Geologic Resource Evaluation Scoping Summary
Bandelier National Monument, New Mexico

This report highlights a geologic resource evaluation scoping session that was held at Bandelier National Monument on July 13–14, 2005. The NPS Geologic Resources Division (GRD) organized this scoping session in order to view and discuss the monument's geologic resources, address the status of geologic maps and digitizing, and assess resource management issues and needs. In addition to GRD staff, participants included park staff and cooperators from the New Mexico Bureau of Geology and Mineral Resources and Colorado State University (table 1).

Table 1. Participants of Bandelier's GRE Scoping Session

Name	Affiliation	Phone	E-Mail
Kay Beeley	Bandelier National Monument	505-672-3861, x542	kay_beeley@nps.gov
Doug Bland	New Mexico Bureau of Geology and Mineral Resources	505-466-6696	dbland@gis.nmt.edu
Tim Connors	NPS Geologic Resources Division	303-969-2093	tim_connors@nps.gov
Nelia Dunbar	New Mexico Bureau of Geology and Mineral Resources	505-835-5783	nelia@nmt.edu
Fraser Goff	New Mexico Bureau of Geology and Mineral Resources (formerly Los Alamos National Laboratory)	505-662-0805	candf@swcp.com
Bruce Heise	NPS Geologic Resources Division	303-969-2017	bruce_heise@nps.gov
Brian Jacobs	Bandelier National Monument	505-672-3861, x545	brian_jacobs@nps.gov
Elaine Jacobs	Colorado State University (formerly Bandelier National Monument)	505-672-3861, x545	elaine_jacobs@contractor.nps.gov
Katie KellerLynn	Colorado State University	970-586-7243	kellerlynn@estesvalley.net
Shari Kelley	New Mexico Bureau of Geology and Mineral Resources	505-661-6171	sakelley@ix.netcom.com
Ifer McCollom	NPS Geologic Resources Division	303-987-6954	ifer_mccollom@nps.gov
Lauren Meyer	Bandelier National Monument	505-672-3861, x549	lauren_meyer@nps.gov
Greer Price	New Mexico Bureau of Geology and Mineral Resources	505-835-5752	gprice@gis.nmt.edu
Peter Scholle	New Mexico Bureau of Geology and Mineral Resources	505-835-5294	scholle1@nmt.edu
Mike Timmons	New Mexico Bureau of Geology and Mineral Resources	505-835-5237	mtimmons@gis.nmt.edu
Stacy Wagner	New Mexico Bureau of Geology and Mineral Resources	505-835-6951	swagner@gis.nmt.edu

Wednesday, July 13, involved a welcome and introduction to the Geologic Resource Evaluation (GRE) Program, including status of reports and map products. The morning's discussion focused on map coverage of the monument and other "quadrangles of interest" in the vicinity of the monument. Nelia Dunbar (New Mexico Bureau of Geology and Mineral Resources) presented an overview of the geologic setting of Bandelier National Monument, with a focus on the chronical development of the Jemez Mountains volcanic field. Peter Scholle and Doug Bland (New Mexico Bureau of Geology and Mineral Resources) presented information and inquired about park support of the upcoming American Association of State Geologists field trip in 2006. Elaine Jacobs (graduate student at Colorado State University, formerly of Bandelier National Monument) presented an outline of her M.S. project on the paleohydrology of Bandelier. In the afternoon, Bruce Heise facilitated a group discussion regarding the geologic processes and features of Bandelier.

On ***Thursday, July 14,*** Fraser Goff (New Mexico Bureau of Geology and Mineral Resources, formerly of the Los Alamos National Laboratory) led a field trip for participants. The selected stops (overlook and Falls Trail) highlighted the monument's volcanic features. In addition, Lauren Meyer (Vanishing Treasures Program, Bandelier National Monument) guided participants along the trail near the cliff dwellings (Long House).

Overview of Geologic Resource Evaluation Program

The Geologic Resource Evaluation (GRE) Program is a collaborative effort of the NPS Geologic Resources Division and the NPS Inventory and Monitoring (I&M) Program with assistance from the U.S. Geological Survey (USGS), state geological surveys, and numerous individual volunteers and cooperators at National Park System units, colleges, and universities. The Geologic Resources Division administers the Abandoned Mine Lands (AML) and Geoscientists-in-the-Parks (GIP) Programs, which also contribute to the inventory. The focus of the collaborative effort is to provide park managers with baseline geologic data and assist them with geologic resource issues.

Geology is one of 11 inventories defined by Director's Order 77 (NPS 75): geology, species lists, bibliographies, base cartography, vegetation, water quality, soils, species surveys, species distribution (vascular plants and vertebrates), air quality, and climatic data.

