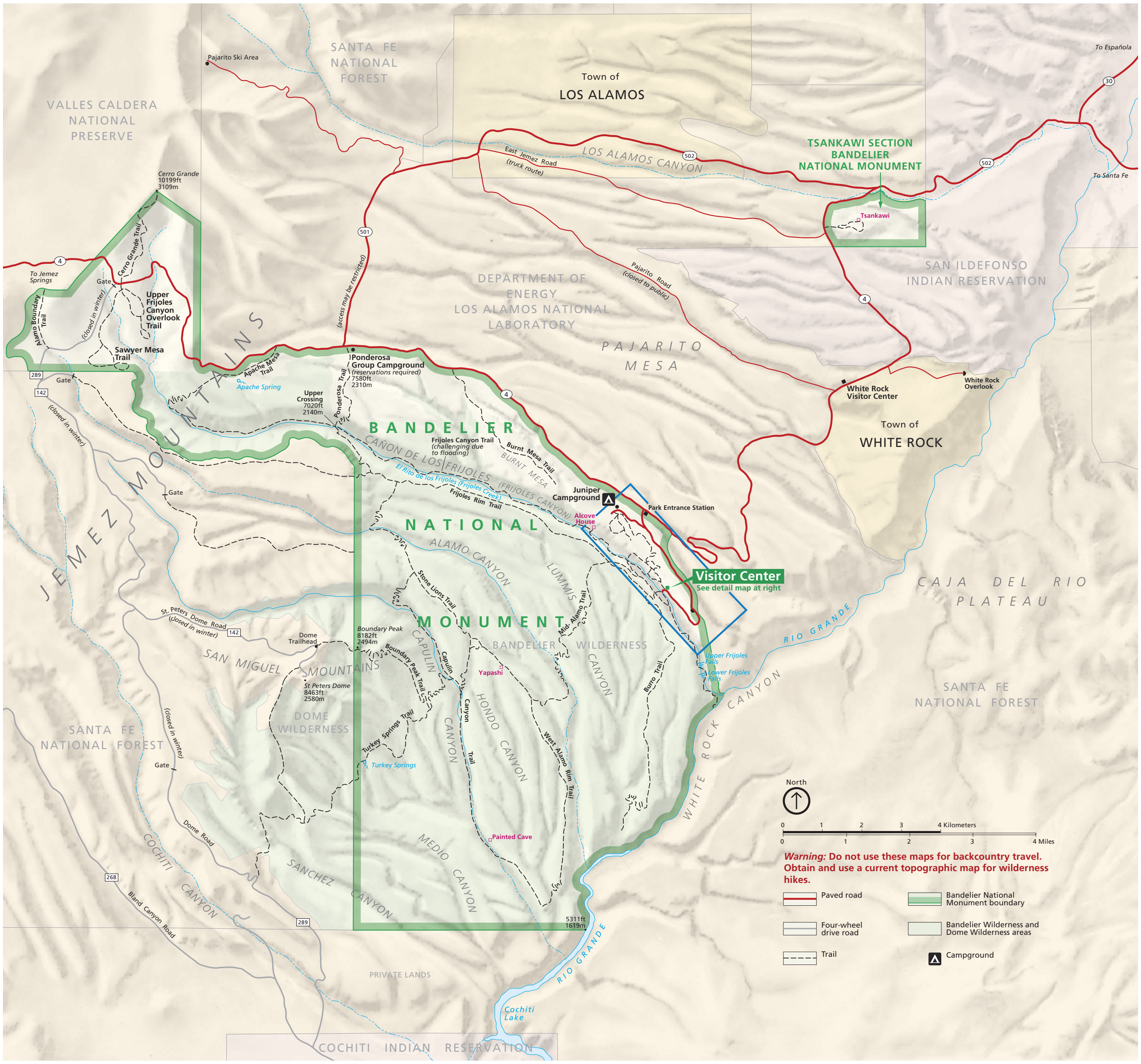


Figure 4A. Map of Bandelier National Monument. Bandelier National Monument protects approximately 13,300 ha (33,000 ac) of canyon and mesa country in the Jemez Mountains of northwestern New Mexico. Canyons in the monument include Sanchez, Medio, Capulin, Hondo, Alamo, Lummis, and Frijoles (fig. 4B). The monument is composed of two units; Tsankawi is northeast of the main unit. Valles Caldera National Preserve, Santa Fe National Forest, and Los Alamos National Laboratory are principal neighbors, with New Mexico State Lands on the south and an easement with the US Army Corps of Engineers on the Rio Grande. National Park Service graphic.

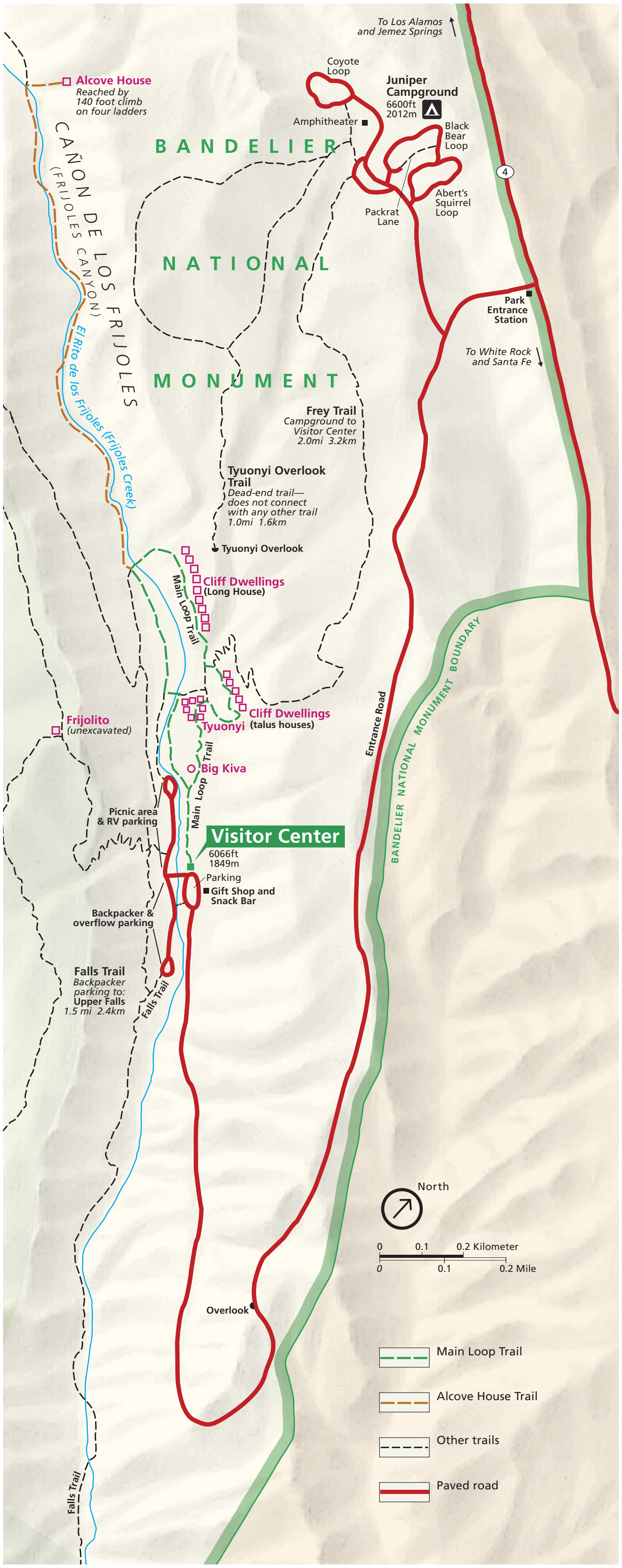


Figure 4B. Map of Frijoles Canyon in Bandelier National Monument. National Park Service graphic.

Geologic Features and Processes

This chapter describes noteworthy geologic features and processes in Bandelier National Monument.

During the 2005 scoping meeting (see National Park Service 2005) and 2014 conference call, participants (see Appendix A) identified the following geologic features and processes of significance at Bandelier National Monument:

- Volcanic Rocks and Volcanoes
- Jemez Mountains Volcanic Field
- Bandelier Tuff
- Features in Bandelier Tuff
- Rio Grande Rift
- Cerros del Rio Volcanic Rocks
- Lithic Resources
- El Cajete Pyroclastic Beds
- Paleontological Resources
- High-Elevation Features
- Galisteo Formation

Volcanic Rocks and Volcanoes

Geologists use silica (silicon dioxide, SiO_2) content as a means for classifying volcanic rocks (table 1). The amount of silica influences many properties of magma, including viscosity (internal friction) and explosiveness. In general, lavas with more silica are more viscous and more explosive. Flows of andesite (57%–63% SiO_2) and dacite (63%–68% SiO_2), for example, tend to be thick and sluggish, traveling only short distances from a vent (an opening at Earth's surface through which magma erupts or volcanic gases are emitted). Dacite and rhyodacite (68%–72% SiO_2) lavas often squeeze out of a vent to form irregular mounds or lava domes. Two dacite domes—Sawyer Dome (**Ttsd**) and Cerro Grande (**Ttcg**)—are on the northern boundary

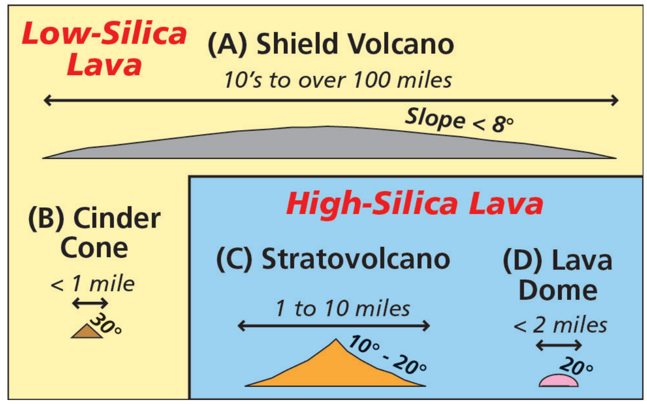


Figure 5. Schematic illustration of volcano types. The size and shape of volcanoes are influenced by the amount of silica and gas in the erupting lava. Low-silica lavas, such as basalt, produce broad shield volcanoes (A). If basaltic lava has a lot of gas, a central vent may erupt like a fire hose, forming a cinder cone (B). Higher silica lavas, andesite to rhyolite, form composite volcanoes, also called "stratovolcanoes" (C). Lava domes form around a vent that erupts high-silica lava such as dacite (D). Graphic by Jason Kenworthy (NPS Geologic Resources Division) after Lillie (2005, figure 2.18).

Table 1. Classification and characteristics of volcanic rocks

Rock Name:	Rhyolite	Rhyodacite	Dacite	Andesite	Basaltic Andesite	Basalt
Silica (SiO_2) content[1]	>72%	68%–72%	63%–68%	57%–63%	52%–57%	<52%
Color	Lighter					Darker
Viscosity of magma	Thick (less mobile flows)					Fluid (more mobile flows)
Typical style of eruption	Explosive					Effusive
Eruption temperature[2]	Cooler, 800°C (1,500°F)					Hotter, 1,160°C (2,120°F)

[1]Silica percentages from Clynne and Muffler (2010). [2]Eruption temperatures from Price (2010).

of the monument. By contrast, low-silica basalts (<52% SiO_2) form lava flows that spread out in broad, thin sheets up to several kilometers wide. Repeated eruptions of basaltic flows in a volcanic field may build a shield volcano (fig. 5). Individual eruptions of basalt commonly form cinder cones. A notable cinder cone, composed of Cerros del Rio volcanic rocks (**QTcrv**), occurs in Frijoles Canyon.

The most explosive volcanoes on Earth are generally rhyolitic (>72% SiO_2). After an eruption of rhyolite, volcano edifices often do not look like volcanoes because the eruptions are so explosive that the volcano ends up collapsing in on itself, creating a caldera. The eruption that formed Valles caldera was this type. It is the oldest of three young caldera-forming volcanoes in the United States; the others are Yellowstone in Wyoming and Long Valley in California (US Geological Survey 2014b). In addition to the Yellowstone caldera within the National Park System, the Bursum and Gila Cliff Dwellings calderas, which surround Gila Cliff Dwellings National Monument in New Mexico (see GRI report by KellerLynn 2014), are the result of rhyolitic explosions that took place about 28 million years ago.

Jemez Mountains Volcanic Field

Bandelier National Monument is on the eastern flank of the Jemez Mountains, which is the geographic expression of a volcanic field so large—72 km (45 mi) across—that it is best recognized in aerial photographs or satellite imagery (fig. 6). Displayed on geologic maps (see poster, in pocket) or digital elevation models (fig. 7), distinctive features also "pop."

Initial activity of the Jemez Mountains volcanic field exhibited a wide range of chemical compositions and eruption styles, from effusive basaltic (less than 53% SiO_2; table 1) to eruptive rhyolitic (more than 72% SiO_2). Overall, andesite (57%–63% SiO_2) is the dominant rock type in the Jemez Mountains volcanic field, though rhyolite, which represents the most recent eruptions, has come to characterize the "Bandelier type."

Valles Caldera

Valles caldera is at the center of the Jemez Mountains volcanic field. It is the world's premier example of a resurgent cauldron or caldera—a giant circular volcano with an uplifted central floor (Goff et al. 2011). During the 1960s, R. L. Smith and R. A. Bailey published several widely recognized papers that summarized their many years of work in the region. Based on their study of Valles caldera, Smith and Bailey (1968) proposed a model of caldera formation that has served as the global standard for other calderas and facilitated recognition and understanding of calderas around the world (Goff et al. 2011). For example, Yellowstone was not recognized as a resurgent caldera until many years after the Valles model was studied, published, and applied to other suspects (Goff 2010). With minor modifications, the Smith and Bailey model has stood the test of time (Goff et al. 2011). Figure 8 presents a modified version of this model.

Toledo Caldera

The Toledo caldera was created 1.61 million years ago during the first of two caldera-forming eruptions of Bandelier Tuff. The second caldera-forming eruption emplaced the Tshirege Member of Bandelier Tuff 1.25 million years ago and created Valles caldera. Because the Toledo caldera was largely obliterated by the later Valles caldera, it is commonly overlooked and considerably less is known about it. The Tshirege Member filled the Toledo caldera, burying much of the preexisting rock. Nevertheless, the explosion that created the Toledo caldera was no less spectacular than the one that created the Valles caldera 400,000 years later. Explosion of the Toledo volcano produced a giant cauldron roughly 14 km (9 mi) across. Each climactic eruption deposited an estimated 400 km^3 (100 mi^3) of material (Fraser Goff, New Mexico Bureau of Geology and Mineral Resources, volcanologist, written communication, 28 April 2015).

Rocks of the Jemez Mountains Volcanic Field

Geologists have divided the rocks of the Jemez Mountains volcanic field into two major groups: Keres and Tewa. All volcanic and volcaniclastic rocks that are younger than 14 million years old but older than Bandelier Tuff belong to the Keres Group. All Bandelier Tuff and younger volcanic and volcaniclastic units belong to the Tewa Group (Gardner et al. 2010; Goff et al. 2011; Kelley et al. 2013).

Keres Group

In Bandelier National Monument, rocks of the Keres Group include, from oldest to youngest, the Canovas Canyon Rhyolite (**Tcct**; 12 million–8 million years old), Paliza Canyon Formation (**Tphd**, **Tppa**, **Tpdt**, and **Tpa**; 10 million–7 million years old), Bearhead Rhyolite (**Tkpt**

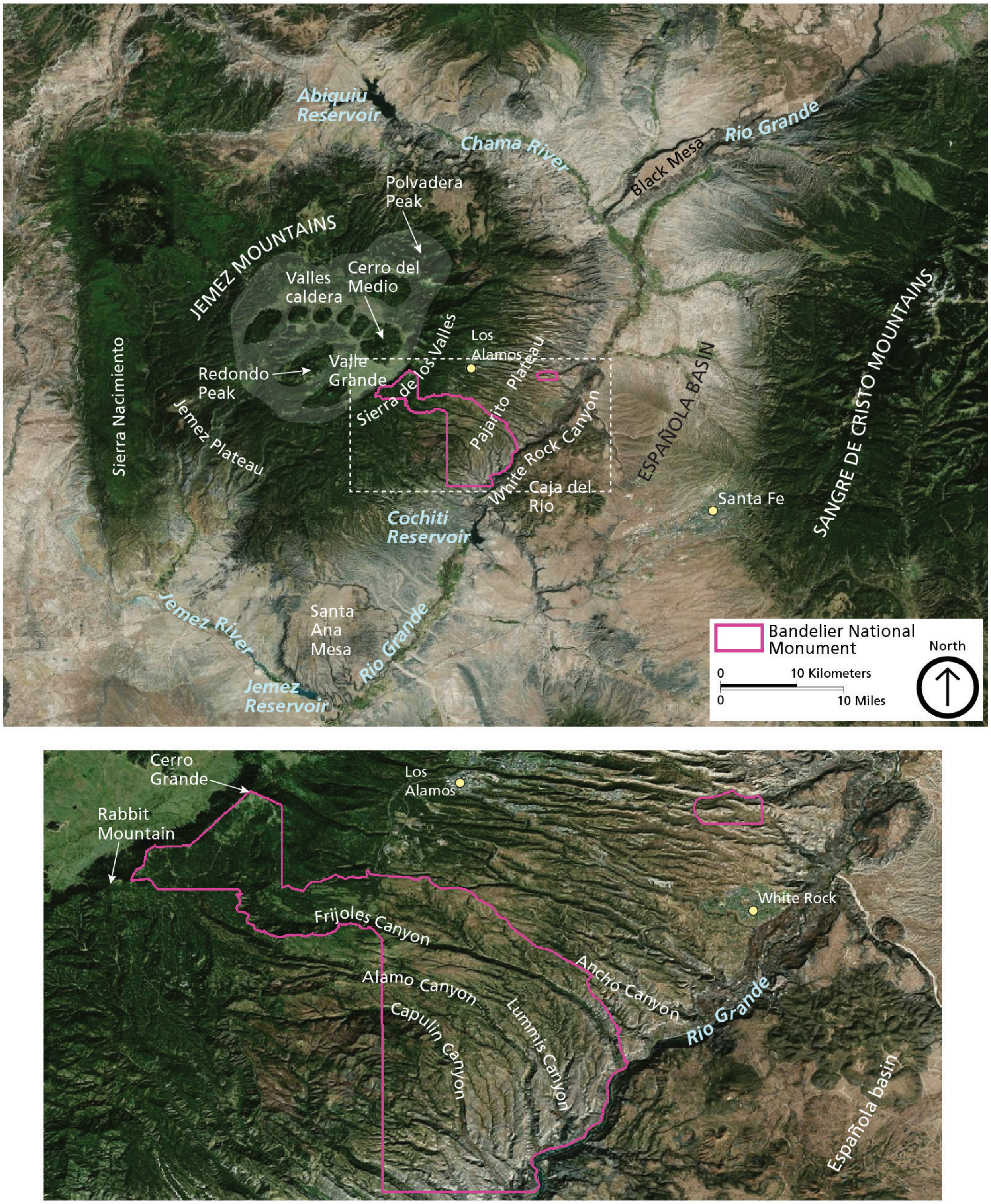


Figure 6. Satellite imagery of Bandelier National Monument and vicinity. Bandelier National Monument is in the Jemez Mountains volcanic field, which is marked by the stunning Valles caldera. The monument spreads across the Pajarito Plateau to the Rio Grande (river) that flows through White Rock Canyon. Caja del Rio and Santa Ana Mesa represent areas of peripheral volcanism adjacent to the Jemez Mountains volcanic field. Española basin to the east of the monument is part of the active Rio Grande rift. Dashed box indicates extent of detailed map. Graphic by Trista Thornberry Ehrlich (Colorado State University). Base imagery from ESRI ArcGIS World Imagery (accessed 11 February 2015).

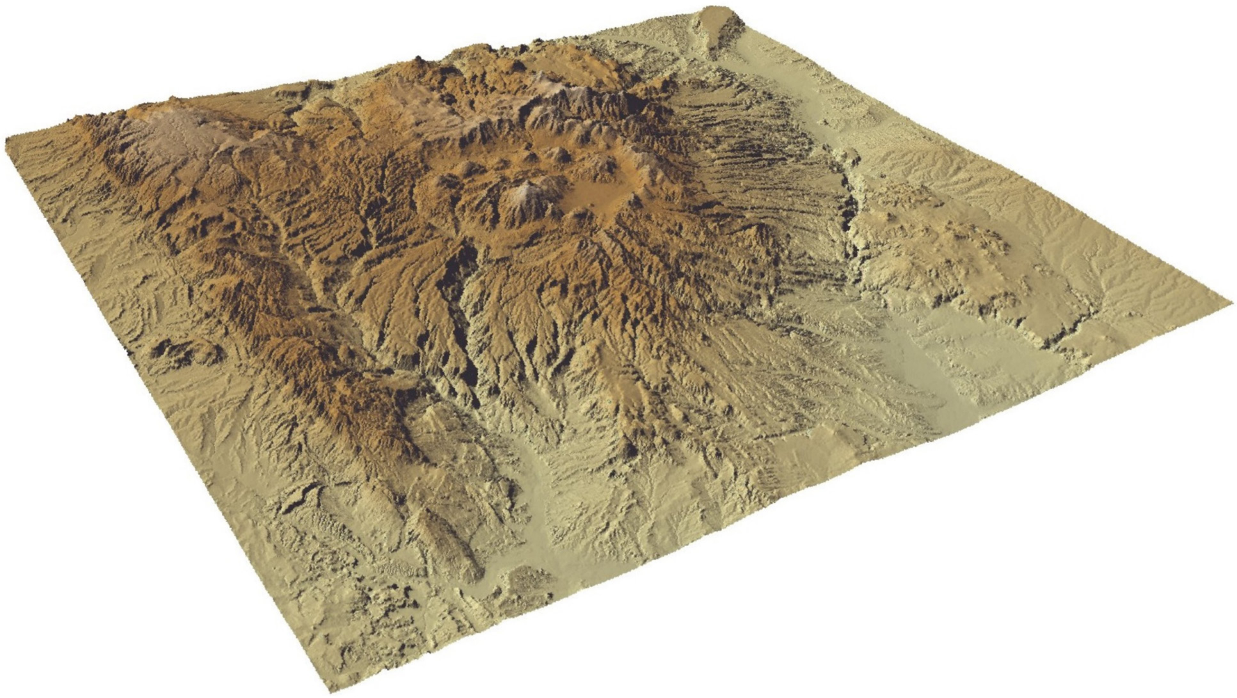


Figure 7. Digital elevation model of the Jemez Mountains volcanic field. This image clearly illustrates the shape of Valles caldera; the striking, circular arrangement of rhyolitic domes within the caldera; and the radial pattern of drainages away from the rim. The flat area within the caldera is Valle Grande. Pajarito Plateau and Bandelier National Monument are on the right side of the crater rim. White Rock Canyon is at the base of the plateau. The impressive ridge to the west of the caldera is the Sierra Nacimiento. New Mexico Bureau of Geology and Mineral Resources graphic, available at https://geoinfo.nmt.edu/faq/volcanoes/ (accessed 21 May 2015).

and **Tbh**; 7 million–6 million years old), and Tschicoma Formation (**Ttsd**, **Ttcg**, and **Ttpm**; 5 million–2 million years old). These rocks represent volcanic domes and lava flows of andesite, dacite, and rhyolite.

The resultant volcaniclastic material from erosion of these volcanic domes is also part of the Keres Group (Shari Kelley, New Mexico Bureau of Geology and Mineral Resources, field geologist, email communication, 18 May 2015). Erosion of the Bearhead Rhyolite domes is recorded in the volcaniclastic Cochiti Formation (**QTc**; 6.5 million–2 million years old), which formed as alluvial fans shed into the evolving Rio Grande rift (Goff and Gardner 2004). The fans consist of a pinkish-gray mixture of sands reworked out of the Santa Fe Group and volcanic rocks of the Keres Group (Kelley et al. 2013).

Similarly, erosion of domes of the Tschicoma Formation is preserved in the volcaniclastic Puye Formation (**QTpt**; Kelley et al. 2013). The Puye Formation is a "fanglomerate," consisting of a huge alluvial fan complex that shed eastward from these volcanoes. In outcrops along the Rio Grande (river), the Puye Formation also contains basaltic debris derived from contemporaneous volcanism and erosion of the Cerros del Rio volcanic field (figs. 6 and 9). Development of the Cerros del Rio volcanic field may have significantly influenced deposition of the Puye Formation by effectively blocking the Rio Grande valley and imposing a major base level rise at the toe of the alluvial fan (Reneau and Dethier 1996; see "Cerros del Rio Volcanic Rocks" section).

The Puye Formation ancestral Rio Grande facies (**QTpt**, slightly lithified pebble to cobble gravel) was deposited in the rift between 5.3 million and 2.6 million years ago (Pliocene Epoch; fig. 1).

Tewa Group

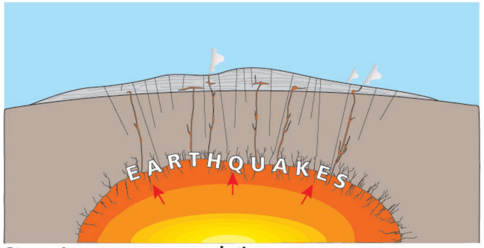
Three formations comprise the Tewa Group: Bandelier Tuff, Cerro Toledo Formation, and Valles Rhyolite. These formations consist of the volcanic and volaniclastic rocks and deposits directly associated with the evolution and eruptions of the Toledo and Valles calderas (Gardner et al. 2010), including the two caldera-forming eruptions that deposited the

Otowi (**Qbo**) and Tshirege (**Qbt**) members of Bandelier Tuff (see “Bandelier Tuff” section). In addition, large rhyolite domes such as Rabbit Mountain were emplaced in the Toledo caldera in between these two cataclysmic explosions. Rabbit Mountain rhyolite (**Qcrm**) is part of the Cerro Toledo Formation. Also, ash fall deposits (**Qct**; also called “pyroclastic fall deposits”), debris flow deposits (**Qrd1**), and colluvial deposits of reworked pumice and blocks of the Otowi Member (Pueblo Canyon Member; **Qcpc**) are part of the Cerro Toledo Formation and thus the Tewa Group. Finally, Valles Rhyolite is part of the Tewa Group and represents the most recent volcanism of the Jemez Mountains volcanic field (see “Volcano Hazards” and “Geologic History”). The youngest eruption occurred 45,000–37,000 years ago, extruding the Banco Bonito flows. These flows do not occur in the national monument, but other members of Valles Rhyolite, such as **Qrd2**, **Qtoal**, and **Qvec**, do.

Bandelier Tuff

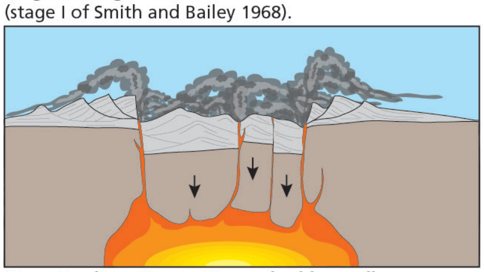
Bandelier Tuff, which erupted in three episodes starting approximately 1.85 million years ago (Spell et al. 1996; Goff et al. 2011), is part of the Tewa Group. The two caldera-forming members of Bandelier Tuff—Otowi and Tshirege—began as “Plinian eruption” columns that rose rapidly into the air to heights exceeding 35 km (20 mi). Plinian eruptions are explosive and characterized by large amounts of tephra and a tall eruption column from which a steady, turbulent stream of fragmented magma and magmatic gas is released at a high velocity. These eruptions are documented in the rock record by ash fall (also called “pyroclastic fall”) deposits, and resulted in pumice strewn across the landscape.

