National Park Service
US Department of the Interior

Natural Resource Stewardship and Science

Gila Cliff Dwellings National Monument

Geologic Resources Inventory Report

Natural Resource Report NPS/NRSS/GRD/NRR—2014/849

ON THE COVER
Between about the 1270s and 1290s CE (common era), people of the Mogollon culture built structures and inhabited caves in Cliff Dweller Canyon. These caves occur in the sedimentary Gila Conglomerate. Photograph by Katie KellerLynn (Colorado State University).

THIS PAGE
Gila Conglomerate is exposed in the bluffs along the Middle Fork Gila River. Differential erosion and weathering have etched the face of the bluffs and accentuated the bedding planes of the exposed rock. Photograph by Katie KellerLynn (Colorado State University).

Gila Cliff Dwellings National Monument

Geologic Resources Inventory Report

Natural Resource Report NPS/NRSS/GRD/NRR—2014/849

Katie KellerLynn
Colorado State University Research Associate
National Park Service Geologic Resources Division
Geologic Resources Inventory
PO Box 25287
Denver, CO 80225

August 2014

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

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

The Natural Resource Report Series is used to disseminate high-priority, current natural resource management information with managerial application. The series targets a general, diverse audience, and may contain NPS policy considerations or address sensitive issues of management applicability.

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.

Printed copies of this report are produced in a limited quantity and they are only available as long as the supply lasts. This report is available from the Geologic Resources Inventory website (http://www.nature.nps.gov/geology/inventory/gre_publications.cfm) and the Natural Resource Publications Management website (http://www.nature.nps.gov/publications/nrpm/). To receive this report in a format optimized for screen readers, please email irma@nps.gov.

Please cite this publication as:

KellerLynn, K. 2014. Gila Cliff Dwellings National Monument: Geologic resources inventory report. Natural Resource Report NPS/NRSS/GRD/NRR—2014/849. National Park Service, Fort Collins, Colorado.

NPS 349/126226, August 2014

Contents

List of Figures

List of Tables

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 Gila Cliff Dwellings National Monument (New Mexico) on 14 November 2007 and a follow-up conference call on 7 December 2011, which were held by the Geologic Resources Division to determine geologic resources, the status of geologic mapping, and geologic resource management issues and needs. It is a companion document to previously completed GRI digital geologic map data.

This GRI report was written for resource managers to support science-informed decision making. It may also be useful for interpretation. The report was prepared using available geologic information, and the NPS Geologic Resources Division conducted no new fieldwork in association with its preparation. Sections of the report discuss distinctive geologic features and processes within Gila Cliff Dwellings National Monument, highlight geologic issues facing resource managers, describe the geologic history leading to the present-day landscape, and provide information about the GRI geologic map data. A poster (in pocket) illustrates these data. The Map Unit Properties Tables (in pocket) summarizes report content for each geologic map unit.

The GRI data set that accompanies this report includes source maps by Ratté and Gaskill (1975) and Ratté et al. (2014), which have been converted to a geographic information system (GIS) format and conform to the GRI GIS data model. Ratté and Gaskill (1975) mapped the geology of the Gila Wilderness study area at a scale of 1:62,500. The GRI data set includes the eastern half of this map, in particular the Gila Cliff Dwellings caldera in which the monument lies. At a scale of 1:24,000, Ratté et al. (2014) mapped the monument and adjacent Gila Hot Springs quadrangle at greater detail. The geologic maps graphics (in pocket) highlight the geologic data of Ratté et al. (2014). The combination of these two source maps provides an overview of smaller scale geologic features at the monument within a regional geologic setting of widespread volcanism. Figure 9 of this report serves as a correlation chart for the map units of Ratté and Gaskill (1975) and Ratté et al. (2014).

The rocks in the monument and surrounding area are either volcanic rocks—such as the Bloodgood Canyon Tuff (map unit Tbc of Ratté and Gaskill 1975, or Tbt of Ratté et al. 2014) and Bearwallow Mountain Andesite (Tya of Ratté and Gaskill 1975, or Tba of Ratté et al. 2014)—or sedimentary rocks derived from volcanic rocks. Sediments comprising the Gila Conglomerate (QTs of Ratté and Gaskill 1975 or QTg of Ratté et al. 2014) were shed from the surrounding mountains (volcanoes) and transported by streams into a subsiding basin—the Gila Hot Springs graben. Stream incision followed basin filling. As a result of stream erosion and groundwater sapping (a form of erosion), caves developed in the Gila Conglomerate. Humans occupied these caves during two phases: Between about the 1270s and 1290s CE (common era, preferred to AD), people of the Mogollon culture inhabited the caves. An earlier Archaic group of inhabitants used the caves before 500 CE.

During the 2007 scoping meeting and 2011 follow-up conference call, participants (see Appendix A) identified the following geologic features of significance for resource management and interpretation:

Geologic features and processes include the following:

- Mogollon-Datil Volcanic Field. Gila Cliff Dwellings National Monument lies in the Mogollon-Datil volcanic field in southwestern New Mexico. Extending from northern Mexico to Colorado, it is part of one of the world's great volcanic provinces. Over a 35-million-year history, from 40 million to less than 5 million years ago, the field hosted 13 supervolcanoes-a popularized term used to describe the largest volcanic eruptions on Earth. The Bursum and Gila Cliff Dwellings calderas are the remnants of two of these supervolcanoes. The monument lies in the Gila Cliff Dwellings caldera. The expulsion of tremendous volumes of lava and pyroclastic material about 28 million years ago caused the collapse of these volcanoes.
- Gila Hot Springs Graben. The present landscape of Gila Cliff Dwellings National Monument is largely an outcome of erosion and faulting of mid-Tertiary volcanoes. The Gila Hot Springs graben-an elongate, downdropped block of Earth's crust, bounded by faults-is the primary, resultant structural feature.
- Hot Springs. Hot springs form along faults in the deepest part of the Gila Hot Springs graben. Gila National Forest, which surrounds the monument, is known for its geothermal resources. Middle Fork (Light Feather) hot spring, which is 0.8 km (0.5 mi) north-northeast up the Middle Fork trail, is the closest hot spring to the monument.
- Gila Conglomerate. While the Gila Hot Springs graben was forming, rivers and streams were transporting and depositing material shed from the surrounding mountains (volcanoes) into the subsiding basin. The thick accumulation of basin fill in the graben (and elsewhere) is known as Gila Conglomerate. This rock unit makes up the walls of Cliff Dweller Canyon and

the prominent bluffs that border the river at the junction of the West Fork and Middle Fork Gila River.

- Terraces and Valley Incision. As rivers episodically dissected older fill, they left a distinct geomorphic record of valley alluvium and stream terraces. The various terrace levels at the monument show where the Gila River paused in its downcutting; multiple terraces indicate that incision of the valley was not steady. Terraces provided adequate soil development, extent, and drainage for prehistoric farming in an area of mostly narrow, steep-sided canyons.
- Paleontological Resources. Fossils are rare in volcanic settings such as the Mogollon-Datil volcanic field. However, packrat (Neotoma spp.) middens in the caves at the monument may provide paleontological information of the past 20,000 years. At present, these middens have been neither studied nor dated. Quaternary deposits, such as alluvium and terrace gravels, may contain fossils. The Gila Conglomerate is a source of fossils elsewhere in the region, but none yet discovered at Gila Cliff Dwellings National Monument.
- Geological Features with Cultural Significance. Interesting connections exist between the geological and archeological resources at Gila Cliff Dwellings National Monument. For instance, people of the Mogollon culture and an earlier Archaic group inhabited the caves in the Gila Conglomerate and used the conglomerate as building stone in cliff dwellings. Many examples of human-made depressions occur on the floors and flat-lying boulders within the caves, including grinding surfaces and cup-shaped indentations, called cupules. The combination of rock types such as rhyolite, andesite, and welded tuff in the area provided raw material for manufacturing tools. Also, particular cave deposits link geology and archeology. For instance, a lustrous, tan-colored coating on many flat, sloping cave surfaces has the same mineral assemblage as kidney stones. Because urine was used as a tanning agent in historic times, these coatings may mark areas of hide processing. Moreover, black amorphous carbon on cave ceilings and walls suggests persistent use of fires for cooking and heating during occupation of the caves. Soot accumulations in the caves provide an informal dating method for determining rockfall events since the time of occupation 700 years ago. Finally, pictures painted on rocks, called pictographs, link geology and archeology. Pictographs occur in at least two of the caves and along the trail to the cliff dwellings.

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

- Cave Features and Processes. A series of seven closely spaced caves occur on the northwestern side of Cliff Dweller Canyon. They are between 400 and 600 m (1,300 and 2,000 ft) from the mouth of the canyon, and approximately 60 m (200 ft) above the narrow canyon floor. These caves developed in the Gila Conglomerate
- Fluvial Features and Processes. Gila Cliff Dwellings National Monument is situated in the Gila River drainage basin. Three forks of the Gila River (West, Middle, and East) converge in the valley near the monument. In addition, a small, unnamed stream, referred to as Cliff Dweller creek, flows in Cliff Dweller Canyon. During summer, monsoons and resultant flash floods may cause the West Fork and Cliff Dweller creek to fill their channels. Winter storms also increase flow. The high, sheltered location of the cliff dwellings protects them from heavy rains and ensuing floods. However, access to the site is often impeded, with bridges commonly damaged and trails inundated by floodwaters. The T J unit is situated on a stream terrace above the present-day floodplain.
- Rockfall Hazards. The walls of Cliff Dweller Canyon are susceptible to rockfall, which is an ongoing management concern. The areas of relatively higher rockfall hazards are fairly obvious; they are rock "pillars" that extend outwards from cliff faces between caves.
- Spalling. Caves are sites of spalling (rock slabs breaking away from rock faces), which is a visitor safety concern and results in the loss and damage of archeological resources, such as pictographs and structures, respectively.
- Post-Wildfire Sedimentation and Debris Flows. Wildfire can affect recreation, residents, and infrastructure, as well as have immediate and profound effects on the hydrologic and geologic response of a watershed. Sedimentation, induced by storm-water runoff, occurs after wildfires in the Gila River watershed. Debris flows are most frequent within two to three years after wildfires when vegetative cover is absent or reduced, and abundant materials are available for erosion and transport. Both sedimentation and debris flows are expected at the monument, though debris flows are uncommon.
- Seismic Activity. Earthquakes have the potential to impact Gila Cliff Dwellings National Monument. The main management concern is the potential to induce rockfall from cliff faces.
- Geothermal Development. Geothermal resources have been developed in the community of Gila Hot Springs, about 6 km (4 mi) southeast of the monument. Because of the cost savings, and to reduce the reliance on propane, monument managers are interested in using geothermal energy to heat (and cool) facilities.
- Climate Change. Participants at the 2007 scoping meeting identified possible outcomes of climate change at Gila Cliff Dwellings National Monument, including changes in flooding cycles and increases in the number and intensity of monsoons and forest fires.

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 section 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” section 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://www.nature.nps.gov/geology/inventory/. The current status and projected completion dates of products are available at: http://www.nature.nps.gov/geology/GRI_DB/Scoping/Quick_Status.aspx.

Acknowledgments

Additional thanks to: the participants at the **2007 scoping meeting** (see Appendix A); **James C. Ratté** (US Geological Survey, emeritus geologist) for sharing his extensive knowledge of the Gila area, reviewing this report, and, of course, mapping the monument; **Steve Riley** (Gila Cliff Dwellings National Monument, superintendent, now retired) for answering numerous questions, providing monument-specific information, and suggesting additional resources; **Carl Litsinger** (Gila Cliff Dwellings National Monument, volunteer) for providing photographs, reference materials, and background information on the archeology of the monument, and suggesting links between archeological and geological resources; **Matt Smith** (Western Archeological and Conservation Center, librarian), **Rod Sauter** (Gila Cliff Dwellings National Monument, chief of interpretation), and **Michelle Schneider** (NPS Technical Information Center, archives technician) for their assistance in locating pertinent archeological publications; **James R. Chappell** (Colorado State University, research associate) for his persistence and coordination with the US Geological Survey in completing the 1:24,000-scale geologic data for Gila Cliff Dwellings National Monument; and **Julia Brunner** (NPS Geologic Resources Division, regulatory specialist) for her review of management options in the rockfall section.

Author

Katie KellerLynn (Colorado State University)

Review

James C. Ratté (US Geological Survey)
Hugh Hawthorne (Gila Cliff Dwellings National Monument)
Jason Kenworthy (NPS Geologic Resources Division)

Report Editing, Formatting, and Distribution

Jason Kenworthy (NPS Geologic Resources Division)
Rebecca Port (NPS Geologic Resources Division)

Source Maps

James C. Ratté (US Geological Survey)
David L. Gaskill (US Geological Survey)
James R. Chappell (Colorado State University)

GRI Digital Geologic Data Production

James R. Chappell (Colorado State University)
Jeremy Hurshman (Colorado State University)
Stephanie O’Meara (Colorado State University)
Aaron Rice (Colorado State University)

GRI Map Poster Design

Georgia Hybels (NPS Geologic Resources Division)
James Winter (Colorado State University)

GRI Map Poster Review

Georgia Hybels (NPS Geologic Resources Division)
Rebecca Port (NPS Geologic Resources Division)

Geologic Setting and Significance

This section describes the regional geologic setting of Gila Cliff Dwellings National Monument and summarizes connections among geologic resources, other park resources, and park stories.

Gila Cliff Dwellings National Monument—which is under the stewardship of the US Department of the Interior, National Park Service—is in the vast Gila Wilderness (figs. 1 and 2) that is administered by the US Department of Agriculture, Forest Service. The Gila Wilderness encompasses 226,000 ha (558,000 ac) and was the first congressionally designated wilderness area, established in 1934, 50 years before the Wilderness Act of 1964. The wilderness area is part of the even larger 1.3-million-ha (3.3-million-ac) Gila National Forest in southwest New Mexico. This national forest contains more federal land than any other national forest outside of Alaska (Forest Service 1998). The Gila Wilderness was designated largely as a result of the efforts of Aldo Leopold, a dedicated conservationist and Forest Service official.

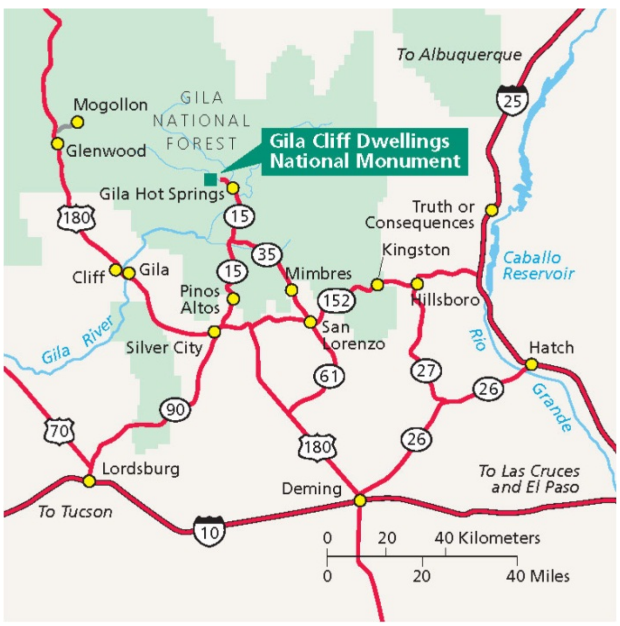

Figure 1. Location map for Gila Cliff Dwellings National Monument. The monument, administered by the National Park Service, is surrounded by the expansive Glia National Forest, administered by the Forest Service. National Park Service map, available online: http://www.nps.gov/hfc/cfm/carto-detail.cfm?Alpha=GICL (accessed 25 August 2014).

By comparison to the wilderness and national forest, Gila Cliff Dwellings National Monument is small, comprising 216 ha (533 ac). However, the monument contains many significant geological and archeological resources, including the distinctive cliff dwellings high above the floor of Cliff Dweller Canyon (fig. 3). The cliff dwellings are the primary reason the site was designated as a national monument. They are the only structures in the National Park System representative of the major Southwestern culture known as the Mogollon.

Figure 2. Gila Wilderness Overlook from New Mexico Highway 15. Gila Cliff Dwellings National Monument is surrounded by the Gila Wilderness, which was the first congressionally designated wilderness area in the United States. US Geological Survey photograph by James C. Ratté.

Figure 3. Caves and cliff dwellings. Approximately 60 m (200 ft) above the floor of Cliff Dweller Canyon, seven closely spaced caves house cliff dwellings that people of the Mogollon culture inhabited between about the 1270s and 1290s CE. The cave opening on the far left of the photograph is a small alcove referred to as "Cave 0" by monument staff. The view is from the east across Cliff Dweller Canyon. National Park Service photograph by Carl Litsinger (Gila Cliff Dwellings National Monument).

A second, smaller unit—the T J unit—is 2.4 km (1.5 mi) east of the main unit that contains the cliff dwellings (figs. 4 and 5). The T J unit was added to the monument in 1962 by presidential proclamation and hosts a largely unexcavated and rarely visited pueblo, formerly known as the T J Ruins (McKenna and Bradford 1989) and currently referred to as the T J Site. With the addition of this pueblo, the monument came to contain all the major architectural representations of the Mogollon culture. The cliff dwellings are from the Tularosa phase between

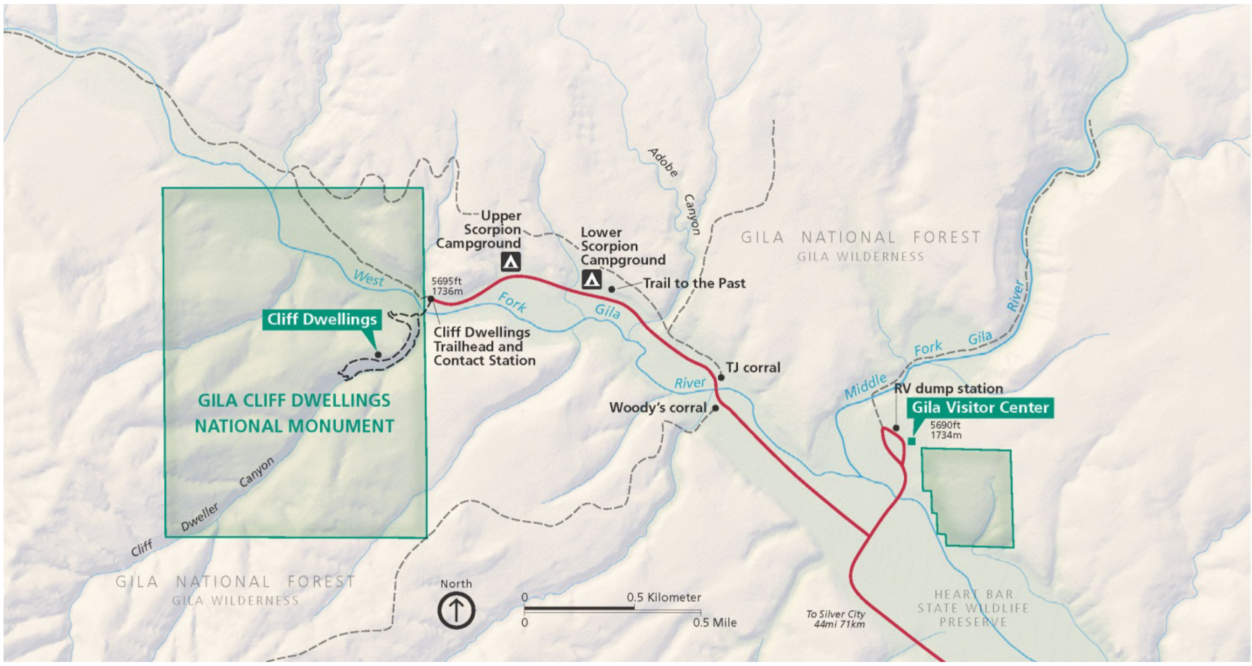

Figure 4. Map of Gila Cliff Dwellings National Monument. Gila Cliff Dwellings National Monument consists of two units—the main unit that contains the cliff dwellings, and the rarely visited T J unit that contains the largely unexcavated T J Site. National Park Service map, available online: http://www.nps.gov/hfc/cfm/carto-detail.cfm?Alpha=GICL (accessed 25 August 2014).