The following are the objectives of the GRE scoping meetings:

- Identify geologic mapping coverage and needs.
- Identify distinctive geologic processes and features.
- Identify resource management issues.
- Identify potential monitoring and research needs.

The scoping process will result in the following outcomes:

- A scoping summary (this document)
- A bibliography
- A digital geologic map
- A geologic resource evaluation report

The scoping process includes a site visit with local experts, evaluation of the adequacy of existing maps, and discussion of park-specific geologic management issues. The emphasis of the geologic evaluation is not to routinely initiate new mapping projects but to aggregate existing information and identify where serious geologic data needs and issues exist.

Status of Scoping and Products

As of July 2005, the NPS Geologic Resources Division had completed the scoping process for 153 of 272 "natural resource" parks. Staff and cooperators have completed digital maps for 56 parks. The U.S. Geological Survey, various state geological surveys, and investigators at academic institutions are in the process of preparing mapping products for 57 parks. Pending ongoing data validation and updates, bibliographies for all parks are in progress. Writers have completed reports for 10 parks, with reports for 65 parks in progress.

Geologic Maps for Bandelier National Monument

During the July 13, 2005, scoping session, Tim Connors (GRD) presented a demonstration of some of the main features of the digital geologic map model used by the GRE Program. This model incorporates the standards for digitization set for the GRE Program. The model reproduces all aspects of a paper map, including notes, legend, and cross-sections, with the added benefit of being GIS compatible. Staff digitizes maps using ESRI ArcView/ArcInfo format with shape files and other features, including a built-in help file system to identify map units.

All units in the National Park System have "quadrangles of interests" mapped at one or more of the following scales: 7.5' × 7.5' (1:24,000), 15' × 15' (1:62,500), or 30' × 60' (1:100,000). For the purpose of geologic resource evaluations, GRE staff would like to obtain digital geologic maps of all identified 7.5-minute (1:24,000-scale) quadrangles of interest for a particular park. Often for simplicity, geologic map makers compile maps at 1:100,000 scale (30’ × 60’), which provides greater consistency and covers more area. The 12 quadrangles of interest for Bandelier National Monument are shown in figure 1 and listed in table 2. The contents of this document reflect what participants know about the published geologic maps as of October 21, 2005 (see table 2).

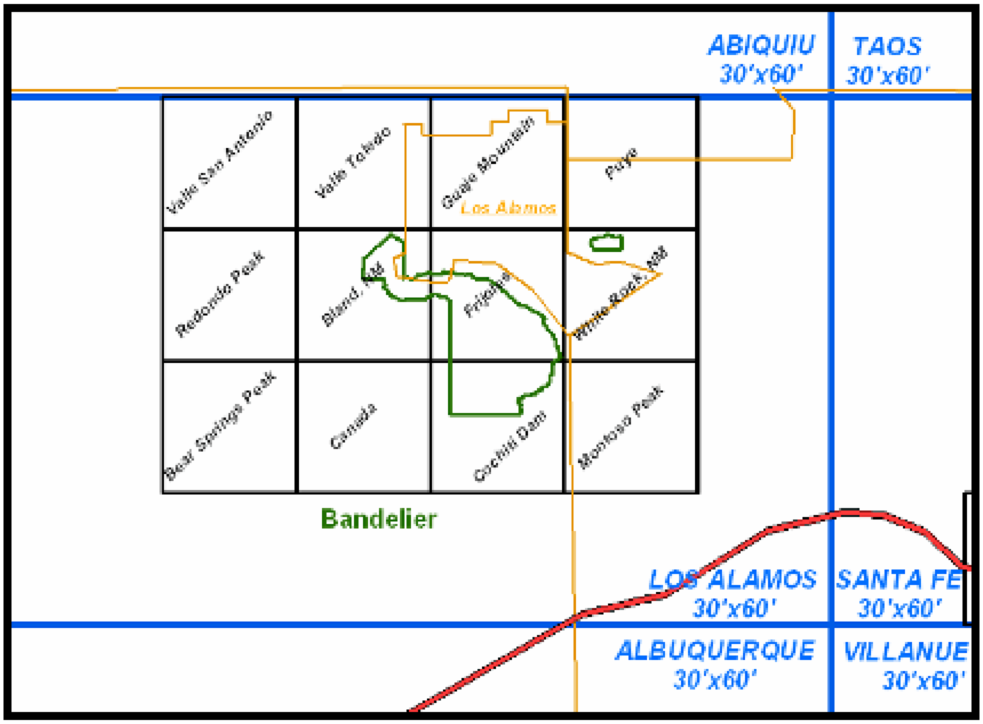

Figure 1. Quadrangles of interest for Bandelier National Monument. 7.5-minute quadrangles are shown in black outline and 30' × 60' in blue outline. The orange line indicates the county boundary.