Following the ash fall phase, the eruption column collapsed, resulting in pyroclastic flows (also



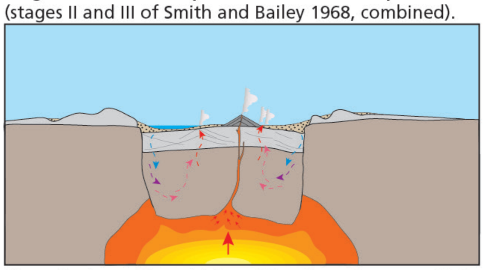
Stage 1—magma accumulation
(stage I of Smith and Bailey 1968).

Stage 1—As large volumes of magma accumulate a few miles below Earth’s surface, the ground swells, fractures and faults rupture, and earthquakes occur.



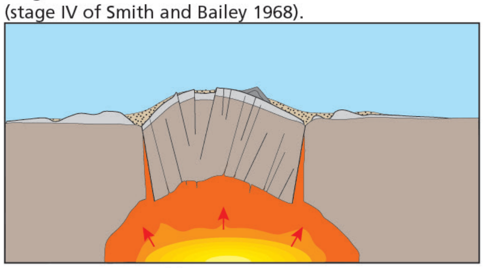
Stage 2—climactic eruption and caldera collapse
(stages II and III of Smith and Bailey 1968, combined).

Stage 2—As the volcano erupts, the caldera collapses. Immense ash falls and pyroclastic flows are produced.



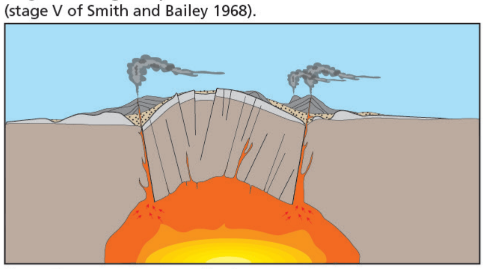
Stage 3—formation of intracaldera lava domes and lakes
(stage IV of Smith and Bailey 1968).

Stage 3—After the caldera forms, the following take place almost simultaneously: caldera walls slough downward into the depression, slope movements occur on adjacent slopes, a lake or lakes develop in the caldera depression from rain and snowmelt, and small lava domes and lava flows erupt into the lake or lakes. Also, as groundwater interacts with hot rock, hydrothermal activity occurs.



Stage 4—resurgent uplift
(stage V of Smith and Bailey 1968).

Stage 4—The caldera floor begins to lift from the continued rise of magma below.



Stage 5—post-resurgent volcanism
(stage VI of Smith and Bailey 1968).

Stage 5—After resurgence, more magma erupts along a ring of buried faults, forming lava domes and flows between the resurgent dome and caldera wall.

Figure 8. Model of resurgent caldera formation. The Smith and Bailey (1968) model has survived the test of time with some modifications. Research since Smith and Bailey’s time has suggested that caldera-forming eruptions and caldera collapse occur simultaneously. Also, the timing of hydrothermal activity is now thought to begin earlier and is not considered “terminal” as represented by the original Smith and Bailey model. Much more is known about the timing of caldera collapse and resurgent uplift than was known in the 1960s. Phillips (2004) and Phillips et al. (2007) obtained many $^{40}Ar/^{39}Ar$ ages to determine the timing and duration of Valles caldera resurgence. These findings show that resurgence began within at most 54,000 years after caldera formation. Graphic by Trista Thornberry-Ehrlich (Colorado State University) after Smith and Bailey (1968, figure 5), Williams and Bacon (1988, topographic map with illustrations and diagrams), Goff (2009, figure 33), and Goff (2010, general model of caldera formation).

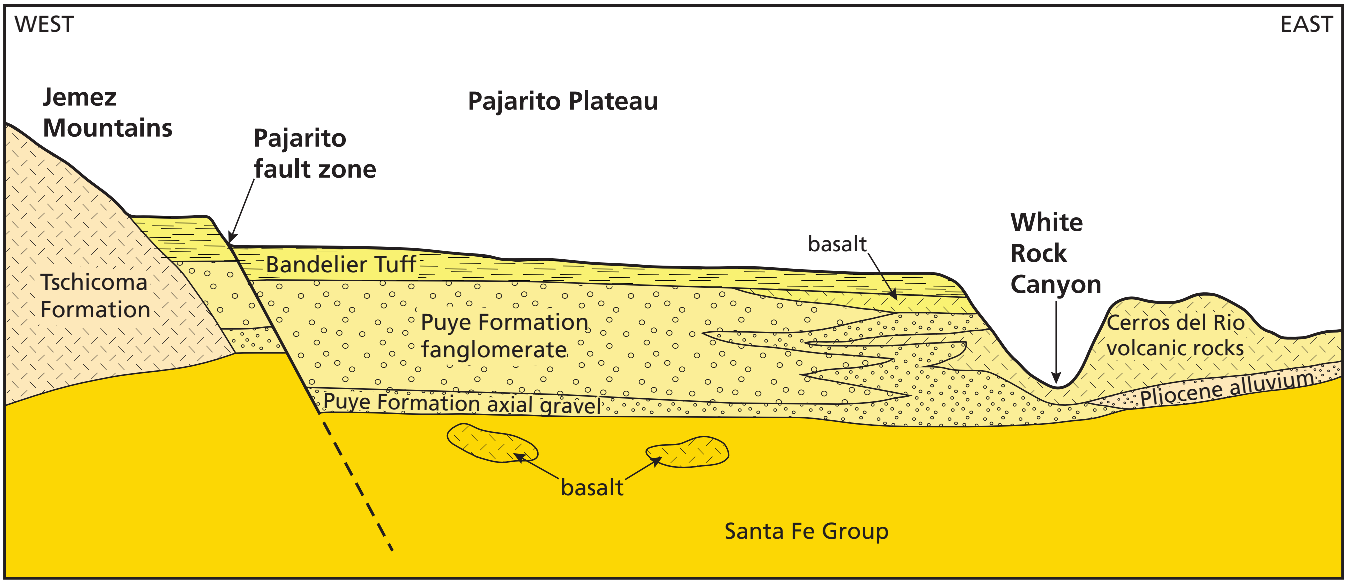


Figure 9. Geologic sketch of the Pajarito Plateau. Bandelier National Monument is on the northeastern Pajarito Plateau, which exposes deep canyons that separate narrow mesas capped by Bandelier Tuff. Volcanoes that produced the Tschicoma Formation shed sediment to form ancient alluvial fans (Puye Formation). Rio Grande rift–filling sediments (Santa Fe Group) underlie cobbles, pebbles, and gravels of the Puye Formation. Cerros del Rio volcanic rocks erupted on the periphery of the Jemez Mountains volcanic field. Graphic by Trista Thornberry-Ehrlich (Colorado State University) after Reneau and McDonald (1996, figure 6 *in* Introduction) and Waresback and Turbeville (1990, figure 2).

called "ash flows" or "ignimbrites") spreading swiftly across the landscape. Pyroclastic flows are very hot, density currents composed of gases and pyroclastic material that radiate outward from a collapsing caldera at speeds of 80 to 320 kph (50 to 200 mph). Bandelier pyroclastic flows created the Pajarito Plateau and covered more than 21 km (13 mi) across the western Española basin.

As a result of work by Smith and Bailey, along with USGS colleague C. S. Ross (Smith and Bailey 1966; Bailey et al. 1969), the Bandelier Tuff became what is probably the world's most famous ash-flow tuff (Goff 2009). The term "Bandelier Rhyolite Tuff" was first used by H. T. U. Smith (1938, figure 4, p. 937), who mapped the tuff in the Abiquiu quadrangle, Rio Arriba County, north-central New Mexico, on the northern side of the Jemez Mountains. Today, geologists have subdivided the Bandelier Tuff into three formal members—La Cueva, Otowi, and Tshirege (fig. 10; Gardner et al. 2010; Goff et al. 2011; Kelley et al. 2013).

La Cueva Member

The La Cueva Member consists of rhyolitic pyroclastic flows and ash fall that predate the Otowi Member; it has argon-40/argon-39 ($^{40}Ar/^{39}Ar$) ages of 1.85 ± 0.07 and 1.85 ± 0.04 million years ago (Spell et al 1996). The La Cueva Member is volumetrically smaller than the other two members but lithologically very similar. Smith (1979) described the material as part of an early leakage of the Bandelier magma chamber. This preliminary eruption took place some 200,000 years before the formation of Toledo caldera and the eruption of the Otowi Member.

The La Cueva Member was previously called the San Diego Canyon ignimbrites by Self et al. (1986). In addition to San Diego Canyon, the La Cueva Member is found in the walls of Valles caldera, underlying Redondo Peak, as thin beds layered with the Puye Formation north of Los Alamos, and beneath the Otowi Member in the lower reaches of Alamo Canyon in Bandelier National Monument (Gardner et al. 2010). The proposed type locality is in a canyon known informally as "Cathedral Canyon," so named for the spectacular tent rocks developed in the Otowi and La Cueva members (Gardner et al. 2010). The type locality is the feature labeled "Tent Rocks" on the Jemez Springs USGS 7.5-minute topographic map (see "Tent Rocks" section). The La Cueva Member is not included in the GRI GIS data.

Otowi Member

The Otowi Member erupted during formation of the

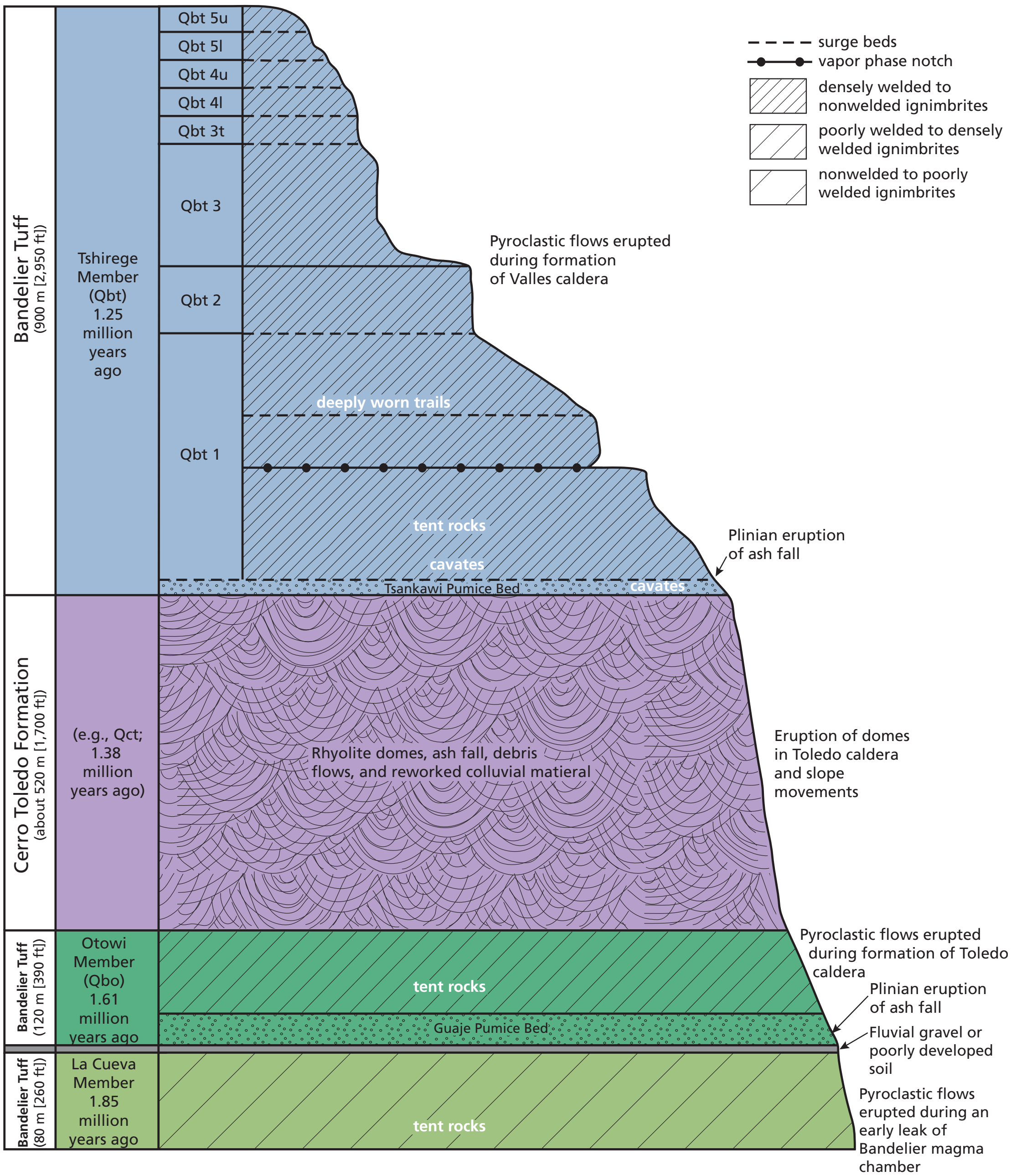


Figure 10. Stratigraphic column for Bandelier Tuff. Bandelier Tuff is divided into three members: La Cueva, Otowi, and Tshirege. Notably, in no one place—neither within nor beyond Valles caldera—can the entire stratigraphic column be seen. The two gigantic explosions that deposited the Otowi and Tshirege members were separated by about 400,000 years, during which time rhyolite domes erupted in Toledo caldera; lava flows, domes, ash, and colluvial material from slope movements at that time make up the Cerro Toledo Formation. About 200,000 years separates deposition of the La Cueva and Otowi members. The Tshirege Member has no major unconformities between its flow units, neither within nor outside Valles caldera. The lack of sediments, debris flows, lacustrine deposits, lava flows, or soils suggests that the Tshirege Member was emplaced in a relatively short period of time, possibly less than a week or two and certainly less than a few months. Geologists have divided the Tshirege Member (Qbt) into subunits using geologic, stratigraphic, chemical, and mineralogical data. The Qbt1 subunit contains cavates, trails, and tent rocks. In the Tsankawi Section of Bandelier National Monument, some cavates occur in the underlying Tsankawi Pumice Bed. Like the Tshirege Member, the Otowi and La Cuesta members host tent rocks. Graphic by Trista Thornberry-Ehrlich (Colorado State University) after Broxton and Reneau (1995, figure 4), Warren et al. (2007, figure 2), information from Gardner et al. (2010), Sussman et al. (2011, figure 3), and Goff et al. (2014, figure 3).

Toledo caldera. It has $^{40}Ar/^{39}Ar$ ages of 1.61 ± 0.01 to 1.62 ± 0.04 million years ago (Izett and Obradovich 1994; Spell et al. 1996). The generally poorly welded Otowi Member varies greatly in thickness as a result of burial of preexisting topography and subsequent erosion (Broxton and Reneau 1996). The maximum thickness of the Otowi Member is 120 m (390 ft) (Goff et al. 2011). The basal unit of the Otowi Member, the Guaje Pumice Bed (**Qbog**), is too thin to have been mapped as a separate unit within the national monument, but exposures of it crop out in several canyons (Fraser Goff, New Mexico Bureau of Geology and Mineral Resources, volcanologist, written communication, 28 April 2015).

Tshirege Member
The Tshirege Member forms the orange to pink cliffs characteristic of the Pajarito Plateau (fig. 11). It erupted in conjunction with the formation of Valles caldera as multiple flows of variable thicknesses. It has an $^{40}Ar/^{39}Ar$ age of 1.25 ± 0.01 million years ago (Phillips et al. 2007). Like the Otowi Member, the variable thickness of the Tshirege Member is associated with burial of preexisting topography and subsequent erosion (Broxton and Reneau 1996). The maximum thickness of the Tshirege Member is 900 m (2,950 ft) (Goff et al. 2014).

Since the 1960s, geologists studying volcanism of Valles caldera have identified and divided the Tshirege Member into numerous distinct units. Smith and Bailey (1966) first defined five (I through V) "cooling units" for the entire Jemez Mountains volcanic field. A "cooling unit" consists of a single flow or a sequence of flows that cooled as a single entity. Later workers defined various subunits for the Pajarito Plateau that closely corresponded to the original definitions (Broxton and Reneau 1995). More recently, Goff et al. (2014) revised the stratigraphy of the Tshirege Member to include more subunits (fig. 10), reflecting the evolution of the Bandelier magma chamber and associated eruptions.

The cliffs in Frijoles Canyon are composed of subunit 1 (**Qbt1**; fig. 10). This subunit was originally divided into a lower glassy part (**Qbt-1g**; g for "glassy") and an upper devitrified (crystalline) part (**Qbt-1v**; v for "vapor phase") by Vaniman and Wohletz (1990; 1991). A vapor-phase notch—a thin, horizontal zone of preferential weathering—forms an easily recognizable horizon throughout much of the Pajarito Plateau. This notch, which was first described by Crowe et al. (1978),

Figure 11. Photograph of Tshirege Member of Bandelier Tuff. The lower part of subunit Qtb1 (see fig. 10) of the Tshirege Member is characterized by the presence of abundant volcanic glass, lack of welding, and a distinctive Swiss cheese–like appearance. These characteristics allowed for the excavation of cavates. The tuff shown in the figure is of a cliff face above Long House in Frijoles Canyon. National Park Service photograph by Ron Kerbo (Geologic Resources Division).

marks the transition from glassy tuffs to the crystallized tuffs in subunit **Qbt1**. The bench of the vapor-phase notch marks the base of the "**Qbt-1v** unit"; in the most recent revision of Tshirege Member stratigraphy, the "v" and "g" designations of this subunit were dropped (Goff et al. 2014).

The base of the Tshirege Member consists of the Tsankawi Pumice Bed, which is found in only a few gullies around Valles caldera (Goff 2009). It was not mapped as a separate unit in Bandelier National Monument (see GRI GIS data). The Tsankawi Pumice Bed is less than 2 m (7 ft) thick and consists of a pyroclastic surge deposit that is composed of thin, stratified layers of pumice (fig. 10; Goff et al. 2011). Pyroclastic surge deposits represent turbulent flow as an eruption column collapses.

Features in Bandelier Tuff
The soft and easily eroded nature of Bandelier Tuff allowed the deep Frijoles Canyon to be incised by El Rito de los Frijoles (Frijoles Creek), and then provided an ideal setting for a prehistoric Puebloan community (Dunbar 2010a). Ancient peoples carved dwellings, called "cavates," into cliffs of the Tshirege Member. They also eroded, and in some cases intentionally constructed, a trail system in the member. In addition

to these culturally significant features, distinctive tent rocks (hoodoolike features) formed in all three members of Bandelier Tuff.

Cavates

Bandelier Tuff and cavates (hollowed-out chambers) go hand-in-hand. According to Toll (1995, p. 2), "although it is not possible. . .to draw the absolute limits of cavate distribution in northern New Mexico, there is little doubt that the line would follow the boundaries of the Bandelier Tuff."

During the 12th through 16th centuries, ancestral Puebloans who lived on the Pajarito Plateau hollowed out these chambers in cliff walls. In Bandelier National Monument, abundant cavates were excavated in several canyons, notably Frijoles. In addition, cavates were excavated on the southern and eastern slopes of the mesa at the Tsankawi unit of the monument (Toll 1995).

Today, cavates appear as groups of chambers in the lower cliff faces. When they were in use, however, most were concealed back rooms of larger cliff-side villages constructed of masonry. Most of the masonry structures have collapsed (see "Cavate Deterioration" section).

By definition, cavates are primarily the result of excavation of the Bandelier Tuff by humans (Toll 1995). Geologic factors such as welding and surface weathering, however, influenced where excavation occurred. Using tools such as digging sticks and sharpened stones, builders pecked, carved, and chiseled out nonwelded tuff, cutting progressively deeper into the cliff face until a room reached a desired shape and size. In locations where cavates were excavated, the tuff is commonly "case hardened" by dissolved silica that reprecipitated as a thin crust on the canyon wall. Breaking through this outer hard layer provided access to more easily worked material (Kiver and Harris 1999).

Most cavates were carved into the lowest part of the Tshirege Member (unit **Qbt1**; fig. 10), which is white-to-gray nonwelded tuff that weathers to pale orange. This portion of the Tshirege Member has a distinct "Swiss-cheese" appearance, containing abundant holes as much as 1.5 m (5 ft) across (fig. 11). These holes are caused by preferential erosion of pumice clasts in the unit (Goff 1995), which are commonly 2 to 5 cm (0.8 to 2 in) across but can be as much as 14 cm (6 in) across (Broxton et al. 1995). With the loss of these clasts, large holes penetrated case-hardened cliff faces and exposed the soft underlying material to further wind and water erosion (Broxton et al. 1995).

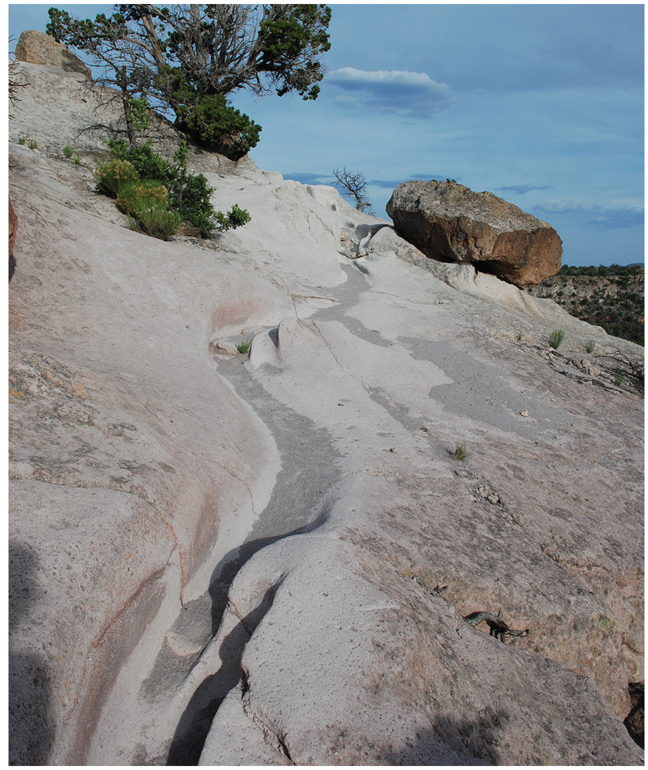


Figure 12. Photograph of trail in Bandelier Tuff. Generations of use have worn a trail into Bandelier Tuff at the Tsankawi Section of Bandelier National Monument. National Park Service photograph by Sally King (Bandelier National Monument), available at http://www.nps.gov/band/photosmultimedia/photogallery.htm (accessed 20 August 2014).

Although most of the cavates occur in subunit **Qbt1** (fig. 10) of the Tshirege Member, the stratigraphically lowest cavates at Tsankawi Section were hollowed out of a distinctive reddish layer of the tuff—the Tsankawi Pumice Bed of the Tshirege Member (fig. 10). This layer contains large chunks of pumice and is much softer than the overlying gray tuff at this location. Toll (1995) noted that Tsankawi Pumice Bed is thicker at this location than elsewhere (as described by Bailey et al. 1969).

Trails

Ancestral people of the Pajarito Plateau developed a trail system that originally stretched for hundreds of kilometers (Snead 2005). The same soft bedrock that allowed ancient inhabitants to carve cavates into sheer canyon walls became eroded by the passage of human feet (fig. 12). Many of these trails show signs of having

Figure 13. Photograph of petroglyphs at Tsankawi Mesa. Some ancient trails, still used today, are “announced” by petroglyphs. The examples shown in the figure are part of the interpretive trail in the Tsankawi Section of the monument. They were pecked and chipped into subunit Qbt2 (see fig. 10) of the Tshirege Member of Bandelier Tuff. National Park Service photograph by Sally King (Bandelier National Monument).

been constructed intentionally, for example, with steps carved into bedrock by hand (Snead 2005).

The trail system in the Tsankawi Section of the monument linked mesa-top homes to fields and springs in the canyons below. Deeply worn sections of the trail occur in the upper part of subunit **Qbt1** (fig. 10). By contrast, subunit **Qbt2** is relatively resistant to erosion and constitutes the main cap rock of the mesas on the eastern side of the Pajarito Plateau (Reneau and McDonald 1996).

Many petroglyphs—pictures or signs, consisting of humanlike figures and geometric forms (fig. 13)—pecked or chipped into **Qbt2** probably served as trail markers. Petroglyphs along the trail usually appear on rock faces where people climbing up from below could easily see them (Snead 2005). Although the symbolic repertoire of trail markers is not understood today, a reasonable conclusion is that they were indicators of territory or local identity that people traveling through would have readily recognized (Snead 2005).

Tent Rocks

Conical, teepee-shaped landforms (fig. 14)—locally called “tent rocks” by Griggs (1964)—occur in all three members of Bandelier Tuff. Notable tent rocks in the Otowi Member occur along the rim of Valles caldera and in Alamo Canyon. In the Tshirege Member (particularly the lower part of subunit **Qbt1**; fig. 10), tent rocks occur in Frijoles Canyon (Griggs 1964; Self et al. 1996; Dethier and Kampf 2007; Jacobs and Kelley 2007). Tent rocks are also common in some tuffs of the Valle Toledo Member of the Cerro Toledo Formation (Gardner et al. 2010), parts of the Puye Formation, and parts of the volcaniclastic sequence interbedded within the Paliza Canyon Formation (Fraser Goff, New Mexico Bureau of Geology and Mineral Resources, written communication, 28 April 2015).

Scientific literature describing the origin of tent rocks at Bandelier National Monument is lacking, though Griggs (1964, p. 48) noted that tent rocks are “erosional remnants.” Hoard (1989) suggested that some tent rocks along the Falls Trail may represent areas where hot ash (heated from fumaroles) flowed over small bodies of

Figure 14. Photograph of tent rocks. Conical, teepee-shaped landforms, locally called "tent rocks" by Griggs (1964), occur in all members of the Bandelier Tuff. The tent rocks in this photograph are in the Tshirege Member in Frijoles Canyon, adjacent to Tyuonyi. National Park Service photograph, available at https://www.flickr.com/photos/bandeliernps/4749225916/ (accessed 26 December 2014).

water. The resultant steam caused chemical reactions that hardened the ash at these locations, making them more likely to be preserved as tent rocks as the softer surrounding rock eroded away. Commonly, a large boulder or cobble will cap tent rocks. This has led to all kinds of speculations about earthquake magnitudes and stability of the Pajarito Plateau (Fraser Goff, New Mexico Bureau of Geology and Mineral Resources, written communication, 28 April 2015).

Tent rocks have similarities to pillarlike, erosional "hoodoos" common in some parks on the Colorado Plateau such as Bryce Canyon National Park (see National Park Service 2014b and the GRI report by Thornberry-Ehrlich 2005). The conical shape of tent rocks, however, is typically found in volcanic rocks whereas hoodoo pillars usually form in sedimentary rocks.

Notable examples of tent rocks formed in tuff outside of Bandelier National Monument include the Peralta Tuff Member in Kasha-Katuwe Tent Rocks National Monument, which is southwest of Bandelier National Monument and administered by the Bureau of Land Management (see Smith 1996; Dunbar 2010b). Like Bandelier, Kasha-Katuwe is part of the Jemez Mountains volcanic field. The Clarno Formation (tuff beds) in John Day Fossil Beds National Monument, Oregon (Merriam 1901), also host tent rocks (see the GRI report by Graham 2014), as do the Rhyolite Canyon Tuff in Chiricahua National Monument, Arizona (Enlows 1955; see the GRI report by Graham 2009), and Racer Canyon Tuff in Washington County, Utah (Cook 1960). Perhaps the most spectacular tent rocks in the Jemez Mountains are in the Puye Formation of Rendija Canyon north of Los Alamos (Fraser Goff, New Mexico Bureau of Geology and Mineral Resources, written communication, 28 April 2015).