Figure 5. T J Site. The T J unit of Gila Cliff Dwellings National Monument was added in 1962. It contains the T J Site, a largely unexcavated, multi-component pueblo. The T J unit is east of the main unit. Photograph by Katie KellerLynn (Colorado State University).

about 1270s and 1290s CE. The T J Site is from the Mimbres phase, which ended abruptly at this location in 1150 CE (Bradford 1992).

The earliest recorded visit to the cliff dwellings in Cliff Dweller Canyon was in 1878 by Henry B. Ailman, an early emigrant to southwestern New Mexico who had become a prosperous co-owner of the Naiad Queen silver mine in Georgetown, now a ghost town about 24 km (15 mi) east of Silver City (Russell 1992). The journals of Adolph Bandelier—the well-known amateur archeologist and namesake of Bandelier National Monument in the northern part of the state—clearly indicate that many people knew about the cliff dwellings at the time of his visit in 1884, and note that the dwellings had been “rifled” by cowboys, prospectors, and curiosity seekers.

In 1907, President Theodore Roosevelt signed a proclamation that recognized the “group of cliff-dwellings known as the Gila Hot Springs Cliff-Houses” as a national monument. The proclamation identified the dwellings as being “of exceptional scientific and educational interest” and “as the best representative of the Cliff-Dwellers’ remains of that region.” This proclamation was intended to prevent further damage and vandalism.

Today, archeological preservation, research, and visitor interpretation are the monument’s primary objectives (Parent 2004). The monument’s geologic setting gives shape to its archeological resources. For instance, local landforms guided the overall site structure and orientation at the T J Site (Bradford 1992).

Gila Cliff Dwellings National Monument is part of the Mogollon–Datil volcanic field, which covers 40,000 km^2 (15,000 mi^2) in southwestern New Mexico and southeastern Arizona (fig. 6). The volcanic field lies on the southeastern margin of the relatively undeformed Colorado Plateau that is characterized by crustal thicknesses that exceed 40 km (25 mi) in some locations (fig. 7). The Colorado Plateau is bounded by the Basin and Range physiographic province, which in contrast to the Colorado Plateau is characterized by crustal thinning. A primary feature of the Basin and Range in New Mexico is the Rio Grande rift—a northerly oriented zone of profound crustal extension (Kelley 2012).

Mogollon-Datil volcanism began about 40 million years ago, during the Eocene Epoch (56 million–34 million

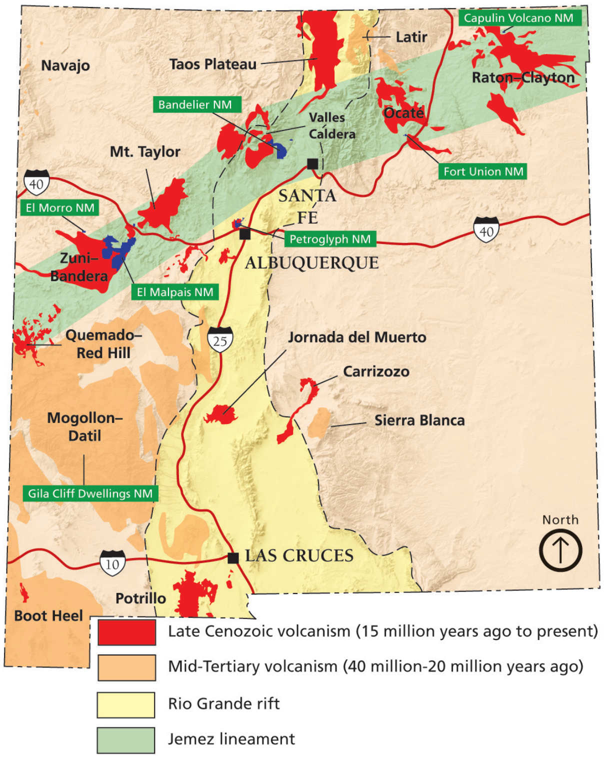

Figure 6. Major volcanic fields in New Mexico. Gila Cliff Dwellings National Monument is part of the Mogollon–Datil volcanic field in southwestern New Mexico. National Park System units are well represented in the volcanic areas of the state. Fort Union National Monument is surrounded by the Ocaté volcanic field. El Malpais and El Morro national monuments are part of the Zuni–Bandera volcanic field. Bandelier National Monument is part of the Valles Caldera. Capulin Volcano National Monument is in the Raton–Clayton volcanic field. Petroglyph National Monument is in the Albuquerque volcanic field. New Mexico Bureau of Geology and Mineral Resources graphic (used with permission), modified by Philip Reiker (NPS Geologic Resources Division).

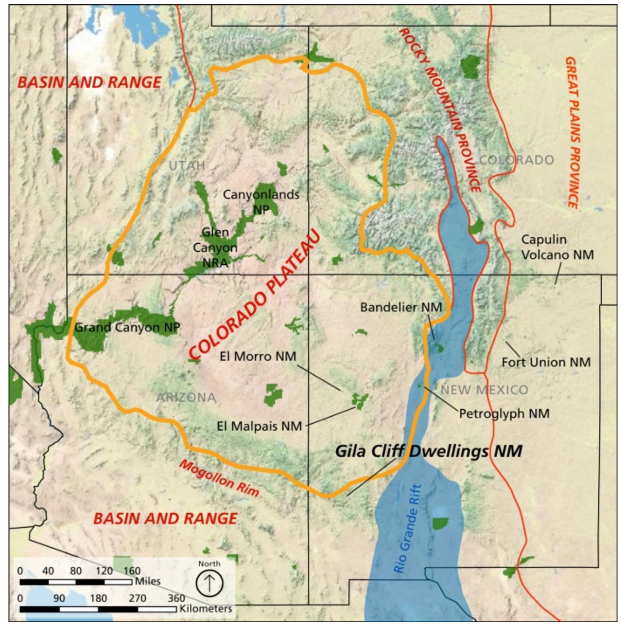

Figure 7. Colorado Plateau. The Colorado Plateau is roughly centered on the Four Corners area of Utah, Colorado, Arizona, and New Mexico. The plateau is bounded by the Basin and Range physiographic province. A primary feature of the Basin and Range in New Mexico is the Rio Grande rift. The Great Plains and Rocky Mountain physiographic provinces also occur in New Mexico. Green areas on the figure represent the locations of National Park System units, some of which are labeled. National Park Service graphic by Philip Reiker and Rebecca Port (NPS Geologic Resources Division).

years ago; figs. 8 and 9), culminated during the Oligocene Epoch (34 million–23 million years ago), and ended early in the Miocene Epoch (23 million–5.3 million years ago). Later, during the Pliocene Epoch (5.3 million–2.6 million years ago), minor volcanism related to the Rio Grande rift produced basalt and rhyolite flows in the volcanic field (Chapin et al. 2004).

The Mogollon–Datil volcanic field is composed of clusters of calderas, including the Bursum and Gila Cliff Dwellings calderas. A broad outflow apron of ignimbrites and lavas, which rests upon an older complex of andesitic lavas and volcaniclastic deposits, surrounds the calderas (Chapin et al. 2004). The monument lies within the Gila Cliff Dwellings caldera.

The volcanic rocks of the Mogollon–Datil volcanic field overlap older intrusions and volcanic rocks related to the Laramide Orogeny—the mountain-building event that resulted in the rise of the Rocky Mountains. Laramide rocks are between about 75 million and 50 million years old in the area (Chapin et al. 2004). Several Laramide plutons and porphyry copper deposits occur along lineaments that run through the Silver City area. These deposits are partly buried by the younger rocks of the Mogollon–Datil volcanic field (Chapin et al. 2004).

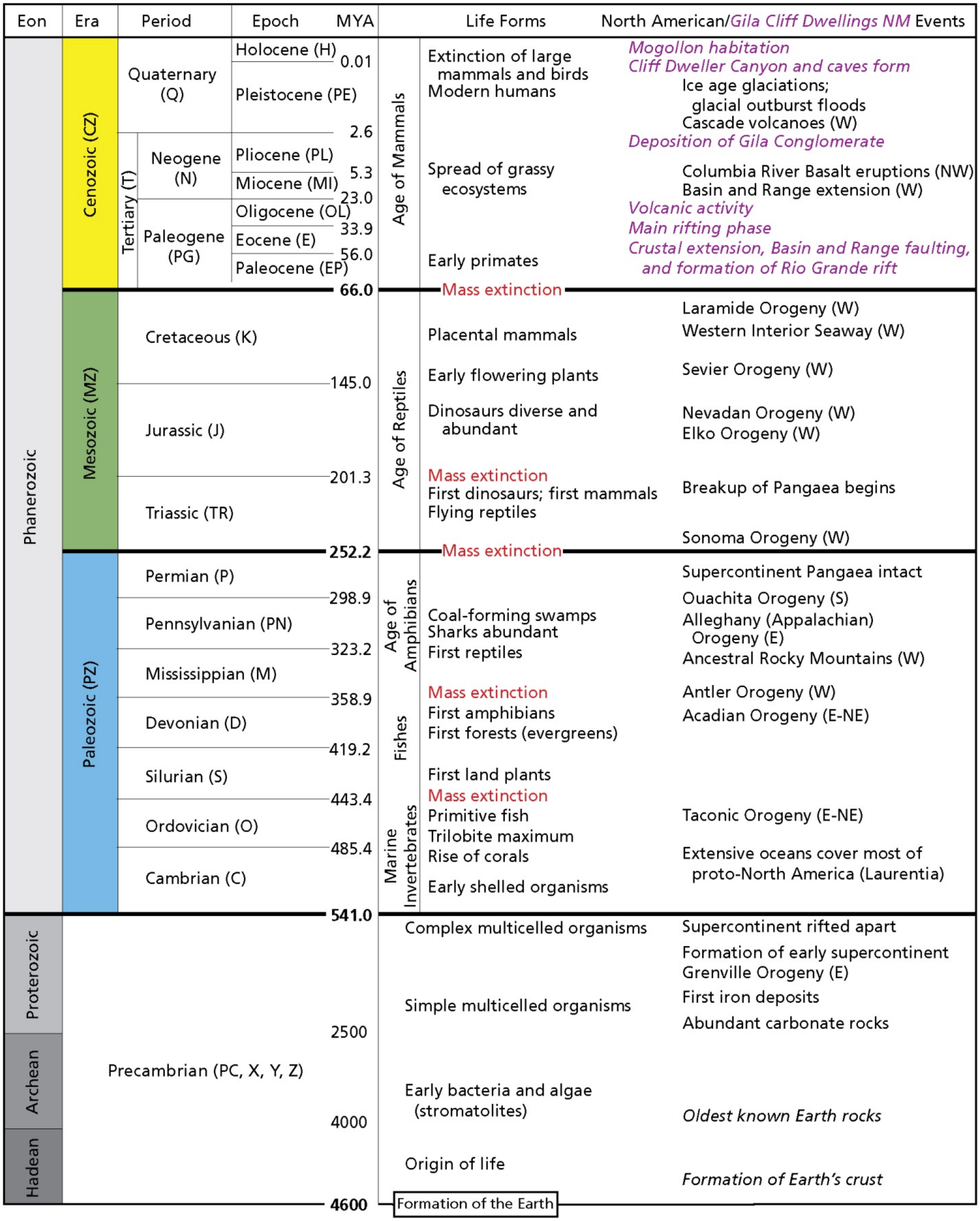

Figure 8. Geologic time scale. The divisions of the geologic time scale are organized stratigraphically, with the oldest at the bottom and youngest at the top. Boundary ages are millions of years ago (MYA). Major life history and tectonic events occurring on the North American continent are included. Compass directions in parentheses indicate the regional locations of events. Significant events for Gila Cliff Dwellings National Monument also are included (in purple). The term "Tertiary" is no longer a formal geologic period, but is still in common use. It was used by Ratté and Gaskill (1975) and is used in this report. Tertiary covers the Paleogene and Neogene (66.0 million–2.6 million years ago) periods. GRI map abbreviations for each time division are in parentheses. National Park Service graphic using dates from the International Commission on Stratigraphy (http://www.stratigraphy.org/index.php/ics-chart-timescale; accessed 13 August 2014).

Era	Period	Epoch	Age (mya)	Ratté et al. (2014) Scale 1:24,000	Corresponding units of Ratté and Gaskill (1975) Scale 1:62,500
Cenozoic	Quaternary	Holocene	0.01–present	Alluvium (Qa)	Valley alluvium and terrace gravels (Qag)
		Holocene? and Pleistocene	2.6–present	Alluvial terrace deposits (Qt)	
				Highest perched terrace deposit (Qt1)	
		Pleistocene	2.6–0.01	Middle perched terrace deposit (Qt2)	
				Lowest perched terrace deposit (Qt3)	

Cenozoic	Tertiary	Quaternary	Holocene	0.01-present	Qa, Qt, Qt1, Qt2, Qt3 *(see above)*	Sedimentary rocks (mainly Gila Conglomerate) (QTs) ***Note***: Also includes alluvium and terrace gravels where they are not mapped separately as Qag.
			Pleistocene	2.6-0.01		
		Neogene	Pliocene	5.3-2.6	Gila Conglomerate* (QTg)	
			Miocene	23-5.3		
		Paleogene and Neogene	Miocene and Oligocene	34–5.3	Andesitic to dacitic lava flows of the Middle Fork (Tmd)	Younger andesitic and latitic lava flows (includes Bearwallow Mountain Andesite) (Tya) ***Note***: Estimated Miocene and Miocene? age by Ratté and Gaskill (1975).
		Paleogene	Oligocene	34–23	Volcaniclastic rocks of Adobe Canyon (Tav)	
					Bearwallow Mountain Andesite (Tba)	
					Bloodgood Canyon Tuff (Tbt)	Bloodgood Canyon Rhyolite Tuff of Elson (1968) (Tbc) ***Note***: Estimated Miocene or Oligocene? age by Ratté and Gaskill (1975).

Depending on the investigation, the age of QTg ranges from late Oligocene to middle Pleistocene. It is older than Qt3 deposits.

Figure 9. Correlation of map units at Gila Cliff Dwellings National Monument. The GRI data set contains digital data of two source maps: Ratté and Gaskill (1975; scale 1:62,500) and Ratté et al. (2014; scale 1:24,000). This table shows the correlation of maps units between these two data sources. Units are limited to those mapped within the monument. Colors shown on the figure correspond to standards approved by the US Geological Survey to indicate different time periods on geologic maps (see also Map Unit Properties Tables, in pocket).

Geologic Features and Processes

This section describes noteworthy geologic features and processes in Gila Cliff Dwellings National Monument.

During the 2007 scoping meeting and 2011 conference call, participants (see Appendix A) identified the following geologic features and processes:

- Mogollon–Datil Volcanic Field
- Gila Hot Springs Graben
- Hot Springs
- Gila Conglomerate
- Terraces and Valley Incision
- Cave Features and Processes
- Paleontological Resources
- Geological Features with Cultural Significance

Mogollon–Datil Volcanic Field

Gila Cliff Dwellings National Monument lies in the Mogollon–Datil volcanic field, one of the world's great volcanic provinces (Ratté 1997). The entire province extends from northern Mexico to Colorado. In the Gila region, the volcanic rocks are part of a mid-Tertiary sequence of volcanism (fig. 8); the field was active for approximately 35 million years, from 40 million to less than 5 million years ago (Chapin et al. 2004).

Ignimbrite Flare Up and Caldera Collapse

Chapin et al. (2004) separated the rocks and activity of the Mogollon–Datil volcanic field into five units (T2–T6) based on age. Unit T4 (30 million–21 million years ago) is significant for the monument because it includes the Bursum and Gila Cliff Dwellings calderas. The upper boundary of the unit is marked by the Gila Conglomerate (see "Gila Conglomerate" section).

Unit T4 covers the climax of ignimbrite volcanism in the Mogollon–Datil volcanic field (Chapin et al. 2004). Referred to as a "flare up," volcanism was characterized by violent eruptions that produced widespread sheets of ash-flow tuff called ignimbrites, which would have been spectacular displays of swiftly flowing ash and other pyroclastic materials exploding as turbulent, incandescent clouds. The volume of material involved and the rapidity with which it was erupted caused volcano collapse, creating the Gila Cliff Dwellings and Bursum calderas (Ratté et al. 1979) (fig. 10).

Unit T4 also incorporates the greatest rates of extension of the Rio Grande rift (Davis and Hawkesworth 1995). Regional extension coincided with the ignimbrite flare up in the Mogollon–Datil volcanic field and a change to more mafic lavas; that is, from silica-rich andesite (58%–67% silica) to basaltic andesite (52%–56% silica). Generally speaking, as silica content increases, so does the explosive nature of the lava. Investigators relate these events to the transition from contractional deformation and crustal shortening of the Laramide Orogeny, which built the Rocky Mountains, to strong extension of the Basin and Range and Rio Grande rift (Chapin et al. 2004).

Gila Cliff Dwellings Caldera and Bloodgood Canyon Tuff

Gila Cliff Dwellings National Monument is in the 24-km-(15-mi-) wide Gila Cliff Dwellings caldera (fig. 10). The estimated center of the caldera is 6 km (4 mi) west of the mouth of Cliff Dweller Canyon. The buried eastern margin of the caldera is tentatively identified on both sides of the Gila River at Melanie hot spring, about a 0.8 km (0.5 mi) upstream from the bottom of the Alum Canyon trail where it reaches the river (fig. 11).