While various agencies have published numerous “paper” geologic maps at suitable scale for Bandelier National Monument, the monument does not have full digital coverage. Pending completion of current mapping projects, USGS and NMBGMR maps will cover the quadrangles of interest for Bandelier National Monument at the 1:24,000 scale.

During the digitization process, GRE staff will compile the 12 quadrangles of interest (1:24,000 scale) to create the digital map of Bandelier National Monument. However, other maps also provide useful information for managing the monument’s geologic resources, though they will not be part of the final digital map product. For example, the New Mexico Bureau of Geology and Mineral Resources has published the following large-scale (1:24,000) geologic map, which covers portions of the Bland, Frijoles, Canada, and Cochiti Dam quadrangles:

Goff, F., Gardner, J.N., and Valentine, G., 1990, Geology of St. Peter’s Dome area, Jemez Mountains, New Mexico: New Mexico Bureau of Geology and Mineral Resources Geologic Map GM-69, scale 1:24,000 [2 sheets].

The quadrangles of interest for Bandelier National Monument lie entirely on the Los Alamos 30’ × 60’ sheet. Coverage of this sheet exists as a “preliminary landslide map” by Carrara and Dethier (see reference below). The Geologic Resources Division has obtained digital data of this map from the U.S. Geological Survey but has not reviewed the map using NPS-GRE standards.

Carrara, P.E., and Dethier, D.P., 1999, Preliminary map of landslide deposits in the Los Alamos 30’× 60’ quadrangle, New Mexico: U.S. Geological Survey Miscellaneous Field Studies Map MF-2328, scale 1:100,000.

In addition, two maps provide complete coverage for Bandelier National Monument at the 1:125,000 scale:

Kelley, V.C., 1978, Geology of Espanola Basin, New Mexico: New Mexico Bureau of Geology and Mineral Resources Geologic Map GM-48, scale 1:125,000.

Smith, R.L., Bailey, R.A., and Ross, C.S., 1970, Geologic map of the Jemez Mountains, New Mexico: U.S. Geological Survey Miscellaneous Geologic Investigations Map I-571, scale 1:125,000.
Note: The GIS team at the NPS Intermountain Region has a digitized version of this map; however, it lacks metadata and the map does not meet current “GRE standards.”

Another notable geologic map of the area is Kelley (1977):

Kelley, V.C., 1977, Geology of Albuquerque Basin, New Mexico: New Mexico Bureau of Geology and Mineral Resources Memoir 33, 59 p., scale 1:190,000.

The U.S. Geological Survey has published the following non-quadrangle based, large-scale (1:24,000) geologic maps in the vicinity of Bandelier National Monument. The numbers in parentheses represent the USGS GMAP identification code, which are cross-referenced with the GRE database.

(6644) Manley, K., 1977, Geologic map of the northeastern part of the Espanola Basin, New Mexico, showing the Cejita Member (new name) of the Tesuque Formation: U.S. Geological Survey Miscellaneous Field Studies Map MF-877, scale 1:24,000.

(6678) Santos, E.S., Hall, R.B., and Weisner, R.C., 1975, Mineral resources of the San Pedro Parks Wilderness and vicinity, Rio Arriba and Sandoval Counties, New Mexico: U.S. Geological Survey Bulletin 1385-C, scale 1:24,000.

(6217) Baltz, E.H., and O’Neill, J.M., 1986, Geologic map and cross sections of the Sapello River area, Sangre De Cristo Mountains, Mora and San Miguel Counties, New Mexico: U.S. Geological Survey Miscellaneous Geologic Investigations Map I-1575, scale 1:24,000.

(6189) Baltz, E.H., 1972, Geologic map and cross sections of the Gallinas Creek area, Sangre De Cristo Mountains, San Miguel County, New Mexico: U.S. Geological Survey Miscellaneous Geologic Investigations Map I-673, scale 1:24,000.

(6686) Spiegel, Z., and Baldwin, B., with contributions by Kottlowski, F.E., Barrows, E.L., and Winkler, H.A., 1963, Geology and water resources of the Santa Fe area, New Mexico [out of print]: U.S. Geological Survey Water-Supply Paper 1525, 258 p., scale 1:24,000.

(2854) Johnson, R.B., 1969, Pecos National Monument, New Mexico—its geologic setting: U.S. Geological Survey Bulletin 1271-E, 11 p., scale 1:24,000.

(6687) Thomas, C.L., Stewart, A.E., and Constantz, J., 2000, Determination of infiltration and percolation rates along a reach of the Santa Fe River near La Bajada, New Mexico: U.S. Geological Survey Water-Resources Investigations Report 2000-4141, 65 p., scale 1:24,000.