Rio Grande Rift

Spanning 1,000 km (600 mi), from Chihuahua in northern Mexico to Leadville in central Colorado, the Rio Grande rift is a major feature of crustal extension stretching across New Mexico (fig. 15). The southern part of the rift began to pull apart about 36 million years ago (Eocene Epoch; fig. 1). In the north, rifting began

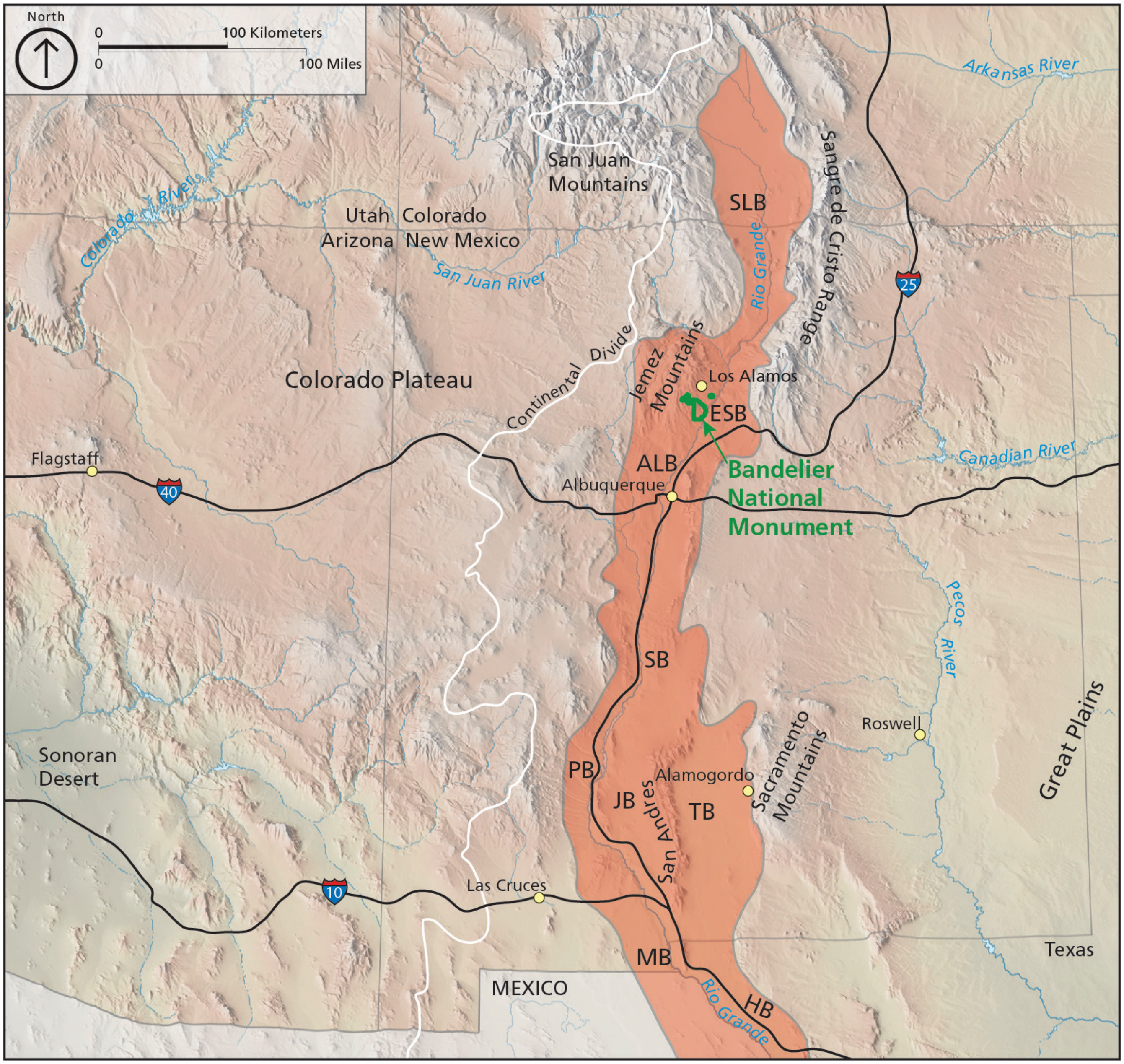


Figure 15. Map of the Rio Grande rift. Bandelier National Monument lies on the western edge of the Española basin, which is one of nine basins along the Rio Grande rift. These basins have dropped down as Earth's crust has pulled apart in the rift. From north to south, these basins are the San Luis basin (SLB), Española basin (ESB), Albuquerque basin (ALB), Socorro basin (SB), Palomas basin (PB), Jornada basin (JB), Tularosa basin (TB), Mesilla basin (MB), and Hueco basin (HB). Graphic by Trista Thornberry-Ehrlich (Colorado State University) after Connell et al. (2005). Base map by Tom Patterson (National Park Service).

about 22 million years ago (Miocene Epoch) (Price 2010).

Santa Fe Group

As the Rio Grande rift began pulling apart, basins such as the Española basin dropped down along normal faults (fig. 16) and sediments began filling them. In parts of the Española basin, sediments are as much as 1,450 m (4,800 ft) thick (Galusha and Blick 1971). These rift sediments, referred to as the Santa Fe Group, include material deposited by the ancestral Rio Grande. Modern alluvium and terrace deposits are not included as part of the Santa Fe Group (Spiegel and Baldwin 1963).

According to Kelley et al. (2013), the two primary formations within the Santa Fe Group are the Tesuque Formation (19 million–13.5 million years old), which

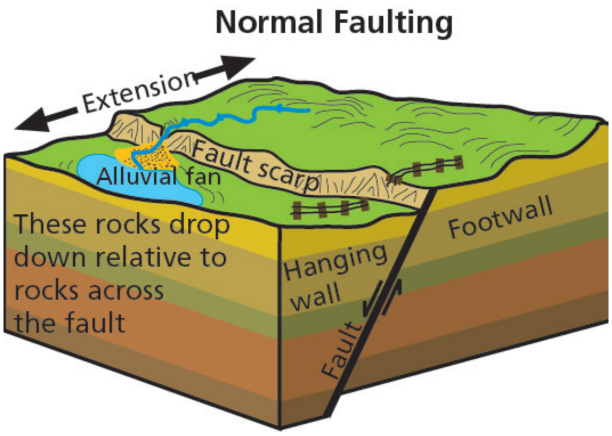


Figure 16 (above). Schematic illustration of a normal fault. The Pajarito fault zone, which displaces the Bandelier Tuff in Bandelier National Monument, consists of normal faults. Faulting occurs along a fault plane. Footwalls are below the fault plane and hanging walls are above. In a normal fault, crustal extension (pulling apart) moves the hanging wall down relative to the footwall. A steep cliff or topographic step, called a "fault scarp," separates the upthrown and downthrown sides of the fault. In the presence of a stream, an alluvial fan may form at the base of a fault scarp. Graphic by Trista Thornberry-Ehrlich (Colorado State University).

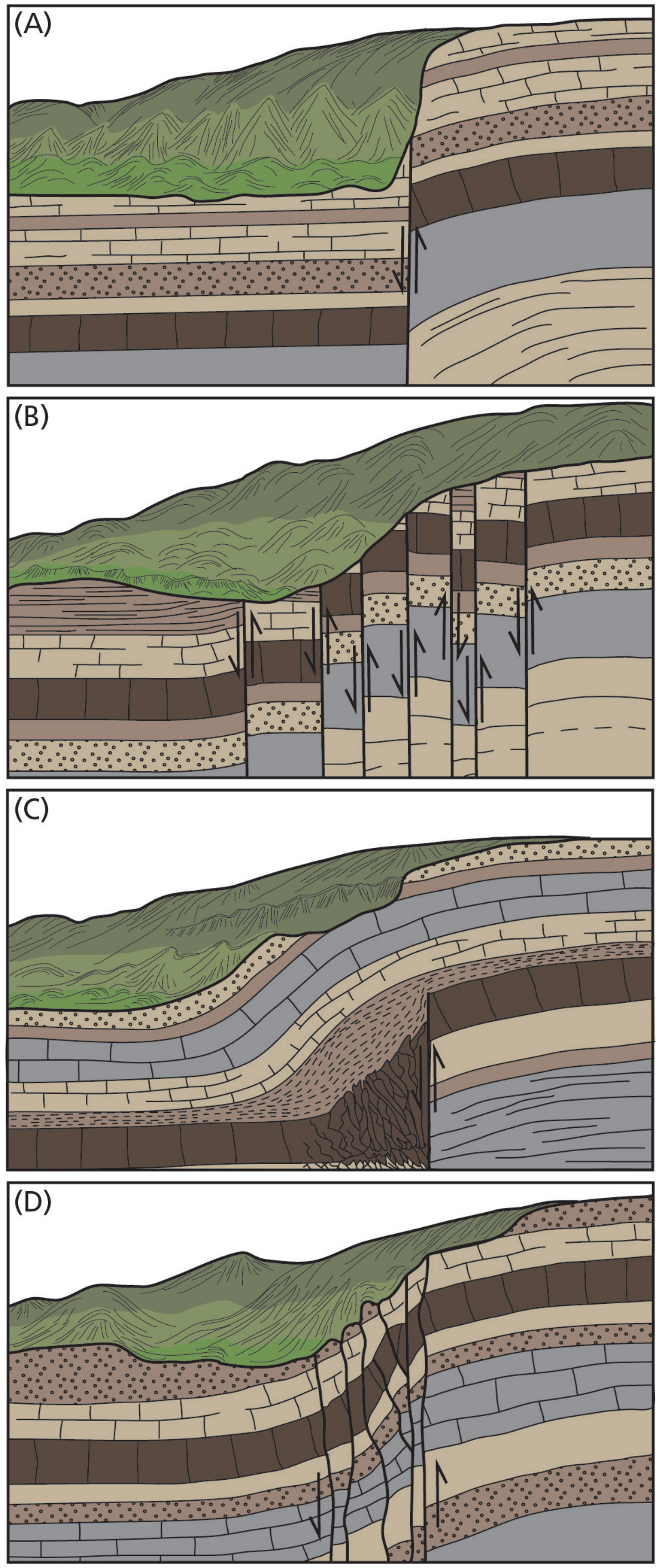


Figure 17 (right). Schematic illustration of surface expressions of deformation within normal fault zones. The structural geology of Bandelier National Monument is dominated by normal faulting within the Pajarito fault zone. The figure shows a series of schematic sketches, originally drawn by John Wesley Powell in 1873, that highlight the contrasting styles of deformation that investigators have mapped along strike in the Pajarito fault zone. Along the strike of a given structure, deep-seated normal faulting can be expressed at the surface as a spectrum of styles that show a simple normal fault with prominent scarp (A), broad zone of small normal faults (B), monocline with normal fault at depth (C), and faulted monocline (D). This figure does not represent actual cross sections at Bandelier National Monument. Graphic by Trista Thornberry-Ehrlich (Colorado State University) after Powell (1873) and Gardner et al. (1999, figure 10).

is the principal basin-filling unit in the region, and Chamita Formation (13.5 million–7.5 million years old). The Tesuque Formation consists of sandstone (**Tstc**) and basalt flows (**Tstb**). The Chamita Formation (**Tscv**) is sandstone, composed of fluvial sand and gravel (Koning et al. 2005).

Minor amounts of basaltic lava extruded into Santa Fe Group sediments from roughly 25 million to 16 million years ago (late Oligocene to Miocene; fig. 1), thus providing an indication for timing of deposition (Goff 2009). As mapped by Dethier et al. (2011), some basalt flows and cinders (**Tsfb**) that erupted into the rift occur near the southwestern boundary of Bandelier National Monument.

The youngest member of the Santa Fe Group in Bandelier National Monument is the axial channel facies (**QTsfa**). This unit represents the main channel of the ancestral Rio Grande flowing in the deepest part of the valley. The rock unit is interlayered with 2.5-million-year-old basalt flows from the Cerros del Rio volcanic field (Bachman and Mehnert 1978).

Pajarito Fault Zone

The Pajarito fault zone, which runs across Bandelier National Monument, delineates the western active margin of the Rio Grande rift (see "Seismic Activity" section). The zone is composed of numerous unnamed and named faults (e.g., Cerro Colorado, Cerro Micho, Cerro Portillo, Cochiti Cone, Cochiti, East Buckman, Pines Canyon, San Ildefonso, Totavi, Twin Hills, West Buckman, and White Rock faults; see GRI GIS data). In map view, the main trace of the fault zone is 1.5 to 3 km (0.9 to 2 mi) wide and about 50 km (30 mi) long. The swath of deformation consists of north–south-oriented normal faults (figs. 16 and 17) where rocks have moved down to the east, forming a prominent 120-m- (390-ft-) high escarpment (Olig et al. 1996). Topographically, the fault zone defines the boundary between the mountains and mesas (Broxton and Vaniman 2005; Jacobs and Kelley 2007). Vertical displacement along the fault zone ranges from about 40 m (130 ft) to more than 200 m (660 ft) (Olig et al. 1996; Gardner et al. 1999; Goff et al. 2002a, 2002b). Displacement of the 1.25-million-year-old Tshirege Member in Frijoles Canyon is about 145 m (480 ft) (Reneau 2000). The amount of displacement is highest in the central part of the fault zone and decreases north of Los Alamos Canyon where the fault zone is primarily exposed as a monocline (one-limbed fold in otherwise flat-lying strata; fig. 17) (Olig et al. 1996). This monocline is delineated as a "fold" in the GRI GIS data.

Cerros del Rio Volcanic Field

As a consequence of extension, Earth's crust has thinned within the Rio Grande rift, allowing higher heat flow from Earth's mantle to reach the surface. Some volcanism in the monument area occurred in

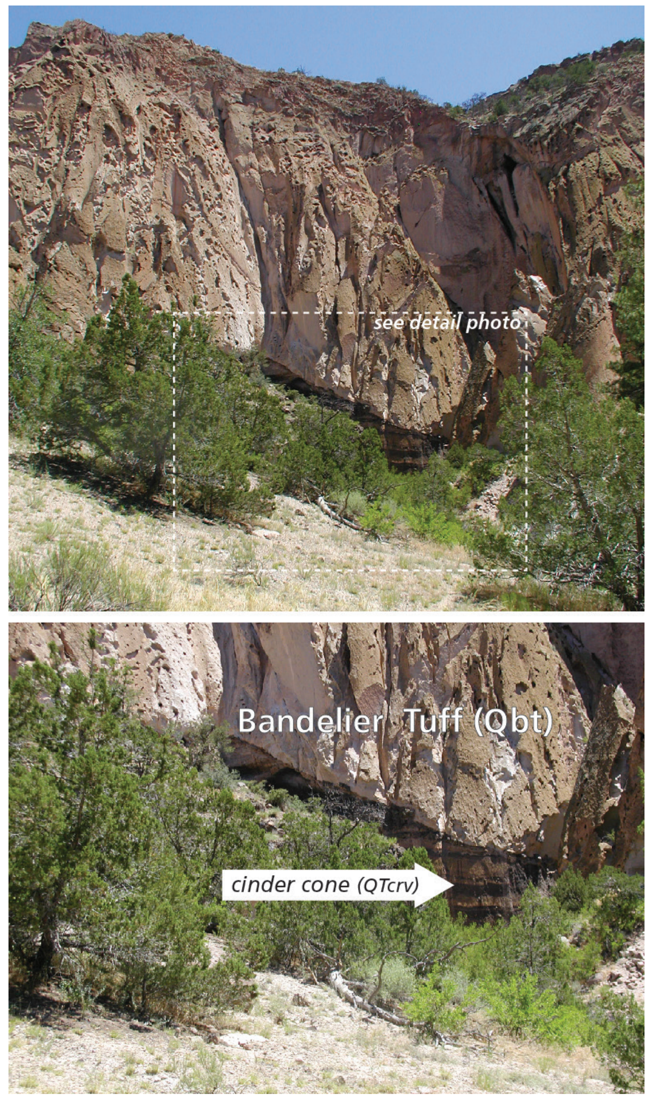


Figure 18. Photographs of a Cerros del Rio cinder cone. The Tshirege Member of the Bandelier Tuff (Qbt) overlies a Cerros del Rio cinder cone (QTcrv and as indicated by arrow) near Upper Frijoles Falls in Frijoles Canyon. About 3 million years ago, basalt erupted as part of the Cerros del Rio volcanic field and built up this cone. At 1.25 million years ago, a pyroclastic flow composed of Bandelier Tuff emanating from the Valles caldera covered the cinder cone. Photographs by Katie KellerLynn (Colorado State University).

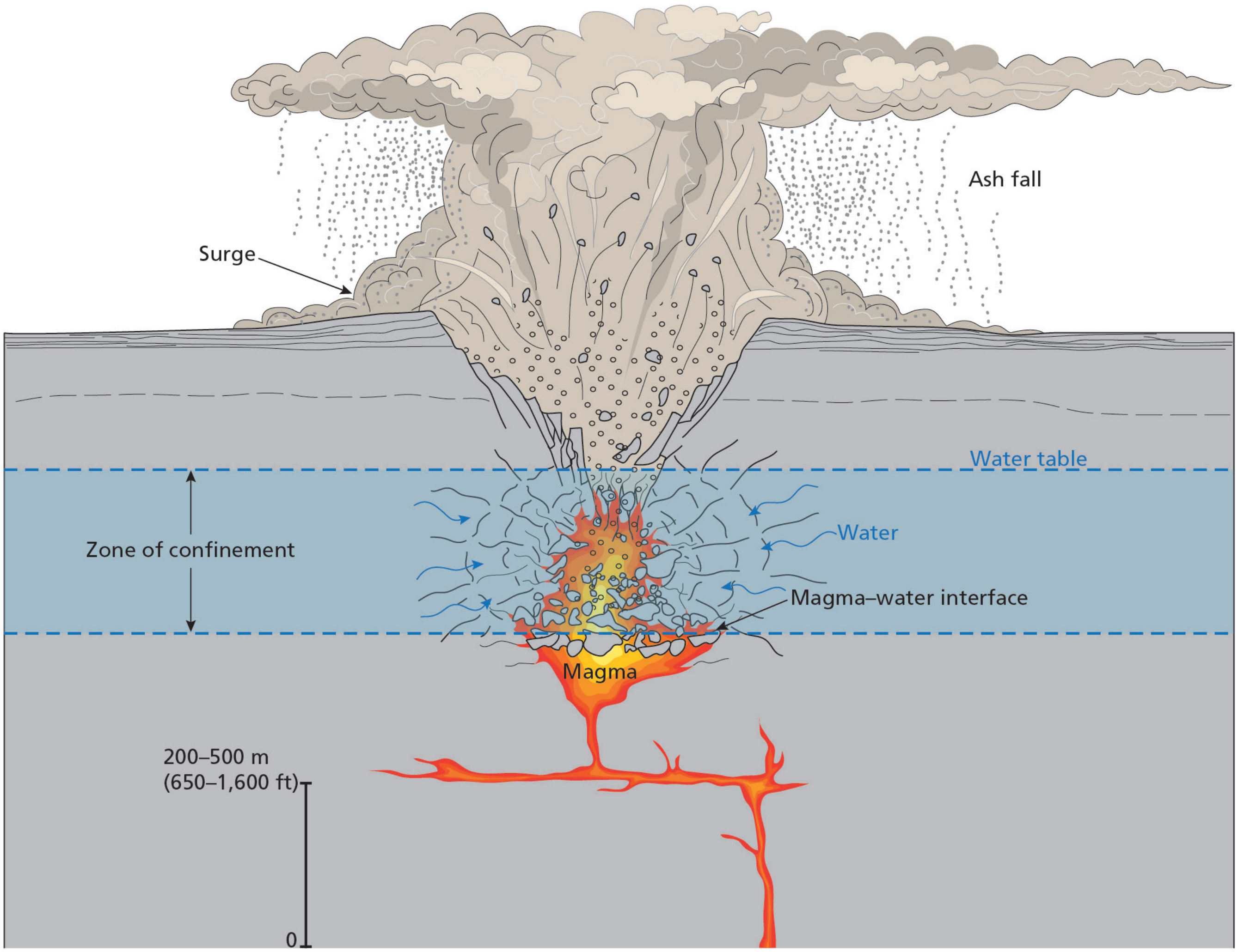


Figure 19. Schematic illustration of a maar explosion. During phreatomagmatic eruptions in the Cerros del Rio volcanic field, explosive magma–water interactions formed maar deposits. Graphic by Trista Thornberry-Ehrlich (Colorado State Univerisyt) after Heiken et al. (1996, figure W11) and Wohletz and McQueen (1984).

connection with the development of this rift. For example, lava erupted from a group of vents at the edge of the Española basin. These vents were part of the Cerros del Rio volcanic field and are now buried under rocks of the Jemez Mountains volcanic field.

The Cerros del Rio volcanic field was one of three peripheral volcanic fields to the Jemez Mountains; the other two were El Alto and Santa Ana Mesa. The Caja del Rio basalt plateau east of the Rio Grande (river) is a major geographic feature associated with the Cerros del Rio volcanic field (fig. 6).

Cerros del Rio volcanic rocks (**QTcrv**) and other rocks of this volcanic field (**Tcbm**, **Tcbc**, **Tcba**, and **Tclf**) erupted between about 2.7 million to 1.0 million years ago. Most Cerros del Rio eruptions took place before the formations of the Toledo and Valles calderas, though some late-stage eruptions post-date the Tshirege Member (1.25 million years ago; Thompson et al. 2011).

Cerros del Rio volcanic rocks are primarily basaltic, with silica contents ranging mainly from 48% to 60%, but as high as 65% (table 1; Koning and Read 2010). Ancestral Puebloans used higher silica volcanic rocks such as dacite (63%–68% silica) from this volcanic field for tool making (see “Lithic Resources” section).

Peripheral volcanic fields were dominated by cinder cones and low shield volcanoes (fig. 5). Frijoles Canyon contains the remains of a Cerros del Rio cinder cone (fig. 18). The Cerros del Rio volcanic field also is marked by maar volcanoes that formed when hot, rising magma interacted with a water source, such

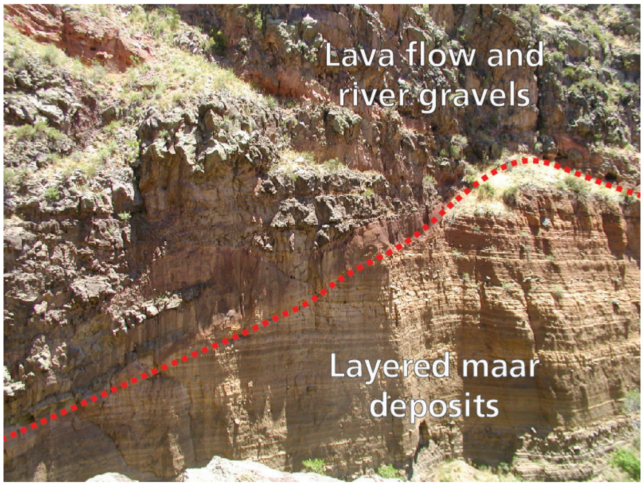


Figure 20. Photograph of maar and lava flow in Frijoles Canyon. Colorful, bedded rock layers along the Falls Trail are maar deposits overlain by a massive lava flow and river gravels. A maar volcano in the Cerros del Rio volcanic field created these deposits as magma interacted with groundwater and/or surface water associated with the ancestral Rio Grande. Photograph by Katie KellerLynn (Colorado State University).

as shallow groundwater, a stream, or a lake (fig. 19). These eruptions are "phreatomagmatic," with phreato meaning "reservoir" or "well" in Greek. In the case of Cerros del Rio maar volcanoes, magma-water interactions occurred near the ancestral Rio Grande (Aubele 1978; Dethier 1997; Heiken et al. 1996). Fittingly, the name "Cerros del Rio" means "Mountains of the River" in Spanish. A maar volcano—about 3 km (2 mi) across and 30 m (100 ft) high at the crater rim—is exposed in Frijoles Canyon (fig. 20). Colorful layered deposits in the canyon walls are remnants of this volcano. Thick Cerros del Rio andesite flows, which probably erupted from a vent east of the ancestral river, overlie maar deposits at this location.

After the maar volcano built up above the level of the water, or water level dropped, the eruption style changed to basaltic lava flows and cinders from intermittent lava fountains. Eventually activity ceased, and lava in the throat of the volcano hardened in place. Today, water cascades over this resistant basalt at Upper Frijoles Falls (fig. 21).

Figure 21. Photograph of Upper Frijoles Falls. Water cascades over resistant basalt, which erupted from the Cerros del Rio volcanic field. The red-bedded deposits are remnants of a maar volcano, which was also part of the Cerros del Rio volcanic field. National Park Service photograph by Hal Pranger (NPS Geologic Resources Division).

Figure 22. Photograph of paleocanyon of the Rio Grande. High on the eastern wall of Frijoles Canyon, Bandelier Tuff fills a large channel of the ancestral Rio Grande (dotted line) that had cut into basalt as it flowed across the Cerros del Rio volcanic field. The modern channel is 2 km (1.2 mi) east of this paleochannel. New Mexico Bureau of Geology and Mineral Resources photograph.

Above Upper Frijoles Falls, Frijoles Canyon broadens. Along the northeastern canyon wall, a paleocanyon of the Rio Grande (river) is exposed (fig. 22). This paleocanyon is a spectacular example of past topography captured in stone and preserved by a pyroclastic flow. The Tshirege Member of Bandelier Tuff (**Qbt**) completely filled this earlier canyon, which the ancestral river created as it ran through the Cerros del Rio volcanic field. Thus 1.25 million years ago, the Rio Grande (river) was located as much as 2 km (1.2 mi) west of the modern river. Moreover, the canyon was much narrower than in modern times, with a maximum width of about 600 m (2,000 ft). Also, the canyon was apparently unmodified by slope movements, such as extensive slumps like those along the modern channel (Reneau et al. 1995).

Lithic Resources

The rocks of the Jemez Mountains yielded a variety of lithic resources, as detailed by Head (1999). People living on the Pajarito Plateau used three primary types to fashion tools for hunting, harvesting, food preparation, defense, and rituals; these are obsidian, dacite, and chert. Sources for these raw materials occur in the vicinity of Bandelier National Monument (fig. 23).

Obsidian

Obsidian (fig. 24) is volcanic glass found most commonly in lava flows or domes of rhyolitic composition. High-quality obsidian is usually jet black and free of bubbles, crystals, and imperfections (Goff 2009). The glassy texture of obsidian is produced by the lack of a crystalline structure and gives rise to conchoidal (smoothly curved, referring to a conch shell) fractures, which are useful for scraping. Conchoidal fractures generally produce razor-sharp edges, useful for cutting. These properties made obsidian a valued resource for making hunting points and cutting tools (National Park Service 2014d). Because of its sharp cutting edge (sharper than stainless steel), obsidian is used in some surgical procedures today (Goff 2009).

Glassy obsidian is abundant in several areas of the Jemez Mountains, including Valles caldera (fig. 23). Cerro del Medio, on the eastern edge of the caldera, is composed of Valles Rhyolite, which contains obsidian. Valles Rhyolite accompanied the development of the resurgent caldera, building up into domes around the perimeter of the uplifted caldera floor (see "Geologic History" chapter). Other domes in the caldera, for example Cerro del Abrigo and Cerros del los Posos, also yield obsidian (Baugh and Nelson 1987), but unlike Cerro del Medio, these other two domes are composed of rhyolite of the Cerro Toledo Formation, which erupted in the Toledo caldera between the eruptions of the Otowi and Tshirege members of Bandelier Tuff.

The Valle Toledo Member of the Cerro Toledo Formation (**Qct**) represents a major source of obsidian, with Obsidian Ridge as its best known locality. Deposits also occur in the walls of Capulin and Alamo canyons. Rabbit Mountain, which is composed of rhyolite (**Qcrm**), has deposits of obsidian. Additionally, blocks of obsidian occur in the Old Rabbit Mountain debris flow (**Qrd1**), which is also part of the Cerro Toledo Formation. Furthermore, erosion through the millennia has transported obsidian into various streams, such as El Rito de los Frijoles, where it occurs in alluvial sediment and stream cobbles (Allen 2004).