Both the Gila Cliff Dwellings and Bursum calderas have been dated at 28 million years ago, but the Gila Cliff Dwellings caldera collapsed first. This is known because the Gila Cliff Dwellings caldera is filled with 300 m (1,000 ft) or more of Bloodgood Canyon Tuff (Tbc or Tbt; fig. 9) that was erupted from and caused the collapse of the slightly younger Bursum caldera. Investigators used sanidine crystals, which flash blue in the sun and are popularly known as "moonstones," to date the tuff.

Identification of the ignimbrite that erupted from and caused the collapse of the Gila Cliff Dwellings caldera is uncertain, but may be the Shelley Peak Tuff (Tsp; see geologic map graphic, in pocket) or Davis Canyon Tuff (Tdc or part of Tao; see Map Unit Properties Table for Ratte and Gaskill 1975, and attached GRI data set) (Ratté and Stotelmeyer 1984; Ratté 2008; Ratté et al. 2014).

Bursum Caldera

The Bursum caldera is nearly 40 km (25 mi) across and covers the western half of the Gila Wilderness (fig. 10). This huge caldera transects the western margin of Gila Cliff Dwellings caldera at Hells Hole, about 16 km (10 mi) up the West Fork from the mouth of Cliff Dweller Canyon. It formed by collapse after the eruption of the Bloodgood Canyon Tuff. Younger rhyolite flows and domes (Try; Ratté and Gaskill 1975), younger andesitic and latitic lava flows (Tya; Ratté and Gaskill 1975), and possibly Mineral Creek Andesite (Tmc; Ratté and Gaskill 1975) fill the eastern part of the vast Bursum caldera. Tuff of Apache Spring (Tas) and rhyolite pyroclastic and volcaniclastic rocks fill the western part (Ratté and Gaskill 1975).

Bearwallow Mountain Andesite

The dark-colored lava flows of Bearwallow Mountain Andesite, which overlie the Bloodgood Canyon Tuff at the monument, are evidence of more recent volcanic activity. At a scale of 1:62,500, Ratté and Gaskill (1975)

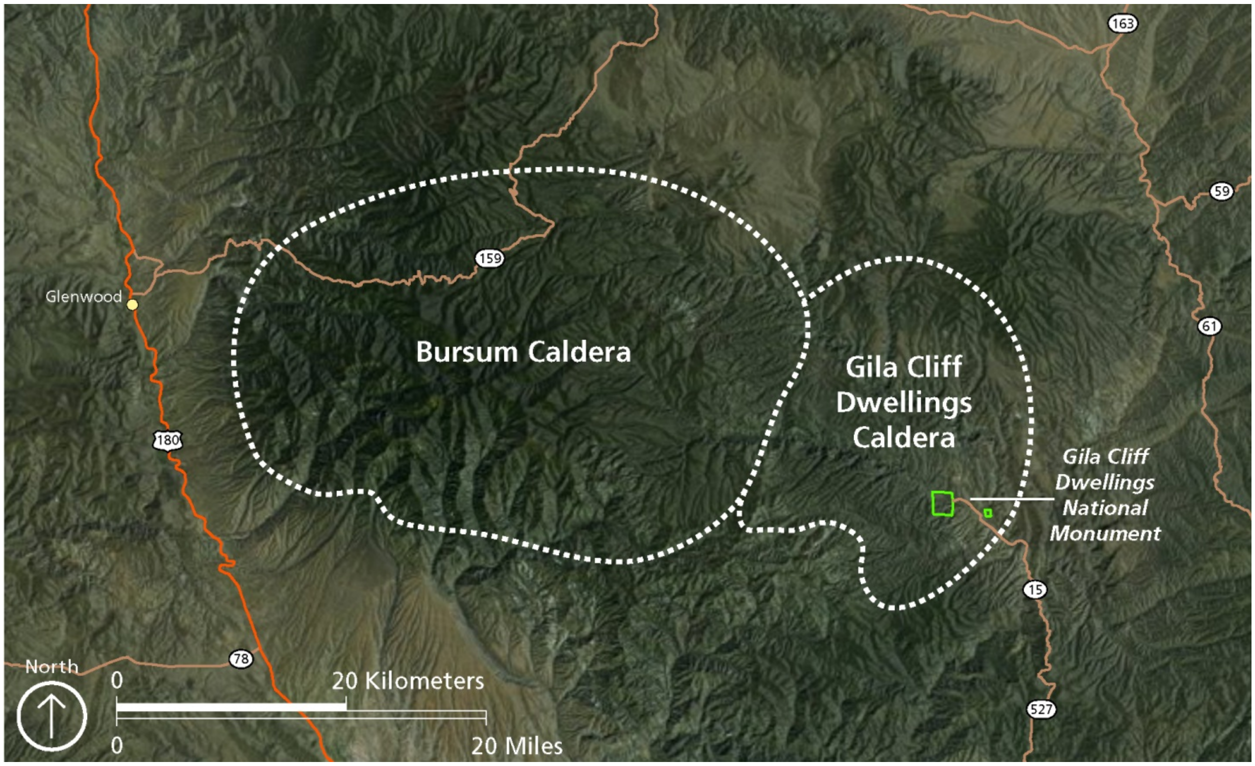

Figure 10. Bursum and Gila Cliff Dwellings calderas. After a climactic eruption of ignimbrites, referred to as a "flare up," within the Mogollon–Datil volcanic field, the Bursum and Gila Cliff Dwellings calderas collapsed. Violent eruption and collapse, as well as filling in with younger volcanic lava flows and Gila Conglomerate, make the features difficult to see on the landscape today. National Park Service graphic by Rebecca Port (NPS Geologic Resources Division) using ESRI World Imagery basemap.

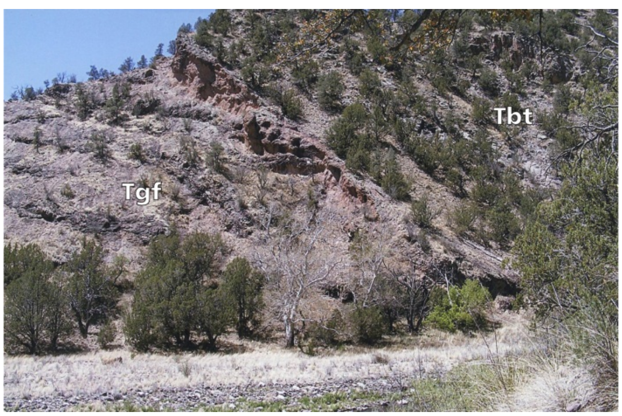

Figure 11. Eastern margin of Gila Cliff Dwellings caldera. Bloodgood Canyon Tuff (Tbt) represents the climactic eruption that resulted in the formation of the Gila Cliff Dwellings caldera. This exposure of the tuff near Melanie hot spring marks the eastern wall of the caldera. The Oligocene lava flows and associated rocks of Gila Flat (Tgf) do not occur in the monument; they are older than the Bloodgood Canyon Tuff. US Geological Survey photograph and annotation by James C. Ratté.

mapped the Bearwallow Mountain Andesite as part of a unit of younger andesitic and latitic lava flows (Tya). At a scale of 1:24,000, Ratté et al. (2014) singled out the Bearwallow Mountain Andesite (Tba) and delineated these particular flows within the monument (see poster, in pocket).

Bearwallow Mountain Andesite has not been dated within the monument, but numerous samples have been dated within the Gila Wilderness and surrounding areas, resulting in ages ranging between 27 million and 24 million years old (Marvin et al. 1987). Bearwallow Mountain Andesite is related to the shield volcanoes that formed after ignimbrite formation and caldera collapse (Ratté 2007). The type locality of the Bearwallow Mountain Andesite is Bearwallow Mountain, from which it erupted. The mountain is 40 km (25 mi) northwest of the monument and is one of the andesite shield volcanoes along the Morenci lineament—a northeast-oriented zone of crustal weakness within the Mogollon–Datil volcanic field (Ratté 1989a).

Vesicles lined with zeolites are a distinctive feature of the Bearwallow Mountain Andesite (fig. 12). These vesicles formed when volcanic gases were released as the lava flow solidified. Then as a result of interactions with groundwater, well-formed zeolite crystals developed in these cavities. Of note for resource protection, these crystals are popular with mineral collectors. The minerals chabazite, mesolite, stillbite, heulandite, analcime, and levyne have been found in Bearwallow Mountain Andesite (Haynes 1983). Mineral collection is prohibited within the National Park System (see Appendix B).

Andesitic to Dacitic Lava Flows

The uppermost and youngest volcanic rocks within the monument consist of the andesitic to dacitic lava flows of the Middle Fork (Tmd). Tiny green pyroxene phenocrysts and quartz xenocrysts distinguish these flows (fig. 13) from the underlying Bearwallow Mountain

Figure 12. Zeolite. The occurrence of vesicles filled with crystals (known as zeolites) is a characteristic of the Bearwallow Mountain Andesite at Gila Cliff Dwellings National Monument. Vesicles formed when volcanic gases were released as the lava flow cooled. The zeolite developed as mineral-rich groundwater flowed through the cavity. The zeolite shown here in Cliff Dweller Canyon is approximately 2.5 cm (1 in) across. National Park Service photograph by Sonya Berger.

Figure 13. Andesitic to dacitic lava flows of the Middle Fork. The uppermost lava flow at Gila Cliff Dwellings National Monument consists of andesitic to dacitic lava (unit Tmd of Ratté et al. 2014). This unit is similar to the underlying Bearwallow Mountain Andesite (Tba), but contains bright green pyroxene pheocrysts that distinguish it from the older, underlying flows. Photograph by Katie KellerLynn (Colorado State University).

Andesite. Ratté and Gaskill (1975) included these andesitic to dacitic lava flows as part of unit Tya. As mapped by Ratté et al. (2014), the andesitic to dacitic lava flows of the Middle Fork crop out at the southwestern corner of the T J unit (see poster, in pocket).

A notable exposure of this flow is visible from the parking lot at the Middle Fork trailhead. On a nearby hillside, faulting has offset the flow (fig. 14). Ancestors of Geronimo—the prominent Apache leader—believe he was born at this location (KellerLynn 2008). Thus the site has both geologic and cultural significance.

Contact between Bearwallow Mountain Andesite and Gila Conglomerate

The contact between the Bearwallow Mountain Andesite and the overlying Gila Conglomerate is another

Figure 14. Geronimo's birthplace. Near the parking lot for the Middle Fork trailhead, andesitic and dacitic lava flows of the Middle Fork (Tmd) are exposed in a hillside. These are the youngest lava flows at Gila Cliff Dwellings National Monument. The hillside also shows the Gila Hot Springs fault and is the site of Geronimo's birthplace. Tba = Bearwallow Mountain Andesite. Tav = volcaniclastic rocks of Adobe Canyon. QTg = Gila Conglomerate. US Geological Survey photograph and annotation by James C. Ratté.

interesting feature preserved in the rock record at the monument (fig. 15). In geologic terms, a contact is a surface between two types or ages of rocks. This contact is of geologic interest because below it the rocks signify volcanism, including ignimbrite eruptions and calderas collapse; above it, rocks represent the rifting and faulting of the Basin and Range physiographic province, including the Gila Hot Springs graben, which the Gila Conglomerate filled. The contact is exposed along the trail from the mouth of Cliff Dweller Canyon to about the point where the trail leaves the canyon floor and climbs the slope to the ruins (Trauger 1963).

Figure 15. Contact between Gila Conglomerate and Bearwallow Mountain Andesite. The contact between the Gila Conglomerate (QTg) and underlying (older) Bearwallow Mountain Andesite (Tba) is exposed along the trail to the cliff dwellings. Above the contact (marked with a black line), Basin and Range rifting and faulting were the dominant geologic processes; below the contact, volcanism dominated landscape evolution. US Geological Survey photograph and annotation by James C. Ratté.

Gila Hot Springs Graben

The present landscape of the monument is largely a result of erosion and faulting of mid-Tertiary volcanoes, as well as deposition of the eroded material by streams into local sedimentary basins, such as the Gila Hot Springs graben. This graben, which is an elongate, downdropped block of Earth's crust, is the main structural feature in the Gila Hot Springs quadrangle (Ratté et al. 2014)—the 7.5-minute quadrangle in which the T J unit lies (see poster, in pocket).

Like all grabens, the Gila Hot Springs graben is bounded by faults. Ratté et al. (2014) provided names for two faults near the monument: the Brushy Mountain fault bounds the southwestern side of the graben and has a maximum displacement of 30 m (100 ft), with little or no displacement as it extends southeast toward the Gila River. The North Mesa fault, which defines the northeastern side of the graben, has a displacement that ranges from about 240 m (800 ft) at the northern edge of the Gila Hot Springs quadrangle to about 30 m (100 ft) east of the East Fork Gila River. The Brushy Mountain fault runs between the main and T J units of Gila Cliff Dwellings National Monument (see Ratté et al. 2014). Notably, hot springs occur along faults in the deepest part of the graben (see "Hot Springs" section). Ratté and Gaskill (1975) mapped additional faults within the Gila Hot Springs graben; a local example occurs at the Upper Scorpion Campground (fig. 16).

Figure 16. Faulting at Upper Scorpion Campground. At the Upper Scorpion Campground, located between the main and T J units of Gila Cliff Dwellings National Monument (fig. 4), the Gila Conglomerate (QTg) is dropped down several hundred feet on the right-hand side of the fault relative to the Bearwallow Mountain Andesite (Tba). US Geological Survey photograph and annotation by James C. Ratté.

Hot Springs

In the Gila Cliff Dwellings area, most of the hot springs occur on the East Fork Gila River (Ratté et al. 2014). The closest hot spring to Gila Cliff Dwellings National Monument is on the Middle Fork Gila River and is typically referred to as the Middle Fork hot spring but is also known as the Light Feather hot spring (fig. 17). To access this hot spring, visitors must hike into the Gila Wilderness, 0.8 km (0.5 mi) from the Middle Fork trailhead at the Gila Visitor Center (fig. 4).

At 60°C (140°F), the water that comes out of the ground at the Middle Fork hot spring is scalding, so soakers must find a cooler spot downstream for comfort (Ransom 2006). The hot spring is located at the river's edge beneath an unusual rock outcrop of travertine that sits 9–12 m (30–40 ft) above the present spring (fig. 18). The travertine ledge represents a higher river level in the past when this rock was deposited from a spring along the river's edge. The travertine at this site could be dated, using techniques developed at the University of New Mexico, Earth & Planetary Sciences Department (Dave Love, New Mexico Bureau of Geology and Mineral Resources, geologist, written communication, 12 May 2008). Dating would determine when geothermal waters began flowing at this location, as well as when the river flowed at this higher level, helping to define the timing of canyon cutting. As of August 2014, this deposit had not been dated. However, staff at the University of New Mexico is interested in exploring ideas to obtain radiometric dates on this geothermal system (Laura Crossey, University of New Mexico, Department of Earth & Planetary Sciences, professor, email correspondence, 7 August 2014).

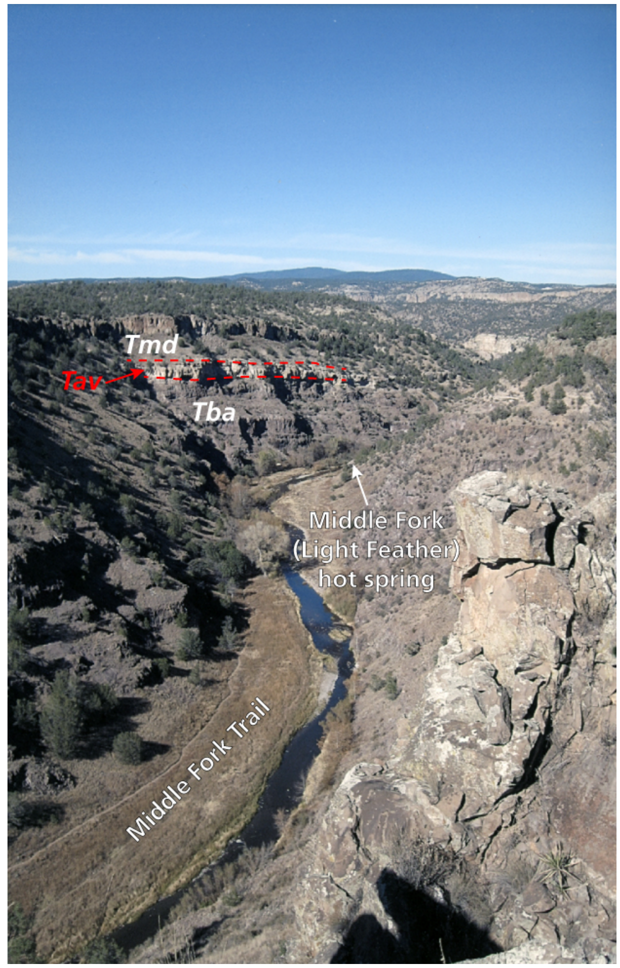

Figure 17. Middle Fork (Light Feather) hot spring. The Middle Fork or Light Feather hot spring in the Gila National Forest is the closest hot spring to Gila Cliff Dwellings National Monument. The undeveloped spring is easily accessible from the Middle Fork trailhead near the Gila Visitor Center (fig. 4). US Geological Survey photograph by James C. Ratté.

Middle Fork hot spring is one of three undeveloped hot springs that are easily accessible from the monument. The others are the Jordan and Melanie hot springs; Melanie hot spring is also known as the Gila River hot

Figure 18. Travertine deposit above the Middle Fork (Light Feather) hot spring. Travertine forms from precipitation of calcium carbonate in saturated waters, especially near hot springs. This travertine deposit (arrow) sits high above the hot spring and was deposited before the river downcut to its present elevation. The age of the deposit is unknown. Note person standing under the deposit (circle) for scale. US Geological Survey photograph by James C. Ratté.

spring (fig. 19). Jordan hot spring is about 10 km (6 mi) from the visitor center via Little Bear Canyon and 13 km (8 mi) via the Middle Fork route (fig. 4). The hot-spring pool is about 6 m (20 ft) in diameter, about 0.9 m (3 ft) deep, and has a water temperature of about 34°C (94°F). Melanie hot spring is 2.4 km (1.5 mi) from Grapevine Campground, where warm water cascades over a rock outcrop and collects in a very shallow pool at the base of a cliff (Ransom 2006).

Figure 19. Melanie (Gila River) hot spring. Warm water cascades down a slope and collects in a very shallow pool at Melanie hot spring, which is also known as Gila River hot spring. This hot spring is in Alum Canyon near Gila Cliff Dwellings National Monument. US Geological Survey photograph by James C. Ratté.