Table 2. Quadrangles of Interest for Bandelier National Monument

7.5' quadrangle	Best extent of coverage	Map citation	Paper	Digital
GRE Plan: Digitize NMBGMR hard copy data to NPS digital format				
White Rock	Dedicated "1:1" 7.5'-quadrangle	Dethier, D.P., 1997, Geology of White Rock quadrangle, Los Alamos and Santa Fe Counties, New Mexico: New Mexico Bureau of Geology and Mineral Resources Geologic Map GM-73, scale 1:24,000.	Yes	No
GRE Plan: Convert NMBGMR digital format to NPS digital format				
Guaje Mountain	Dedicated "1:1" 7.5'-quadrangle	Kempter, K.A., Kelley, S., Gardner, J.N., Reneau, S.L., Broxton, D.E., and Goff, F., 2002, Geology of the Guaje Mountain 7.5 minute quadrangle, Los Alamos and Sandoval Counties: New Mexico Bureau of Geology and Mineral Resources Open-File Geologic Map OF-GM 55, scale 1:24,000.	Yes	Yes
Frijoles	Dedicated "1:1" 7.5'-quadrangle	Goff, F., Gardner, J.N., and Reneau, S.L., 2002, Geology of the Frijoles 7.5-minute quadrangle: New Mexico Bureau of Geology and Mineral Resources Open-File Geologic Map OF-GM 42, scale 1:24,000.	Yes	Yes
Canada	Dedicated "1:1" 7.5'-quadrangle	Lynch, S.D., Smith, G.A., and Kuhle, A.J., 2004, Preliminary geologic map of the Canada 7.5 minute quadrangle, New Mexico [unpublished]: New Mexico Bureau of Geology and Mineral Resources, scale 1:24,000.	Yes	Yes
Bear Springs Peak	Dedicated "1:1" 7.5'-quadrangle	Kempter, K.A., and Kelley, S., 2003, Geology of the Bear Springs Peak 7.5 minute quadrangle, Sandoval County, New Mexico: New Mexico Bureau of Geology and Mineral Resources Open-File Geologic Map OF-GM 74, scale 1:24000.	Yes	Yes
Bland	Dedicated "1:1" 7.5'-quadrangle	Goff, F., Reneau, S.L., Lynch, S., Goff, C.J., Gardner, J.N., Drakos, P., and Katzman, D., 2005, Preliminary geologic map of the Bland 7.5-minute quadrangle, Sandoval and Los Alamos Counties, New Mexico: New Mexico Bureau of Geology and Mineral Resources Open-file Geologic Map OF-GM 112, scale 1:24,000.	Completed (NMBGMR will send to GRD)	Completed (NMBGMR will send to GRD)
Redondo Peak	Dedicated "1:1" 7.5'-quadrangle	Goff, F., Gardner, J.N., Reneau, S.L., and Goff, C.J., 2005, Preliminary geologic map of the Redondo Peak 7.5-minute quadrangle, Sandoval County, New Mexico: New Mexico Bureau of Geology and Mineral Resources Open-file Geologic Map OF-GM 111, scale 1:24,000.	Completed (NMBGMR will send to GRD)	Completed (NMBGMR will send to GRD)
Valle Toledo	Dedicated "1:1" 7.5'-quadrangle	In progress by NMBGMR	In progress (completion of field work slated for spring 2006)	In progress (completion: unknown)
Valle San Antonio	Dedicated "1:1" 7.5'-quadrangle	In progress by NMBGMR	In progress (completion of field work slated for spring 2006)	In progress (completion: unknown)
GRE Plan: Convert USGS digital format to NPS digital format				
Puye	Dedicated "1:1" 7.5'-quadrangle	Dethier, D.P., 2003, Geologic map of the Puye quadrangle, Los Alamos, Rio Arriba, Sandoval, and Santa Fe Counties, New Mexico: U.S. Geological Survey, Miscellaneous Field Studies Map MF-2419 scale 1:24,000.	Yes	Yes

7.5' quadrangle	Best extent of coverage	Map citation	Paper	Digital
Montoso Peak	Dedicated "1:1" 7.5'-quadrangle	In progress by USGS (Contacts: Ren Thompson [mapper] and Jim Cole)	In progress (completion: unknown)	In progress (completion: unknown)
Cochiti Dam	Dedicated "1:1" 7.5'-quadrangle	In progress by USGS (Contacts: Ren Thompson and David Dethier [mappers] and Jim Cole)	In progress (completion: unknown)	In progress (completion: unknown)

Geologic Resource Evaluation Report

Geologic Resource Evaluation reports include sections about geologic resources of concern for management (referred to as "issues"), geologic features and processes, the park's geologic history, a map unit properties table that highlights the significant features and resource concerns for each map unit in the park, references (different from the bibliography), and various appendices (e.g., map graphics and scoping report). This scoping summary will serve as a starting point for information to be included in the GRE report for Bandelier National Monument.