Dacite

Lithic assemblages within Bandelier National Monument are commonly 80% or more dacite (Civitello and Gauthier 2013). Cerros del Rio volcanic rocks (**QTcrv**) are the main source of this dacite. Although the Cerros del Rio volcanic field is primarily composed

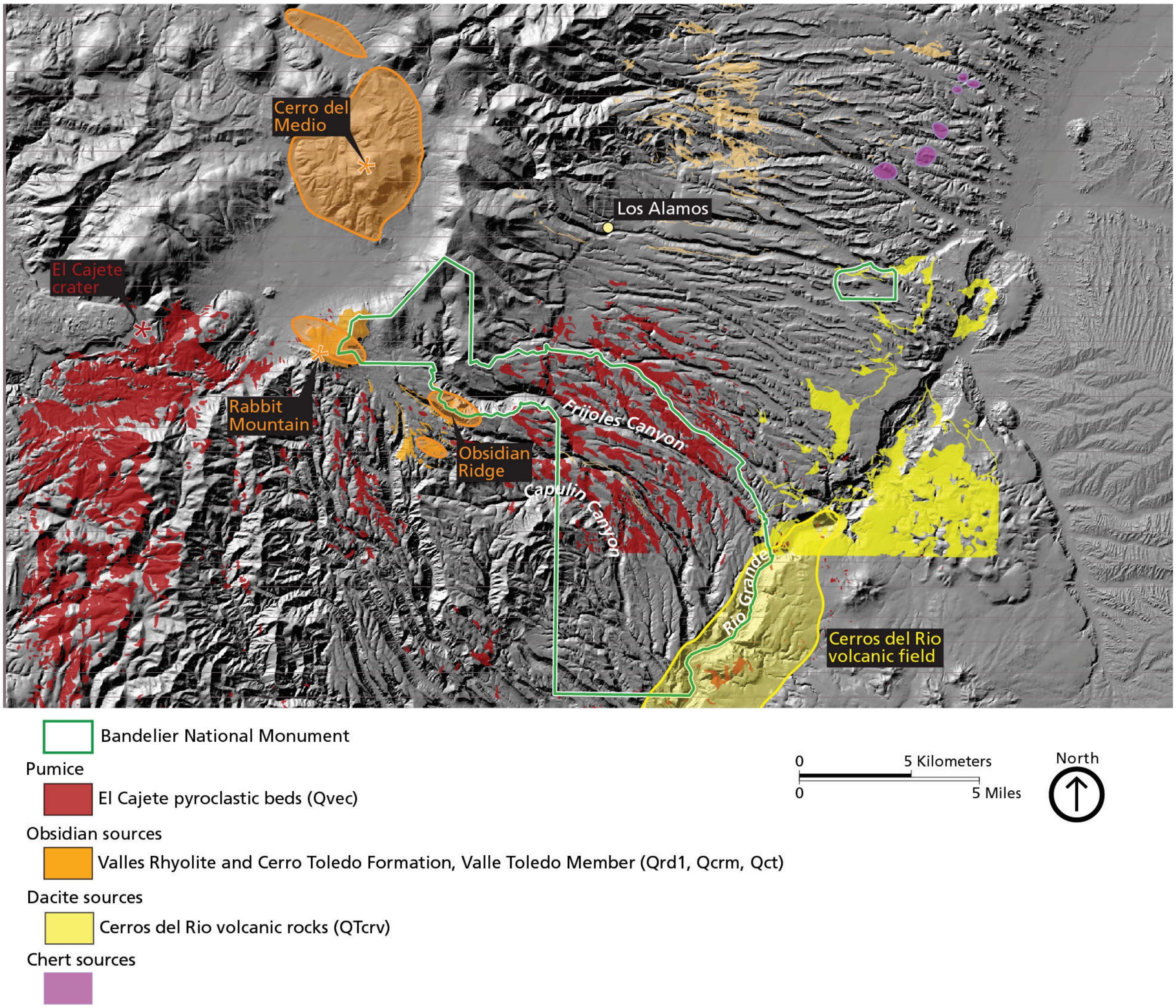


Figure 23. Map of lithic resources. The graphic shows the extent of El Cajete pyroclastic beds (Qvec) and its source (El Cajete crater). Ancestral Puebloans took advantage of the water-retention capabilities of the pumice material for farming. The graphic also shows source areas of obsidian (orange), including Cerro del Medio, Rabbit Mountain, and Obsidian Ridge, and source areas of chert. At the mouths of tributaries to the Rio Grande (within yellow area on the graphic), Cerros del Rio volcanic rocks (QTcrv) yielded dacite suitable for tool making. Bandelier National Monument contains a dacite quarry that exploited this material (see fig. 25). Graphic by Trista Thornberry-Ehrlich (Colorado State University) using GRI GIS data set for Bandelier National Monument and information from Baugh and Nelson (1987), Kilby and Cunningham (2002), Walsh (2005), Gauthier et al. (2007), and Civitello and Gauthier (2013). Digital elevation data from USDA NRCS Geospatial Data Gateway (https://gdg.sc.egov.usda.gov/; accessed 7 May 2015).

of basalt, some dacite (interpreted as remelted crustal material) also occurs (Thompson et al. 2001). This has caused some confusion in archeological studies, where dacite has mistakenly been identified as basalt (Shackley 2011).

Late in the eruption of the Cerros del Rio volcanic field, dacite domes and lava flows extruded onto the surface. Exposures of dacite occur at the mouths of tributary canyons to the Rio Grande (Dethier 1997; Thompson et al. 2011), and include a dacite quarry in Bandelier National Monument that was utilized by ancestral Puebloans. Today, it is a popular field trip stop for archeology students (fig. 25). The dacite quarry at the monument exploited an aphanitic (fine-grained) variety of dacite (table 1).

Figure 24. Photograph of obsidian. Obsidian (volcanic glass) has properties that make it a valuable source for tool making. Conchoidal (smoothly curved) fracturing produces edges useful for scraping. Also, obsidian can be "flaked" into pieces with razor-sharp edges useful for cutting. Photograph by Elaine Jacobs (Los Alamos National Laboratory).

The Tschicoma Formation also contains dacite. Cerro Grande (**Ttcg**), Pajarito Mountain (**Ttpm**), and Sawyer Dome (**Ttsd**) are composed of various dacites of the Tschicoma Formation. Additionally, reworked gravels of late Quaternary stream terraces in Frijoles Canyon are composed of 40% dacite (Reneau 2000). Tschicoma dacites, however, are porphyritic, having abundant coarse-grained crystals, and most are highly porphyritic. Also, the dacite in terrace gravels discussed by Reneau (2000) is porphyritic. The texture of porphyritic dacite would have made it unsuitable for making tools and projectile points (Fraser Goff, New Mexico Bureau of Geology and Mineral Resources, volcanologist, written communication, 28 April 2015).

Chert

Cerro Pedernal ("Flint Peak")—a flat-topped mountain west of the town of Abiquiu, New Mexico, in the northern Jemez Mountains, north of Bandelier National Monument (and beyond the GRI GIS data set)—is the primary source area of Pedernal chert, which occurs within the Miocene Abiquiu Tuff (Smith 1938; Church and Hack 1939). This formation consists of stream-laid tuff and volcanic conglomerate, with a few small interbedded lava flows. Additionally, lenses of the formation crop out in San Pedro Parks, about 20 km (12 mi) to the west/southwest of Cerro Pedernal, and are discontinuously exposed between Cerro

Figure 25. Photograph of dacite quarry. Students participating in an archeological field trip visit the dacite quarry in Bandelier National Monument. Photograph by M. Steven Shackley (taken in 2006, used by permission).

Figure 26. Photograph of El Cajete pyroclastic beds. The presence of El Cajete pumice aided in ancient agriculture. Pumice, which is essentially rhyolitic froth, has the capacity to store water. Also, larger clasts serve as mulch. National Park Service photograph, available at http://www.nps.gov/band/historyculture/artfarm.htm (accessed 21 August 2014).

Pedernal and San Pedro Parks (Kilby and Cunningham 2002). Pedernal chert occurs closer to Bandelier National Monument as cobbles along the Rio Grande (river), perhaps explaining its abundance in the lithic assemblages at many local archeological sites (Acklen 1993).

Pedernal chert is typically translucent and varies in color from white to gray with dendritic and amorphous discolorations ranging from black to red, blue, and yellow. The colors vary widely across small areas of the material and may all be visible within a single small specimen. Pedernal chert is of high quality for flaking (creating flakes of material for tool production), but useful pieces are occasionally limited in size due to "vugs" (cavities) and internal fractures (Kilby and Cunningham 2002).

El Cajete Pyroclastic Beds

After the collapse of Valles caldera, a series of rhyolitic domes erupted within the bowl-shaped depression (see "Geologic History" chapter). El Cajete crater in the southern part of the caldera (see figs. 23 and 38) marks one of the vents that erupted at that time. The El Cajete pyroclastic beds (**Qvec**) were ejected from this vent. During the eruption, the wind blew mostly to the south and east, transporting pumice throughout the southeastern Jemez Mountains. Now, the pumice-rich El Cajete pyroclastic beds serve as a time-stratigraphic marker east, southeast, and south of Valles caldera (Reneau et al. 1996). The El Cajete eruption has been dated at about 60,000–50,000 years ago (Toyada et al. 1995; Reneau et al. 1996). This "marker bed" helps to date rocks and deposits with respect to their relative position to this distinctive layer.

Beginning in the 1200s, ancestral Puebloan populations began to settle and farm areas of El Cajete pyroclastic beds. Even the smallest pumice fields—less than 1 ha (2 ac)—commonly had an ancestral Puebloan "field house" structure associated with them. Surveys within Bandelier National Monument were the first to note the relationship between field houses and pumice soils (Powers and Orcutt 1999; Gauthier and Herhahn 2005).

The pumice clasts in pumice-derived soils are as much as 15 cm (6 in) across. Given the relatively high proportion of these coarse clasts, at first glance pumice-derived soils would seem a poor medium for storing water, which is an essential factor in the success of "dry farming" that relied on precipitation falling directly on the fields. Because pumice is composed of thousands of small, interconnecting cavities, however, its capacity to store water is great. Instead of only storing water between soil particles, pumice stores water within clasts (Gauthier et al. 2007).

A second benefit of soils containing pumice is their ability to insulate as surface mulch (fig. 26). Elsewhere in the northern Rio Grande region Puebloan farmers mulched their fields with gravel and cobbles, which they excavated and then spread over the ground surface (Lightfoot and Eddy 1995; White et al. 1998).

By planting in soils with a surface layer of pumice, Bandelier farmers more than likely would have realized the same benefits of conserving soil moisture and moderating soil temperature without any of the labor required for mulching of other soils (Gauthier et al. 2007).

Paleontological Resources

Published reports of fossils at Bandelier National Monument document a packrat (*Neotoma* spp.) midden; and charcoal, wood, and cones of Douglas-fir (*Pseudotsuga menziesii*) from Holocene deposits in Frijoles Canyon. Spaulding (1992) reported on this midden, which occurs at an elevation of 1,933 m (6,342 ft) near where El Rito de los Frijoles enters the Rio Grande. This midden dates to 3,195 ± 85 radiocarbon years before present (Spaulding 1992), which is 2,878–3,112 calendar years before present, as converted using Stuiver et al. (2015).

Packrat middens are important tools for reconstructing the paleoecology and paleoclimate of the last 126,000 years (late Pleistocene and Holocene epochs; fig. 1) in western North America (Tweet et al. 2012). Thirty-three National Park System units, including Bandelier National Monument, are known to contain packrat middens (Tweet et al. 2012). Packrat middens are primarily examined for plant macrofossils, but also pollen (Anderson and Van Devender 1995), insects (Elias et al. 1992), vertebrates (Mead and Phillips 1981), stomatal density/carbon isotopes in leaves (Van de Water et al. 1994), and fecal pellets (Smith et al. 1995; Smith and Betancourt 1998); the dung of extinct mammals contained in packrat middens yields paleobotanical information (Davis et al. 1984; Mead et al. 1986; Mead and Agenbroad 1992; Hunt et al. 2012).

In addition, charcoal occurs in Holocene terraces, rockfall deposits, and alluvium at the monument. Such material can be used to interpret landscape evolution, including changes in drainages under different climate regimes (Reneau 2000). Reneau (2000) dated 16 charcoal samples from Frijoles Canyon, with ages spanning the past 8,000 years.

Humans were present on the Pajarito Plateau by at least 10,000 years ago (Goff et al. 2002b), and some artifacts made from fossils such as petrified wood or fossiliferous chert have been found at Bandelier National Monument (Tweet et al. 2009). Kenworthy and Santucci (2006) presented an overview of fossils found in cultural resource contexts in the National Park System.

With respect to units older than the Holocene Epoch (see Map Unit Properties Table, in pocket), the Galisteo Formation (**Tgs**), Santa Fe Group (**Tstb**, **Tstc**, **Tscv**, **Tsf**, and **QTsfa**), and unconsolidated Quaternary deposits (**Qp2, 3, 4**; **Qa2, 3, 4**; **Qt**; **Qpa**, **Qa5**; and **Qfa**) are the most likely to contain fossils. Also, fossils may be found in ash deposits of the Bandelier Tuff (**Qbo** and **Qbt**) (Tweet et al. 2009). No fossils at Bandelier National Monument have been reported from these units to date, but fossils from these units are known elsewhere. Future field investigations within the monument may recover fossils from one of more of these units (Tweet et al. 2009).

High-Elevation Features

At high elevations, prevailing temperatures are so low that the ground remains frozen for much, or all, of the year. In such environments, the effects of repeated freezing and thawing and the growth of ice masses in the ground are so pervasive to give rise to a characteristic range of landforms. The highest elevations at Bandelier National Monument occur on the slopes of Cerro Grande; the summit is 3,109 m (10,199 ft) above sea level. Boulder fields, rock glaciers, patterned ground, and felsenmeer are landforms that occur at high elevations in the monument.

Boulder Fields and Rock Glaciers

Goff et al. (2011) mapped boulder fields (**Qrx**) at high elevations at the rim of Valles caldera, including Cerro Grande and Sawyer Dome in Bandelier National Monument. Boulder fields consist of boulders as much as 3 m (10 ft) in diameter derived from the underlying rock unit. They are generally devoid of vegetation. Their thicknesses are unknown. Goff et al. (2011) estimated the age of these features as Pleistocene and Holocene (fig. 1), though the lower limit of Pleistocene timing is uncertain. As a consequence, the connection to ice-age (Pleistocene) conditions is unclear.

Many boulder fields appear to be rock glaciers (Goff et al. 2011), which move in large part through the deformation of interstitial ice or ice cores (Blagbrough 1994). Rock glaciers exhibit flow features such as transverse arcuate ridges (Blagbrough 1994). The Holocene age of these boulder fields suggests that rock glaciers may still be active.

Patterned Ground and Felsenmeer

Patterned ground, consisting of asymmetrical circles, polygons, or stripes of rock, and felsenmeer (German for "sea of rocks") are high-elevation features at Bandelier National Monument (fig. 27), for example, above tree line on Cerro Grande (National Park Service 2005). Unlike rock glaciers, which move as a result of the ice they contain, patterned ground and felsenmeer develop from frost heaving (subsurface freezing of water and the growth of ice masses that lift up soils, rocks, and vegetation).

Patterned ground and felsenmeer have not been thoroughly studied or mapped at Bandelier National Monument and their ages are unknown. However, the observed abundance of felsenmeer at high elevations in the Jemez Mountains may reflect near-glacial conditions during the most recent ice age, known as the Wisconsinan glaciation (Tierney and Potter 1985; Allen 2004), which took place approximately 85,000 to 11,000 years ago.

Galisteo Formation

Although volcanism dominates the geologic story at Bandelier National Monument, the oldest rocks in the monument were deposited by rivers. Between 56 million and 34 million years ago, sediments of the Galisteo Formation (**Tgs**) were deposited in a broad, deep, inland basin (Stearns 1943). The Galisteo Formation, which is primarily sandstone but also siltstone and conglomerate. It predates the Jemez Mountains volcanic field by at least 20 million years. Stratigraphically, the formation unconformably underlies the Santa Fe Group, indicating that a significant period of time passed between final deposition of the Galisteo Formation and initial development of the Rio Grande rift. The Galisteo Formation has been brought to the surface along a fault near the southwestern boundary of the monument (see poster, in pocket). Cannon (1997) noted an exposure of brick red Galisteo sandstone and siltstone in the west wall of Capulin Canyon.

Figure 27. Photograph of felsenmeer. Large, angular blocks of rocks in an accumulation known as felsenmeer, meaning "sea of rocks" in German, are conspicuous displays of frost action on Cerro Grande. National Park Service photograph by Sally King (Bandelier National Monument, taken September 2011).

Geologic Resource Management Issues

This chapter describes geologic features, processes, or human activities that may require management for visitor safety, protection of infrastructure, and preservation of natural and cultural resources in Bandelier National Monument. The NPS Geologic Resources Division provides technical and policy assistance for these issues.

During the 2005 scoping meeting (see National Park Service 2005) and 2014 conference call, participants (see Appendix A) identified the following geologic resource management issues:

- Fires, Fluvial Geomorphology, and Slope Movements
- Cliff Retreat and Rockfall
- Seismic Activity
- Cavate Deterioration
- Volcano Hazards
- Cochiti Dam and Reservoir
- Disturbed Land Restoration
- Paleontological Resource Inventory, Monitoring, and Protection

Resource managers may find *Geological Monitoring* (Young and Norby 2009) useful for addressing these geologic resource management issues. The manual provides guidance for monitoring vital signs—measurable parameters of the overall condition of natural resources. Each chapter covers a different geologic resource and includes detailed recommendations for resource managers and suggested methods of monitoring. An online version of *Geological Monitoring* is available at http://go.nps.gov/geomonitoring (accessed 13 August 2015).

As this report was in final review, the foundation document was completed for Bandelier National Monument (National Park Service 2015). The foundation document lists the following as fundamental resources or values:

- Archeological resources (including cavates)
- Continuing cultural connections
- Science and research
- Natural landscape
- Wilderness
- Museum collection and archives

Other important resources in the monument as identified in the foundation document are recreational values/visitor experiences, New Deal era legacy/Civilian Conservation Corps Historic Landmark District, and other cultural resources. Geologic features and processes and some of the resource management issues described in this chapter affect those values and resources.

Fires, Fluvial Geomorphology, and Slope Movements

Fire has tremendous effects on the landscape of Bandelier National Monument (fig. 28; National Park Service 2014a). Over the last 40 years, the most notable fires affecting the monument were La Mesa Fire in June 1977, which burned 6,180 ha (15,270 ac) in and near Frijoles Canyon and adjacent Santa Fe National Forest; Dome Fire in April 1996, which burned 6,690 ha (16,520 ac) in and near Capulin Canyon and the surrounding Dome Wilderness Area; Cerro Grande Fire in May 2000, which started in upper Frijoles Canyon and burned approximately 19,020 ha (47,000 ac) in the Santa Fe National Forest and Los Alamos National Laboratory; and Las Conchas Fire in June 2011, which burned more than 63,100 ha (156,000 ac), impacting all major watersheds in the monument including more than 75% of Frijoles Canyon. Burn severities were high on 6,600 ha (16,300 ac) or 35% of the total burned area in the monument. The Las Conchas Fire is the largest wildfire in New Mexico's history, to date (National Park Service 2014c).

Fire is a driving component in an interconnected system that includes streamflow, sediment transport, stream channel morphology, and slope movements. In general after each of these fires, peak storm-water flows increased, erosion and corresponding sediment transport increased, channel morphology changed, and debris flows occurred (Cannon and Reneau 2000; Veenhuis and Bowman 2002; Monroe 2012; Jacobs et al. 2014). All of these responses are considered threats to archeological resources in the monument, which are

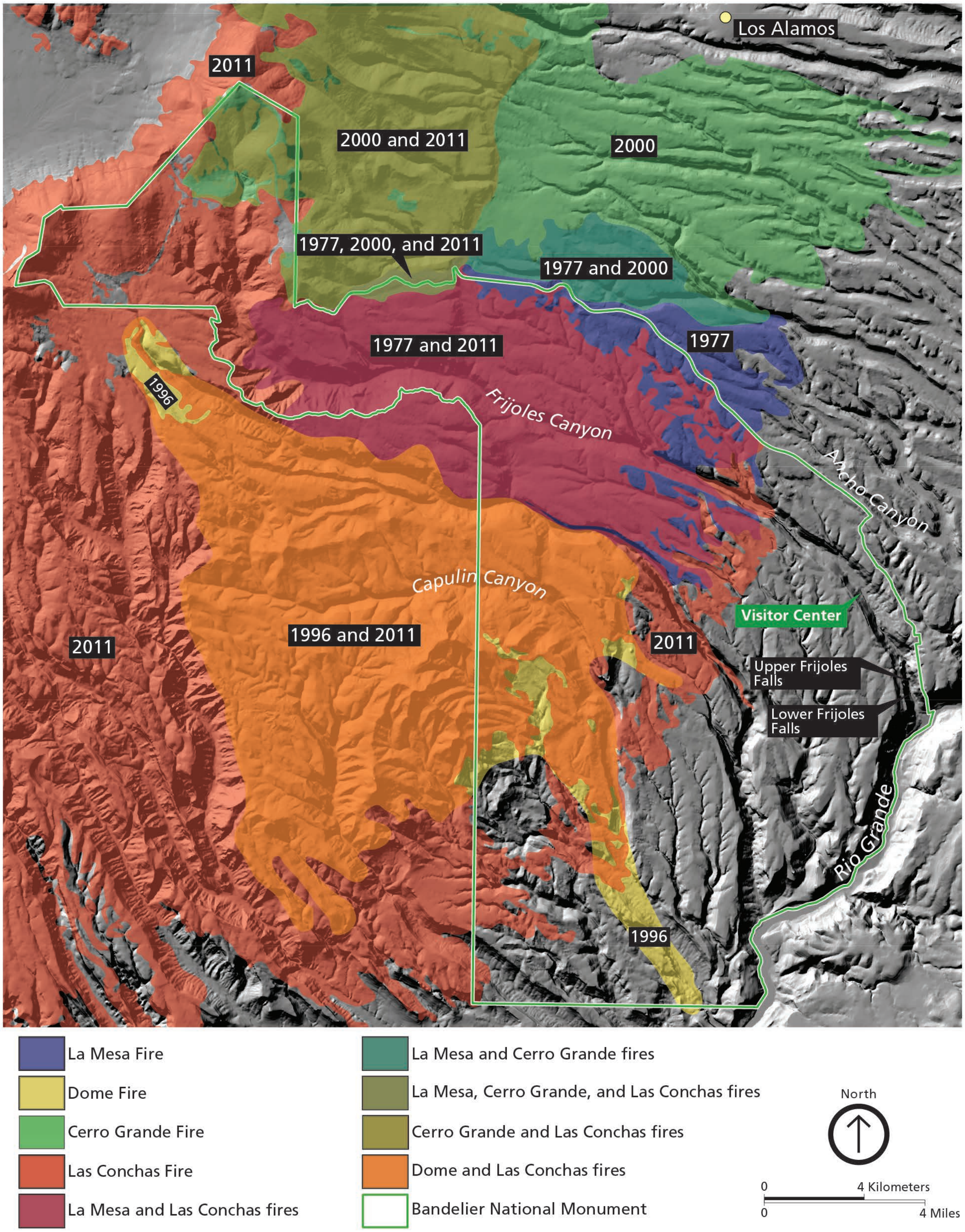


Figure 28. Map of fire extents at Bandelier National Monument. Over the last 40 years, major fires have impacted Bandelier National Monument: La Mesa Fire in 1977, Dome Fire in 1996, Cerro Grande Fire in 2000, and Las Conchas Fire in 2011. After each fire, peak storm-water flows increased, erosion and corresponding sediment transport increased, debris flows occurred, and channel geometry changed in the canyons of the monument. Graphic by Trista Thornberry-Ehrlich (Colorado State University) after Veenhuis and Bowman (2002, figure 1) and Monroe (2012, poster figure). Digital elevation data from USDA NRCS Geospatial Data Gateway (https://gdg.sc.egov.usda.gov/; accessed 7 May 2015).

fundamental resources as defined by the foundation document (National Park Service 2015). As climate continues to change, fire, precipitation, and streamflow patterns will also change. The development of a climate change vulnerability assessment and scenario plan is a high priority for the monument (National Park Service 2015).

Streamflow

Storm–water flow magnitude increases dramatically after a wildfire, varying in response to fire severity, soil characteristics, and weather patterns. The maximum recorded peak flow in Frijoles Canyon before the 1977 La Mesa Fire was 0.5 m^3/s (19 ft^3/s). Following this fire, maximum peak flows in Frijoles Canyon were 86 m^3/s (3,030 ft^3/s) in July 1978 (Veenhuis 2002). After the 2011 Las Conchas Fire, maximum peak flows were 269 m^3/s (9,500 ft^3/s) in September 2013 (US Geological Survey 2014a). During the first year after the La Mesa Fire, annual peak flow was 160 times greater than before the fire. As vegetation reestablished, annual maximum peak flows decreased each year. In the 22 years between 1977 (the year of the La Mesa Fire) and 1999, however, flood magnitudes had not completely returned to pre-fire magnitudes (Veenhuis 2002). By comparison, two months after the Las Conchas Fire, a flood occurred in Frijoles Canyon that was 368 times greater than the largest recorded peak flow prior to 1977. More than two years later (September 2013), the largest flood on record occurred (Stephen Monroe, National Park Service, Southern Colorado Plateau Network, hydrologist, written communication, 28 May 2015).

Additionally, the frequency of large storm-water flows increases in response to wildfire (Veenhuis 2002). For example, after the 1977 La Mesa Fire in Frijoles Canyon, the number of peak storm-water flows greater than the pre-fire maximum flow of 0.5 m^3/s (19 ft^3/s) was 15 in 1977, nine in 1978, and five in 1979 (Veenhuis 2002). The number of peak flows per year in Frijoles Canyon was low from the early 1980s through 2010. During the four years since the 2011 Las Conchas Fire, more than 10 storm-water flows have occurred each year (Stephen Monroe, National Park Service, Southern Colorado Plateau Network, hydrologist, written communication, 28 May 2015).

Sediment Transport

The amount of suspended sediment (and bed load; see “Stream Channel Geometry” section) in a stream increases after a fire (fig. 29). After the 1977 La Mesa Fire, suspended-sediment concentrations showed similar patterns to streamflow; that is, a substantial increase in sediment transport the first year after the fire with a gradual decrease for about three years thereafter.

Figure 29. “Before” and “after” photographs of El Rito de Los Frijoles. Increased sediment load is an outcome of fire, as shown here in Frijoles Canyon. The top photograph shows the El Rito de Los Frijoles channel “before” the 2011 Las Conchas Fire. The bottom photograph shows “after.” National Park Service photographs. Top photograph by Dale Coker (Bandelier National Monument). Bottom photograph available at http://www.nps.gov/band/flashflood.htm (accessed 17 September 2014).

For the first year after the La Mesa Fire, the annual sediment load calculated from regression equations compared to streamflow was 220 times the annual load for the post-recovery period (Veenhuis 2002). For the first four years following the Las Conchas Fire, large volumes of sediment were transported through all of the major drainages at Bandelier National Monument. The National Park Service elected not to re-vegetate or apply other hillslope stabilization treatments to burned areas in Bandelier National Monument and regional drought conditions leading up to the fire continued in subsequent years, slowing re-establishment of slope stabilizing vegetation.