Various explanations have been offered for the source of the thermal waters near the monument. In general, the two main sources are a magma body below the surface or an increase in temperature due to deep circulation of groundwater. Summers and Colpitts (1980) and Witcher and Lund (2002)—the most thorough studies of the geothermal resources in the area—favor deep circulation of groundwater along faults. Ponding of groundwater in the more pervious zones of the Bloodgood Canyon Tuff and Bearwallow Mountain Andesite may occur. Exposures of altered, pinkish-white Bloodgood Canyon Tuff in the cliffs near Doc Campbell's trading post indicate geothermal activity in the area. Water is heated by geothermal gradient and returned to the surface along faults. The geothermally heated waters seep out along the banks and bottom of the Gila River and tributaries (Trail of the Mountain Spirits National Scenic Byway 2010). The rate of flow depends upon the size, frequency, and distribution of fractures in the rock (Summers and Colpitts 1980). Geothermal waters in the Gila Hot Spring graben range in temperature from 32°C to 65°C (90°F to 150°F).

Gila Conglomerate

The Gila Hot Springs graben is filled with rock debris, called basin fill, which was shed from the surrounding mountains (volcanoes) and transported by streams as the basin subsided. This basin-filling material is Gila Conglomerate. Within the monument, the conglomerate consists of clasts that range in size from sand to boulders of primarily Bloodgood Canyon Tuff (Tbc or Tbt; fig. 9). Sanidine feldspar crystals, which are embedded in the Gila Conglomerate and characteristic of the tuff, reflect blue (Ratté 2007).

Originally described in 1875 by G. K. Gilbert to encompass the clastic deposits in the upper Gila River drainage (Gilbert 1875), the Gila Conglomerate covers a broad area, and the unit's name has a long history and widespread use. According to Leopoldt (1981, p. 12), the Gila Conglomerate serves as a "formational waste basket" for Neogene terrestrial basin-fill deposits. Deposits of at least eight major basins, covering an area of 1.7 million km^2 (660,000 mi^2) in southeastern Arizona and southwestern New Mexico, have been described as Gila Conglomerate (Leopoldt 1981). To compound matters, some investigators have referred to the Gila Conglomerate as the "Gila Formation" and divided it into members, whereas others have raised the unit to group status, subdividing it into formations. Additionally, for the purpose of mapping groundwater aquifers and flow systems between the United States and Mexico, investigators have divided the Gila Conglomerate into upper, middle, and lower hydrostratigraphic units (Hawley et al. 2000; Kennedy et al. 2000).

In basins along the Rio Grande rift, the basin-fill unit equivalent to the Gila Conglomerate is the Santa Fe Group (Hawley 1969; King et al. 1971; Seager et al. 1982; Seager 1995). "Santa Fe" is used in areas where the surface drainage is to the Rio Grande, whereas "Gila" is used in areas where the surface drainage is towards the Colorado River and its tributaries (Elston and Netelbeek 1965). Both "Gila" and "Santa Fe" include all types of sediments in a basin-fill environment, ranging from clay-rich lake beds and aeolian sands to alluvial-fan and river gravels. However, alluvial deposits are by far the largest component of the basin fill (Hawley et al. 2000).

Depending on the study, the age of the Gila Conglomerate ranges from late Oligocene to middle Pleistocene (Hawley et al. 2000). Ratté and Gaskill (1975) suggested that the unit was Pleistocene and Pliocene, and possibly older; Ratté et al. (2014) provided an age of Oligocene to Miocene (figs. 8 and 9).

The Gila Conglomerate locally contains fossils that help to bracket the age of the unit and timing of deposition (Leopoldt 1981) (see "Paleontological Resources" section). Deposits contain late-Miocene to late-Pleistocene mammalian faunas and volcanic ash beds (Leopoldt 1981).

Terraces and Valley Incision

Basin-fill deposits record the aggradational (building-up) phase of a basin as it fills with sediment. Basin filling of Gila Conglomerate was completed by the middle Pliocene Epoch (3.5 million–2.5 million years ago) (Hawley et al. 2000). By the middle of the Pleistocene Epoch, around 1.2 million–700,000 years ago, the Gila River had begun incising the Gila Conglomerate and forming its valley (Connell et al. 2005).

As rivers episodically dissect older fill, they leave a distinct record of landforms and deposits that represent valley incision (Connell et al. 2005). Ratté and Gaskill (1975) mapped valley alluvium and terrace gravels (Qag) as representatives of incision. Ratté et al. (2014) subdivided these deposits into Quaternary alluvium (Qa) and four units of terrace deposits—Qt1 (highest; Holocene? and Pleistocene), Qt2 (middle; Pleistocene), Qt3 (lowest; Pleistocene), and Qt, which is undivided and spans the age range of the three numbered levels. Various terrace levels show where the Gila River paused in its downcutting (Elston et al. 1965). Multiple terraces indicate that incision of the valley was not steady (Connell et al. 2005).

As recorded by Elston et al. (1965), three terrace levels are generally preserved in the wider parts of the Gila River. Ratté et al. (2014) mapped terrace deposits near the junction of the Middle Fort and West Fork Gila River—one each of Qt1, Qt2, and Qt3, and three undivided alluvial terrace deposits (Qt) (see poster, in pocket). The fire-training building and T J Site are on the highest perched terrace deposit (Qt1). The residences are on the middle perched terrace deposit (Qt2). The visitor center is on the lowest perched terrace deposit (Qt3) (James C. Ratté, US Geological Survey, emeritus, email communication, 11 December 2007).

Terraces supplied adequate soil development, extent, and drainage for 13th-century farming in an area of mostly narrow, steep-sided canyons (McKenna and Bradford 1989). Work by Sandor et al. (1986a, 1986b, 1986c) provided information about agriculture and long-term effects of land use, including agricultural impacts and nutrient depletion of soils 700 years after occupation.

In another study discussing valley incision by the Gila River, Leopoldt (1981) mapped a series of seven well-developed pediment and stream-terrace surfaces in the Mangas graben southwest of the monument. These surfaces indicate 250 m (820 ft) of downcutting since latest Pliocene or early Pleistocene time (Leopoldt 1981). However, these units have not been correlated with similar sequences along other valleys in the region (Leopoldt 1981), thus the rate of incision in the Mangas graben only provides an approximation for the West Fork, Middle Fork, and Cliff Dweller Canyon.

Pazzaglia and Hawley (2004) provided a broad estimate of the rate of base level fall for New Mexico at 0.1 to 0.25 mm (0.004 to 0.01 in) per year. Base level fall drives the rate of valley incision. This estimated rate allows for valleys hundreds of meters deep to have been carved during the past 1 to 2 million years of the Quaternary Period (Pazzaglia 2005).

"Geology of the Gila Cliff Dwellings" (Forest Service 2003) made an attempt at quantifying the rate of downcutting in Cliff Dweller Canyon. The calculation is based on the rate of the Grand Canyon of the Colorado River at 0.2 mm (0.008 in) per year. Long-distance comparisons and calculations can be spurious, but based on this calculation, Cliff Dweller Canyon is an estimated 0.6 m (2 ft) deeper now than when the caves were occupied in the late 1200s (Forest Service 2003), which is an interesting piece of information for interpretation.

Cave Features and Processes

Caves are naturally occurring underground voids such as solutional (commonly associated with karst), lava tubes, sea caves, talus caves (a void among collapsed boulders), regolith caves (formed by soil piping), and glacier caves (ice-walled caves) (Toomey 2009). Karst is a landscape that forms through the dissolution of soluble rock, most commonly carbonates such as limestone or dolomite (Toomey 2009). Caves, sinkholes, "losing streams," springs, and internal drainage are characteristic features of karst landscapes. As of August 2014, cave or karst resources are documented in at least 140 parks. The NPS Geologic Resources Division Cave and Karst Resources website, http://www.nature.nps.gov/geology/caves/index.cfm, provides more information.

In 1885 Army Lieutenant G. H. Sands described the cliff dwellings in what is now Gila Cliff Dwellings National Monument as "quite a long row of houses…set like a nest in the face of the wall." The "houses" or "nests" are located in natural caves, 60 m (200 ft) above the floor of Cliff Dweller Canyon. The caves, also called alcoves, extend back 30 m (100 ft) and are as wide as 45 m (150 ft). To be clear, all alcoves are caves, but not all caves are alcoves. In general, the use of "alcove" implies that the back of the cave opening is relatively shallow and the cave's location is precipitous.

The caves in Cliff Dweller Canyon formed in Gila Conglomerate, which makes up the canyon's cliffs and the prominent bluffs that border the river channel at the junction of the West Fork and Middle Fork Gila River. Caves and other openings are characteristic features of the Gila Conglomerate in this region (figs. 20 and 21).

According to Ratté (2000, 2001), stream action probably initiated cave development in Cliff Dweller Canyon. As the stream cut down through the Gila Conglomerate, incising the canyon (see "Terraces and Valley Incision" and "Geologic History" sections), it likely encountered a relatively soft layer of rock and cut laterally through it,

Figure 20. Weathering of Gila Conglomerate. Gila Conglomerate is susceptible to the effects of weathering, resulting in the formation of cavities (shown here). Photograph by Katie KellerLynn (Colorado State University).

Figure 21. Gila Conglomerate. The sedimentary Gila Conglomerate consists of volcaniclastic material shed from surrounding mountains and deposited as basin fill in the subsiding Gila Hot Springs graben. Caves are characteristic features of the conglomerate. Prehistoric people were drawn to the caves, and built dwellings inside. Photograph by Katie KellerLynn (Colorado State University).

thus initiating cave formation. Moreover, stabilization of base level probably resulted in the stream staying at more or less the same level for an extended period of time, thus facilitating cave development.

In concert with fluvial activity, groundwater sapping—weathering and erosion of rock as groundwater flows through and emerges at the surface of an outcrop (Howard and Kochel 1988)—aided in cave formation and enlargement (fig. 22). Movement of groundwater through the Gila Conglomerate is particularly apparent during wet periods, with water seeping out along fractures (Bradford 1992). Contacts between rock units, where exposed, also produce seeps of varying amounts of water (Bradford 1992). In some places, for instance in the canyon of the Middle Fork, cave formation occurred at the contact between the Bearwallow Mountain Andesite and the Gila Conglomerate (James C. Ratté, US Geological Survey, emeritus geologist, written communication, 3 March 2008).

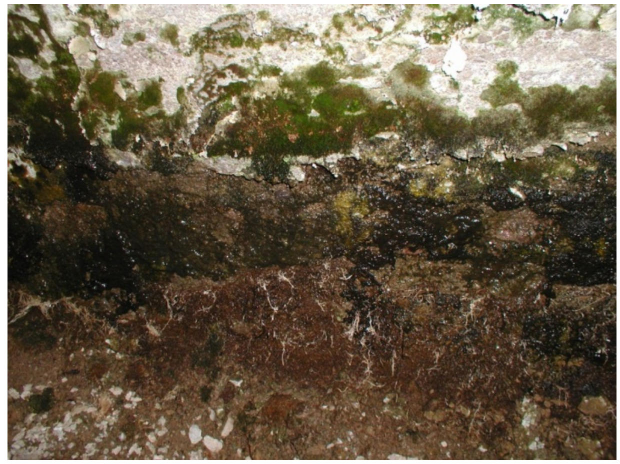

Figure 22. Groundwater sapping. In conjunction with fluvial erosion, groundwater sapping results in the formation and enlargement of caves in the Gila Conglomerate. The presence of groundwater is apparent during wet periods. This photograph was taken on 17 November 2007 at the back of a rock overhang in Cliff Dweller Canyon. The green material is moss; the white stringers are roots. Neither is out of the ordinary or of exceptional size. Photograph by Katie KellerLynn (Colorado State University).

Today, caves at the bottom of Cliff Dweller Canyon are probably forming by the same processes as the caves above. However, the zone of weakness localizing these new alcoves is the contact between the Gila Conglomerate and the underlying andesitic lava flows (Ratté 2000, now mapped as unit Tmd), not fractures or softer layers within the conglomerate. A modern analog for cave formation occurs near the bridge along the trail to the cliff dwellings (fig. 23). At this bend in the stream channel, the creek impinges on the canyon wall, undercutting it. With time, this opening may reach the size of the higher, well-known caves.

Figure 23. Present-day cave development. The seven caves in Cliff Dweller Canyon were probably excavated by a combination of stream action and groundwater sapping. As the stream incised the Gila Conglomerate, it likely encountered a relatively soft layer of rock and cut laterally through it. Also, base level probably stabilized, resulting in the stream staying at more or less the same level for an extended period of time. Today, these processes are occurring near the bridge along the trail to the cliff dwellings. Rockfall, as shown here, can accompany cave formation. Photograph by Katie KellerLynn (Colorado State University).

Cave features are non-renewable resources. The Federal Cave Resources Protection Act of 1988 requires the identification of "significant caves" in NPS areas, the regulation or restriction of use as needed to protect cave resources and inclusion of significant caves in land management planning. The act also imposes penalties for harming a cave or cave resources and exempts park managers from releasing specific location information for significant caves in response to a FOIA request (see also Appendix B). A park-specific cave management plan has not yet been completed for Gila Cliff Dwellings National Monument. Such plans include a comprehensive evaluation of current and potential visitor use and activities, as well as a plan to study known and discover new caves. The NPS Geologic Resources Division can facilitate the development of such a plan.

In the chapter about caves and associated landscapes in *Geological Monitoring*, Toomey (2009) described methods for inventorying and monitoring cave-related vital signs, including (1) cave meteorology such as microclimate and air composition of the cave; (2) airborne sedimentation, including dust and lint; (3) direct visitor impacts such as breakage of cave formations, trail use in caves, graffiti, and artificial cave lighting; (4) permanent or seasonal ice; (5) cave drip and pool water, including drip locations, drip rate, drip volume, drip water chemistry, pool microbiology, and temperature; (6) cave microbiology; (7) stability associated with breakdown, rockfall, and partings; (8) mineral growth of speleothems such as stalagmites and stalactites; (9) surface expressions and processes that link the surface and the cave environment, including springs, sinkholes, and cracks; (10) regional groundwater levels and quantity; and (11) fluvial processes, including underground streams and rivers. Not all of these vital signs are applicable at Gila Cliff Dwellings National Monument. Managers at the monument are encouraged to contact the NPS Geologic Resources Division for assistance.

Paleontological Resources

Paleontological resources (fossils) are any evidence of life preserved in a geologic context (Santucci et al. 2009). Body fossils are any remains of the actual organism such as bones, teeth, shells, or leaves. Trace fossils are evidence of biological activity; examples include burrows, tracks, or coprolites (fossil dung). Fossils in NPS areas occur in rocks or unconsolidated deposits, museum collections, and cultural contexts such as building stones or archeological resources. As of August 2014, 246 parks had documented paleontological resources in at least one of these contexts. 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 2014, Department of the Interior regulations associated with the Act were being developed. The NPS Geologic Resources Division Paleontology website, http://www.nature.nps.gov/geology/paleontology/index.cfm, provides more information.

Packrat (*Neotoma* spp.) middens, which are important tools for reconstructing the paleoecology and climate of the late Pleistocene and Holocene of western North America (Tweet et al. 2012), occur in the caves at Gila Cliff Dwellings National Monument. Thirty-three National Park System units, including Gila Cliff Dwellings 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, as well as cave sediments, yields paleobotanical information (Davis et al. 1984; Mead et al. 1986; Mead and Agenbroad 1992; Hunt et al. 2012).

The middens at the monument have been neither studied nor dated. GRI scoping participants suggested that work on packrat middens by Ken Cole at the Colorado Plateau Cooperative Ecosystems Study Unit in Flagstaff, Arizona, may be of interest to monument managers. Cole's study area is the Colorado River drainage (Cole 1990). Additionally, work by Holmgren et al. (2003), which focused on the USA-Mexico borderlands, may also be useful (Dave Love, New Mexico Bureau of Geology and Mineral Resources, geologist, written communication, 12 May 2008). If monument managers choose to study packrat middens, the NPS Geologic Resources Division could facilitate communication between monument managers and various researchers in the Southwest.

Quaternary deposits, such as valley alluvium and terrace gravels, also may contain fossils, including testudinids, equids, camelids, and proboscideans (Tweet et al. 2008). For example, the New Mexico Bureau of Mines and Mineral Resources (1980), Wolberg (1981), and Sandor (1983) documented the skull of a Pleistocene horse (*Equus conversidens*) in a roadcut exposure of a Pleistocene stream terrace along Sapillo Creek, a tributary of the Gila River.

In addition, the Gila Conglomerate is a potential source of fossils, though none have been found in the monument (Tweet et al. 2008). The lacustrine and floodplain depositional environments of the conglomerate have yielded many fossils elsewhere (Knetchel 1936; Lindsay and Tessman 1974; Lindsay 1978; Nations and Landye 1984; Morgan and White 2005), including the Walnut Canyon and Buckhorn faunas (see discussion below). If fossils are present in the conglomerate at the monument, discovery of a large articulated specimen is unlikely, but finding pieces of sturdy abraded bone or wood is possible (Tweet et al. 2008).

The nearest documented fossils in the Gila Conglomerate are from two areas 40–48 km (25–30 mi) south and southwest of the monument. These localities comprise the Walnut Canyon and Buckhorn local faunas (Morgan and Sealey 1995, 1997; Morgan et al. 1997;

Morgan and Lucas 2003). The Walnut Canyon fauna includes upper Miocene and lower Pliocene rodents, rabbits, foxes, felids, equids, peccaries, camelids, cervids, and antelopes (Morgan and White 2005). The Miocene Buckhorn fauna is more diverse than the Walnut Canyon fauna and includes fish, frogs, salamanders, colubrid snakes, ducks, turkeys, flamingos, rails, passeriforms, rabbits, ground squirrels, murids, felines, sabercats, badgers, bears, equids, peccaries, camelids, and gomphotherid proboscideans (Morgan and White 2005). Additionally, vertebrate fossils from the Gila Conglomerate occur near Pleasanton, New Mexico, about 56 km (35 mi) west of the monument (James C. Ratté, US Geological Survey, geologist, personal communication *in* Tweet et al. 2008, p. 50). This locality was not discussed in reviews by Morgan et al. (1997) or Morgan and Lucas (2003).

A field-based paleontological resource survey can provide detailed, site-specific descriptions and resource management recommendations that are beyond the scope of this report. Tweet et al. (2008) compiled paleontological information for the Sonoran Desert Network, including Gila Cliff Dwellings National Monument, and encouraged monument staff to be aware that the Gila Conglomerate and river deposits (i.e., alluvium, Qa) have the potential to contain fossil material. If a fossil is discovered during the course of a staff member's usual duties, he or she should document the find, preferably taking a photograph of the fossil alongside a readily identifiable item such as a pocketknife for scale. Staff may send such photographs to the NPS Geologic Resources Division for assistance in identification and potential future research. A fossil and its associated geologic context (rock matrix) should be documented but left in place unless the fossil is subject to imminent degradation by artificially accelerated natural processes or direct human impacts.