Geologic Setting of Bandelier National Monument

Bandelier National Monument is part of the Jemez Mountains volcanic field. This field began developing 13.4 million years ago. Between 13.4 and 1.7 million years ago, a wide range of volcanic styles were displayed at the field: basaltic, andesitic, dacitic, and rhyolitic. Single eruptions were relatively small, but together produced a large volume of material, which underpins the Jemez Mountains today. Geologists have categorized the eruptions into various rock units including the Bearhead and Canovas Canyon rhyolites, the Paliza Canyon Formation, the Cerro Rubio dome, the Tshicoma Formation, and the Cerros del Rio basalts.

About 1.7 million years ago, eruptions resulting in the deposition of the Bandelier Tuff began to take place. At this time, the eruptive style of the Jemez Mountains volcanic field changed. The "classic volcanic rocks" of the Jemez Mountains are the result of two very large, explosive volcanic eruptions that occurred at 1.61 and 1.25 million years ago. The eruptions had a combined volume of about 160 cubic miles (650 km^3). These eruptions have tremendous geological significance; researchers and educators have used studies of these deposits to understand the behavior of such large-volume volcanic eruptions. The second of the two eruptions produced a caldera 12 miles (7.5 km) in diameter, called the Valles Caldera.

Shortly after the eruption of the upper Bandelier Tuff (1.25 million years ago), a series of domes erupted, ending about 500,000 years ago. Domes also erupted during the 400,000-year interval between the major caldera-forming eruptions. The youngest eruptive activity in the Jemez Mountains volcanic field is the El Cajete–Banco Bonito eruptive event, which occurred about 60,000 years ago. This deposit overlies the Bandelier Tuff in most of Bandelier National Monument.

The volcanic features of the Jemez Mountains volcanic field affected the ancient peoples of Bandelier in at least three ways. First, they built cliff dwellings in the Bandelier Tuff. Ancient peoples took advantage of natural erosion processes and further excavated caves to make them habitable. In addition, they "excavated" trail systems into the tuff, some of which are "announced" by petroglyphs. Second, the location of many Puebloan communities in the area correlates to the presence of the El Cajete ash fall (pumice). Because the pumice retains water, it was important for prehistoric farming. Third, volcanic domes and deposits provide a source of obsidian, which they used for making tools.

Geologic Features, Processes, and Issues at Bandelier National Monument

The scoping session at Bandelier provided the opportunity to capture a list of geologic features and processes operating in the monument, which will be highlighted and expanded in the GRE report. Some of these features and processes may be of concern for resource mangers.

Participants discussed the following features and processes:

Caves and Karst

Many natural caves occur in Bandelier National Monument. Most of these caves are in the Upper Tshirege Member of the Bandelier Tuff. Some of the caves formed during the escape of volcanic gases. Bats, birds, and spotted owls now use the caves for shelter. Roosting bats use a few of the fissures

Making use of naturally eroded areas, ancient peoples further excavated the caves for habitation. Upon excavation the natural caves are referred to as “cavates” (pronounced cave-ates). Most of the cavates are in Frijoles Canyon. Ancient people also took advantage of erosional processes for excavating trails (including steps and handholds). Some of the trails are “announced” by petroglyphs. They also used the tuff as building stone.

Once cavates have been excavated, the tuff loses its hard (protective) casing, resulting in collapse. Continued (natural) erosion is a concern for the long-term preservation of the cavates. Most of the cavates are located on cliffs with a southern exposure where diurnal temperature changes accelerate natural cycles of freeze thaw and cliff retreat. This results in major rockfalls which can take out whole sections of cavates or petroglyph panels. Hence, an understanding of the composition of the tuff in which the cavates are excavated is important for managing these cultural resources.

Park staff has completed the first phase of the surveys of the 1,060 cavates in the monument. However, the monument’s general management plan does not yet contain a mitigation scenario for preserving the cavates.

Disturbed Lands

Although the Ancient Puebloans mined obsidian in the area adjacent to Bandelier National Monument, active, large-scale mining has not taken place in the monument. However, pumice is being mined just outside the monument for “stone-washed” jeans. Some quarrying took place in the monument for building stone during the CCC era. The quarry now serves as the park amphitheater.

A landfill is associated with the amphitheater area. Park staff believes that the former atomic energy commission used this landfill; however, no documentation of what was dumped exists. General thinking is that all or most of the debris in the landfill came from the park. However, Los Alamos National Laboratory has not preformed characterization or remediation of the landfill. Park staff does not know when or if Los Alamos National Laboratory will address this particular legacy site, but it is on the list (Brian Jacobs, written communication, October 21, 2005).