Stream Channel Morphology

After a fire, a stream channel commonly responds to the increased magnitude and frequency of streamflow and the resultant increase in suspended-sediment loads by downcutting and widening. Notably, incision may not occur uniformly along the length of a stream channel. Areas of incision are strongly influenced by lithology. Where exposed in the stream bed, resistant lavas impeded incision in Capulin Canyon following the 1996 Dome Fire (Reneau et al. 1999). Incision also may occur beyond a stream channel proper. For example, as a result of flooding events that followed the Las Conchas Fire—one in July 2013 and two in September 2013 when 19.1 cm (7.52 in) of rain fell in a five day period—notable incision occurred elsewhere (fig. 30). Significant slope and channel erosion took place in Capulin, Alamo, and Frijoles Canyons during each of the four years after the Las Conchas Fire (Stephen Monroe, National Park Service, Southern Colorado Plateau Network, hydrologist, written communication, 28 May 2015).

Prior to the 1996 Dome Fire, the stream channel in Capulin Canyon had a continuous gravel mantle. Post-fire floods excavated large volumes of gravel from the stream bed and locally exposed erodible bedrock (sandstone and nonwelded tuff) beneath the stream bed, triggering rapid incision. As much as 2 m (7 ft) of incision into bedrock took place in 1996 (Reneau et al. 1999). A similar dynamic downcutting also took place following the Las Conchas Fire in Frijoles Canyon (fig. 31; Stephen Monroe, National Park Service, Southern Colorado Plateau Network, hydrologist, written communication, 28 May 2015).

Figure 30. Photograph of post-fire incision. In September 2013 during an epic precipitation and flooding episode when 19.1 cm (7.52 in) of rain fell in five days, slopes were incised and new channels were created. This photograph shows incision on a bench on the northeastern flank of Boundary Peak. Boundary Peak is on the western boundary of Bandelier National Monument. National Park Service photograph by Luke Gommermann (Bandelier National Monument).

Prior to the 2011 Las Conchas Fire, stream channel substrates in both Capulin Creek and Rito de los Frijoles were dominated by cobbles and coarse gravel (Stumpf and Monroe 2012). Extensive post-fire, watershed-scale erosion mobilized large volumes of fine sediments into stream channels. In 2012 substrates in the Capulin and Frijoles channels were primarily sand and gravel, 88% and 90%, respectively (Stumpf and Monroe 2014). These conditions persisted in 2014 (Stumpf in progress).

Following the 1996 Dome Fire, channel aggradation was generally associated with obstructions such as log jams or stands of trees along the channel. Some areas that had aggraded during the first flood after the Dome Fire subsequently were incised by later flood waters. Erosion initiated in Capulin Canyon following the

Figure 31. Photographs of effects of fire in Frijoles Canyon. At Bandelier National Monument, fire is a driving component in an interconnected system that includes streamflow, stream channel geometry, sediment transport, and slope movements. Following the 2011 Las Conchas Fire, some areas of Frijoles Canyon were severely incised while others significantly aggraded. This photo pair shows an area below the Narrows in Frijoles Canyon where bedrock was exposed in the stream channel following the flood event of 26 July 2013 (left). Three months later (October 2013; right), the channel is sediment laden. Photographs by Elaine Jacobs (left; Los Alamos National Laboratory) and Anne Tillery (right; US Geological Survey).

Dome Fire was reactivated by floods after the 2011 Las Conchas Fire (Stumpf and Monroe 2014). The primary effect of repeated flooding was excavation and transport of previously stored channel sediment (Reneau et al. 1999).

At the site of maximum incision following the Dome Fire in Capulin Canyon, the elevation of the channel apparently stabilized within one year, and subsequent channel evolution was dominated by lateral erosion (Reneau et al. 1999). As a result of vegetation recovery in the second year following the fire, magnitude and frequency of peak flows decreased, and the stream channel began to readjust. The channel at the most downstream crest-stage gage, which has the shallowest initial valley slope, showed the first signs of aggradation (Veenhuis 2002).

Floods and Debris Flows

Rainfall following a fire can trigger floods and debris flows. Although both floods and debris flows can be destructive, debris flows can occur with little warning, are capable of transporting large material over relatively gentle slopes, and develop momentum and impact forces that can cause considerable destruction. As a result, mitigation of debris-flow hazards can be more difficult than mitigation of flood hazards (Cannon 2001).

Since the 2011 Las Conchas Fire, many large debris flows have occurred in Frijoles Canyon (Stephen Monroe, National Park Service, Southern Colorado Plateau Network, hydrologist, written communication, 30 March 2015). These have not been studied extensively, but repeat light detection and ranging (LiDAR) imagery was acquired for the Frijoles Canyon

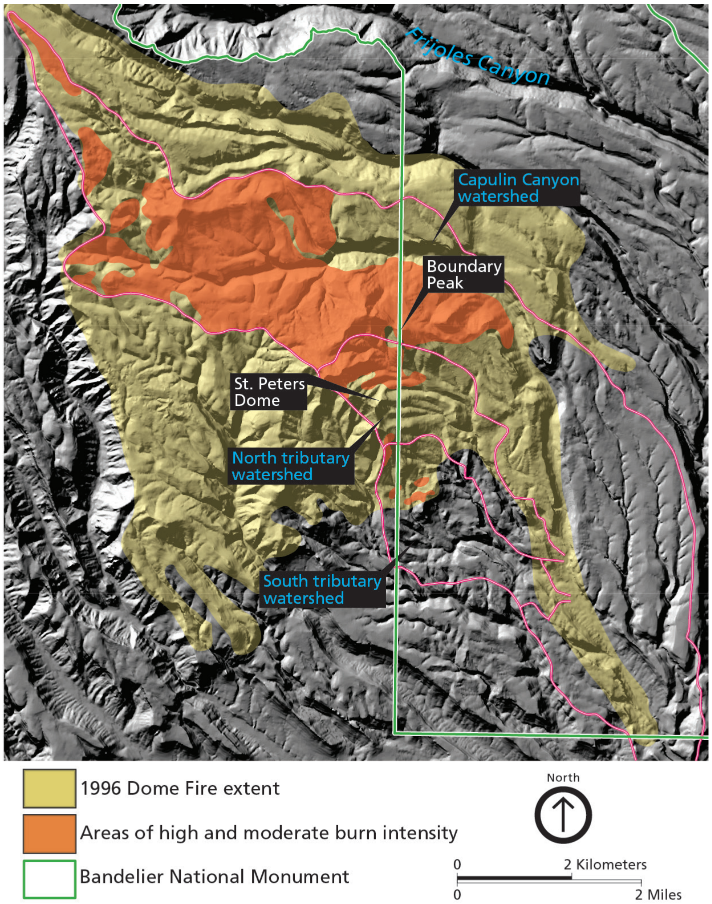


Figure 32. Map of Capulin Canyon watershed. After the 1996 Dome Fire, investigators studied Capulin Canyon in order to identify hillslope, channel, and fire characteristics as indicators of susceptibility for wildfire–related debris flows. The pink lines on the map delineate the Capulin Creek, North Tributary (Red Canyon), and South Tributary (Yellow Canyon) drainage basins. Yellow shading indicates the extent of the Dome Fire. Orange shading indicates areas of high and moderate burn intensities. Graphic by Trista Thornberry-Ehrlich (Colorado State University) after Cannon and Reneau (2000, figure 1). Digital elevation data from USDA NRCS Geospatial Data Gateway (https://gdg.sc.egov.usda.gov/; accessed 7 May 2015).

watershed in May 2010 and again in September 2013. This sequence captured landscape-scale changes that occurred as a result of the Las Conchas Fire (Jacobs et al. 2014). Tillery et al. (2011) provided a preliminary hazard assessment of debris-flow potential from 321 basins burned by the 2011 fire. Models incorporating burn severity, topography, soils, and storm rainfall predicted Frijoles, Alamo, and Capulin canyons to have a greater than 80% probability of debris-flow occurrence.

Cannon and Reneau (2000) found that the factors that best distinguished between debris flow–producing drainages and flood-producing drainages in Capulin Canyon were lithology (rock type and physical characteristics) and drainage-basin morphology, including area, height, average gradient, and ruggedness (basin height divided by the square root of the basin area; Melton 1965). Cannon and Reneau (2000) compared the response of Capulin Creek (i.e., Capulin Canyon basin) and its two tributaries—"North Tributary," locally known as Red Canyon, and "South Tributary," locally known as Yellow Canyon (fig. 32). In North Tributary basin, a rugged drainage basin morphology, an average 12% channel gradient, and steep, rough hillslopes coupled with colluvium and soil weathered from volcaniclastic and volcanic rocks (Paliza Canyon Formation, **Tppa**; and Cochiti Formation, **QTc**, as indicated on the GRI GIS data) promoted erosion and the generation of at least one debris flow. In the Capulin Canyon basin, less rugged basin morphology, an average gradient of 5%, and long, smooth slopes mantled with pumice (El Cajete pyroclastic beds, **Qvec**) resulted in flooding. The South Tributary basin exhibited negligible surface runoff, which Cannon and Rveneau (2000) attributed to the limited extent and severity of the Dome Fire in this basin.

Falls Trail after Las Conchas Fire

Following the 2011 Las Conchas Fire, Pranger (2012) provided an evaluation of geologic hazards at the Lower Frijoles Falls section of the Falls Trail in Frijoles Canyon. Post–fire storm water and coarse debris had scoured the bedrock slope in the canyon, causing collapse, including an entire section of the trail, which failed into the stream channel (fig. 33). Another section was left precariously perched above a 10-m- (30-ft-) high vertical bedrock slope. This section ultimately failed in September 2013 (Hal Pranger, NPS Geologic Resources Division, Geologic Features and Systems Branch chief, written communication, 24 October 2014).

As a result of fire-related impacts, the Falls Trail had to be closed, creating significant access issues for both administrative and public use (Pranger 2012). The trail below Upper Frijoles Falls to the Rio Grande remained closed as of August 2015 (http://www.nps.gov/band/planyourvisit/falls-trail.htm; accessed 11 August 2015).

Figure 33. Photographs of Falls Trail in Lower Frijoles Canyon. Falls Trail was built by the Civilian Conservation Corps in the 1930s. Workers excavated the trail into the side of a cliff face near Lower Frijoles Falls. As an outcome of the 2011 Las Conchas Fire, the severely damaged trail had to be closed between Upper Frijoles Falls and the Rio Grande (river) due to undercutting and collapse of the canyon wall. National Park Service photographs.

High-resolution LiDAR data sets completed in 2010, 2013, and 2014, provide a possible means to track changes along Falls Trail over a short time span. These data could be used to aid trail design if monument managers choose to reroute the affected segments of the Falls Trail. Such a decision would weigh the expense of trail design, construction, and increased visitor risk against the benefit of connectivity to the Rio Grande (river) (Bilderback 2014). LiDAR analysis could be the subject of a future technical assistance request; monument managers are encouraged to contact the NPS Geologic Resources Division.

Recovery and Monitoring

Watershed recovery is a complex function of fire severity, soil conditions, weather patterns, and treatment, and can range in time from a few years to 20 years or longer (Livingston et. al. 2005). Work by Cannon (1997, 2001), Reneau et al. (1999), Cannon and Reneau (2000), Veenhuis (2002), and Veenhuis and Bowman (2002) following the La Mesa and Dome fires identified watershed recovery periods of approximately four years. Due to the severity of the Las Conchas Fire and ongoing drought, Frijoles watershed conditions are recovering more slowly than they did following the 1977 La Mesa Fire (Stephen Monroe, National Park Service, Southern Colorado Plateau Network, hydrologist, written communication, 28 May 2015).

After the record-breaking Las Conchas Fire, Bandelier National Monument staff began documenting recovery in the burned areas by establishing photo points (see http://www.nps.gov/band/firerecover.htm; accessed 19 September 2014). Photographs taken at these points will illustrate recovery over time and are a valuable tool for park planning (fig. 34). Due to the extreme watershed degradation caused by the fire, much of the watershed has yet to establish much vegetative cover, leaving it vulnerable to large flash floods, even more than four years after the initial disturbance event (Kay Beeley, Bandelier National Monument, cartographic technician, written communication, 10 April 2015).

In the *Geological Monitoring* chapter about fluvial geomorphology, Lord et al. (2009) described methods for inventorying and monitoring the following six vital signs of stream systems: (1) watershed landscape (vegetation, land use, surficial geology, slopes, and hydrology), (2) hydrology (frequency, magnitude, and duration of streamflow rates), (3) sediment transport

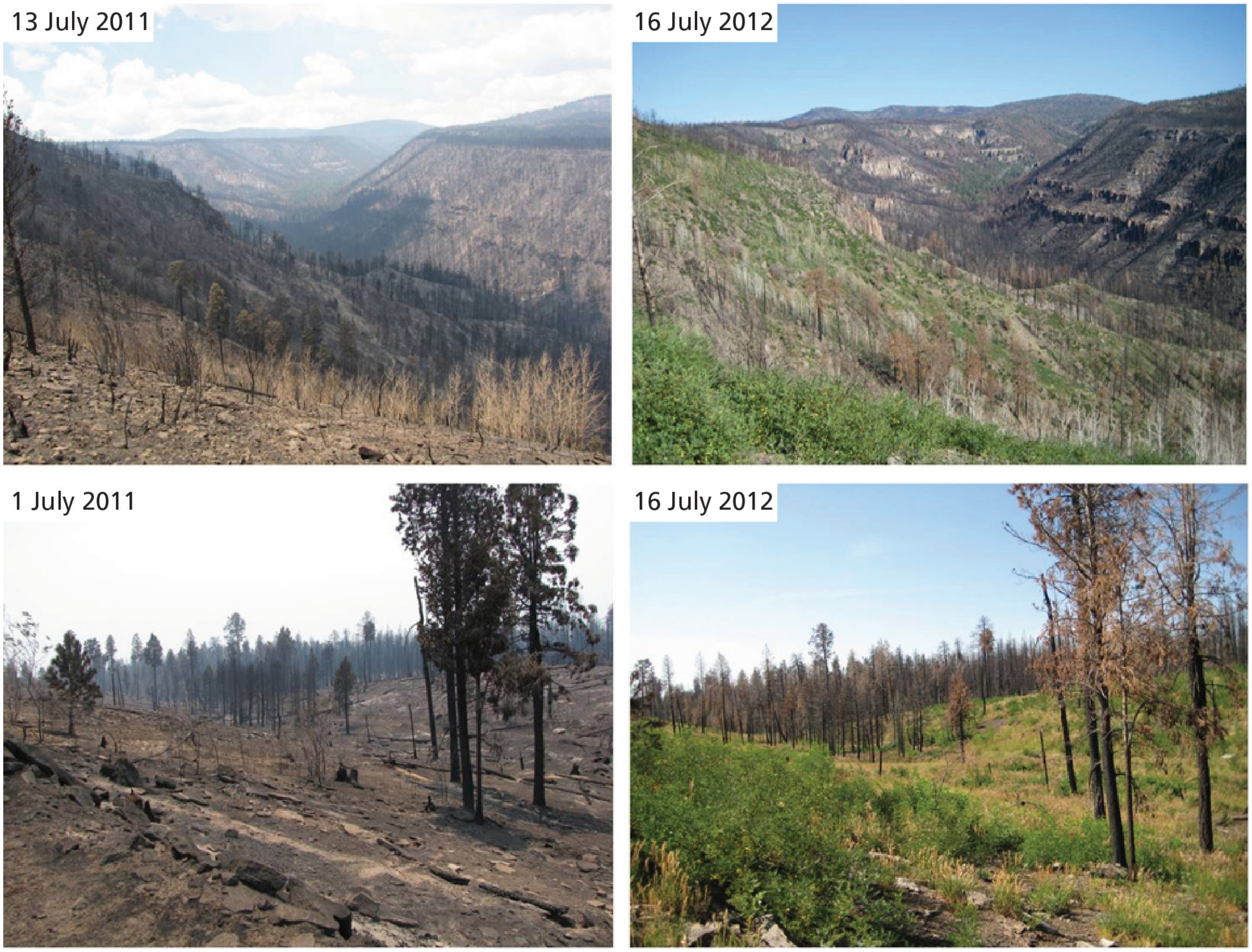


Figure 34. Photographs of landscape recovery. As vegetation reestablishes following the Las Conchas Fire, annual maximum peak flow and suspended sediment transport concentrations will decrease. Top photo pair: Upper Frijoles Canyon from Sawyer Mesa Road. Bottom photo pair: Headwaters of Capulin Canyon. National Park Service photographs, available at http://www.nps.gov/band/firerecover.htm (accessed 21 January 2015).

(rates, modes, sources, and types of sediment), (4) channel cross section, (5) channel planform, and (6) channel longitudinal profile. 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. This information may be of interest and use for monitoring stream channels and slope movement in burned areas at Bandelier National Monument.

Cliff Retreat and Rockfall

The Tshirege Member of Bandelier Tuff (**Qbt**) dominates the landscape at Bandelier National Monument. A combination of welded and nonwelded units in the member promotes differential weathering: nonwelded units typically erode into broad, gentle slopes, whereas slightly to moderately welded units tend to form vertical cliffs. Rubble from rockfalls, called talus or colluvium (**Qc**), commonly obscures less welded sections, creating a dramatic contrast between vertical cliffs of welded units and talus-covered slopes of nonwelded units (Ross and Smith 1961). In addition, where exposed at the base of Tshirege cliffs in Frijoles Canyon, the poorly consolidated deposits of the Cerro Toledo Formation (**Qct**) facilitate cliff retreat, which negatively impacts archeological sites including cavates (Jacobs and Kelley 2007; National Park Service 2015).

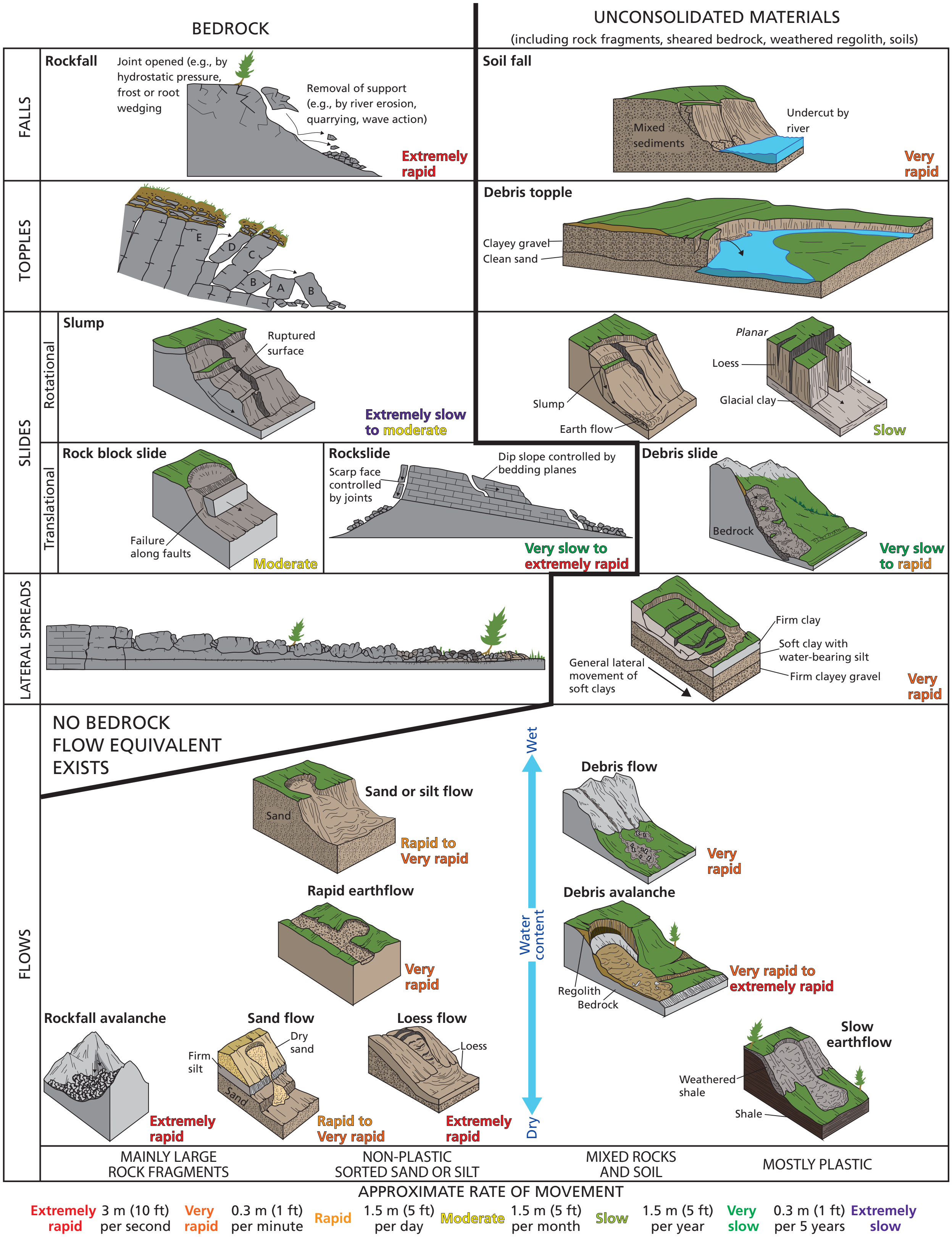


Figure 35. Schematic illustrations of slope movements. Different categories of slope movement are defined by material type, nature of the movement, rate of movement, and moisture content. The most common type of slope movement in Bandelier National Monument is rockfall from cliffs, though landslides and debris flows have also occurred. Graphic by Trista Thornberry-Ehrlich (Colorado State University) after Varnes (1978, figure 4.33 and information therein).

Cliff retreat at Bandelier National Monument occurs by a combination of small rockfalls from cliffs; detachment of rocks from slopes; and larger, deep-seated landslides (fig. 35). Small rockfalls from cliffs are the most common type at the monument (Reneau 1995). In 2005, scoping participants identified the cliffs above the visitor center at the monument as susceptible to rockfall. Additionally, the area along the park road, referred to as the "big curve," on the way to the visitor center has rockfall hazards (National Park Service 2005).

In March 2014, Eric Bilderback (NPS Geologic Resources Division) responded to a technical assistance request from monument staff to assess rockfall hazards at the headquarters area and along the Main Loop Trail, which leads from the visitor center and includes the Nature Trail. Potential mitigation measures that could reduce the risk for employees stationed at headquarters include avoidance, for example, reducing or removing people from the hazard area. Other options include targeted scaling of boulders that threaten the headquarters building or constructing a rockfall protection barrier. Though effective, the latter can be expensive; the rockfall protection barrier in the maintenance area at Zion National Park is 80 m (250 ft) long and cost about $500,000 (Bilderback 2014).

Bilderback (2014) suggested that monument staff could educate visitors about the rockfall hazard along the Main Loop Trail using simple warning signs at the trail head and/or distributing pamphlets at the visitor center. Bilderback (2014) also suggested rockfall monitoring along the Main Loop Trail, which would include recording the date, approximate time, and weather conditions of a rockfall event; taking photographs; and documenting the location of the event with geographic positioning system (GPS) coordinates, which could be stored as GIS or tabular data in a spreadsheet. Data acquired during rockfall monitoring could help refine understanding of the conditions that are conducive to rockfall events at the monument, in turn, leading to a policy that would directly reduce risk to individuals (Bilderback 2014).

Seismic Activity

In Bandelier National Monument, the Pajarito fault zone defines the local, western boundary of the Rio Grande rift (see "Rio Grande Rift" section). Holocene movements and historic seismicity indicate that the fault zone is active (Gardner and House 1987; Gardner et al. 1990). In the last 1.25 million years, since the Tshirege Member was emplaced, a total of 200 m (660 ft) of displacement has occurred along the fault zone (Goff et al. 2005b). Earthquake magnitude and recurrence intervals along the fault zone are poorly constrained, but available data suggest that earthquakes of magnitude 6.5 to 7 may occur at intervals of 10,000 to 60,000 years (Wong et al. 1995).

The most recent surface-rupturing earthquake on the Pajarito fault zone occurred between 2,200 and 1,400 years ago (McCalpin 1998). Although strong earthquakes have occurred in historic times (described below), no historic surface-rupturing earthquakes have occurred (Olig et al. 1996). Two other surface ruptures have been documented in the fault system: one at 10,900 to 9,000 years ago, and the other at 6,400 to 4,200 years ago (Jamie N. Gardner, Los Alamos National Laboratory, geologist, unpublished data as documented in Kelley et al. 2007, p. 101).

The most recent relatively large earthquake in the area with strong local effects occurred on 18 May 1918 in Santa Fe County. At the town of Cerrillos, people were thrown off their feet and fallen plaster was reported, indicating Modified Mercalli Intensities of VII to VIII (estimated magnitude 6.0 or greater on the Richter scale) (US Geological Survey 2013). In the 1990s, three small earthquakes on the Pajarito fault zone were felt throughout the area with intensities as high as Modified Mercalli Intensity VI (estimated magnitude 5.0) (Gardner and House 1994, 1999).

A search of the USGS earthquake archive (http://earthquake.usgs.gov/earthquakes/search/; accessed 4 September 2014) for Bandelier National Monument—using primary latitude and longitude in decimal degrees, 35.7883593 and -106.3028053, respectively—revealed three documented earthquakes since 2000: (1) magnitude 3.0 on 15 August 2007, (2) magnitude 2.7 on 7 February 2011, and (3) magnitude 3.5 on 17 October 2011. The probability of a moderate earthquake (magnitude 5.0 or greater) occurring in the next century at Bandelier National Monument is more than 50% (http://geohazards.usgs.gov/eqprob/2009/index.php; accessed 17 September 2014). An earthquake of this size or greater near the monument would cause significant damage to facilities and probably widespread rockfall in the canyons (National Park Service 2014a).

No data are available to evaluate the importance of seismic events on rockfall at the monument, but addressing this lack of information seems significant, given the active Pajarito fault zone crosses the monument. Seismic activity along the Pajarito fault zone is also of interest to Los Alamos National Laboratory for similar geologic hazard planning (Bilderback 2014). Thus any opportunities to collaborate with Los Alamos National Laboratory on research that could refine NPS understanding of the fault zone should be fully evaluated because the results of such a study could have bearing on park planning (Bilderback 2014).

In the chapter in *Geological Monitoring* about seismic monitoring, 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. The NPS Geologic Resources Division Seismic Monitoring and USGS Earthquakes Hazards websites provide more information (see http://go.nps.gov/seismic_monitoring and http://earthquake.usgs.gov/; accessed 21 January 2015).

Cavate Deterioration

As described in the "Bandelier Tuff" section, most cavates were excavated into the lower part of subunit **Qtb1** of the Tshirege Member (fig. 10). Ancestral Puebloans took advantage of preexisting holes to hollow out cavates. More than 1,000 cavates were constructed in Frijoles Canyon. Gaining a better understanding of the material (i.e., Bandelier Tuff) in which the cavates occur will assist in the preservation of these fundamental resources.

Preliminary geomorphic assessment of cavates and cliff bases in Frijoles Canyon revealed that deterioration of the Bandelier Tuff occurs primarily through small-scale spalling and granular erosion, and to a lesser extent from large-scale rockfalls (Bass Rivera and Meyer 2009). Discharge of water from the vadose zone at the cliff base, capillary rise of moisture into the tuff, and surface-water flow down the cliff face, which often streams directly into the cavates through entrances, smoke holes, and vents, are the primary processes contributing to deterioration of cavates (Bass Rivera and Meyer 2009). This finding corroborates condition-assessment data that revealed that cavates on the ground level and in contact with talus slopes are generally more eroded and in poorer condition than those higher in the cliff (Bass Rivera and Meyer 2009). It also complements findings by McMillan et al. (2011), which suggested that groundwater percolation from the mesa top is not an important erosive process in Bandelier National Monument.