In the chapter about monitoring in situ paleontological resources in *Geological Monitoring*, Santucci et al. (2009) outlined potential threats to fossil resources and suggested monitoring vital signs to qualitatively and quantitatively assess the potential impacts of these threats. Santucci et al. (2009) discussed the following vital signs: (1) erosion (geologic factors), (2) erosion (climatic factors), (3) catastrophic geohazards, (4) hydrology/bathymetry, and (5) human access/public use; and presented detailed methodologies for monitoring each of them.

Geological Features with Cultural Significance

Many interesting connections exist between the geological and archeological resources at Gila Cliff Dwellings National Monument, including the following:

Caves in Gila Conglomerate

The most conspicuous geologic feature with cultural significance at Gila Cliff Dwellings National Monument is the Gila Conglomerate and the caves and cliff dwellings it contains (fig. 24). Due to the nature of the rock, many cavities, overhangs, and caves formed within

Figure 24. Cave and cliff dwelling. People of the Mogollon culture built masonry walls composed of Gila Conglomerate in the caves in Cliff Dweller Canyon. The use of caves as shelter and the conglomerate as building stone are obvious connections between geological and archeological resources at the monument. Photograph by Katie KellerLynn (Colorado State University).

the unit, inviting use by humans (Bradford 1992). These natural caves served as dwellings for two phases of occupation—the Mogollon (between about the 1270s and 1290s CE) and an earlier Archaic group of inhabitants (pre-500 CE). The seven closely spaced caves (fig. 3), which formed as a result of fluvial processes and groundwater sapping, are located on the northwestern side of Cliff Dweller Canyon, between 400 and 600 m (1,300 and 2,000 ft) from the mouth of the canyon, approximately 60 m (200 ft) above the narrow canyon floor. The dwellings within the caves consist of 50 coursed rock and masonry rooms and 50 additional open areas composed of courtyards, corridors, walkways, or patios (Nordby 2011). The shapes of the rooms were determined by the contours of the cave walls (Anderson et al. 1986).

Gila Conglomerate as Building Stone

In the cliff dwellings and rock shelters of Cliff Dweller Canyon, people of the Mogollon culture used the locally available Gila Conglomerate to build masonry walls, lintels for doors and windows, and hearths. The stone used in wall construction does not show evidence of shaping or trimming, or a deliberate pattern of placement (Anderson et al. 1986). Most stones were apparently placed into the walls as they were collected or quarried, without modification (Nordby 2011). As such, the distinction between human masonry and natural conglomerate is often difficult to make (fig. 25).

Separate quarries for building stone have not been identified in or near the monument (KellerLynn 2008). Some areas of hammered and fractured bedrock are visible in and around the cliff dwellings, and probably served as stone quarries (Nordby 2011). In some cases, quarried areas form the back walls of dwellings, such as in Cave 3 (Nordby 2011). Along with acquiring building stone, some in-cave quarries may be related to attempts to fine-tune a house's location (Nordby 2011). In the masonry walls in Cave 6, the building stone was likely taken from the thin-bedded floor and slopes within the

Figure 25. Masonry wall and Gila Conglomerate. Walls constructed of Gila Conglomerate show no evidence of trimming, cutting, or deliberate pattern placement of stones. As such, human masonry and natural bedrock blend into each other at the caves in Gila Cliff Dwellings National Monument. Photographs by Katie KellerLynn (upper; Colorado State University) and James C. Ratté (lower; US Geological Survey).

cave. As stones were removed they were used to build walls (Anderson et al. 1986).

Mortar and Plaster

Little is known about the mortar and plaster used in construction of the cliff dwellings. No detailed mortar study has occurred, and no borrow pit has been discovered nearby (Nordby 2011). Monument staff would find research conducted on these geologic materials helpful in management and interpretation (KellerLynn 2008). Until research is conducted, the "working theory" is that mud, clay, and sand were mined from nearby areas, perhaps from within the caves (Nordby 2011). The mortar and plaster used in construction was sandy clay (Anderson et al. 1986). For plaster, the builders used a single heavy coat to even out inconsistencies in the stones' edges or to provide a smooth interior surface (Anderson et al. 1986).

Tools

The combination of rock types in the Gila Cliff Dwellings area provided many lithic resources for human use (Bradford 1992). Stone artifacts include tools for cutting, chopping, scraping, and drilling; projectile points; hammer stones; and ground stones for grinding (Bradford 1992). According to *Archeological Survey, Gila Cliff Dwellings National Monument* (Bradford 1992), the most common raw material in the artifacts found at the monument is white chert (29%), which occurs locally as small nodules that fill fissures in the Gila Conglomerate. Bradford (1992) remarked that this finding was surprising because although chert has some of the best tool-making qualities, locally the size of nodules is usually less than 5 cm (2 in). Rhyolite welded tuff, which is locally available from the mouth of Cliff Dweller Canyon downstream to Gila Hot Springs, was the second most abundant raw material (13.3%). Agate, which occurs in the same context as local chert and is similar in size, was third in abundance at 12.3%. Notably, agate is less often used as a tool than chert (Bradford 1992). Andesite, which is locally available, was the fourth most common material (12%). Andesitic welded tuff, which occurs in the region but not in the vicinity of the cliff dwellings, was fifth at 9.3%. Chalcedony, which occurs in the same context as chert and agate, provided 8% of the amount of lithic material.

According to Anderson et al. (1986), stone of the kind found in artifacts at the monument is available within 60 km (40 mi), thus no elaborate exchange network is needed to account for the supply of lithic raw materials to the site. Ratté and Gaskill (1975) mapped rhyolite, andesite, and welded tuff in the monument and surrounding area. All of these materials are quite workable and well-suited for manufacturing cutting and piercing tools (Bradford 1992). In general, preferred lithic materials for manufacturing tools are obsidian (volcanic glass) and various forms of quartz (crystalline silica) such as chert, chalcedony, agate, and jasper. Obsidian and crystalline silica possess surfaces of conchoidal (smoothly curved) fracture that are utilized for cutting and scraping. In the Gila Cliff Dwellings area, andesite is often fine grained enough to show conchoidal fractures, and rhyolitic welded tuff (e.g., Bloodgood Canyon Tuff) often approaches the glassiness of opaque obsidian (Bradford 1992).

Ratté and Brooks (1983)—the geologic map for the Mule Creek quadrangle in Grant County, south of the monument—documented obsidian in the Tertiary rhyolite of Mule Mountains and "Apache tears" (nodular obsidian) in the Gila Conglomerate along Mule and Tennessee creeks. The Mule Creek obsidian area, which is about 67 km (42 mi) west of the cliff dwellings, is a well-known regional source (Findlow and Bolognese 1982; Shackley 1988, 1992, 1995). Shackley (1996) identified obsidian artifacts from an adobe mound pueblo of the Salado culture near the monument as originating from Mule Creek.

Similar material types, such as chalcedony and chert, used in manufacturing tools also were available within a reasonable distance from the cliff dwellings (Bradford 1992). According to Kuellmer (1954), Magdalena and Lake Valley limestones, which contain lenses and nodules of white, gray, and black chert, are exposed on the western slope of the Black Range, about 50 km (30 mi) east of the monument. Also in the Black Range, Harley (1934) reported small amounts of chalcedony in the Taylor Creek area at the headwaters of the Middle Fork Gila River. Chapman et al. (1985) described similar sources of silica materials in the gravels along Duck Creek, Mogollon Creek, and the Gila River within 80 km (50 mi) southwest of the monument.

Depressions

Many examples of human-made depressions occur on the floors and flat-lying boulders within the caves. Anderson et al. (1986) noted a slab-lined hearth and two adjacent depressions in Cave 1 (fig. 26). Many of these depressions are assumed to be grinding surfaces used in food preparation. Buonasera (2011) conducted a study of these features at the monument and showed the depressions to be coated with an organic residue, specifically lipids from plants (e.g., sunflower seeds and wood smoke).

Figure 26. Human-made depressions. Many examples of human-made depressions occur within the caves at Gila Cliff Dwellings National Monument, including two grinding depressions associated with a slab-lined hearth in Cave 1. The circular grinding depressions are in the foreground; the square-shaped hearth is to the right. Photograph by Carl Litsinger (Gila Cliff Dwellings National Monument).

Other human-made depressions on bedrock and boulders include curious, cup-shaped indentations, primarily on horizontal surfaces but also vertical surfaces (figs. 27 and 28). These features, called cupules, have caused great speculation, and some scientific analysis (e.g., Bednarik 2008). Interest stems from the ubiquitous nature of cupules throughout the world in Europe, Asia, Australia, North America, and South America; the longevity of their production, from Lower Paleolithic—

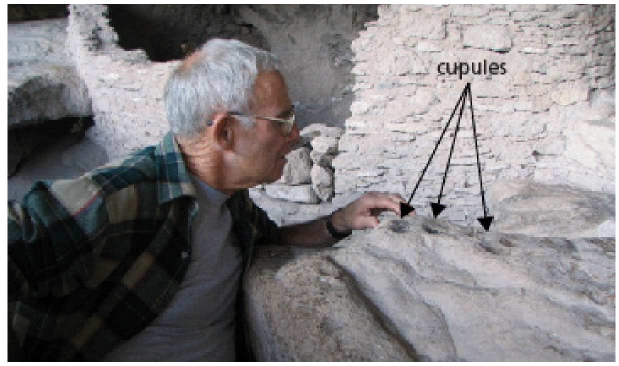

Figure 27. Cupules and masonry wall. James C. Ratté (US Geological Survey, geologist emeritus) inspects curious, cup-like indentations, called "cupules," at Gila Cliff Dwellings National Monument. Speculation abounds, but the function of these cupules, and those throughout the world, is unknown. The masonry wall in the background shows the use of mortar, made of heavy, sandy clay. National Park Service photograph by Sonya Berger.

Figure 28. Cupules. Based on a worldwide study, nearly all cupules are between 1.5 and 10 cm (0.6 and 4 in) in diameter; almost always occur in groups; are found on horizontal, sloping, and vertical surfaces, but almost never on overhead panels; and often occur on large boulders, rather than bedrock pavements or walls. The cupules at Gila Cliff Dwellings, shown here, conform to these global characteristics. Photograph by Katie KellerLynn (Colorado State University).

which more or less coincides with the Pleistocene Epoch (2.6 million–11,700 years ago)—to the 20th century; how cupules were made, which appears to be no easy task; and the unsolved nature of their purpose. Bednarik (2008) noted that the skill and sheer persistence of ancient cupule makers are almost beyond comprehension. In replication experiments in 2002 in Daraki-Chattan, India, for example, a 1.9-mm- (0.07-in-) deep cupule was made in 72 minutes of actual working time with 8,490 blows with a hammer stone. A second cupule required 8,400 blows in 66 minutes and reached a maximum depth of 4.4 mm (0.17 in), after which the maker was exhausted. These "modern" cupules tended to be slightly larger than the ancient ones in the Daraki-Chattan Cave, illustrating a lack of skill (striking precision) compared to the Paleolithic cupule makers (Bednarik 2008). Bednarik (2008) noted that nearly all cupules are of diameters between 1.5 and 10 cm (0.6 and 4 in). In addition, cupules almost always occur in groups, and frequently in very large accumulations, numbering hundreds at single sites, even thousands in some locations. They are found on horizontal, sloping, and vertical surfaces, but almost never on overhead panels. Additionally, cupules were commonly created on large boulders, rather than bedrock pavements or walls.

In summer 2012, volunteer Chris Reed documented human-made depressions within the caves at the monument. The goals of the project were to document the depressions with scale drawings, photographs, measurements, and maps; conduct a literature review; and interview monument staff and visitors about possible functions. Reed (2012) recorded 14 “features” consisting of more than 250 depressions; a feature in this study was “a boulder, bedrock, or cave wall containing one or more areas exhibiting a depressed surface that was created by human activity” (Reed 2012, p. 4). Possible functions of cupules include use in food processing, fertility rituals (e.g., collection of fertilizing dust made during cupule creation), weather control (e.g., pounding mimicking thunder), preparation of paints or medicines; and as astronomical charts, musical instruments, or board games (Bednarik 2008; Reed 2012).

Cave Deposits

Cave deposits are another geologic feature with cultural significance at the monument. Lambert (1990) analyzed samples of substances, including a sample of the lustrous, tan-colored coating found on many rocks in the caves, primarily Caves 4 and 5. The sample contained weddellite (dihydrated calcium oxalate), whewellite (monohydrated calcium oxalate), and uric acid hydrate—the mineral assemblage found in kidney stones. The laminated structure of the material suggested repeated activity, and the presence of these deposits on flat-topped, tilted rocks may indicate that these accumulations were sites of hide processing (Lambert 1990), as urine was used as a tanning agent in historic times (Sonya Berger, Gila Cliff Dwellings National Monument, chief of interpretation, personal communication, 15 November 2007).

Using x-ray diffraction, Lambert (1990) also analyzed two samples of a black coating—one shiny and one dull—from a cave ceiling. The shiny sample was amorphous carbon and thus confirmed the popular theory of soot accumulation from smoke. The dull substance did not contain enough carbon to show up in x-ray, but was also presumed to be the product of smoke.

Soot accumulations in the caves provide an informal dating method for determining rockfall events since the time of occupation 700 years ago (KellerLynn 2008). Areas of post-occupation rockfall are now pale colored due to spalling of soot-covered rock surfaces (fig. 29).

An interesting rockfall-dating scenario occurs in Cave 5, where a huge slab now forms a low roof over a well-used grinding depression (fig. 30). The space between the grinding depression and the overlying slab would have made grinding awkward at best, and probably humanly impossible. Furthermore, a masonry wall has been built on top of the fallen slab. This evidence suggests that the slab fell before the Tularosa Mogollon (who built the wall) arrived, thus the grinding surface was likely made during an earlier phase of occupation (Carl Litsinger, Gila Cliff Dwellings National Monument, volunteer, e-mail communication, 28 September 2012).

Figure 29. Soot and spalling. The ceiling in Cave 1 shows soot, spalling, and a pictograph. More than 700 years ago, during occupation of the cave, black soot from fires used for cooking and heating accumulated on the ceiling. Spalling occurred since that time and is represented by “clean” (non-black) areas. In addition, a single red line, approximately 30 cm (1 ft) in length, is a pictograph painted during Mogollon occupation of this cave. Thus soot apparently had accumulated and spalled prior to Mogollon occupation when the pictograph was painted. The scenario suggests an earlier phase of occupation. Photograph by Carl Litsinger (Gila Cliff Dwellings National Monument).

Figure 30. Rockfall and grinding surface. A flat-lying surface used for grinding lies beneath a fallen slab of rock in Cave 5. Working in the space between the fallen slab and the grinding surface would have been awkward or even humanly impossible. Furthermore, a Mogollon wall was built on top of the slab, indicating that the slab fell before the second phase of occupation (between about the 1270s and 1290s CE). Therefore, the grinding surface was used during the first phase of occupation (pre-500 CE) before the rockfall occurred. Photograph by Carl Litsinger (Gila Cliff Dwellings National Monument).

Pictographs

One other geological–archeological resource connection worthy of discussion is pictographs. The definition provided in *Glossary of Geology* (Neuendorf et al. 2005)—“a picture painted on rock by primitive peoples and used as a sign”— is a nice geological–archeological

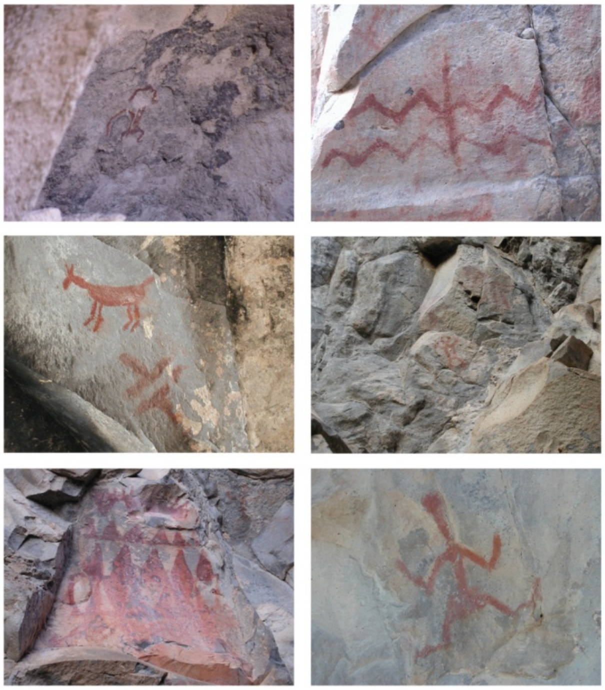

Figure 31. Pictographs. Pictures painted on rock, called "pictographs," are an interesting geological–archeological resource connection at Gila Cliff Dwellings National Monument. Identified from the period known as Mogollon Red, the images occur in the caves and along the trail in Cliff Dweller Canyon. The red pigment has not been chemically analyzed, but is referred to as "hematite red" by monument staff. The source of the pigment is unknown. Photographs by Carl Litsinger (upper left and bottom right; Gila Cliff Dwellings National Monument) and Katie KellerLynn (Colorado State University).

connection in itself. Of the 106 sites recorded in *The Archeology of Gila Cliff Dwellings* (Anderson et al. 1986), which covered Gila Cliff Dwellings National Monument and 8 km^2 (3 mi^2) of adjoining Gila National Forest, five were pictograph sites. None of these sites occur within the monument, but individual pictographs do occur, for example, in Caves 1 and 5, and along the trail to Cliff Dweller Canyon (fig. 31). Nordby (2011, p. 24) noted "several pictograph panels" in Cave 1, and Anderson et al. (1986, p. 57) noted a "few anthropomorphic, zoomorphic, and concentric-circle pictographs" in Cave 5. Geometric shapes and life-forms are common images in the Gila Cliff Dwellings pictographs (Anderson et al. 1986).

Schaafsma (1980) discussed the pictographs in the caves at the monument and dated the designs to the 13th century thus classifying the images as Mogollon Red, which is a style that appears most commonly in the drainages of the San Francisco River, upper Gila River, and in extreme southeastern Arizona and southwestern New Mexico (Russell 1992). Red is the most common color used in the pictographs, though some black is occasionally seen (Anderson et al. 1986). Monument staff and volunteers refer to this pigment as "hematite red," though no known analysis of the pigment has been conducted.

Geologic Resource Management Issues

This section 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 Gila Cliff Dwellings National Monument. The NPS Geologic Resources Division provides technical and policy assistance for these issues.

During the 2007 scoping meeting and 2011 conference call, participants (see Appendix A) identified the following geologic resource management issues:

- Fluvial Features and Processes
- Rockfall Hazards
- Spalling
- Post-Wildfire Sedimentation and Debris Flows
- Seismic Activity
- Geothermal Development
- Climate Change

Resource managers may find *Geological Monitoring* (Young and Norby 2009; http://go.nps.gov/geomonitoring) 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.