Eolian (Windblown) Features and Processes

Soils on mesa tops have an eolian (windblown) component. Some soils in woodland areas also have an eolian component, for example, mounded topography. In an effort to document the extent of different erosional agents, Craig Allen is collecting samples of eolian deposits from mesa tops. Allen is investigating wind erosion as part of a climate study in conjunction with Los Alamos National Laboratory. Since January 2003, park staff has used BSNE (Big Springs Number Eight) samplers to monitor soil movement.

In the front country, eolian deposits are protecting floors in cavates, while eolian transport is causing erosion on walls.

Fluvial (Stream) Features and Processes

Most canyon cutting occurs during flood events. Floods at Bandelier have run at 3,000 cubic feet per second (85 m^3/s). Water erosion is exacerbated after fires, and water quality is affected by increased sediment loads. Additionally, landslides may be reactivated after fires. Steve Reneau published a study (see following reference) about stream incision and erosion over time in Frijoles Canyon.

Reneau, S.L., 2000, Stream incision and terrace development in Frijoles Canyon, Bandelier National Monument, New Mexico, and the influence of lithology and climate: Geomorphology v. 32, p. 171–193

Steven Reneau is a geomorphologist at Los Alamos National Laboratory. This study looks at the development of Frijoles Creek within a volcanic terrain. It includes discussion of the drainage basin, stream source, knickpoints, and base level for the creek. In addition, information about past climatic conditions and their effects on aggradation and incision are examined. It provides a nice overview of fluvial processes in the Frijoles watershed.

Floods impact park infrastructures; for example, the administrative building and visitor center are in the floodplain. Basalt flows create scenic waterfalls in Frijoles Canyon. Droughts or wet cycles influence springs. Though very precious for wildlife, vegetation, and human consumption in the backcountry, no one has thoroughly inventoried the springs in the monument; Paul Christensen (NPS Water Resources Division in Fort Collins, Colorado) conducted a survey of springs in Frijoles Canyon (see reference below). Furthermore, investigators have studied the geohydrology of the monument.

Christensen, Paul, 1980, Base flow sources in the upper reaches of Rito de los Frijoles, Bandelier National Monument: National Park Service Water Resources Report 80-5, 17 p.

Purtyman, W., 1980, Geohydrology of Bandelier National Monument, New Mexico: Los Alamos National Laboratory Report LA-8461-MS, 25 p.

The monument's water resources management plan goes into some depth about water resources at Bandelier. The author is a NPS hydrologist based at Buffalo National River, Arkansas. In the process of preparing this NPS internal document he met with several scientists from Los Alamos National Laboratory, the Department of Energy oversight group for the national laboratory, and the State of New Mexico Environment Department. In addition he received assistance from local park personnel and the NPS Water Resources Division. This document summarizes the area's water resources and identifies, assesses, and makes recommendations concerning pertinent water resource issues affecting Bandelier National Monument. Appendix D of the plan contains a set of project statements for high priority issues; however, these projects require external funding or expertise. In particular, the plan focuses on water quality issues arising from operations at Los Alamos National Laboratory that may impact the monument. In 1998 after investigators found high-explosive residues in the Rio Grande, Los Alamos National Laboratory was put under court order by the State of New Mexico to determine contaminant pathways to the local aquifer.

Mott, D., 1999. Water resources management plan, Bandelier National Monument: Los Alamos, New Mexico, Bandelier National Monument [report on file], 165 p.

Geologic Interpretation

The monument's natural history association (Western National Parks Association) sells books and materials about geology in the visitor center. For example, "A Guide to the Falls Trail" includes geologic stops. Several former employees of Los Alamos National Laboratory provided information for this guide. Fraser Goff has conducted training about the geologic resources of Bandelier National Monument for park interpreters in the past. Interpreters lead geology hikes along the Falls Trail for interested visitors.

Because so many field camps come through the monument, park staff suspects that many unpublished field guides would be available for park use. By collecting these field guides, park staff could obtain already prepared information for interpretive use, as well as monitor the accuracy of what is being taught. When groups apply for educational fee waivers, park staff could request materials at that time. The New Mexico Bureau of Geology and Mineral Resources has published field excursions for New Mexico that would be appropriate for selling in the monument's book store.

Geothermal Features and Processes

Starting in the 1960s (and continuing until the early 1980s), individuals and companies explored the region of the caldera for its potential to provide geothermal energy (Goff, 2002; Goff and Gardner, 1988). This resource is 428°F–572°F (220°C–300°C) at depths of 1,970 to 6,560 feet (600 to 2000 m) within the southwestern sector of Valles Caldera. A temperature measurement of the main aquifer, beneath Pajarito Plateau, recorded 86°F (30°C) at 1,970 feet (600 m) below the ground surface (Vuataz and Goff, 1986); however, no identified aquifers occur in the monument.