Moisture infiltration (from the bottom up) is probably combined with other physical processes that accelerate tuff disintegration and loss (Bass Rivera and Meyer 2009). Physical processes likely include dissolution and crystallization of salts in the bedrock, diurnal-temperature changes, wet–dry cycling, windblown particle abrasion, and freeze–thaw cycles. Research into the effects of these processes on the Bandelier Tuff has begun. For example, Riggins et al. (2009) conducted weathering experiments on samples of the Tshirege Member. In freeze–thaw experiments, samples were immersed in water before being frozen. A significant loss of cohesion resulted in the disintegration of all samples after just six freeze–thaw cycles.

Heating experiments conducted by Riggins et al. (2009) involved heating separate pieces of unaltered tuff to 300°C (572°F), 400°C (772°F), 500°C (932°F), and 600°C (1,112°F). Interestingly, all samples experienced increased surficial cohesion. This finding has a correlation to archeological observations that builders likely heated the interior of chambers with a fire (Bass Rivera and Meyer 2009). Thus, Ancestral Puebloans may have taken steps to actively reduce cavate deterioration. Additionally, studies revealed that soot deposits on the ceiling increase the coherence of freshly excavated surfaces (Riggins et. al. 2009). The exceptional preservation of some cavates is due in part to this sooty layer (Bass Rivera and Meyer 2009).

Since 2000, the National Park Service Vanishing Treasures Program has been working to preserve the cavates at Bandelier National Monument. The Frijoles Canyon Cavate Pueblo Conservation Project administered by the Vanishing Treasures Program is a multidisciplinary, multiphase project set up to document the cavates and develop a conservation plan for their long-term protection. To this end, the project has initiated field and laboratory testing, materials analysis, detailed graphic documentation, environmental monitoring, and implementation of conservation treatments. Studies that examine the causes of cavate deterioration, both at the landscape level and in individual cavates, are significant for the project (Bass Rivera and Meyer 2006). Completion of a cavate conservation plan is a medium priority for the monument (National Park Service 2015).

Volcano Hazards

No eruptions as large as the ones that formed the Valles or Toledo calderas have occurred anywhere in the world in historic time. Only six such eruptions have occurred in the United States during the current geologic period (Quaternary Period; fig. 1). These include the last two Bandelier Tuff eruptions; three of the other eruptions were from Yellowstone, and one was from Long Valley, California.

Another caldera-forming eruption in the Jemez Mountains volcanic field is unlikely (Goff et al. 2011). Far more probable are smaller, but still potentially explosive, eruptions similar to those that occurred in Valles caldera 60,000–40,000 years ago. These eruptions produced the Valles Rhyolite, including the El Cajete pyroclastic beds (**Qvec**), which occur in Bandelier National Monument. Consequences of such an event would likely be localized, resulting in the development of a lava dome (fig. 5) in the caldera or small-volume pyroclastic flows within the caldera and its stream drainages (fig. 36). If future eruptions emanated from a vent in the eastern part of Valles caldera, pyroclastic flows would likely impact Bandelier National Monument (Walkup 2013). In addition, ash fall beyond the caldera's rim is a potential hazard (Goff et al. 2011). Bandelier National Monument would probably experience ash fall regardless of where in the caldera an eruption took place (Walkup 2013). Smaller eruptions are likely to have relatively small amounts of ash associated with them. However, even minor ash fall can create hazards with respect to air quality and air travel (Walkup 2013). Experience with the eruption of Mount St. Helens in 1980 indicates that as little as 0.5 cm (0.2 in) of ash is sufficient to slow vehicle traffic to a crawl and close businesses for one to two weeks (US Geological Survey 2012).

During an eruption in Valles caldera, volcanic projectiles ranging from lapilli to large volcanic bombs would be a significant hazard in areas adjacent to a volcanic vent (fig. 36). Projectiles are a localized hazard, but very large rocks ("bombs") can be thrown out of an erupting volcano if the eruption has sufficient power, and even small rock fragments can be lethal and cause injury at distances of as much as 5 km (3 mi) from a vent (Walkup 2013).

Although the prediction of the timing and outcome of a volcanic eruption is not precise, monitoring can detect changes in a volcano's behavior that precede impending eruptions. Past experience at Mount St. Helens and other volcanoes shows that ascending magma produces earthquakes as it pushes its way to the surface, thus giving local residents ample warning of an impending volcanic eruption (Goff 2009). Other indicators of a pending eruption might be ground deformation, increased hot spring or fumarolic activity, and plumes of smoke or ash rising from existing vents or new holes (Goff 2009).

Wolff and Gardner (1995) recommended geophysical monitoring of the Jemez Mountains area, so that if an eruption were to occur, forewarning would be possible. In the *Geological Monitoring* chapter about volcanoes, Smith et al. (2009) described seven vital signs and methodologies for understanding and monitoring volcanoes: (1) earthquake activity, (2) ground deformation, (3) emission at ground level, (4) emission of gas plumes and ash clouds, (5) hydrologic activity, and (6) slope instability. This information may be of interest and use to managers at Bandelier National Monument. At present, no seismic monitoring stations occur within Bandelier National Monument (Walkup 2013). However, Yellowstone Volcano Observatory monitors volcanic activity in New Mexico, as well as Montana, Wyoming, Colorado, and Utah (see http://volcanoes.usgs.gov/observatories/yvo/; accessed 19 May 2015).

Cochiti Dam and Reservoir

Cochiti Dam is 10 km (7 mi) downstream from Bandelier National Monument (figs. 4 and 6). Originally constructed in 1935, the "rolled earth" dam was enlarged and redesigned in 1973 and is now more than 8 km (5 mi) wide and 80 m (250 ft) high. Its primary purpose is flood and sediment control, holding back water and sediment from the Rio Grande (river). Seasonally (primarily during spring runoff), water inundates the lower elevations of White Rock Canyon, including the mouth of every canyon in Bandelier National Monument (Mott 1999). Temporary flooding of about 140 ha (350 ac) of NPS lands upstream of

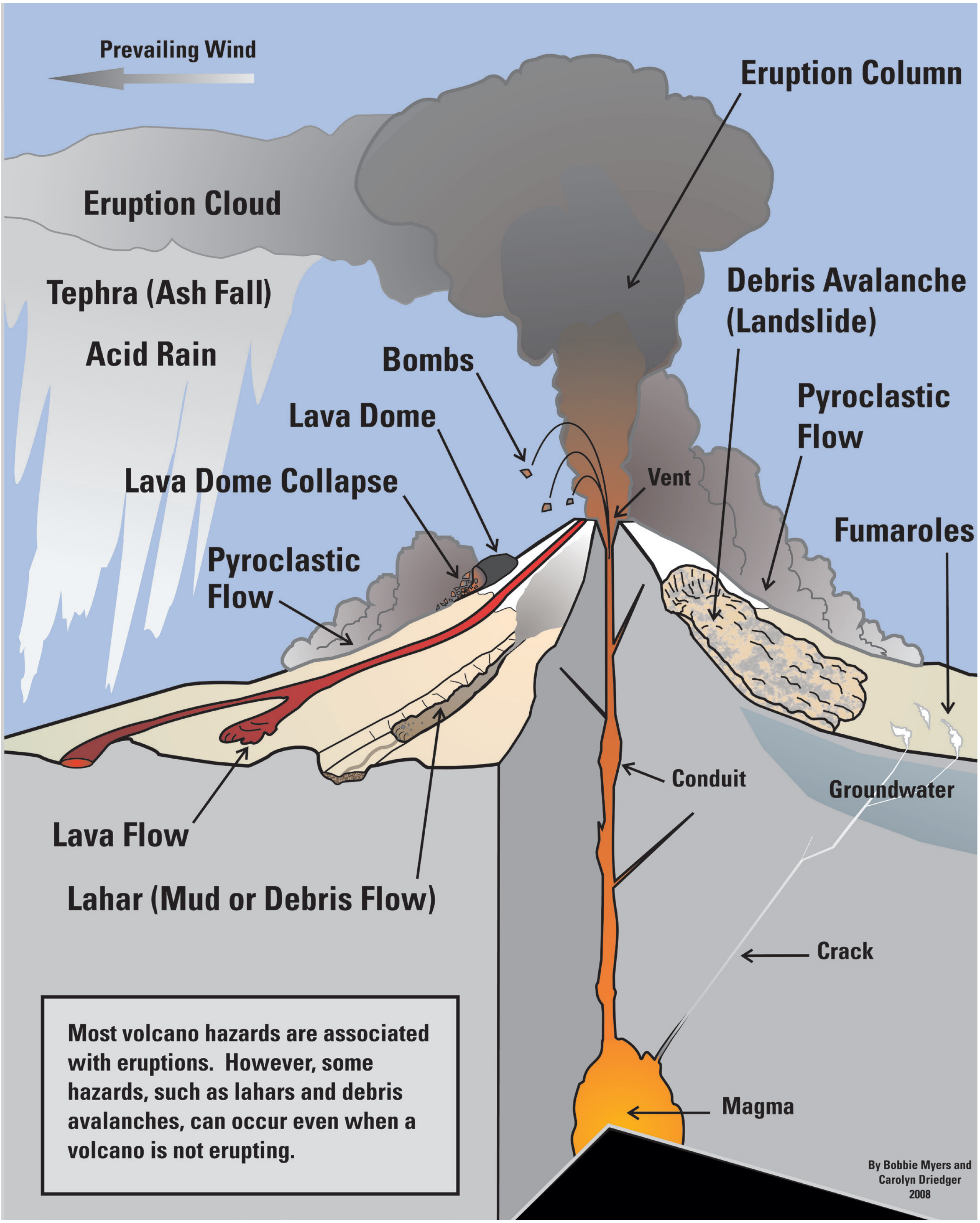


Figure 36. Schematic illustration of volcano hazards. Future volcano hazards that could affect Bandelier National Monument include the construction of a lava dome in Valles caldera, local pyroclastic flows, ash fall, and ejection of bombs. US Geological Survey graphic, available at http://pubs.usgs.gov/gip/64/gip64.pdf (accessed 23 September 2014).

the dam during the spring runoff period is allowed under a 1977 memorandum of understanding (MOU) between the National Park Service and US Army Corps of Engineers. This MOU permits a maximum flood-control contour of 1,665.9 m (5,465.5 ft) (Weeks 2007). Significant for monument resources, however, flooding has exceeded "temporary" time frames and created resource impacts not anticipated by the MOU signatories (Mott 1999). GRI scoping and conference call participants identified extended periods of water holding as an area of concern. Notable water holding occurred during high runoff periods of 1985–1988.

Water storage has caused the following impacts in Bandelier National Monument: loss of native vegetation, including the burial and extirpation of six plant species previously found associated with springs; introduction of exotic plant species, including tamarisk (*Tamarix* spp.); submergence of cultural sites; the general degradation of the area through deposition of debris; and slumping of saturated canyon-wall colluvium (Allen et al. 1993). The final impact in this list is of particular interest for a geologic resources inventory. Although most of the landslides (**Qls**) in the Cochiti Dam quadrangle are inactive, Dethier et al. (2011) identified lake drawdown after high levels in the mid-1980s as the cause of reactivated major slides along the western margin of Cochiti Reservoir (see Map Unit Properties Table, in pocket; and GRI GIS data).

Silting is another geologically related issue at Cochiti Reservoir. Silting within Cochiti Reservoir's backwaters effectively buried most of the native, high-quality riparian areas in the monument, and deposition of layers of river sand and silt provided a favorable medium for pioneer plant succession, including a variety of introduced agricultural weeds and riparian exotics (Potter 1981).

In addition, upstream sediment trapped behind the dam, is "silting up" the reservoir and reducing its capacity (Weeks 2007). The average sedimentation rate is 1.467 million m^3 (1,189 acre-feet) per year (Gallegos 1998). By 1998, an estimated 33.725 million m^3 (27,341 acre-feet) of sediment had accumulated, utilizing 27% of the reservoir's 130 million m^3 (105,000 acre-feet) sediment reserve. At that rate, the designed storage volume for sediment will be fully used by 2063, and sediment will completely fill the reservoir in about 500 years (Allen 1989). In some National Park System units, such as Bighorn Canyon National Recreation Area (see the GRI report by KellerLynn 2011), silting up of a reservoir is a primary management concern. This is not presently a concern, however, for Bandelier National Monument.

Disturbed Land Restoration

Disturbed land restoration is the process of restoring lands to unimpaired natural conditions where natural conditions and processes have been impacted by facilities, roads, mines, dams, abandoned campgrounds, or other development, and/or by agricultural practices such as farming, grazing, timber harvest, and abandoned irrigation ditches. The NPS Geologic Resources Division assists park managers with disturbed land restoration in the National Park System (see http://go.nps.gov/grd_dlr; accessed 21 January 2015).

GRI scoping participants identified two sites near the amphitheater area at the monument that may be candidates for disturbed land restoration (National Park Service 2005). Referred to as "Amphitheater Landfill" and "Tyuonyi Dump Site," the sites were an outcome of quarrying by the Civilian Conservation Corps (CCC) to obtain materials for road construction and building. Following quarrying activities, the sites were used for waste disposal by the US Forest Service (which administered the monument during the CCC era), Atomic Energy Commission (during World War II when the monument was closed to the public, and the lodge housed Manhattan Project scientists and military personnel), the New Mexico Highway Department, and most recently, the National Park Service (from the 1950s until the 1970s).

Kleinkauf (2012) provided a preliminary assessment and site inspection of these sites, and found that the "landfill" contains a variety of common household refuse (e.g., discarded appliances and trash) and debris from the CCC quarry operations and construction projects. The "dump site" contains discarded construction materials from the monument entrance road, headquarters, and lodge, and subsequent operation of these facilities.

Investigators collected samples from both sites for analysis of target compound list (TCL) volatile and semivolatile organic compounds, total petroleum hydrocarbons (TPH) gasoline and diesel range organics, and target analyte list (TAL) metals and mercury. Although contaminants were found, none were detected at levels above background mean concentrations for New Mexico at either site (Kleinkauf 2012). Thus the preliminary assessment and site inspection concluded that the disposal of municipal waste had "little effect" [on human or environmental health] at either site (Kleinkauf 2012, p. 9 and 10).

Kleinkauf (2012) noted the proximity of the sites to visitor use areas and suggested that removal would be consistent with the NPS mission. Furthermore, removal would preclude the possibility of future problems or safety concerns related to exposure of buried waste during heavy rains or flooding. According to Kleinkauf (2012), removal would be less costly than a full investigation and site characterization. Moreover, a full investigation, which would require excavation, may not be possible at the Tyuonyi Dump Site if the site was deemed eligible for the National Register of Historic Places. Notably, the dump site was considered "not significant" under the eligibility criteria of the National Register of Historic Places in 1994, but since then was re-evaluated and may be eligible under criterion (d), which deems sites eligible "that have yielded, or may be likely to yield, information important in prehistory or history" (http://www.achp.gov/nrcriteria.html; accessed 30 December 2014) (Kleinkauf 2012). The National Park Service is more likely to remove or restore a site considered "not significant."

At present, both sites remain in place, with no plan for removal. In short, the project has not risen to a level that calls for action relative to other resource management issues (Barbara Judy, Bandelier National Monument, chief of resources, email communication, 12 September 2014).

Paleontological Resource Inventory, Monitoring, and Protection

Tweet et al. (2009) compiled paleontological information for the Southern Colorado Plateau Network, including Bandelier National Monument, but did not conduct a field-based inventory. Managers at Bandelier National Monument are encouraged to contact the NPS Geologic Resources Division for assistance with such an inventory, which would provide detailed, site-specific descriptions and resource management recommendations. The Tweet et al. (2009) publication included preliminary resurce management recommendations. In the meantime, monument managers may find the chapter about monitoring in situ paleontological resources in *Geological Monitoring* of interest and use. In their chapter, Santucci et al. (2009) outlined potential threats to fossil resources: (1) erosion (geologic factors), (2) erosion (climatic factors), (3) catastrophic geohazards, (4) hydrology/bathymetry, and (5) human access/public use.

All paleontological resources are non-renewable and subject to science-informed inventory, monitoring, protection, and interpretation as outlined by the 2009 Paleontological Resources Preservation Act (see Appendix B). As of August 2015, Department of the Interior regulations associated with the act were being developed.

Geologic History

This chapter describes the chronology of geologic events that formed the present landscape of Bandelier National Monument.

Bandelier National Monument is in the Jemez Mountains volcanic field, which is best known for the Bandelier Tuff and Valles caldera (see “Bandelier Tuff” and “Valles Caldera” sections). The volcanic field became active about 14 million years ago (Miocene Epoch; fig. 1), though the earliest volcanism in the area began about 25 million years ago (Oligocene Epoch) and is contemporaneous with development of the Rio Grande rift. About 3 million years ago (Pliocene Epoch), several peripheral volcanic fields were active to the north, south, and east of the Jemez Mountains volcanic field. All the while the Rio Grande rift was stretching apart, and the ancestral Rio Grande (river) flowed within it.

Rio Grande Rift

As Earth’s crust began pulling apart in the northern part of the Rio Grande rift, the Española basin dropped down along normal faults (fig. 16). Sediment of the Santa Fe Group, which is dated to about 25 million years ago (WoldeGabriel et al. 2006), began filling the basin. Volcanic activity and fluvial activity of the ancestral Rio Grande (river) contributed to basin filling. Sedimentation has continued to the present day, though modern sediments are not included in the Santa Fe Group (see “Landscape Evolution” section). Volcanic rocks interbedded with sedimentary deposits in the lower part of the Santa Fe Group record early volcanic activity in the Bandelier area.

Peripheral Volcanism

Volcanic rocks peripheral to the Jemez Mountains volcanic field occur within and on the boundary of the Rio Grande rift. Three peripheral volcanic fields—El Alto to the north, Santa Ana Mesa to the south, and Cerros del Rio to the east (fig. 6)—started erupting about 4.6 million years ago and mostly ended about 2.0 million years ago (Bachman and Mehnert 1978; Baldridge et al. 1980). The Cerros del Rio volcanic field erupted mainly between 2.7 million and 1.1 million years ago (Thompson et al. 2011). Cerros del Rio volcanic rocks (**QTvrc**) record this volcanic activity at Bandelier National Monument (see “Cerros del Rio Volcanic Rocks” section).

Jemez Mountains Volcanic Field

The Jemez Mountains volcanic field began erupting about 14 million years ago. The rocks of the field occur in two major groups: (1) Keres, which erupted 14 million to 2 million years ago; and (2) Tewa, which erupted 1.8 million to 40,000 years ago. The Canovas Canyon Rhyolite, Bearhead Rhyolite, Paliza Canyon Formation, and Tschicoma Formation (see Map Unit Properties Table, in pocket) are rocks of the Keres Group within the monument.

The Tewa Group is particularly important for Bandelier National Monument because during “Tewa time” volcanism reached a climax with two caldera-forming eruptions of Bandelier Tuff (fig. 8). The first event, which corresponds to the collapse of Toledo caldera, deposited the Otowi Member (**Qbo**), 1.61 million years ago. The second deposited the Tshirege Member (**Qbt**) and created the Valles caldera 1.25 million years ago. These explosions were at a scale never witnessed by humans (Dunbar 2010a). Eruption of Bandelier Tuff effectively buried most of the former topography, twice, reshaping the landscape between Sierra de los Valles and the Rio Grande.

A period of about 400,000 years separated the eruptions of the Otowi and Tshirege members. During this time, rhyolite of the Cerro Toledo Formation erupted to form domes, such as Rabbit Mountain, in Toledo caldera. Cerro Toledo rhyolites represent post–caldera collapse volcanism associated with the formation of the Toledo caldera. Moreover, Cerro Toledo deposits record an interval of rapid landscape evolution when poorly welded Otowi Member and other rock units were eroded by streams into a landscape of mesas and canyons rimmed by sloping hillsides and tent rocks (Jacobs and Kelley 2007).

Soon after the eruption of the Tshirege Member and within 54,000 years of collapse of Valles caldera (Phillips et al. 2007), the floor of the caldera, which is composed of Tshirege Member, began to rise up more than 1,000 m (3,300 ft), creating what would become the text book example of a resurgent caldera (fig. 8).

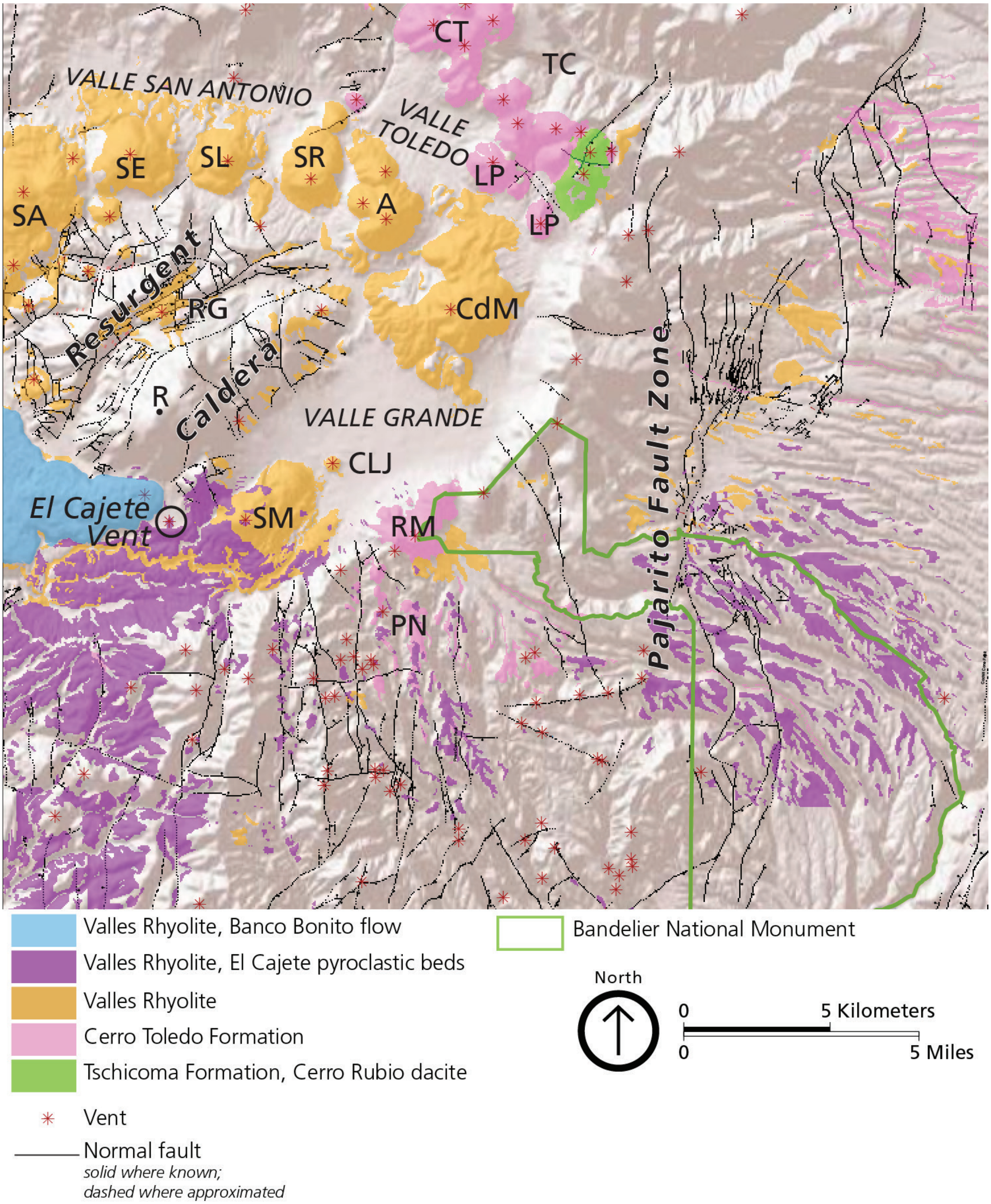
Figure 37. Photograph of Valle Grande. Valles Grande is the largest valley in Valles caldera. Cerro La Jara—a rhyolite dome that formed in the caldera about 540,000 years ago—rises above the meadow floor. In the background, a flank of Redondo Peak ultimately rises to 3,434 m (11,266 ft) above sea level, the high point in Valles caldera. Redondo Peak represents the resurgent caldera; the uplifted floor is composed primarily of the Tshirege Member of the Bandelier Tuff. Photograph by Brian0918 on Wikimedia Commons, available at https://commons.wikimedia.org/wiki/File:Valle_Grande_dome.jpg (accessed 14 August 2014).

The highest dome in Valles caldera—Redondo Peak—represents this uplift (fig. 37).

Renewed volcanism of extruding Valles Rhyolite accompanied the development of the resurgent caldera (fig. 8). Rhyolitic lava domes erupted around the perimeter of the uplifted caldera floor (fig. 38). These domes create a striking display in satellite imagery (fig. 6), digital elevation models (fig. 7), and geologic maps (see poster, in pocket). Cerro del Medio, which was emplaced about 1.23 million years ago (Phillips et al. 2007), was the first rhyolite dome to erupt (fig. 38). The domes become progressively younger in a counterclockwise direction (Dunbar 2005). The youngest domes—South Mountain and Cerro La Jara (figs. 37 and 38)—erupted about 52,000 years ago (Goff 2009).

Materials from Valles Rhyolite eruptions are interlayered with lake deposits, indicating that the caldera has been at least partially filled by water since its collapse. Past shorelines of these lakes are included in the GRI GIS data set and delineated as "paleoshorelines."

Figure 38 (facing page). Geologic sketch map of Valles caldera. The rocks of Valles caldera are from the Tewa Group. The Tshirege Member of Bandelier Tuff, represented by the background color on this figure, filled the caldera and built up adjacent plateaus. The floor of Valles caldera was uplifted during caldera resurgence (fig. 8); Redondo Peak (R) represents this resurgence. Faults (bold black lines) split the caldera floor and adjacent plateaus. Normal faults bound the Redondo Creek graben (RG) at the center of the caldera. Plugs of Cerro Rubio dacite (green) are part of the Tschicoma Formation, which predates eruption of Bandelier Tuff. No Cerro Rubio dacite occurs within Bandelier National Monument, although other members of the Tschicoma Formation do. Cerro Toledo Formation (pink) postdates the Toledo caldera (TC), occurring between the eruptions of Otowi and Tshirege members of Bandelier Tuff. Features composed of Cerro Toledo Formation (rhyolite) include Cerro Toledo (CT) dome, two Los Posos (LP) domes, Rabbit Mountain (RM), and Paseo del Norte (PN). Valles Rhyolite (yellow) erupted as domes surrounding the uplifted caldera floor. These domes are Cerro del Medio (CdM), which erupted first; followed in a counterclockwise direction by the eruption of Cerro del Abrigo (A), Cerro Santa Rosa (SR), Cerro San Luis (SL), Cerro Seco (SE), and San Antonio (SA) Mountain. In the southern part of the caldera, South Mountain (SM) dome and flow, and Cerro La Jara (CLJ) dome erupted last in the Valles Rhyolite series. El Cajete pyroclastic beds (purple), also part of Valles Rhyolite, erupted from the El Cajete vent in the caldera and spread across the landscape between 60,000 and 50,000 years ago. The most recent eruption in the caldera deposited the Banco Bonito flow (blue) about 45,000–37,000 years ago. Graphic by Jason Kenworthy (NPS Geologic Resources Division) after Goff (2009, figure 26), using GRI GIS data for Bandelier National Monument. Base imagery from ESRI World Imagery (accessed 17 February 2015).