Fluvial Features and Processes

Gila Cliff Dwellings National Monument is within the Gila River drainage basin (fig. 32). The entire basin encompasses 145,500 km^2 (56,180 mi^2) and includes part of southwestern New Mexico and more than half the state of Arizona (Connell et al. 2005). Surface elevations in the basin range from about 700 m (2,300 ft) at San Carlos Reservoir, east of Phoenix, Arizona, to about 3,400 m (11,000 ft) in the Mogollon Mountains of western New Mexico. The Gila River ends at the junction with the lower Colorado River at Yuma, Arizona (Connell et al. 2005). The course of the Gila River flows through a series of troughs, outlined by north–northwest-oriented mountain ranges. Narrow strips of alluvium line the river and its tributaries.

The Gila Wilderness protects the upper Gila River watershed surrounding Gila Cliff Dwellings National Monument (fig. 32). Three forks of the Gila River converge in the valley near the monument: the West Fork joins the Middle and East forks southeast of Cliff Dweller Canyon. From there, the Gila River cuts through the Diablo and Pinos Altos ranges before reaching the broad grasslands of the Gila River valley toward the Arizona state line (Parent 2004). The West Fork Gila River provides 0.9 km (0.6 mi) of riparian habitat in the northeastern part of the monument.

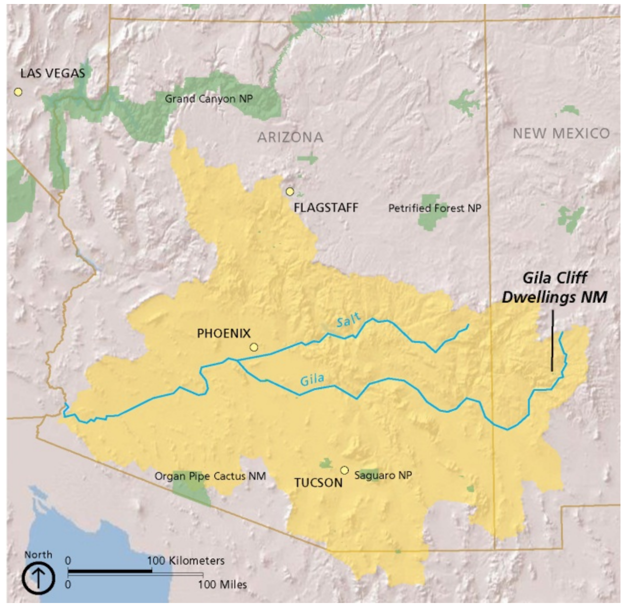

Figure 32. Gila River drainage basin. The Gila River watershed (yellow area on figure) includes more than half the state of Arizona and part of southwestern New Mexico. It encompasses approximately 145,500 km^2 (56,180 mi^2). Gila Cliff Dwellings National Monument lies in the upper watershed area. Graphic by Rebecca Port (NPS Geologic Resources Division) after Connell et al. (2005) using ESRI World Shaded Relief basemap.

During most of the year, an unnamed stream, referred to as Cliff Dweller creek, flows through Cliff Dweller Canyon and disappears into layers of gravel that line the streambed. A small spring at the head of Cliff Dweller Canyon ensures a flow of water, which reaches the West Fork at the monument's eastern boundary. The Gila Conglomerate, which is a groundwater aquifer, is the source of the spring's water, and thus the creek's source (Trauger 1963). Water that feeds the spring issues from a joint in the conglomerate. In addition, creek water issues from the contact between the Gila Conglomerate and underlying volcanic rocks (Trauger 1963), which depending on local stratigraphy may be Bloodgood Canyon Tuff (Tbc or Tbt; fig. 9), Bearwallow Mountain Andesite (Tya or Tba; fig. 9), or andesitic to dacitic lava flows of the Middle Fork (Tya or Tmd; see fig. 9 and poster, in pocket). The spring and creek sustain an oasis of walnut, oak, grapes, and pine in Cliff Dweller Canyon.

Flooding

Summer rain and winter snow provide moisture for the Gila River watershed (Douglas et al. 1993); recharge is directly dependent on precipitation that falls within the drainage area (Bradford 1992). During summer, monsoons and resulting flash floods may cause the West

Figure 33. High water on the Middle Fork. Summer monsoons and winter storms can cause flooding of the rivers and streams in the Gila Cliff Dwellings area. This photograph was taken on 1 December 2007. For a comparison to "normal" conditions, see the photograph on the inside front cover. National Park Service photograph by Sonya Berger.

Fork and Cliff Dweller creek to fill their channels. Winter storms also increase flow (Sonya Berger, Gila Cliff Dwellings National Monument, chief of interpretation, e-mail communication, 12 December 2007) (fig. 33).

The high, sheltered location of the cliff dwellings protects them from heavy rains and flooding, but access to the site is impeded during floods, with bridges commonly damaged and trails inundated; flood waters occasionally wash out the trail that runs along the creek bed in Cliff Dweller Canyon (KellerLynn 2008). Though rare, floods have historically washed out foot bridges in Cliff Dweller Canyon. The contact station and parking lot for the Cliff Dwellings trailhead is in a floodplain (fig. 4). In the 40 years prior to 2007, flood waters had reached the parking lot twice (KellerLynn 2008). All other major facilities in the main and T J units are above the present floodplain on the alluvial terraces of the West Fork (see "Terraces and Valley Incision" section).

Within Cliff Dweller Canyon, floods primarily leave their mark as scour depressions and deposited debris along the creek channel. Flash floods can induce slope movements; minor debris flows are the expected outcome within the monument (KellerLynn 2008). Additionally, as water pours off the mesas during monsoon storms, waterfalls form, transporting water and debris onto trails (KellerLynn 2008). Trail erosion and access up Cliff Dweller Canyon adds to the sediment supply into Cliff Dweller creek (KellerLynn 2008).

The larger area of the West Fork watershed, 4,200 km^2 (1,600 mi^2), results in greater flooding than Cliff Dweller creek (KellerLynn 2008). Along Highway 15, the bridge across the West Fork is periodically washed out (Ratté 2007). These washouts have required the closure of the monument, ranging from two to six weeks (Russell 1992). Repair and maintenance of the paved roads and bridges are the responsibility of the New Mexico Department of Transportation; the Forest Service is responsible for local road repairs (Russell 1992).

Inventory and Monitoring

Starting in 2012, the Sonoran Desert Network began monitoring the spring in Cliff Dweller Canyon and flow in the West Fork (Steve Riley, Gila Cliff Dwellings National Monument, superintendent, conference call, 7 December 2011). Geologic features and processes associated with monitoring include stream channel morphology and stream discharge. For the spring, monitored features related to geology include wetted area, water depth, and soil moisture (National Park Service 2012b, 2012c).

In the chapter in about fluvial geomorphology in *Geological Monitoring*, Lord et al. (2009) described methods for inventory and monitoring the following vital signs: (1) watershed landscape (vegetation, land use, surficial geology, slopes, and hydrology), (2) hydrology (frequency, magnitude, and duration of streamflow rates), (3) sediment transport (rates, modes, sources, and types of sediment), (4) channel cross-section, (5) channel planform, and (6) channel longitudinal profile. Sonoran Desert Network and monument staff members may find the discussion in Lord et al. (2009) useful for monitoring stream systems at Gila Cliff Dwellings National Monument.

Rockfall Hazards

Rockfall is one type of slope movement—the downslope transfer of soil, regolith, and/or rock under the influence of gravity. Slope movements, which are commonly and collectively referred to as "landslides," occur on time scales ranging from seconds to years. Slope movements create geologic hazards and associated risk in many parks. Wieczorek and Snyder (2009), Highland and Bobrowsky (2008), the US Geological Survey landslides website (http://landslides.usgs.gov/), and the NPS Geologic Resources Division Geohazards (http://www.nature.nps.gov/geology/hazards/index.cfm) and Slope Movement Monitoring (http://www.nature.nps.gov/geology/monitoring/slopes.cfm) websites provide detailed information regarding slope movements, monitoring, and mitigation options.

The walls of Cliff Dweller Canyon are susceptible to rockfall, which is an ongoing concern for monument managers (KellerLynn 2008). Rockfall occurs via exfoliation—the process by which concentric scales, plates, or shells of rock of less than 1 cm (0.4 in) to several meters in thickness are successively spalled or stripped from the bare surface of a large rock mass (Neuendorf et al. 2005). Exfoliation fractures in the Gila Conglomerate give rise to rockfall at the monument, generally producing thin, plate-like fragments with volumes less than 1 m^3 (35 ft^3). Thicknesses of fragments vary from several millimeters up to about 10 cm (4 in), with a few fragments that exceed 50 cm (20 in) in thickness and have volumes of several cubic meters (Harp 2000).

Where pieces of rock have fallen from exfoliation fractures, the rock face appears relatively unweathered and correspondingly light colored. According to Harp (2000), the areas of relatively higher rockfall hazard are fairly obvious; they are the "pillars" between the caves that extend out toward the canyon farther than other parts of the cliff face (fig. 34). These pillars have more loose pieces of rock than other parts of the cliff face. The distribution of fresh surfaces and pieces of rock that appear to be loose along these fractures is markedly higher on the cliff faces between the caves, where the evidence of water flow (dark staining) is minimal (Harp 2000). Staining occurs where running water has deposited thin coatings of iron and manganese dissolved out of the rocks and re-precipitated from solution as the water ran down the cliffs (Ratté 2001).

Figure 34. Rockfall hazards. Areas of the cliff face between caves, referred to as "pillars" by Harp (2000), have a greater potential for rockfall than other sections of the cliff face. Pillars extend farther outward than other parts of the cliff face, lack black staining, and host loose rock (see red circle). National Park Service photograph by Sonya Berger.

Stabilization inspections of the cliff dwellings in the 1970s noted areas of deteriorated bedrock (Russell 1992). However, work by Wachter (1985) was the first to systematically document rockfall hazards at the monument. The primary concern in 1985 was rock deterioration below Cave 2, though Wachter (1985) provided observations for all seven caves. His observations at Cave 6 remain pertinent for resource management today. Wachter (1985) observed high, loose slabs of rock around the entrance to Cave 6, and some instability on the cliff face between the entrance and 12 m (40 ft) west of the entrance. Failure appeared imminent for very loose slabs of up to 230 kg (500 lb) on the western arch of the entrance. The higher, larger slabs posed a threat to the trail traffic below as well as to visitors who might enter the cave. The potential hazard included a rock mass of 45 metric tons (50 tons) that was perched on the cliff slope above and 6 m (20 ft) west of the cave entrance. The interior of the cave was quite stable, but the closure at the time was warranted due to instability at the entrance (Wachter 1985).

On 2 August 2000, Edwin L. Harp of the US Geological Survey conducted a site visit as a result of several pieces of Gila Conglomerate falling from the cliff face near Cave 6, narrowly missing a visitor on 20 July 2000. Ultimately, the rockfall may have been induced by the action of rainfall on the rock surface from afternoon thunderstorms that are more frequent during summer. Harp (2000) noted that although rockfall occurred recently, the hazard to the public did not appear to be high.

In 2007, scoping participants observed two sites of potential rockfall hazards on the cliff faces near Caves 2 and 6. The potential hazards are large, jointed rocks along the cliff face. Participants thought that the potential rockfall hazard near Cave 6 looked more serious than the one near Cave 2 (KellerLynn 2008).

In 2010, monument managers contacted the NPS Geologic Resources Division for technical assistance concerning rockfall hazards. GRD staff member Deanna Greco conducted a site visit on 20 August 2010. Harp and Greco had essentially the same analysis and recommendations, and Greco did not submit a separate report to monument managers (Deanna Greco, Grand Canyon National Park, physical sciences program manager, e-mail communication, 29 August 2012). The NPS Geologic Resources Division provided managers with Harp's report, and will provide additional assistance to address rockfall hazards as needed in the future (Bruce Heise, NPS Geologic Resources Division, geologist, conference call, 7 December 2011).

Harp (2000) suggested some possible mitigation measures for rockfall hazards at the monument although rockfall is infrequent and the volume of material is relatively small. Trail signs and/or literature could alert visitors to the possibility of rockfall. Harp (2000) recommended a modest effort to remove the loose rock from the surfaces of the cliffs at Cave 6. In 1985, Wachter made a similar recommendation for Cave 6, stating "some of the high slabs could be removed with a long pry bar from below, though some would require prying or jacking by climbers from above" (p. 4). Removal could be done by capable climbers or by subcontractors that commonly do similar work for the New Mexico Department of Transportation. A few of the thickest tabular masses near the eastern end of the cliffs might have to be removed with light blasting (Harp 2000).

Harp (2000) proposed rerouting the trail closer to the cliff, potentially providing more protection from overhanging sections with loose rock. However, rerouting the trail could pose new issues such as steepening of grade, poor drainage, increased erosion, or impacts to sensitive resources. Such actions may be subject to competing policy considerations and are a matter of park manager discretion.

Managers at Gila Cliff Dwellings National Monument have mitigated rockfall hazards in the past. In 1987, for example, monument managers removed benches from the interior of Cave 1 and constructed a metal railing to deter entrance into this cave (see Wachter 1985 for documentation of this hazard). Also in 1987, monument managers placed a similar railing across the western end of Cave 2. Additional railings were positioned in front of the small cavity beneath Room 25 and across the entrance to Cave 6. Loose rock was removed from over the trail in Cave 5 (Russell 1992).

In the chapter about slope movements in *Geological Monitoring*, Wieczorek and Snyder (2009) described five vital signs: (1) types of landslides, (2) landslide triggers, (3) geologic materials in landslides, (4) measurement and assessment of landslide movement, and (5) regional assessment of landslide hazards and risks. Monument managers may find this information useful in addressing and mitigating the effects of rockfall, spalling within caves, and post-wildfire sedimentation in the watershed (see "Spalling" and "Post-Wildfire Sedimentation and Debris Flows" sections).

Spalling

As water seeps through a rock body and weakens natural cement, groundwater sapping commonly results in spalling, causing flakes, slabs, and blocks of rock to break away from a rock face (fig. 35). Large boulders within the caves are probably a result (fig. 36). This type of erosion is a major contributor to continued enlargement of the caves at the monument (KellerLynn 2008).

Though natural, spalling is a visitor safety concern. Moreover, falling material can damage masonry walls and structures in the caves. Spalling may also result in the loss of pictographs from cave ceilings and walls. Thin, large-diameter fragments of rock, as large as 1.8 m (6 ft), have fallen inside the caves since Mogollon occupation. The relative timing is known because black soot that had accumulated on the walls and ceilings during occupation remains on the ceilings that have not experienced spalling. Clear patches in the soot-covered ceilings show where spalling has occurred in the past 700 years (fig. 29). The intact nature of soot in most of the caves indicates that cave interiors have achieved a semblance of stability (KellerLynn 2008).

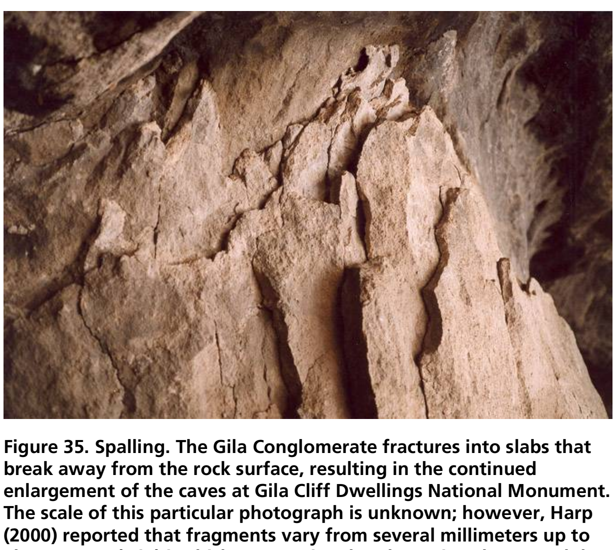

Figure 35. Spalling. The Gila Conglomerate fractures into slabs that break away from the rock surface, resulting in the continued enlargement of the caves at Gila Cliff Dwellings National Monument. The scale of this particular photograph is unknown; however, Harp (2000) reported that fragments vary from several millimeters up to about 10 cm (4 in) in thickness. National Park Service photograph by Barry Nielson.

Figure 36. Rockfall deposits. Large boulders within the caves Gila Cliff Dwellings National Monument are probably the result of past spalling. This photograph was taken on 17 November 2007 in Cave 5, but the timing of the rockfall event (or events) is unknown. Photograph by Katie KellerLynn (Colorado State University).

Post-Wildfire Sedimentation and Debris Flows

In summers 2011 and 2012, Gila Cliff Dwellings National Monument was affected by the Miller and Whitewater-Baldy fires, respectively. In 2011, residents of both the monument and the nearby community of Gila Hot Springs were evacuated. Highway 15 at the junction of Highway 35 was closed. In 2012, heavy smoke and poor air quality resulted in closure of the monument and the Gila Visitor Center (National Park Service 2012a).

Wildfire can affect recreation, residents, and infrastructure, as well as have immediate and profound effects on the hydrologic and geologic response of a watershed. Under unburned conditions, the vegetation canopy, soil, and soil-mantling litter and duff capture and store rainfall, which results in relatively little or no runoff. However, wildfires can consume rainfall-intercepting canopy, litter, and duff (Moody and Martin 2001a, 2001b; Meyer 2002; Cannon and Gartner 2005), affecting hydrologic response after a wildfire due to decrease in vegetation cover and altered soil properties. The intense heat of a wildfire can induce or enhance water-repellent qualities in some soils (DeBano 1981; Doerr et al. 2000; Letey 2001; Woods et al. 2006), potentially increasing overland flow and erosion (Wells 1987; Moody and Martin 2001a, 2001b). Additionally, the presence of ash, which expands when wetted, can block soil pore spaces, further reducing infiltration (Romkens et al. 1990; Woods et al. 2006).

Generally speaking, after a wildfire, watershed response to rainfall shifts from infiltration-dominated to runoff-dominated (Cannon et al. 2010). Runoff can erode surficial materials, including ash, soil, boulders, and dislodged vegetation. As sediment is entrained by overland flow, sediment-laden flow can progressively transition into debris flows, which are among the most hazardous consequences of rainfall on burned hill slopes. Debris flows pose a hazard distinct from other sediment-laden flows because of their destructive power. Moreover, debris flows can occur with little warning, exert great impulsive loads on objects in their paths, strip vegetation, block drainage ways, damage structures, and endanger human life (Iverson 1997). Debris flows are most frequent within two to three years after wildfires, when vegetative cover is absent or reduced and abundant materials are available for erosion and transport (Cannon and Gartner 2005; Cannon et al. 2010). Ratté and Gaskill (1975) and Ratté et al. (2014) mapped landslide deposits (Qls and Ql, respectively), but none within the monument.