Goff, F., 2002, Geothermal potential of Valles Caldera, New Mexico: Geo-Heat Center Quarterly Bulletin, v. 23, no. 4, p. 7–12.

Goff, F., and Gardner, J.N., 1988, Valles Caldera region, New Mexico and the emerging Continental Scientific Drilling Program: Journal of Geophysical Research, v. 93(B6), p. 5997–6000.

Vuataz, F-D., and Goff, F., 1986, Isotope geochemistry of thermal and nonthermal waters in the Jemez Mountains, Northern New Mexico: Journal of Geophysical Research, v. 91(B2), p. 1835–1854.

According to NMBGMR staff, although geothermal energy is a potential resource, it is insignificant by comparison to other energy resources in New Mexico; therefore, commercial development close to the monument's boundaries should not be a concern for park managers. The majority of interests in geothermal development were bought when the Valles Caldera National Preserve was established in 2000. However, a 12.5% interest still exists, but it appears that the owners are simply trying to inflate the value in order to receive a better buy-out price from the federal government. However, developers are reconsidering the Fenton Hill geothermal facility to perhaps provide energy to Los Alamos. This facility is outside of park boundaries (Elaine Jacobs, written communication, October 9, 2005).

Heat pumps may be a viable option for heating and cooling buildings in the park. In order to access the energy source, a hole is drilled into substrate into which water is pumped, and water is heated during the winter and cooled during the summer. Typical well depths are 1,000 feet (305 m) or less. According to Peter Scholle (State Geologist of New Mexico), this is one of the most efficient heating/cooling systems.

Lake (Lacustrine) Features and Processes

Steve Reneau studied landslides in White Rock Canyon, which create temporary dams and lakes on the Rio Grande. This study resulted in the following reference:

Reneau, S.L., and Dethier, D.P., 1996. Pliocene and Quaternary history of the Rio Grande, White Rock Canyon and vicinity, New Mexico, *in* Goff, F., Kues, B.S., Rogers, M.A., McFadden, L.D., and Gardner, J.N., eds., The Jemez Mountains Region: New Mexico Geological Society Forty-Seventh Annual Field Conference Guidebook, p. 317–324.

During the 1980s, the modern dam that creates the Cochiti Reservoir caused water to back up into Bandelier National Monument. This event resulted in slumping of the canyon walls, which killed vegetation and caused invasion of exotic plants. The dam back-up also silted springs and eroded a trail. At the time, the Army Corps of Engineers was holding water at the maximum level. More recently, the corps has improved its management practices. However, increased siltation in the reservoir will increase water level, potentially resulting in back-flow into Bandelier again, which would be a concern for long-term park management.

A legacy of ranching resulted in some cattle ponds in the monument.

Mass Wasting (Hill Slope) Features and Processes

In addition to the slumping caused by lacustrine processes, other mass-wasting events have occurred within Bandelier National Monument. For instance, a potential for rockfall occurs throughout the monument. The upper Bandelier Tuff is the rock source for most of the rockfalls. Freeze-thaw processes on south-facing slopes are a major contributor. In particular, the cliffs above the visitor center and other facilities are prone to rockfall. Also, the area around the "big curve" to the visitor center is particularly susceptible to rockfall. Isolated rocks fall onto roads and trails causing hazards. Park staff built retaining walls to mitigate the problem in the headquarters area. Periodically maintenance staff removes the debris.

Permafrost

Cerro Grande, the highest peak in the monument, rises to 10,199 feet (3,109 m) above sea level. At these elevations in other locations, permafrost occurs. However, a soil survey is needed to determine whether permafrost is present in the monument today. In the past, frost heave created features such as patterned ground. Large angular blocks of rock in an accumulation known as felsenmeer (German for "rock sea") are conspicuously displayed above treeline. These features have cultural importance because they served as "eagle pits" for Ancient Puebloans.

Seismic Features and Processes

Seismic processes include earthquakes in the monument; features include fault scarps. A total of 650 feet (200 m) of displacement has occurred in the Bandelier Tuff since 1.25 million years ago. At present, the Pajarito fault poses a significant seismic risk to the monument. Jamie Gardner at the Los Alamos National Laboratory is currently evaluating seismic hazards.

The last major earthquake in the vicinity of Bandelier occurred 6,000 years ago. The closest historic "100-year" quake occurred in May 1918 in Cerrillos, New Mexico. Socorro is the most active area in the state at present. In 1906 a series of earthquakes occurred around Socorro with the greatest being 5.5. Felt earthquakes, which rattle houses and shift dishes, occur at Bandelier National Monument.