CT
TC
VALLE SAN ANTONIO
VALLE TOLEDO
SE
SL
SR
LP
A
SA
LP
Resurgent
RG
CdM
Caldera
R
VALLE GRANDE
Pajarito Fault Zone
CLJ
El Cajete Vent
SM
RM
PN
Valles Rhyolite, Banco Bonito flow
Valles Rhyolite, El Cajete pyroclastic beds
Valles Rhyolite
Cerro Toledo Formation
Tschicoma Formation, Cerro Rubio dacite
Vent
Normal fault
solid where known;
dashed where approximated
Bandelier National Monument
North
0
5 Kilometers
0
5 Miles

About 60,000–50,000 years ago, eruption of the El Cajete vent in the southern part of the caldera (figs. 23 and 38) launched a new cycle of volcanism in the Jemez Mountains volcanic field (Wolff and Gardner 1995; Wolff et al. 1996). Along with this new stage of magmatism came the possibility of future explosive eruptions in the caldera (see "Volcano Hazards" section). The most recent eruption in the caldera deposited the Banco Bonito lava flows about 45,000–37,000 years ago (Kelley et al. 2013). These flows do not occur in Bandelier National Monument (fig. 38).

Landscape Evolution

Incision of canyons since the eruption of the Tshirege Member has produced many mesas consisting of Bandelier Tuff, including Pajarito Plateau east of Valles caldera and home to Bandelier National Monument. Bandelier Tuff is beautifully exposed in the vertical canyon walls of the Pajarito Plateau (Goff 2009).

The dated Tshirege Member of Bandelier Tuff provides an excellent temporal constraint for valley incision and landscape evolution (Reneau 2000). After eruption of the Tshirege Member (**Qbt**) but before eruption of the El Cajete pyroclastic beds (**Qvec**), which like the Tshirege Member is a significant time-stratigraphic marker in the area (Reneau et al. 1996), the Rio Grande and its tributaries experienced net incision separated by episodes of aggradation. At the monument, levels of alluvial deposits—in descending order, from oldest to youngest: **Qa2**, **Qa3**, and **Qa4** (see Map Unit Properties Table, in pocket)—mark the episodic incision of the Rio Grande. For example, when **Qa2** was deposited, the Rio Grande was flowing at an elevation 50 to 70 m (160 to 230 ft) higher than at present. On the flanks of the Jemez Mountains, many levels of piedmont alluvial deposits (**Qp2**, **Qp3**, and **Qp4**) grade towards the Rio Grande valley. These deposits record how slopes have changed over time. Terrace gravel (**Qt**) above present stream channels, beds of sand (**Qa5**) along the Rio Grande, alluvial fan deposits (**Qfa**) within and at the mouths of valleys, and alluvium (**Qal**) at canyon bottoms record the fluvial history at the monument to the present day.

Beyond stream channels, the following units document ongoing changes to the Bandelier landscape: colluvium (**Qc**); landslide deposits (**Qls**), some as old as the Tshirege Member; and sheetwash deposits (**Qpa**; deposited by overland flow of water). Slopes marked by these deposits have been subject to earthquakes, erosion, and slope movements. Along with streamflow, these geologic agents are in league to change the landscape of Bandelier National Monument, usually gradually but sometimes suddenly and swiftly (see "Fire, Fluvial Geomorphology, and Slope Movements" section).

No evidence for glaciation has been reported in the Jemez Mountains, so glaciers are a geologic agent missing from the Bandelier landscape. Boulder fields (**Qrx**), however, which Goff et al. (2011) mapped at the northern boundary of Bandelier National Monument, delineate high-elevation features associated with periglacial conditions. For instance, the nearby Sangre de Cristo Mountains, display much Pleistocene ice-age evidence (Reneau and McDonald 1996).

Humans on the Landscape

Geologic features of the Jemez Mountains volcanic field affected the people who lived on the Pajarito Plateau in a variety of ways. Ancestral Puebloans hollowed out cavates from Bandelier Tuff, taking advantage of natural cavities and further excavating them for habitation and storage, and ancient travelers created trail systems in the tuff (see "Features in Bandelier Tuff" section). Also volcanoes and lava flows yielded lithic resources such as obsidian, dacite, and chert (see "Lithic Resources" section). Furthermore, the locations of Puebloan communities on the Pajarito Plateau correlate to the presence of El Cajete pyroclastic beds (**Qvec**). Because El Cajete pumice retains water, it was important for prehistoric farming (see "El Cajete Pyroclastic Beds" section). For nearly 500 years, pumice fields enabled Puebloan farmers to survive on the slopes of the Jemez Mountains, making labor intensive construction of moisture-trapping features such as terraces, check dams, grid gardens, and cobble mulching unnecessary under most conditions (Gauthier et al. 2007).

Bandelier National Monument provides ample and diverse evidence of the importance of volcanic features to create a landscape well suited for prehistoric Puebloan civilization (Dunbar 2010a), as well as habitation to the present day. A succession of Spanish land grants, homesteads, scattered ranches, logging operations, and parts of the World War II Manhattan Project followed ancient pueblos and cliff dwellings on the Bandelier landscape.

Geologic Map Data

This chapter summarizes the geologic map data available for Bandelier National Monument. A poster (in pocket) displays the GRI GIS data draped over imagery of the monument and surrounding area. The Map Unit Properties Table (in pocket) summarizes this report's content for each geologic map unit within the Bandelier National Monument. Complete GIS data are available at the GRI publications website: http://go.nps.gov/gripubs.

Geologic Maps

Geologic maps facilitate an understanding of an area's geologic framework and the evolution of its present landscape. Using designated colors and symbols, these maps portray the spatial distribution and temporal relationships of rocks and unconsolidated deposits. Geologic maps can be divided into two primary types: surficial and bedrock. Surficial geologic maps typically encompass deposits that are unconsolidated and formed during the past 2.6 million years (Quaternary Period; fig. 1). Surficial map units are differentiated by geologic process or depositional environment. Bedrock geologic maps encompass older, typically more consolidated sedimentary, metamorphic, and/or igneous rocks. Bedrock map units are differentiated based on age and/or rock type.

Geologic maps often depict geomorphic features, structural interpretations (such as faults or folds), and locations of past geologic hazards that may be susceptible to future activity. Anthropogenic features such as mines or quarries, as well as observation or collection locations, may be indicated on geologic maps. The American Geosciences Institute website, http://www.americangeosciences.org/environment/publications/mapping (accessed 21 January 2015), provides more information about geologic maps and their uses.

Source Maps

The GRI team digitizes paper maps and converts digital data to conform to the GRI GIS data model. GRI digital geologic map products include essential elements of the source maps such as map unit descriptions, a correlation chart of units, a map legend, map notes, references, and figures. The GRI team used the following sources to produce the GRI GIS data set for Bandelier National Monument. These sources also provided information for this report.

Dethier, D. P. 2003. Geologic map of the Puye quadrangle, Los Alamos, Rio Arriba, Sandoval, and Santa Fe counties, New Mexico (scale 1:24,000). Miscellaneous Field Studies Map MF-2419. US Geological Survey, Denver, Colorado. http://pubs.usgs.gov/mf/2003/mf-2419/ (accessed 28 May 2014).

Dethier, D. P., R. A. Thompson, M. R. Hudson, S. A. Minor, and D. A. Sawyer. 2011. Geologic map of the Cochiti Dam quadrangle, Sandoval County, New Mexico (scale 1:24,000). Scientific Investigations Map SIM-3194. US Geological Survey, Denver, Colorado. http://pubs.usgs.gov/sim/3194/ (accessed 23 May 2014).

Goff, F., J. N. Gardner, and S. L. Reneau. 2002a. Geology of the Frijoles quadrangle, Los Alamos and Santa Fe counties, New Mexico (scale 1:24,000). Open-File Geologic Map OF-GM 42. New Mexico Bureau of Mines and Mineral Resources, Socorro, New Mexico. http://geoinfo.nmt.edu/publications/maps/geologic/ofgm/details.cfml?Volume=42 (accessed 28 May 2014).

Goff, F., J. N. Gardner, S. L. Reneau, and C. J. Goff. 2005a. Geologic map of the Redondo Peak quadrangle, Sandoval County, New Mexico (scale 1:24,000). Open-File Geologic Map OF-GM 111. New Mexico Bureau of Geology and Mineral Resources, Socorro, New Mexico. http://geoinfo.nmt.edu/publications/maps/geologic/ofgm/details.cfml?Volume=111 (accessed 28 May 2014).

Goff, F., J. N. Gardner, S. L. Reneau, S. A. Kelley, K. A. Kempter, and J. R. Lawrence. 2011. Geologic map of the Valles caldera, Jemez Mountains, New Mexico (scale 1:50,000). Geologic Map GM-79. New Mexico Bureau of Geology and Mineral Resources, Socorro, New Mexico.

Goff, F., S. L. Reneau, S. Lynch, C. J. Goff, J. N. Gardner, P. Drakos, and D. Katzman. 2005c. Geologic map of the Bland quadrangle, Los Alamos and Sandoval counties, New Mexico (scale 1:24,000). Open-File Geologic Map OF-GM-112. New Mexico Bureau of Geology and Mineral Resources, Socorro, New Mexico. http://geoinfo.nmt.edu/publications/maps/geologic/ofgm/details.cfml?Volume=112 (accessed 23 May 2014).

Kempter, K., G. R. Osburn, S. Kelley, M. Rampey, C. Ferguson, and J. Gardner. 2007. Geologic map of the Bear Springs Peak quadrangle, Sandoval County, New Mexico (scale 1:24,000). Open-File Geologic Map OF-GM 74. New Mexico Bureau of Geology and Mineral Resources, Socorro, New Mexico. http://geoinfo.nmt.edu/publications/maps/geologic/ofgm/details.cfml?Volume=74 (accessed 28 May 2014).

Kempter, K. A., S. Kelley, J. N. Gardner, S. L. Reneau, D. E. Broxton, F. Goff, A. Levine, and C. Lewis. 1998. Geologic Map of the Guaje Mountain quadrangle, Los Alamos and Sandoval counties, New Mexico (scale 1:24,000). Open-File Geologic Map OF-GM 55. New Mexico Bureau of Geology and Mineral Resources, Socorro, New Mexico. http://geoinfo.nmt.edu/publications/maps/geologic/ofgm/details.cfml?volume=55 (accessed 28 May 2014).

Koning, D. J., and A. S. Read. 2010. Geologic map of the southern Española basin (scale 1:48,000). Open-File Report 531. New Mexico Bureau of Geology and Mineral Resources, Socorro, New Mexico. http://geoinfo.nmt.edu/publications/openfile/details.cfml?Volume=531 (accessed 23 May 2014).

Lynch, S. D., G. A. Smith, and A. J. Kuhle. 2005. Geologic map of the Canada quadrangle, Sandoval County, New Mexico (scale 1:24,000). Open-File Geologic Map OF-GM 85. New Mexico Bureau of Geology and Mineral Resources, Socorro, New Mexico. http://geoinfo.nmt.edu/publications/maps/geologic/ofgm/details.cfml?Volume=85 (accessed 28 May 2014).

Thompson, R. A., M. R. Hudson, R. R. Shroba, S. A. Minor, and D. A. Sawyer. 2011. Geologic map of the Montoso Peak quadrangle, Santa Fe and Sandoval counties, New Mexico (scale 1:24,000). Scientific Investigations Map SIM-3179. US Geological Survey, Reston, Virginia. http://pubs.usgs.gov/sim/3179/ (accessed 28 May 2014).

GRI GIS Data

The GRI team implements a GIS data model that standardizes map deliverables. The data model 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 team digitized the data for Bandelier National Monument using data model version 2.1. The GRI Geologic Maps website, http://go.nps.gov/geomaps, provides more information about GRI map products.

GRI digital geologic data are available 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.

The following components are part of the data set:

- A GIS readme file (band_gis_readme.pdf) that describes the GRI data formats, naming conventions, extraction instructions, use constraints, and contact information.
- Data in ESRI geodatabase GIS format;
- Layer files with feature symbology (table 2);
- Federal Geographic Data Committee–compliant metadata;
- An ancillary map information document (band_geology.pdf) that contains information captured from source maps;
- An ESRI map document (band_geology.mxd) that displays the digital geologic data; and
- A KML/KMZ version of the data viewable in Google Earth (table 2).

GRI Map Poster

A poster of the GRI digital geologic data draped over a shaded relief image of the monument and surrounding area is included with this report (in pocket). Not all GIS feature classes are included on the poster, as indicated in table 2. Geographic information and features have been added to the poster. Digital elevation data and added geographic information are not included in the GRI GIS data set, but are available online from a variety of sources. Contact GRI staff for assistance locating these data.

Map Unit Properties Table

The Map Unit Properties Table (in pocket) lists the geologic time division, symbol, and a simplified description for each of the geologic map units within Bandelier National Monument. Following the structure of the report, the table summarizes the geologic features and processes, resource management issues, and geologic history associated with each map unit.

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 regarding the locations of geologic features relative to other geologic or geographic features on the poster. Based on US National Map Accuracy Standards and source-map scales—primarily 1:24,000 but also 1:48,000 and 1:50,000—geologic features represented in the geologic map data are horizontally within 12 m (40 ft), or 24 m (80 ft) and 25 m (82 ft), of their true locations at 1:24,000, 1:48,000, or 1:50,000, respectively.

Table 2. Data layers in the Bandelier National Monument GRI GIS data set

Data Layer	On Poster?	Google Earth Layer?
Geologic Cross Section Lines	No	No
Geologic Attitude Observation Localities	No	No
Geologic Sample Localities	No	No
Mine Point Features	No	No
Volcanic Point Features (vents, fumaroles)	Yes	No
Geologic Point Features	No	No
Paleoshorelines	No	No
Volcanic Line Features	Yes	No
Hazard Feature Lines	Yes	No
Geologic Line Features	No	Yes
Map Symbology	Yes	No
Folds	Yes	Yes
Faults	Yes	Yes
Alteration and Metamorphic Area Boundaries	No	No
Alteration and Metamorphic Areas	No	Yes
Linear Dikes	No	Yes
Deformation Area Boundaries	No	No
Deformation Areas	No	Yes
Geologic Contacts	No	Yes
Geologic Units	Yes	Yes

Glossary

These are brief definitions of selected geologic terms relevant to this report. Definitions are based on those in the American Geosciences Institute Glossary of Geology (5th edition; 2005). Additional terms are defined at http://geomaps.wr.usgs.gov/parks/misc/glossarya.html.

accretion. The addition of island-arc or continental material to a continent via collision, welding, or suturing at a convergent plate boundary.

aggradation. The building up of Earth's surface by depositional processes.

alluvial fan. A low, relatively flat to gently sloping, fan-shaped mass of loose rock material deposited by a stream, especially in a semiarid region, where a stream issues from a canyon onto a plain or broad valley floor.

alluvial terrace. A stream terrace composed of unconsolidated alluvium produced by a rejuvenated stream via renewed downcutting of the floodplain or valley floor, or by the covering of a terrace with alluvium.

alluvium. Stream-deposited sediment.

amygdule. A gas cavity or vesicle in an igneous rock that has become filled with secondary minerals.

andesite. A volcanic rock characteristically medium dark in color and containing approximately 57%–63% silica and moderate amounts of iron and magnesium.

aphanitic. Describes the texture of fine-grained igneous rock in which different components are not distinguishable by the unaided eye.

aphyric. Describes the texture of a fine-grained igneous rock that lacks coarse crystals.

ash. Fine-grained material, less than 2 mm (0.08 in) across, ejected from a volcano.

ash fall. Airborne ash that falls from an eruption cloud, and the resulting deposit.

ash flow. A density current, generally a hot mixture of volcanic gases and tephra that travels across the ground surface; produced by the explosive disintegration of viscous lava in a volcanic center, or from a fissure or group of fissures. The solid materials contained in a typical ash flow are generally unsorted and ordinarily include volcanic dust, pumice, scoria, and blocks in addition to ash.

ash-flow tuff. A tuff deposited by an ash flow.

axial stream. The main stream of an intermontane valley, flowing in the deepest part of the valley parallel to it longest dimension. Also, a stream that follows a syncline or anticline.

backwater. A body of water that is parallel to a river but is stagnant or little affected by the river's currents.

bank. A submerged ridge of sand in the sea, a lake, or a river, usually exposed during low tide or low water.

basalt. A volcanic rock that is characteristically dark in color (gray to black), contains approximately 53% silica or less, and is rich in iron and magnesium.

basaltic andesite. A volcanic rock that is commonly dark gray to black and contains approximately 53%–57% silica.

base level. The lowest level to which a stream channel can erode. The ultimate base level is sea level, but temporary, local base levels exist.

basin (structural). A doubly plunging syncline in which rocks dip inward from all sides.

basin (sedimentary). Any depression, from continental to local scale, into which sediments are deposited.

bed. The smallest sedimentary stratigraphic unit, commonly ranging in thickness from about 1 cm (0.4 in) to 1 to 2 m (40 to 80 in) and distinguishable from beds above and below.

bedding. Depositional layering or stratification of sediments.

bedrock. Solid rock that underlies unconsolidated sedimentary deposits and soil.

biotite. A dark-colored, shiny silicate mineral (silicon + oxygen) of the mica group composed of magnesium and/or iron, $K(Mg,Fe)Si_3O_{10}(OH)_2$; characterized by perfect cleavage, readily splitting into thin sheets.

block. A pyroclast ejected in a solid state with a diameter greater than 64 mm (2.5 in).

block (fault). A crustal unit bounded completely or partially by faults.

bomb. A viscous pyroclast ejected then shaped while in flight; commonly more than 64 mm (2.5 in) in diameter and with a hollow or vesicular interior.

braided stream. A sediment-clogged stream that forms multiple channels that divide and rejoin.

breccia. A coarse-grained, generally unsorted sedimentary rock consisting of cemented angular clasts more than 2 mm (0.08 in) across.

breccia (volcanic). A coarse-grained, generally unsorted volcanic rock consisting of partially welded angular fragments of ejected material.

burrow. A tubular or cylindrical hole or opening, made in originally soft or loose sediment by a mud-eating worm, mollusk, or other invertebrate; may be later filled with clay or sand and preserved.

caldera. A large, more-or-less circular, basin-shaped volcanic depression formed by collapse during an eruption.

calcite. A carbonate (carbon + oxygen) mineral of calcium, $CaCO_3$; calcium carbonate. It is the most abundant cave mineral.

capillary action. The action by which a fluid, such as water, is drawn up in small interstices or tubes as a result of surface tension.

cauldron. An inclusive term for all volcanic subsidence structures regardless of shape or size, depth of erosion, or connection with the surface; the term includes caldron subsidences and collapse calderas.

channel. The bed where a natural body of surface water flows or may flow. Also, a natural passageway or depression of perceptible extent containing continuously or periodically flowing water, or forming a connecting link between two bodies of water.

chert. An extremely hard sedimentary rock with conchoidal fracturing, consisting mostly of interlocking crystals of quartz.

cinder. A glassy, vesicular, pyroclastic fragment that falls to the ground in an essentially solid condition.

cinder cone. A conical hill, commonly steep, ranging from tens to hundreds of meters tall, formed by the accumulation of solidified fragments of lava that fell around the vent during a basaltic or andesitic eruption.

clay. Minerals and sedimentary fragments that are less than 1/256 mm (0.00015 in) across.

clinopyroxene. A group name for pyroxene minerals that crystallize in the monoclinic system and sometimes contain considerable calcium with or without aluminum and the alkali metals.

coarse-grained. Describes a crystalline rock and texture in which the individual minerals are relatively large, specifically an igneous rock whose particles have an average diameter greater than 5 mm (0.2 in). Also, describes sediment or sedimentary rock and texture in which the individual constituents are easily seen with the unaided eye, specifically sediment or rock whose particles have an average diameter greater than 2 mm (0.08 in).

cobble. A rock fragment larger than a pebble and smaller than a boulder, having a diameter in the range of 64–256 mm (2.5–10 in), being somewhat rounded or otherwise modified by abrasion in the course of transport.

cohesion. The intermolecular attraction by which the elements of a body are held together.

colluvium. A loose, heterogeneous, and incoherent mass of rock fragments and soil material deposited via surface runoff or slow continuous downslope creep; usually collects at the base of a slope or hillside, but includes loose material covering hillsides.

conchoidal. Resembling the curve of a conch shell and used to describe a smoothly curved surface on a rock or mineral; characteristic of quartz and obsidian.

conglomerate. A coarse-grained, generally unsorted, sedimentary rock consisting of cemented, rounded clasts larger than 2 mm (0.08 in) in diameter.

coprolite. Fossilized feces.

cross-bed. A single bed, inclined at an angle to the main planes of stratification; the term is commonly restricted to a bed that is more than 1 cm (0.4 in) thick.

cross-bedding. Uniform to highly varied sets of inclined beds deposited by wind or water that indicate flow conditions such as direction and depth.

cross section. A graphic interpretation of geology, structure, or stratigraphy based on mapped and measured geologic extents and attitudes, depicted in a vertical plane (i.e., a cut or profile view).

crust. Earth's outermost layer or shell.

crystalline. Describes a regular, orderly, repeating geometric structural arrangement of atoms.

dacite. A volcanic rock that is characteristically light in color and contains approximately 63%–68% silica and moderate amounts of sodium and potassium.

debris flow. A moving mass of rock fragments, soil, and mud, with more than half of the particles larger than sand size. Slow debris flows may move less that 1 m (3 ft) per year; rapid ones reach 160 kph (100 mph).

deformation. The process of folding, faulting, shearing, or fabric development in rocks as a result of Earth stresses.

dendritic. Describes a branching pattern.

differential erosion. Erosion that occurs at irregular or varying rates due to differences in the resistance and hardness of surface material: softer and weaker rocks are rapidly worn away; harder and more resistant rocks remain to form ridges, hills, or mountains.

discharge. The rate of flow of surface water or groundwater at a given moment, expressed as volume per unit of time.

displacement. The relative movement of the two sides of a fault; also, the specific amount of such movement.

dome. Any smoothly rounded landform or rock mass; more specifically, an elliptical uplift in which rocks dip gently away in all directions.

downcutting. Stream erosion in which cutting is directed primarily downward, as opposed to laterally.

drainage. The manner in which the waters of an area flow off in surface streams or subsurface conduits; also, the processes of surface drainage of water from an area by streamflow and sheet flow, and the removal of excess water from soil by downward flow.

drainage basin. A region or area bounded by a drainage divide and occupied by a drainage system, specifically the tract of country that gathers water originating as precipitation and contributes it to a particular stream channel or system of channels, or to a lake, reservoir, or other body of water.

dune. A low mound or ridge of sediment, usually sand, deposited by the wind.

eolian. Describes materials formed, eroded, or deposited by or related to the action of wind. Also spelled "aeolian."

ephemeral lake. A short-lived lake.

erosion. The general process or group of processes that loosen, dissolve, wear away, and simultaneously move from one place to another, the materials of Earth's crust; includes weathering, solution, abrasive actions, and transportation, but usually excludes slope movements.

escarpment. A steep cliff or topographic step resulting from vertical displacement on a fault or as a result of slope movement or erosion. Synonymous with "scarp."

explosive eruption. An energetic eruption that produces mainly ash, pumice, and fragmental ballistic debris.

extension. Deformation of Earth's crust whereby rocks are pulled apart.

extrusion. The emission of lava onto Earth's surface; also, the rock so formed.

extrusive. Describes an igneous rock that has been erupted onto the surface of the Earth. Extrusive rocks include lava flows and pyroclastic material such as volcanic ash.

facies. The depositional or environmental conditions reflected in the sedimentary structures, textures, mineralogy, fossils, and other components of a sedimentary rock.

fanglomerate. A sedimentary rock consisting of waterworn fragments of various sizes deposited in an alluvial fan and later cemented into rock.

fault. A break in rock characterized by displacement of one side relative to the other.

feldspar. A group of abundant silicate (silicon + oxygen) minerals, comprising more than 60% of Earth's crust and occurring in all types of rocks.

felsenmeer. From the German word meaning "sea of rocks"; a block field consisting of usually angular blocks with no fine sizes in the upper part, over solid or weathered bedrock, colluvium, or alluvium, without a cliff or ledge above as an apparent source.

fine-grained. Describes sediment or sedimentary rock and texture in which the individual constituents are too small to distinguish with the unaided eye, specifically sediment or rock whose particles have an average diameter less than 1/16 mm (0.002 in), that is, silt-size particles and smaller. Also, describes a crystalline or glassy rock and texture in which the individual minerals are relatively small, specifically an igneous rock whose particles have an average diameter less than 1 mm (0.04 in).

fissure. A fracture or crack in rock along which there is a distinct separation; commonly filled with mineral-bearing materials.

fissure (volcanic). An elongated fracture or crack at the surface from which lava erupts.

fissure vent. A volcanic conduit having the form of a crack or fissure at Earth's surface.

floodplain. The surface or strip of relatively smooth land composed of alluvium and adjacent to a river channel, constructed by the present river in its existing regimen and covered with water when the river overflows its banks. A river has one floodplain and may have one or more terraces representing abandoned floodplains.

fluvial. Of or pertaining to a river or rivers.

fold. A curve or bend in an originally flat structure, such as a rock stratum, bedding plane, or foliation; usually a product of deformation.

footwall. The lower wall of a fault.

formation. Fundamental rock-stratigraphic unit that is mappable, lithologically distinct from adjoining strata, and has definable upper and lower contacts.

fossil. A remain, trace, or imprint of a plant or animal that has been preserved in the Earth's crust since some past geologic time; loosely, any evidence of past life.

fracture. The breaking of a mineral other than along planes of cleavage. Also, any break in a rock such as a crack, joint, or fault.

freeze-thaw. The mechanical weathering process caused by alternate or repeated cycles of freezing and thawing water in pores, cracks, and other openings of rock and unconsolidated deposits, usually at the surface.

friable. Describes a rock or mineral that is easily crumbled.

frost action. The mechanical weathering process caused by alternate or repeated cycles of freezing and thawing of water in pores, cracks, and other openings, usually at the surface.

frost heaving. The uneven lifting or upward movement, and general distortion, of surface soils, rocks, vegetation, and structures such as pavements, due to subsurface freezing of water and growth of ice masses.

frost wedging. A type of mechanical disintegration, splitting, or breakup of a rock by which jointed rock is pried and dislodged by ice acting as a wedge.

fumarole. A vent, usually volcanic, from which gases and vapors are emitted.

geology. The study of Earth, including its origin, history, physical processes, components, and morphology.

geomorphology. The study of the general configuration of surface landforms and their relationships to underlying structures, and of the history of geologic changes as recorded by these surface features.

geothermal. Pertaining to the heat of the interior of the Earth.

glassy. Describes the texture of certain extrusive igneous rocks that is similar to glass and developed as a result of rapid cooling of the lava, without distinctive crystallization. Synonymous with "vitreous."

gradient. A degree of inclination (steepness of slope), or a rate of ascent or descent, of an inclined part of Earth's surface with respect to the horizontal; expressed as a ratio (vertical to horizontal), a fraction (such as m/km or ft/mi), a percentage (of horizontal distance), or an angle (in degrees).

graben. An elongated, downdropped trough or basin, bounded on both sides by high-angle normal faults that dip toward one another.

granite. A coarse-grained, intrusive igneous rock in which quartz constitutes 10%–50% of the felsic ("light-colored") components and the alkali feldspar/total feldspar ratio is generally restricted to the range of 65% to 90%; perhaps the best known of all igneous rocks.

gravel. An unconsolidated, natural accumulation of typically rounded rock fragments resulting from erosion; consists predominantly of particles larger than sand; that is, greater than 2 mm (1/12 in) across.

groundwater. That part of subsurface water that is in the zone of saturation, including underground streams.

hanging wall. The upper wall of a fault.

hawaiite. An olivine-rich basalt. Also, a pale-green, iron-poor gem variety of olivine from the lavas of Hawaii.

hoodoo. A bizarrely shaped column, pinnacle, or pillar of rock, commonly produced in a region of sporadic heavy rainfall by differential weathering or erosion of horizontal strata, facilitated by layers of varying hardness and joints.

hornblende. A silicate (silicon + oxygen) mineral of sodium, potassium, calcium, magnesium, iron, and aluminum; commonly black and occurring in distinct crystals or in columnar, fibrous, or granular forms in hand specimens. The most common mineral of the amphibole group.