Seven months after the May 2011 Miller fire, monument staff had begun to observe some fire-related impacts, namely eroded sediment along the trail to the cliff dwellings and in the riverbed in the lower segment of Cliff Dweller Canyon (fig. 37). After the Whitewater-Baldy fire of 2012, summer rains caused the West Fork and Middle Fork to run “cowboy coffee black and gritty” for about two months; monument staff expected additional sedimentation as a result of runoff in spring 2013 (Steve Riley, Gila Cliff Dwellings National Monument, superintendent, e-mail communication, 18 December 2012).

Figure 37. Wildfire and sedimentation. Wildfires periodically impact Gila Cliff Dwellings National Monument. Post-wildfire sedimentation, which affects aquatic habitats and water supplies, may lead to the development of debris flows. Although no debris flows have yet occurred as a result of fires in 2011 and 2012, river channels have experienced post-wildfire sedimentation such as on the Gila River at Murdock’s Hole (lower photo). National Park Service photographs by Steve Riley, taken in summer 2011.

Seismic Activity

Seismic activity is the phenomenon of movements in Earth’s crust, which may be naturally or artificially induced. An earthquake—defined as both the sudden slip on a fault and the associated ground shaking—generates seismic waves that propagate through the Earth and along Earth’s surface across large distances (Braile 2009). Earthquake intensity ranges from imperceptible by humans to total destruction of developed areas and alteration of the landscape. The “Richter magnitude” is a measure of the energy released by an earthquake. Earthquakes can directly damage park infrastructure, or trigger other hazards such as slope movements that may impact park resources, infrastructure, or visitor safety. Braile (2009), the NPS Geologic Resources Division Seismic Monitoring website (http://nature.nps.gov/geology/monitoring/seismic.cfm), and the US Geological Survey Earthquakes Hazards website (http://earthquake.usgs.gov/) provide more information.

New Mexico has a recorded history of seismic activity since 1869 (Sanford et al. 2002; Sanford et al. 2006; US Geological Survey 2009b). This long record aids researchers in evaluating seismic hazards and forecasting the location and magnitude of future earthquakes (Sanford et al. 2002).

The greatest concern related to seismic activity at Gila Cliff Dwellings National Monument is that shaking would induce rockfall. Harp (2000) noted that should moderate seismic shaking produced by a nearby shallow-focus earthquake of magnitude 5.5 or greater (on the Richter scale) occur in the area, rockfall from the cliffs on both sides of Cliff Dweller Canyon would likely take place. Furthermore, rockfall would involve large rocks with diameters of 0.5 to 1.0 m (2 to 3 ft) or larger, resulting in a considerable hazard to people. However, although earthquakes of magnitude 2 or 3 occur fairly regularly in the area (KellerLynn 2008), the potential for an earthquake of magnitude 5.5 or greater over the next 100 years is low—between 0.12 and 0.15—according to the US Geological Survey 2009 Earthquake Probability Mapping tool (fig. 38). Thus, seismically induced rockfall poses relatively low risk (Harp 2000).

Seismic shaking would originate along faults in the area. Ratté and Gaskill (1975) mapped many normal faults (fig. 39; see poster in pocket) of post-Oligocene age (younger than 23 million years ago) in the Gila Wilderness. Most of the faults running through the Gila Cliff Dwellings area run west–northwest and occur in sets. One of these fault sets forms a complex graben—the Gila Hot Springs graben (see “Gila Hot Springs Graben” section)—that is nearly 50-km- (30-mi-) long (see poster, in pocket). One of the major faults of this set crosses the West Fork near the White Creek Ranger Station. Faults also flank the Gila Cliff Dwellings and Bursum calderas (Ratté and Gaskill 1975).

These faults are related to crustal extension of the Basin and Range physiographic province. Extension began 30 million–20 million years ago (Connell et al. 2005).

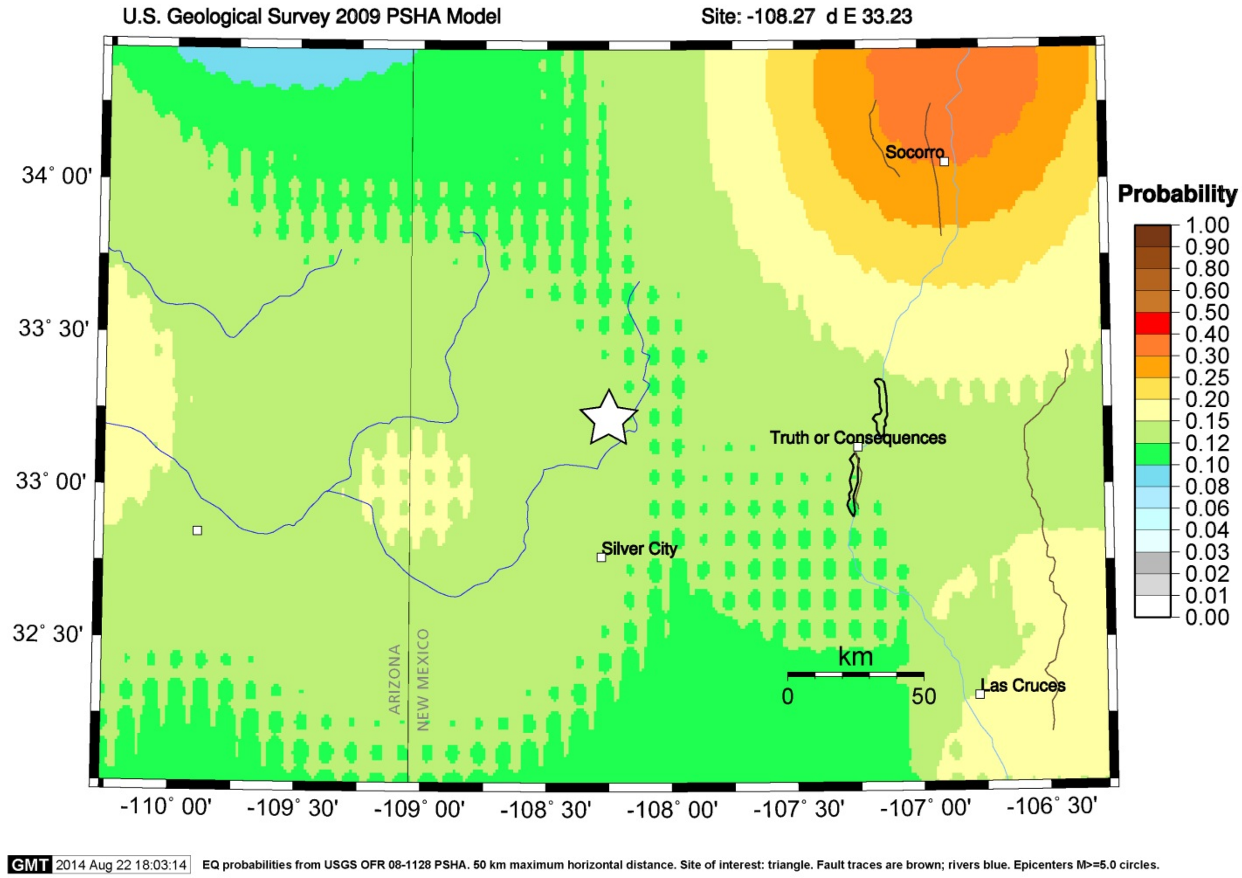

Figure 38. Earthquake probability map. This map shows the probability of a magnitude 5.5 (moderate) earthquake occurring in the next 100 years within 50 km (31 mi) of Gila Cliff Dwellings National Monument (star). Note the low probability (between 0.12 and 0.15) for the area surrounding the monument compared to the much higher probability (between 0.30 and 0.40) closer to Socorro. Map developed using the US Geological Survey 2009 Earthquake Probability Mapping tool, available online http://geohazards.usgs.gov/eqprob/2009/index.php (accessed 22 August 2014).

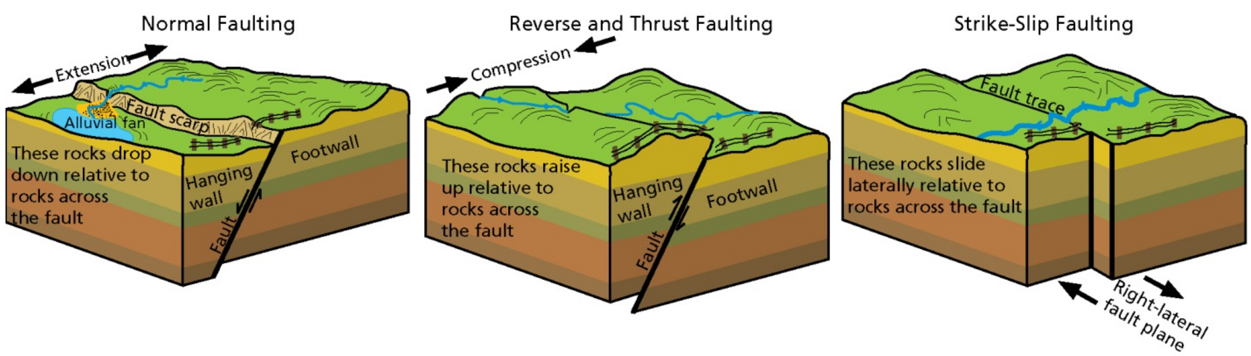

Figure 39. Types of faults. Basin and Range extension manifests itself as normal faults such as those that bound the Gila Hot Springs graben. In a normal fault, crustal extension (pulling apart) moves the hanging wall down relative to the footwall. In a reverse fault, crustal compression moves the hanging wall up relative to the footwall. A thrust fault is similar to a reverse fault but has a dip angle of less than 45°. Thrust faulting occurs at the western edge of the North American continent at the Cascadia subduction zone, for example. In a strike-slip fault, the relative direction of movement of the opposing plate is lateral. The well-known San Andres Fault that runs through Point Reyes National Seashore in California is a strike-slip fault. Graphic by Trista Thornberry-Ehrlich (Colorado State University).

Topographic features that characterize the Basin and Range are long, generally north–south-oriented, fault-bounded mountain ranges (horsts) separated by equally long, relatively flat-bottomed basins (grabens).

The most-significant recent seismic activity in the Gila Cliff Dwellings area occurred between September 1938 and October 1939 when nearly 400 recorded earthquakes rattled the Mogollon Mountains (Taggart and Baldwin 1982). Reports by residents and observers suggest that a few of the larger earthquakes had maximum intensities of VI on the Modified Mercalli Scale (a scale of I to XII), indicating that all people in the affected area felt the earthquake, some heavy furniture moved, some plaster fell, and buildings were slightly damaged (Taggart and Baldwin 1982; US Geological

Survey 2004). The cause of the Mogollon Mountains sequence is unknown, but a possible scenario is reactivation of displacement at depth on the faults mapped by Ratté and Gaskill (1975) in the Gila Wilderness (Taggart and Baldwin 1982).
Recent earthquakes have not been significant enough to cause offset in Quaternary (2.6 million years ago to the present) deposits (e.g., terrace gravels) (Leopoldt 1981). Furthermore, surficial faulting was not reported during the Mogollon Mountains sequence (Taggart and Baldwin 1982). However, rockfalls, which partially blocked access trails to the White Creek Ranger Station, were reported to have occurred during the Mogollon Mountains sequence (Taggart and Baldwin 1982).

Volcaniclastic rocks of Adobe Canyon (Tav) are an interesting and probable seismically related feature in the rock record at Gila Cliff Dwellings National Monument. These rocks consist of pumiceous sandstone (fig. 40) and are interlayered with Bearwallow Mountain Andesite (Tba) and the andesitic to dacitic lava flows of the Middle Fork (Tmd). The unit may represent liquefaction at the time of formation of the Gila Hot Springs graben (Ratté 2007). Today, liquefaction is a geologic hazard in places such as the San Francisco Bay area where earthquake shaking causes water-saturated sediment to temporarily lose strength and act as a fluid (US Geological Survey 2009a). The effects of liquefaction on the "built environment" can be extremely damaging. As a result of earthquake shaking, structures (e.g., buildings and bridges) built on sand that liquefies experience a sudden loss of support, resulting in drastic and irregular settling and structural damage. Obviously no buildings existed when these sandstone features were emplaced at the monument, but the connection to present-day hazards is instructive for how these features may have formed 25 million years ago. Furthermore, visitors, particularly those from California or other areas with liquefaction hazards, may find evidence of a seismic hazard in the rock record interesting.

Figure 40. Volcaniclastic rocks of Adobe Canyon. Sandstone dikes are an interesting feature in the rock record, which Ratté et al. (2014) mapped as volcaniclastic rocks of Adobe Canyon (Tav). These features, which are exposed at the parking lot for the Middle Fork trailhead, may represent liquefaction at the time of formation of the Gila Hot Springs graben. Liquefaction is a geologic hazard, particularly in "built environments," where earthquake shaking causes water-saturated sediment to temporarily lose strength and act as a fluid. US Geological Survey photograph and annotation by James C. Ratté.

In the chapter about earthquakes and seismic activity in *Geological 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. Braile (2009) provided a summary of these methods, including needed expertise, special equipment, cost, necessary personnel, and labor intensity, which monument staff may find useful for interpretation or monitoring purposes.

Geothermal Development

Geothermal resources in the Gila Cliff Dwellings area have been developed, for example at Doc Campbell's Post Vacation Center in the community of Gila Hot Springs. The community, which is about 6 km (4 mi) southeast of the monument, consists of 20 homes and house trailers. Doc Campbell's supplies domestic hot water and heating for a number of residences and other facilities (Ratté 2007). Geothermal waters at Gila Hot Springs come from an artesian well on the hill above the eastern bank of the West Fork, where the actual spring emerges. This well provides hot water to the community through a suspended pipeline over the river. Twenty buildings and two greenhouses are heated from this well that yields 74°C (165°F) water. The system, which was installed in 1987, uses an average of 288 L (76 gal) per minute. Four other systems in the community use spring water at 68°C (155°F), heating individual homes and two swimming pools. Campbell's system also supplies hot water to bathing ponds for use in a primitive RV park next to the river. The estimated installed capacity of the systems is 0.4 MWt with an annual energy use of 2.5 billion btu. The Campbells estimated their annual savings at $5,000 to $10,000, compared to the alternate available energy source of propane and firewood. With the high cost of propane (in 2002), their savings were closer to $25,000 per year (Witcher and Lund 2002).

Because of the cost savings, and to reduce the reliance on propane, monument managers are interested in using geothermal energy to heat (and cool) facilities, including the visitor center, maintenance shop, and six housing units. At the time of GRI scoping, Steve Riley, with the assistance of James C. Ratté, was working on a proposal for utilizing the geothermal waters (National Park Service 2008). If the geothermal water supply under the administrative area is sufficient (and geologic reconnaissance indicates it might be), the entire heating load could be transferred from propane to hot water. In addition, geothermal energy could drive a cooling system for the visitor center in summer (National Park Service 2008).

A research question related to geothermal resources is whether development of heat pumps would affect natural resources, specifically the amount and temperature of water in nearby hot springs (KellerLynn 2008). The NPS proposal includes funding for a professional geologic review and feasibility study of the area, as well as National Environmental Policy Act (NEPA) compliance (National Park Service 2008). Appendix B lists laws, regulations, and NPS policy associated with geothermal development.

Climate Change

Because of the potential disruption that climate change could cause to monument resources, including geologic features and processes, participants at the GRI scoping meeting in 2007 discussed the potential effects of climate change at Gila Cliff Dwellings National Monument. Participants identified the following as possible outcomes of climate change at the monument: (1) changes in flooding cycles, (2) increase in number and intensity of monsoons, and (3) increase in number and intensity of forest fires.

Davey et al. (2007) compiled a weather and climate inventory for the Sonoran Desert Network, including Gila Cliff Dwellings National Monument. The inventory documented past and present climate monitoring efforts, and provided information about broad-scale climatic factors and zones. The report documented 21 weather stations near and one within the monument. Significantly, the station within the monument, referred to as Gila Center, records real-time (approximately hourly) data. The Gila Center data cover 1998 to the present, with the exception of a gap in data during February 2003. Davey et al. (2007) also provided an initial evaluation of the adequacy of coverage for existing weather stations and made recommendations for improvements in monitoring weather and climate.

Monument managers may find these data useful in analyzing the trends in flooding cycles, determining changes in the number and intensity of monsoons, and forecasting weather as it affects the number and intensity of forest fires.

Managers at the monument may also be interested in *Climate Change Impacts in the United States* (Melillo et al. 2014). This state of knowledge report from the US Global Change Research Program summarized the science of climate change and the impacts of climate change on the United States, now and in the future. The report supplied a regional perspective on the Southwest, and identified decreasing surface water supply, increasing warming, drought, and insect outbreaks, and a variety of public health issues as significant concerns for population centers and iconic landscapes, such as the Sonoran Desert. Warming—for example, the period since 1950 has been hotter than any comparably long period in at least 600 years, and annual temperatures is projected to increase another 3°C to 5°C (5.5°F to 9.5°F) by 2070–2099—drives a decline in spring snowpack, soil moisture, and streamflow in the region (Garfin et al. 2014).

Refer to the National Park Service Climate Change Response Program (http://www.nps.gov/subjects/climatechange/index.htm, accessed 26 August 2014) and the “Additional References” section of this report for more information regarding climate change and the National Park System.

Geologic History

This section describes the chronology of geologic events that formed the present landscape of Gila Cliff Dwellings National Monument.

The geologic history of Gila Cliff Dwellings National Monument may be separated into five events:

1. Volcanic activity, primarily during the Oligocene Epoch (approximately 28 million years ago). Volcanism produced the Bloodgood Canyon Tuff (Tbc or Tbt; fig. 9), Bearwallow Mountain Andesite (Tya or Tba; fig. 9), and andesitic to dacitic lava flows of the Middle Fork (Tya or Tmd; fig. 9).
2. Basin and Range faulting. Beginning about 21 million years ago in in southwestern New Mexico, extension (pulling apart) of Earth's crust in the Basin and Range physiographic province caused grabens to drop down. The Gila Hot Springs graben is a manifestation of this activity in the monument area. The Gila Conglomerate (QTs or QTg; fig. 9) filled the graben as it was displaced along normal faults.
3. Valley incision. The development of Cliff Dweller Canyon began about 800,000 years ago. Valley alluvium and terrace gravels (Qag, or Qa and Qt [1, 2, 3]; see fig. 9) provide evidence of valley incision in the monunment.
4. Cave development. About 500,000 years ago, caves began to form in in Gila Conglomerate in Cliff Dweller Canyon and elsewhere.
5. Recent, deep circulation of groundwater along faults of the Gila Hot Springs graben. An outcome of circulation of groundwater deep in the Gila Hot Springs graben is the discharge of thermal waters in hot springs near the monument.