Unique Geologic Features

"Unique geologic features" at Bandelier National Monument include the following:

- Ancient Puebloans used obsidian for making tools. Sources of obsidian are immediately adjacent to the monument, for example, Rabbit Mountain dome, Cerro del Medio, and Obsidian Ridge.
- Bandelier Tuff hosts ancient cave dwellings and trails.
- El Cajete pumice, which retains water, was important for prehistoric farming.
- The abundance of age dates for the tuff, a characteristic of this well-studied resource, is appealing for research.
- Nice examples of tent rocks (eroded cones of soft tuff) occur in Frijoles and Alamo Canyons. The New Mexico Bureau of Geology and Mineral Resources published the following reference, which includes information about tent rocks:

Self, S., Heiken, G., Sykes, M.L., Wohletz, K., Fisher, R.V., and Dethier, D.P, 1996, Field excursions to the Jemez Mountains, New Mexico: New Mexico Bureau of Mines and Mineral Resources Bulletin 134, 72 p.

- The "type section" of Bandelier Tuff is in the vicinity of Bandelier National Monument (possibly on Los Alamos National Laboratory land though). Griggs (1964) formally describes and names many of the formations in the area and lists their type localities or regions. Los Alamos National Laboratory and the town of Los Alamos contracted R. L Griggs (USGS) to study water supply. At the time, they were considering placing water wells in the Valle Grande. Griggs suggests that this action would cut off recharge waters to streams draining the eastern slopes of the Jemez Mountains. His paper gives a good historical overview of the mapping in progress by R. L. Smith, R. A. Bailey, and C. S. Ross at the time. His map is a nice forerunner to the comprehensive map published by Smith, Bailey, and Ross in 1970. The following references discuss the type section:

Bailey, R.A., R.L. Smith, and C.S. Ross, 1969, Stratigraphic nomenclature of volcanic rocks in the Jemez Mountains, New Mexico: U.S. Geological Survey Bulletin 1274-P, 19 p.

Griggs, R.L., 1964, Geology and ground-water resources of the Los Alamos area, New Mexico: U.S. Geological Survey Water-Supply Paper 1753, 107 p., scale 1:24,000.

Volcanic Features and Processes

Bandelier National Monument is a volcanology mecca. It hosts a world-class example of welded tuff and exemplifies large-scale explosive siliceous volcanism. Many of the seminal papers and maps on volcanism feature Bandelier (see references below). C. S. Ross's work dates back to the 1920s; Smith, Bailey, and Ross began mapping the caldera in 1938, finishing in 1970. The resultant map serves as a benchmark for the study of volcanism. Researchers and educators come to Bandelier to see the Bandelier Tuff because of its size and the volcanic structures it preserves. The tuff is very well exposed along trails in the monument, making it accessible to researchers and the public alike. Past researchers have thoroughly studied the tuff's geochemistry and eruption dynamics, making these well-characterized units appealing for current and future researchers in testing their hypotheses.

Smith, R.L., and Bailey, R.A., 1966, The Bandelier Tuff—a study of ash-flow eruption cycles from zoned magma chambers: Bulletin of Volcanology, v. 29, p. 83–104.

Smith, R.L., and Bailey, R.A., 1968, Resurgent cauldrons: Geological Society of America Memoir 116, p. 613–662.

The following list highlights other "classic" volcanic feature preserved in the monument. Specific features should be interpreted in the context of the caldera, that is, as part of a "larger whole."

- Phreatomagmatism (i.e., hot lava interacting with wet sediment)—A good example is the "maar" along the Falls Trail.
- Infilling of paleotopography by volcanic deposits (e.g., ignimbrites going from thin to thick and paleocanyons). A good example is the paleocanyon for the ancestral Rio Grande along the Falls Trail.
- Physical features preserved from a major eruption event: multiple flow units, multiple cooling units, fall deposits, surge beds (turbulent episodes), gas escape pipes—the tuff has it all!
- El Cajete pumice holds water, making habitat for vegetation. This pumice is useful for locating agricultural areas of ancient communities because of this property.
- Tent rocks (hoodoos) in Alamo and Frijoles Canyons outline the distribution of the caldera.

With respect to current resource management, the Jemez Mountains complex is not extinct. The Los Alamos National Laboratory is a source of scientific expertise and information for addressing current issues related to volcanism and geothermal energy. The national laboratory currently contributes to a statewide seismic monitoring network that evaluates earthquakes and possible volcanic events. Earthquakes, which would be detected by the network, are precursors to a volcanic event. A likely location for future eruptions is in the southwestern part of the caldera.