hot spring. A thermal spring whose temperature is above that of the human body.

hydrogeology. The science that deals with subsurface waters and related geologic aspects of surface waters, including the movement of groundwater; the mechanical, chemical, and thermal interaction of groundwater with the porous medium; and the transport of energy and chemical constituents by the flow of groundwater. Synonymous with "geohydrology."

hydrology. The study of liquid and solid water properties, circulation, and distribution, on and under the Earth's surface and in the atmosphere.

hypersthene. A silicate (silicon + oxygen) mineral of the pyroxene group consisting of magnesium and iron.

iddingsite. A reddish-brown mixture of silicate (silicon + oxygen) minerals, including iron, calcium, and magnesium, formed by the alteration of olivine; forms rust-colored patches in basic igneous rocks.

igneous. Describes a rock or mineral that solidified from molten or partly molten material; also, describes processes leading to, related to, or resulting from the formation of such rocks. One of the three main classes or rocks—igneous, metamorphic, and sedimentary.

ignimbrite. A pyroclastic flow deposit.

incision. Downward erosion by a stream, resulting in a deepened channel and commonly a narrow, steep-walled valley.

indurated. Describes a rock or soil hardened or consolidated by pressure, cementation, or heat.

induration. Hardening by heat, pressure, or the introduction of cementing material, especially the process by which relatively consolidated rock is made harder or more compact.

intermediate magma. Describes magma that contains between 62% and 63% silica and is moderately viscous, gas-rich, and sometimes erupts explosively, though it may also produce lava flows.

interstitial. Said of a mineral deposit in which the minerals fill the pores of the host rock.

intrusion. The process of emplacement of magma into preexisting rock. Also, the igneous rock mass formed.

intrusive. Pertaining to intrusion, both the process and the rock body.

joint. A break in rock without relative movement of rocks on either side of the fracture surface.

lahar. A mixture of water and volcanic debris that moves rapidly down the slope of a volcano, characterized by a substantial component (>50%) of fine-grained material that acts as a matrix to give the deposit the strength it needs to carry the bigger clasts.

laminated. Consisting of very thin compositional layers..

landslide. A collective term covering a wide variety of slope-movement landforms and processes that involve the downslope transport of soil and rock material en masse under the influence of gravity.

lapilli. Pyroclastic materials ranging between 2 and 64 mm (0.08 and 2.5 in) across with no characteristic shape; may be either solidified or still viscous upon landing. An individual fragment is called a lapillus.

lava. Molten or solidified magma that has been extruded though a vent onto Earth's surface.

lava dome. A steep-sided mass of viscous, commonly blocky, lava extruded from a vent; typically has a rounded top and covers a roughly circular area; may be isolated or associated with lobes or flows of lava from the same vent; typically silicic (rhyolite or dacite) in composition.

lithify. To change to stone, or to petrify; especially to consolidate from a loose sediment to solid rock.

maar. A low-relief, broad volcanic crater formed by multiple shallow explosive eruptions. It is surrounded by a low-relief rim of fragmental material, and may be filled by water.

magma. Molten rock beneath Earth's surface capable of intrusion and extrusion.

magmatism. The development and movement of magma, and its solidification as igneous rock.

mantle. The zone of the Earth below the crust and above the core.

marker bed. A well-defined, easily identifiable stratum or body of strata that has sufficiently distinctive characteristics (such as lithology or fossil content) to facilitate correlation in field mapping or subsurface work. Also, a geologic formation that serves as a marker.

member. A lithostratigraphic unit with definable contacts; a subdivision of a formation.

mesa. A broad, flat-topped erosional hill or mountain with by steeply sloping sides or cliffs.

mineral. A naturally occurring inorganic crystalline solid with a definite chemical composition or compositional range.

monocline. A one-limbed fold in strata that are otherwise flat-lying.

mugearite. An extrusive or hypabyssal igneous rock of the alkali basalt suite containing oligoclase, alkali feldspar, and mafic minerals.

normal fault. A fault in which the hanging wall appears to have moved downward relative to the footwall; the angle of dip is usually 45°–90°.

obsidian. A black or dark-colored volcanic glass, usually of rhyolite composition, characterized by conchoidal fracture.

olivine. A silicate (silicon + oxygen) mineral of magnesium and iron, $(Mg,Fe)_2SiO_4$; commonly olive-green and an essential mineral in basalt, gabbro, and peridotite.

orogeny. A mountain-building event.

outcrop. Any part of a rock mass or formation that is exposed or "crops out" at Earth's surface.

oxide. A mineral group composed of oxygen plus an element or elements, for example, iron in hematite, Fe_2O_3; or aluminum in corundum, Al_2O_3.

palagonite. An altered volcanic, specifically basaltic, glass that becomes pillow lava or occurs in amygdules.

palagonite tuff. A pyroclastic rock consisting of angular fragments of hydrothermally altered or weathered palagonite, produced by explosive interaction of mafic magma and water.

paleotopography. The topographic relief of an area at a particular time in the geologic past.

patterned ground. Well-defined, more or less symmetrical forms such as circles, polygons, nets, steps, and stripes in surficial material that develop as a result of intense frost action.

pebble. A small rounded rock, especially a waterworn stone, between 4 and 64 mm (0.16 and 2.5 in) across.

period. The fundamental unit of the worldwide geologic time scale. It is lower in rank than era and higher than epoch. The geochronologic unit during which the rocks of the corresponding system were formed.

permeability. A measure of the relative ease with which a fluid moves through the pore spaces of a rock or unconsolidated deposit.

phenocryst. A coarse-grained crystal in a porphyritic igneous rock.

phreatomagmic. A term encompassing all volcanic activity that results from the interaction between lava, magmatic heat, or gases and water at or near the surface of the Earth. Synonymous with "hydrovolcanic."

piedmont. A gently sloping area at the base of a mountain front. Synonymous with "bajada." Also, describes a feature (e.g., plain, slope, or glacier) that lies or formed at the base of a mountain or mountain range.

pillow lava. A general term for lavas displaying pillow structures and considered to have formed in a subaqueous environment; such lava is usually basaltic or andesitic.

pillow structure. A structure observed in certain extrusive igneous rocks that is characterized by discontinuous bun-shaped masses ranging in size from a few centimeters to a meter or more in greatest dimension. They are considered to be the result of subaqueous extrusion.

plagioclase. A silicate (silicon + oxygen) mineral of the feldspar group that contains both sodium and calcium ions that freely substitute for one another; characterized by striations (parallel lines) in hand specimens.

planar. Lying or arranged as a plane or in planes, usually implying more or less parallelism, as in bedding or cleavage.

plateau. A broad, flat-topped topographic high (terrestrial or marine) of great extent and elevation above the surrounding plains, canyons, or valleys.

Plinian eruption. An explosive eruption characterized by large amounts of tephra and a tall eruption column from which a steady, turbulent stream of fragmented magma and magmatic gas is released at a high velocity.

porosity. The percentage of total void space in a volume of rock or unconsolidated deposit.

porphyritic. Describes an igneous rock of any composition that contains conspicuous phenocrysts (larger crystals) in a fine-grained groundmass.

porphyry. An igneous rock consisting of abundant coarse-grained crystals in a fine-grained groundmass.

potassium feldspar. A feldspar mineral rich in potassium such as orthoclase, microcline, and sanidine.

Precambrian. A commonly used term to designate all rocks older than the Cambrian Period of the Standard Global Chronostratigraphic Scale. It includes the Archean and Proterozoic eons and represents 90% of geologic time.

pumice. A highly vesicular pyroclast with very low bulk density and thin vesicle walls.

pumiceous. Describes a texture of volcanic rock consisting of tiny gas holes such as in pumice; finer than scoriaceous.

pyroclast. An individual particle ejected during a volcanic eruption; usually classified according to size.

pyroclastic. Describes clastic rock material formed by volcanic explosion or aerial expulsion from a vent; also, describes a rock texture of explosive origin. It is not synonymous with "volcanic."

pyroclastic flow. A hot, typically >800°C (1,500°F), chaotic mixture of rock fragments, gas, and ash that travels rapidly (tens of meters per second) away from a volcanic vent or collapsing flow front.

pyroclastic surge. Low-density, dilute, turbulent pyroclastic flow. The deposits may be thinly bedded, laminated, and cross-bedded.

pyroxene. A group of silicate (silicon + oxygen) minerals composed of magnesium and iron with the general formula (Mg,Fe)SiO3; characterized by short, stout crystals in hand specimens.

quartz. Silicon dioxide, SiO_2. The only silicate (silicon + oxygen) mineral consisting entirely of silicon and oxygen. Synonymous with "crystalline silica."

quartzite. Metamorphosed quartz sandstone. A medium-grained, nonfoliated metamorphic rock composed mostly of quartz.

radiocarbon age. An isotopic age expressed in years and calculated from the quantitative determination of the amount of carbon-14 remaining in an organic material. Synonymous with "carbon-14 age."

red bed. Sedimentary strata that is predominantly red due to the presence of ferric iron oxide (hematite) coating individual grains; usually sandstone, siltstone, or shale.

relict. Describes a topographic feature that remains after other parts of the feature have been removed or have disappeared, for example, a "relict beach ridge" or a "relict hill." Also, a landform made by processes no longer operative such as glaciated forms in the northern United States or sand dunes in rain forests.

reservoir. An artificial or natural storage place for water, such as a lake, pond, or aquifer, from which the water may be withdrawn for such purposes as irrigation, municipal water supply, or flood control.

resurgent caldera. A caldera in which the downdropped block is uplifted by magmatic intrusion following crater formation.

resurgent cauldron. A cauldron in which the cauldron block, following subsidence, has been uplifted, usually in the form of a structural dome.

rhyodacite. A volcanic rock that contains approximately 68%–72% silica and is intermediate in composition between rhyolite and dacite.

rhyolite. A volcanic rock that is characteristically light in color, contains approximately 72% or more of silica, and is rich in potassium and sodium.

rift. A region of Earth's crust where extension results in formation of many related normal faults, commonly associated with volcanic activity.

rift valley. A depression formed by grabens along the crest of a mid-ocean ridge or in a continental rift zone.

rock. An aggregate of one or more minerals (e.g., granite), a body of undifferentiated mineral matter (e.g., obsidian), or a body of solid organic material (e.g., coal).

rockfall. The most rapid type of slope movement in which a newly detached fragment of bedrock of any size falls from a cliff or other very steep slope, traveling straight down or in a series of leaps and bounds down a slope.

rock glacier. A mass of poorly sorted angular boulders and fine material, with interstitial ice a meter or so below the surface (ice-cemented) or containing a buried ice glacier (ice-cored).

sand. A clastic particle smaller than a granule and larger than a silt grain, with a diameter ranging from 1/16 to 2 mm (0.0025 to 0.08 in).

sandstone. Clastic sedimentary rock composed of predominantly sand-sized grains.

scarp. A steep cliff or topographic step resulting from displacement on a fault or as a result of slope movement or erosion. Synonymous with "escarpment."

scoria. A bomb-size pyroclast that is irregular in form and generally very vesicular.

sediment. An eroded and deposited, unconsolidated accumulation of rock and mineral fragments.

sedimentary. Pertaining to or containing sediment.

sedimentary rock. A rock resulting from the consolidation of loose sediment that has accumulated in layers; it may be "clastic," consisting of mechanically formed fragments of older rock; "chemical," formed by precipitation from solution; or "organic," consisting of the remains of plants and animals. One of the three main classes of rock—igneous, metamorphic, and sedimentary.

sedimentation. The process of forming or accumulating sediment into layers, including the separation of rock particles from parent rock, the transportation of these particles to the site of deposition, the actual deposition or settling of the particles, the chemical and other changes occurring in the sediment, and the ultimate consolidation of the sediment into solid rock.

seismic. Pertaining to an earthquake or Earth vibration, including those that are artificially induced.

seismicity. The phenomenon of movements in the Earth's crust. Synonymous with "seismic activity."

sequence. A succession of geologic events, processes, or rocks, arranged in chronologic order to show their relative position and age with respect to geologic history as a whole. Also, a rock-stratigraphic unit that is traceable over large areas and defined by sediment associated with a major sea level transgression–regression.

sheet erosion. The removal of thin layers of surface material more or less evenly from an extensive area of gently sloping land by broad continuous sheets of running water, rather than by streams flowing in well-defined channels.

sheet flow. The downslope movement or overland flow of water, in the form of a thin, continuous film, over relatively smooth soil or rock surfaces and not concentrated into channels larger than rills.

sheetwash. A sheetflood occurring in a humid region. Also, the material transported and deposited by the water of a sheetwash. Used as a synonym of "sheet flow" and "sheet erosion."

shield volcano. A broad shield-shaped volcano that is built up by successive, mostly effusive, eruptions of low-silica lava.

sierra. A high range of hills or mountains, especially one having jagged or irregular peaks that resemble the teeth of a saw.

silica. Silicon dioxide, SiO_2, an essential constituent of many minerals, occurring as crystalline quartz, cryptocrystalline chalcedony, and amorphous opal.

siliceous. Describes a rock or other substance containing abundant silica.

silt. Clastic sedimentary material intermediate in size between fine-grained sand and coarse clay, 0.0039 to 0.063 mm (0.00015 to 0.0025 in) across.

silting. The accumulation of silt suspended throughout a body of standing water or in some considerable portion of it. In particular, the choking, filling, or covering with stream-deposited silt behind a dam or other place of retarded flow, or in a reservoir. Synonymous with "siltation."

slope. The inclined surface of any part of Earth's surface, such as a hillslope. Also, a broad part of a continent descending into an ocean.

slope movement. The gradual or rapid downslope movement of soil or rock under gravitational stress. Synonymous with "mass wasting."

slope wash. Soil and rock material that is or has been transported down a slope under the force of gravity and assisted by running water not confined to channels; also, the process by which slope-wash material is moved.

slump. A generally large, coherent slope movement with a concave failure surface and subsequent backward rotation relative to the slope.

soil. The unconsolidated portion of the Earth's crust modified through physical, chemical, and biotic processes into a medium capable of supporting plant growth.

spalling. The process by which scales, plates, or flakes of rock, from less than a centimeter to several meters thick, successively fall from the bare surface of a large rock mass; a form of exfoliation.

spatter. An accumulation of initially very fluid pyroclasts, usually stuck together, coating the surface around a vent.

spring. A place where groundwater flows naturally from a rock or the soil onto the land surface or into a body of surface water.

strata. Tabular or sheetlike layers of sedimentary rock that are visually distinctive from other layers above and below. The singular form of the term is stratum, but is less commonly used.

stratigraphy. The geologic study of the origin, occurrence, distribution, classification, correlation, and age of rock layers, especially sedimentary rocks.

stream. Any body of water moving under gravity flow in a clearly confined channel.

stream channel. A long, narrow depression shaped by the concentrated flow of stream water.

stream terrace. A planar surface alongside a stream valley representing the remnants of an abandoned floodplain, stream bed, or valley floor produced during a former stage of erosion or deposition.

strike. The compass direction of the line of intersection of an inclined surface with a horizontal plane.

strike-slip fault. A fault with measurable offset where the relative movement is parallel to the strike of the fault. Described as left-lateral (sinistral) when relative motion of the block opposite the observer is to the left, and right-lateral (dextral) when relative motion is to the right.

structural geology. The branch of geology that deals with the description, representation, and analysis of structures, primarily on a moderate to small scale. The subject is similar to tectonics, but the latter term is generally used for the analysis of broader regional or historical phases.

structure. The attitudes and relative positions of the rock masses of an area resulting from such processes as faulting, folding, and igneous intrusion.

talus. Rock fragments, usually coarse and angular, lying at the base of a cliff or steep slope from which they have fallen.

tectonic. Describes a feature or process related to large-scale movement and deformation of Earth's crust.

tectonics. The geologic study of the broad structural architecture and deformational processes of the lithosphere and asthenosphere.

tephra. A collective term used for all pyroclastic material, regardless of size, shape, or origin, ejected into the air during a volcanic eruption.

terrace. Any long, narrow, relatively level or gently inclined surface (i.e., a bench or steplike ledge) that is bounded along one edge by a steeper descending slope and along the other edge by a steeper ascending slope, thus breaking the continuity of the slope; commonly occurs along the margin and above the level of a body of water, marking a former water level.

topography. The general morphology of Earth's surface, including relief and locations of natural and human-made features.

trace (structural geology). The intersection of a geological surface with another surface, for example, the trace of bedding on a fault surface, or the trace of a fault or outcrop on the ground.

trace fossil. A fossilized feature such as a track, trail, burrow, or coprolite (dung), that preserves evidence of an organism's life activities, rather than the organism itself. Compare to "body fossil."

transverse. Said of an entity that is extended in a crosswise direction, especially of a topographic feature that is oriented at right angles to the grain or general strike of a region.

trend. The direction or bearing of an outcrop of a geologic feature such as an ore body, fold, or orogenic belt.

tuff. Consolidated or cemented volcanic ash and lapilli.

tuffaceous. Describes non-volcanic, clastic sediments that contain ash-size pyroclasts.

type locality. The place where a geologic feature such as an ore occurrence, a particular kind of igneous rock, or the type specimen of a fossil species was first recognized and described.

unconformable. Describes strata that do not succeed the underlying rocks in immediate order of age or in parallel position, especially younger strata that do not have the same dip and strike as the underlying rocks. Also, describes the contact between unconformable rocks.

unconformability. The quality, state, or condition of being unconformable, such as the relationship of unconformable strata.

unconformity. A substantial break or gap in the geologic record where a rock unit is overlain by another that is not next in stratigraphic succession, resulting from either a change that caused deposition to cease for a considerable span of time or erosion with loss of the previously formed record.

undercutting. The removal of material at the base of a steep slope by the erosive action of water (such as a meandering stream), sand-laden wind in a desert, or waves along a coast.

uplift. A structurally high area in Earth's crust produced by movement that raises the rocks.

vadose. Refers to the unsaturated zone between the land surface and the water table that includes air, gases, and water held by capillary action.

vent. Any opening at Earth's surface through which magma erupts or volcanic gases are emitted.

vesicle. A cavity of variable shape formed by the entrapment of a gas bubble during solidification of lava.

vesicular. Describes the texture of a rock, especially lava, characterized by abundant vesicles formed as a result of the expansion of gases during the fluid stage of a lava.

viscosity. The property of a substance to offer internal resistance to flow.

volatile. Readily vaporizable.

volatile component. Material in magma, such as water or carbon dioxide, whose vapor pressures is sufficiently high to be concentrated as a gas.

volcanic. Pertaining to the activities, structures, or rock types of a volcano. A synonym of extrusive.

volcaniclastic. Pertaining to all clastic volcanic materials formed by any process of fragmentation, dispersed by any kind of transporting agent, deposited in any environment, or mixed in any significant portion with nonvolcanic fragments.

volcanogenic. Formed by processes directly connected with volcanism.

volcanism. The processes by which magma and its associated gases rise into Earth's crust and are extruded onto the surface and into the atmosphere.

water table. The surface between the saturated zone and the unsaturated zone. Synonymous with "groundwater table" and "water level."

weathering. The physical, chemical, and biological processes by which rock is broken down, particularly at Earth's surface.

welded tuff. A glass-rich pyroclastic rock that has been indurated by the welding together of its glass shards under the combined action of the heat retained by particles, the weight of overlying material, and hot gases.

welding. Consolidation of sediments under pressure. Also, the diagenetic process whereby discrete crystals and/or grains become attached to each other during compaction

Wisconsinan. Pertaining to the classical fourth glacial stage of the Pleistocene Epoch in North America, following the Sangamonian interglacial stage and preceding the Holocene Epoch.

xenocryst. A crystal that resembles a phenocryst in igneous rock but is foreign to the body of rock in which it occurs.

zeolite. A group of silicate (silicon + oxygen) minerals that commonly occur as well-formed crystals in the cavities of mafic igneous rocks, particularly basalt.

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Additional References

This chapter lists additional references, resources, and websites that may be of use to resource managers. Web addresses are valid as of August 2015. Refer to Appendix B for laws, regulations, and policies that apply to NPS geologic resources.

Geology of National Park Service Areas

- NPS Geologic Resources Division
  Energy and Minerals; Active Processes and Hazards; Geologic Heritage:
  http://nature.nps.gov/geology/
- NPS Geologic Resources Inventory: http://www.nature.nps.gov/geology/inventory/index.cfm
- NPS Geoscientist-In-the-Parks (GIP) internship and guest scientist program: http://www.nature.nps.gov/geology/gip/index.cfm
- NPS Views program (geology-themed modules are available for Geologic Time, Paleontology, Glaciers, Caves and Karst, Coastal Geology, Volcanoes, and a variety of geologic parks): http://www.nature.nps.gov/views/
- USGS Geology of National Parks (including 3D imagery): http://3dparks.wr.usgs.gov/

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
- NPS Natural resource management reference manual #77: http://www.nature.nps.gov/Rm77/
- Geologic monitoring manual (Young, R., and L. Norby, editors. 2009. Geological monitoring. Geological Society of America, Boulder, Colorado): http://nature.nps.gov/geology/monitoring/index.cfm
- NPS Technical Information Center (TIC) (Denver, Colorado; repository for technical documents): http://www.nps.gov/dsc/technicalinfocenter.htm

Climate Change Resources

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

Geological Surveys and Societies

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

US Geological Survey Reference Tools

- National geologic map database (NGMDB): http://ngmdb.usgs.gov/
- Geologic names lexicon (GEOLEX; geologic unit nomenclature and summary): http://ngmdb.usgs.gov/Geolex/geolex_home.html
- Geographic names information system (GNIS; official listing of place names and geographic features): http://gnis.usgs.gov/
- GeoPDFs (download searchable PDFs of any topographic map in the United States): http://store.usgs.gov (click on "Map Locator")
- Publications warehouse (many publications available online): http://pubs.er.usgs.gov
- Tapestry of time and terrain (descriptions of physiographic provinces): http://tapestry.usgs.gov/Default.html

Appendix A: Scoping Participants

The following people attended the GRI scoping meeting for Bandelier National Monument, held on 13–14 July 2005, or the follow-up report writing conference call, held on 3 July 2014. Discussions during these meetings supplied a foundation for this GRI report. The scoping summary document is available on the GRI publications website: http://go.nps.gov/gripubs.

2005 Scoping Meeting Participants

Name	Affiliation	Position
Kay Beeley	Bandelier National Monument	Cartographic Technician
Doug Bland	New Mexico Bureau of Geology and Mineral Resources	Geologist / Special Projects Manager
Tim Connors	NPS Geologic Resources Division	Geologist
Nelia Dunbar	New Mexico Bureau of Geology and Mineral Resources	Geochemist
Fraser Goff	New Mexico Bureau of Geology and Mineral Resources	Volcanologist
Bruce Heise	NPS Geologic Resources Division	Geologist
Brian Jacobs	Bandelier National Monument	Natural Resources Manager
Elaine Jacobs	Colorado State University	Geologist
Katie KellerLynn	Colorado State University	Geologist / Research Associate
Shari Kelley	New Mexico Bureau of Geology and Mineral Resources	Geophysicist / Field Geologist
Ifer McCollom	NPS Geologic Resources Division	GIS Specialist
Lauren Meyer	Bandelier National Monument	Vanishing Treasures Program, Architectural Conservator
Greer Price	New Mexico Bureau of Geology and Mineral Resources	Senior Geologist / Chief Editor
Peter Scholle	New Mexico Bureau of Geology and Mineral Resources	Director / State Geologist
Mike Timmons	New Mexico Bureau of Geology and Mineral Resources	Geologic Mapping Program Manager
Stacy Wagner	New Mexico Bureau of Geology and Mineral Resources	Senior Geologic Research Associate

2014 Conference Call Participants

Name	Affiliation	Position
Kay Beeley	Bandelier National Monument	Cartographic Technician
Tom Betts	Bandelier National Monument	Chief Ranger
Eric Bilderback	NPS Geologic Resources Division	Geologic Hazards and Disturbed Lands Program Lead
Tim Connors	NPS Geologic Resources Division	Geologist / GRI Maps Coordinator
Brian Jacobs	Bandelier National Monument	Natural Resources Manager
Barbara Judy	Bandelier National Monument	Chief of Resource Management
Katie KellerLynn	Colorado State University	Geologist / Research Associate
Shari Kelley	New Mexico Bureau of Geology and Mineral Resources	Geophysicist / Field Geologist
Jason Kenworthy	NPS Geologic Resources Division	Geologist / GRI Reports Coordinator
Jason Lott	Bandelier National Monument	Superintendent
Stephen Monroe	NPS Southern Colorado Plateau Network	Hydrologist
Hal Pranger	NPS Geologic Resources Division	Geologic Features and Systems Branch Chief
Dale Coker	Bandelier National Monument	Trails Program
Joseph Gurule	Bandelier National Monument	Facilities Manager

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 National Park Service 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 August 2015. 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. Regulations in association with 2009 PRPA are being finalized (August 2015).	**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.	**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.
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, 16 USC § 5937** protects the confidentiality of the nature and specific location of cave and karst resources.	**36 CFR § 2.1** prohibits possessing/destroying/disturbing…cave resources…in park units. **43 CFR Part 37** states that all NPS caves are "significant" and sets forth procedures for determining/releasing confidential information about specific cave locations to a FOIA requester.	**Section 4.8.1.2** requires NPS to maintain karst integrity, minimize impacts. **Section 4.8.2** requires NPS to protect geologic features from adverse effects of human activity. **Section 4.8.2.2** requires NPS to protect caves, allow new development in or on caves if it will not impact cave environment, and to remove existing developments if they impair caves. **Section 6.3.11.2** explains how to manage caves in/adjacent to wilderness.

Resource	Resource-specific Laws	Resource-specific Regulations	2006 Management Policies
Geothermal	**Geothermal Steam Act of 1970, 30 USC § 1001 et seq. as amended in 1988**, states that -no geothermal leasing is allowed in parks; -"significant" thermal features exist in 16 park units (features listed by the NPS at **52 Fed. Reg. 28793-28800** [August 3, 1987], and thermal features in Crater Lake, Big Bend, and Lake Mead); -NPS is required to monitor those features; and -based on scientific evidence, Secretary of Interior must protect significant NPS thermal features from leasing effects. **Geothermal Steam Act Amendments of 1988, Public Law 100--443** prohibits geothermal leasing in the Island Park known geothermal resource area near Yellowstone and outside 16 designated NPS units if subsequent geothermal development would significantly adversely affect identified thermal features.	None applicable	**Section 4.8.2.3** requires NPS to -preserve/maintain integrity of all thermal resources in parks. -work closely with outside agencies, and -monitor significant thermal features.
Soils	**Soil and Water Resources Conservation Act, 16 USC §§ 2011–2009** provides for the collection and analysis of soil and related resource data and the appraisal of the status, condition, and trends for these resources. **Farmland Protection Policy Act, 7 USC § 4201 et. seq**. requires NPS to identify and take into account the adverse effects of Federal programs on the preservation of farmland; consider alternative actions, and assure that such Federal programs are compatible with State, unit of local government, and private programs and policies to protect farmland. NPS actions are subject to the FPPA if they may irreversibly convert farmland (directly or indirectly) to nonagricultural use and are completed by a Federal agency or with assistance from a Federal agency. Applicable projects require coordination with the Department of Agriculture's Natural Resources Conservation Service (NRCS).	**7 CFR Parts 610 and 611** are the US Department of Agriculture regulations for the Natural Resources Conservation Service. Part 610 governs the NRCS technical assistance program, soil erosion predictions, and the conservation of private grazing land. Part 611 governs soil surveys and cartographic operations. The NRCS works with the NPS through cooperative arrangements.	**Section 4.8.2.4** requires NPS to -prevent unnatural erosion, removal, and contamination; -conduct soil surveys; -minimize unavoidable excavation; and -develop/follow written prescriptions (instructions).

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

NPS 315/129825, September 2015

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