A "snapshot" of the geologic history of the monument occurs at the trailhead to the cliff dwellings (fig. 41). On the northern side of the parking lot, an exposed section of bedrock highlights the sequence of geologic events: The nearly white, 28-million-year-old Bloodgood Canyon Tuff underlies the dark-colored lava flows of the Bearwallow Mountain Andesite. These units represent Oligocene volcanism. Gila Conglomerate, a sedimentary rock composed of volcanic material, tops the sequence at this location, though the conglomerate is not visible from the parking lot. Gila Conglomerate filled the Gila Hot Springs graben, which formed as a result of Basin and Range extension and faulting. Rivers incised the basin-filling conglomerate and initiated cave formation. Caves in the conglomerate invited human use; people inhabited the caves before 500 CE and between about the 1270s and 1290s CE.

Volcanic Activity

Volcanic activity in the Mogollon–Datil volcanic field created the Bursum and Gila Cliff Dwellings calderas. Both calderas have been dated at 28 million years ago, but the Gila Cliff Dwellings caldera collapsed first.

Figure 41. Geologic section at Gila Cliff Dwellings National Monument. Bearwallow Mountain Andesite (Tba) overlies Bloodgood Canyon Tuff (Tbt) in an outcrop on the northern side of the parking lot for the trail to the cliff dwellings. US Geological Survey photograph by James C. Ratté.

Calderas are created when large volumes of pumice, ash, and pyroclastic material are rapidly erupted. The eruption of so much material, so quickly (over a period of days to weeks) from a subsurface magma chamber removes support, causing collapse of the roof into the chamber. As a result, a depression hundreds of meters deep and tens of kilometers across forms (Kelley 2012).

Gila Cliff Dwellings National Monument is on the southeastern edge of a slightly older and smaller—24 km (15 mi) in diameter—caldera that is adjacent to and east of the huge Bursum caldera. The Bursum caldera is 40 km (25 mi) in diameter and extends from Hells Hole on the West Fork of the Gila River to near Glenwood, New Mexico (fig. 10).

The Bursum and Gila Cliff Dwelling calderas are the remnants of two "supervolcanoes" (fig. 42)—a popularized term used to describe the largest volcanic eruptions on Earth (Trail of the Mountain Spirits National Scenic Byway 2010). Remnants of 13 supervolcanoes, or calderas, occur in the Mogollon–Datil volcanic field (Chapin et al. 2004).

More eruptions in the Mogollon–Datil volcanic field followed the Bursum and Gila Cliff Dwellings caldera-forming events, and filled these calderas with lava and pyroclastic debris. As a result, these huge volcanoes are no longer readily apparent on the landscape (National Park Service 1997). Exposures of Bloodgood Canyon Tuff, Bearwallow Mountain Andesite, and andesitic to dacitic lava flows of the Middle Fork are evidence of Oligocene volcanism at the monument.

Basin and Range Faulting and Basin Filling

Following the volcanic activity of the Oligocene Epoch, north–northwest-oriented extension faults related to the development of the Basin and Range physiographic

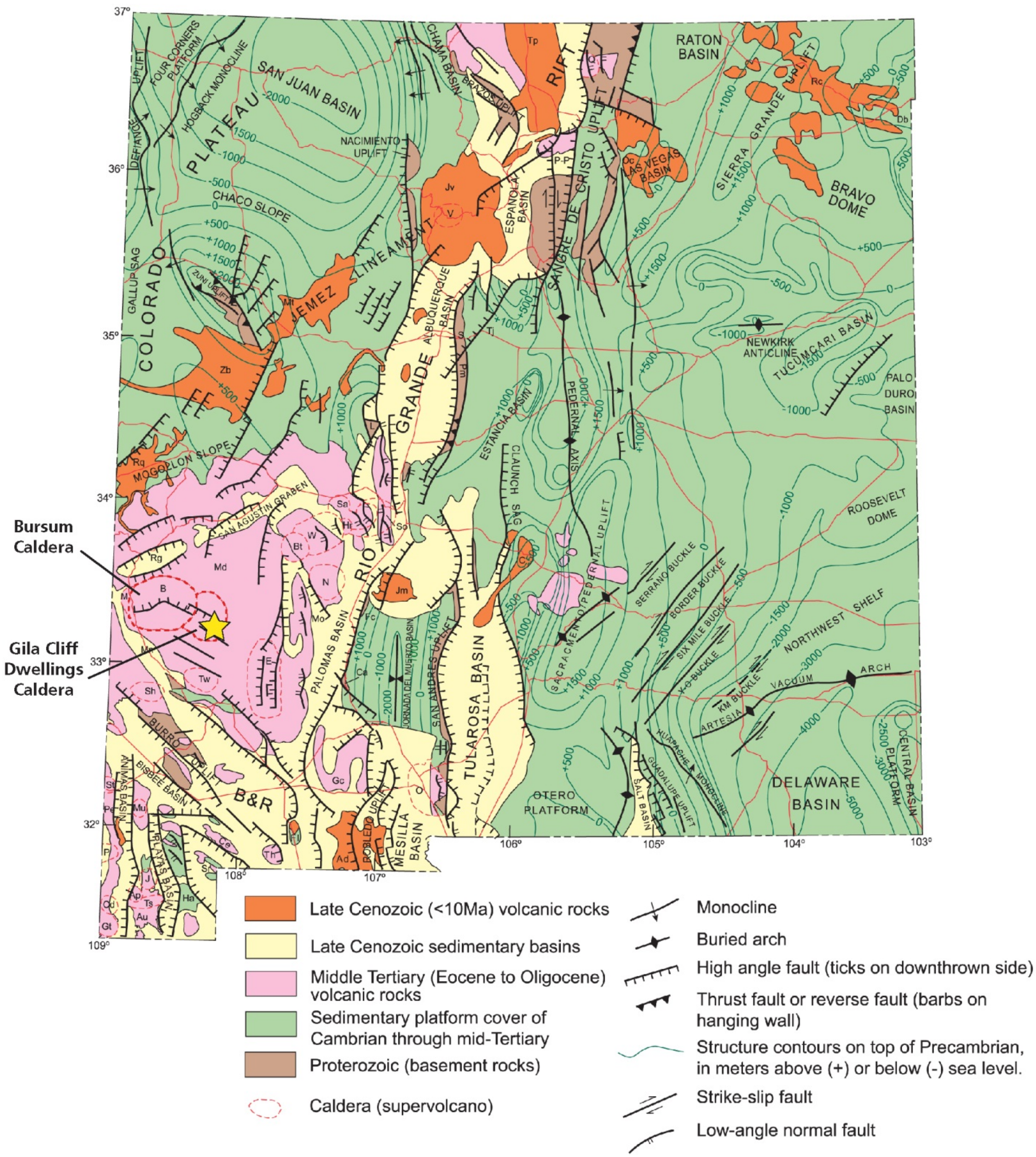

Figure 42. Supervolcanoes in New Mexico. A tectonic map of New Mexico shows the supervolcanoes (dashed red lines) of New Mexico. "Supervolcano" is a term used to describe the largest volcanic eruptions on Earth. The Bursum and Gila Cliff Dwellings calderas, which represent two supervolcanoes, are delineated and labeled on the map. Gila Cliff Dwellings National Monument is labeled with a star. Volcanic activity in the Gila Cliff Dwellings area peaked during the Oligocene Epoch. Pink areas on the map indicate volcanism at that time. The Bursum and Gila Cliff Dwellings calderas collapsed about 28 million years ago, with the Gila Cliff Dwellings caldera collapsing first. Original graphic from Wilks et al. (2005), modified with the permission of the New Mexico Geological Society by Rebecca Port (NPS Geologic Resources Division).

province cut across the Gila Cliff Dwellings area. These faults modified most of the volcanic features that were constructed during the Oligocene Epoch and account for the northwesterly orientation of the present-day physiography (Ratté 1989a, 1989b). Elston et al. (1973) proposed that Basin and Range faulting began about 21 million years ago in southwestern New Mexico. The Gila Hot Springs graben is a representative example of faulting at this time. The elongate graben is bounded by faults and is a primary structural feature in the area (see poster, in pocket).

Faulting was accompanied by deposition of Gila Conglomerate in local basins, such as the Gila Hot

Springs graben (Ratté 2008). The conglomerate, which contains pieces of older volcanic rock, filled the graben. As the basin subsided, material totaling 500–700 m (1,600–2,300 ft) thick (Krohn 1972; Ratté et al. 1979) was shed from the surrounding mountains and transported by streams into the graben. By the end of the Pliocene Epoch (2.6 million years ago) basin filling by the Gila Conglomerate had ceased (Hawley et al. 2000; Connell et al. 2005).

Valley Incision and Development of Cliff Dweller Canyon

Landscape evolution, dominated by basin filling and Basin and Range faulting during the Neogene Period (fig. 8), was replaced by incision and valley formation during the Pleistocene Epoch (2.6 million–11,700 years ago). This change occurred around 800,000 years ago (Connell et al. 2005) and is represented by valley alluvium and terrace gravels within the monument, where three terrace levels are readily apparent (see poster, in pocket).

According to Hawley et al. (2000), although tectonic activity clearly controlled the position of valleys and canyons in the region, it had less influence on incision. Rather, climate shifts during the Quaternary Period (past 2.6 million years) played the major geomorphic role in valley cutting. Extended intervals of accelerated valley deepening and widening appear to be associated with late Pliocene and Pleistocene glacial-pluvial ("wet") stages when the upper Gila drainage basin contributed much more sustained discharge than during interglacial-interpluvial ("dry") stages (Hawley et al. 2000).

Cave Development in Cliff Dweller Canyon

Ratté (2000) estimated that alcove formation began about 500,000 years ago. At that time the stream in Cliff Dweller Canyon was at the level of the caves, or approximately 60 m (200 ft) above the present stream. Fluvial processes initiated cave development as streams cut laterally into the side of the canyon (Ratté 2001). Cave Dweller Canyon is probably only centimeters to 0.6 m (2 ft) deeper today than when the caves were occupied in the late 1200s (James C. Ratté, US Geological Survey, emeritus geologist, written communication, 6 February 2013). Once started by stream action, groundwater sapping helped to enlarge the caves (fig. 22). Erosional processes such as spalling (fig. 35) continue increasing the size of the caves to the present day.

Groundwater Circulation

Hot springs in the Gila Cliff Dwellings area occur as a result of erosion of the landscape and deep circulation of groundwater along major faults in the deepest part of the Gila Hot Springs graben (Ratté 2008). The more pervious zones of the Bloodgood Canyon Tuff, and possibly the Bearwallow Mountain Andesite, serve as a geothermal reservoir (Witcher and Lund 2002; Ratté 2008). The Bloodgood Canyon Tuff, which is one of the most extensive units of the Mogollon–Datil volcanic field, is as much as 300 m (1,000 ft) thick west of the community of Gila Hot Springs (Witcher and Lund 2002). The unit is confined by Tertiary andesitic and latitic lava flows and overlain by the Gila Conglomerate (Witcher and Lund 2002). Northwest-oriented faults intersect the Bloodgood Canyon Tuff in the Gila Hot Springs graben and provide pathways or flow conduits that bring geothermal fluids to the surface.

Geothermal waters in the Gila Hot Springs graben have drawn people into the region throughout history and, probably, prehistory (Bradford 1992). Potentially, people have used the geothermal resources in various ways for thousands of years: people of the Mogollon culture farmed the valleys, perhaps utilizing the warm waters to prolong the growing season; Apache revered the springs for their medicinal and spiritual values; European settlers, trappers, miners, and soldiers enjoyed the benefits and comforts of the springs (Trail of the Mountain Spirits National Scenic Byway 2010). Today, residents of the village of Gila Hot Springs have developed the resource for heating, and other domestic and recreational uses, and hikers in Gila National Forest enjoy backcountry soaks in the undeveloped geothermal pools.

Geologic Map Data

This section summarizes the geologic map data available for Gila Cliff Dwellings National Monument. Posters (in pocket) display the map data draped over imagery of the park and surrounding area. The Map Unit Properties Tables (in pocket) summarize this report's content for each geologic map unit. Complete GIS data are included on the accompanying CD and are also 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 (the Quaternary Period). 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.agiweb.org/environment/publications/mapping/index.html, 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. The GRI digital geologic map product includes 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 digital geologic data set for Gila Cliff Dwellings National Monument. These sources also provided information for this report.

Ratté, J. C., and D. L. Gaskill. 1975 (reprinted 2002). Reconnaissance geologic map of the Gila Wilderness study area, southwestern New Mexico (scale 1:62,500). Geologic Investigations Series Map I-886. US Geological Survey, Washington, DC. http://pubs.er.usgs.gov/publication/i886 (accessed 30 September 2013).

Ratté, J. C., D. L. Gaskill, and J. R. Chappell. 2014. Geologic map of the Gila Hot Springs 7.5' quadrangle and the Cliff Dwellings National Monument, Catron and Grant counties, New Mexico (scale 1:24,000). Open-File Report OFR-2014–1036. US Geological Survey, Denver, Colorado. http://pubs.usgs.gov/of/2014/1036/ (accessed 7 August 2014).

GRI GIS Data

The GRI team implements a GIS data model that standardizes map deliverables. The data model is included on the enclosed CD and is also available at http://science.nature.nps.gov/im/inventory/geology/GeologyGISDataModel.cfm. 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 Gila Cliff Dwellings National Monument using data model version 2.1. The GRI Geologic Maps website, http://www.nature.nps.gov/geology/inventory/geo_maps.cfm, provides more information about GRI map products.

GRI digital geologic data are included on the attached CD and are available through the NPS Integrated Resource Management Applications (IRMA) portal (https://irma.nps.gov/App/Reference/Search?SearchType=Q). Enter "GRI" as the search text and select a park from the unit list.

The following components are part of the data set:

- A GIS readme file (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 (tables 1 and 2);
- Federal Geographic Data Committee (FGDC)–compliant metadata;
- An ancillary map information document (PDF) that contains information captured from source maps such as map unit descriptions, geologic unit correlation tables, legends, cross-sections, and figures;
- An ESRI map document (.mxd) that displays the digital geologic data; and
- A KML/KMZ version of the data viewable in Google Earth (tables 1 and 2).

Table 1. Geology data layers in the Gila Cliff Dwellings National Monument GIS data set (Ratté and Gaskill 1975; scale 1:62,500).

Data Layer	Google Earth Layer?
Geologic attitude observation localities	No
Geologic sample localities	No
Mine point features	No
Volcanic point features	No
Map symbology	No
Geologic line features	Yes
Caldera boundaries	Yes
Linear geologic units	Yes
Linear dikes	Yes
Faults	Yes
Alteration and metamorphic area boundaries	No
Alteration and metamorphic areas	Yes
Geologic contacts	Yes
Geologic units	Yes

Note: No poster was produced from these data.

Table 2. Geology data layers in the Gila Cliff Dwellings National Monument GIS data set (Ratté et al. 2014; scale 1:24,000).

Data Layer	On Poster?	Google Earth Layer?
Geologic cross section lines	No	No
Geologic sample localities	No	No
Geologic attitude observation localities	No	No
Mine point features	No	No
Geologic point features	Yes	No
Map symbology	No	No
Linear geologic units	Yes	Yes
Caldera boundaries	Yes	Yes
Hazard feature lines	Yes	Yes
Linear dikes	Yes	Yes
Faults	Yes	Yes
Deformation area boundaries	Yes	Yes
Deformation areas	Yes	Yes
Geologic contacts	Yes	Yes
Geologic units	Yes	Yes

GRI Map Posters

Posters of the GRI digital geologic data (Ratté et al. 2014) draped over a shaded relief or aerial image of the park and surrounding area are included with this report. Not all GIS feature classes are included on the posters (table 2). Geographic information and selected park features have been added to the posters. 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 for assistance locating these data.

Map Unit Properties Tables

The Map Unit Properties Tables list the geologic time division, symbol, and a simplified description for each of the geologic map units in the GRI GIS data. One table is for the data of Ratté and Gaskill (1975) and the other is for the data of Ratté et al. (2014). Following the structure of the report, the table summarizes the geologic features, processes, resource management issues, and 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 upon the information provided here. Please contact GRI 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 source map scales and the US National Map Accuracy Standards, geologic features represented in the geologic map data are horizontally within 32 m (105 ft) of their true location at scale 1:62,500 (Ratté and Gaskill 1975), and 12 m (40 ft) of their true location at scale 1:24,000 (Ratté et al. 2014).

Glossary

This section contains 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.*

aeolian. Describes materials formed, eroded, or deposited by or related to the action of wind.
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.
andesite. A volcanic rock characteristically medium dark in color and containing approximately 57%–63% silica and moderate amounts of iron and magnesium.
aquifer. A rock or sedimentary unit that is sufficiently porous to hold water, sufficiently permeable to allow water to move through it, and saturated to some level.
ash. Fine-grained material, less than 2 mm (0.08 in) across, ejected from a volcano.
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 flow. Streamflow supported by groundwater and not attributed to direct runoff from precipitation or snow melt.
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.
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.
caldera. A large, basin-shaped volcanic depression formed by collapse during an eruption.
chalcedony. A cryptocrystalline variety of quartz.
chert. An extremely hard sedimentary rock with conchoidal fracturing, consisting mostly of interlocking crystals of quartz.
clast. An individual constituent, grain, or fragment of a rock or unconsolidated deposit, produced by the mechanical or chemical disintegration of a larger rock mass.
clay. Minerals and sedimentary fragments that are less than 1/256 mm (0.00015 in) across.
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.
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.
cryptocrystalline. Describes a rock texture in which individual crystals are too small to be recognized or distinguished with an ordinary microscope.
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.

diatom. A microscopic, single-celled alga that secretes walls of silica, called frustules; lives in freshwater or marine environments.

diatomite. A light-colored, soft, silica-rich sedimentary rock consisting mostly of diatoms.

dike. A narrow igneous intrusion that cuts across bedding planes or other geologic structures.

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 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.

eutaxitic. Describes a stratified mineral deposit.

exfoliation. The spalling, peeling, or flaking of layers or concentric sheets from an exposed rock mass caused by a change in heat or a reduction in pressure when overlying rocks erode away.

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.

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.

felsic. Derived from ***fel***dspar +***si***li***c***a to describe an igneous rock having abundant light-colored minerals such as quartz, feldspars, or muscovite; also, describes those minerals.

fiamme. From "fiamma," meaning "flame" in Italian. Dark, vitric lenses in welded tuffs, averaging a few centimeters in length, perhaps formed by the collapse of fragments of pumice.

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.

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

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.

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

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

geothermal gradient. The rate of change of temperature with depth in the Earth.

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

groundmass. The finer grained and/or glassy material between the large crystals of an igneous rock. Also, sometimes used for the matrix of a sedimentary rock.

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

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.

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

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

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.

latite. A porphyritic volcanic rock with phenocrysts of plagioclase and potassium feldspar minerals in nearly equal amounts, little or no quartz, and a finely crystalline to glassy groundmass.

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

limestone. A carbonate sedimentary rock consisting of more than 95% calcite and less than 5% dolomite.

lineament. A linear topographic feature of regional extent that probably reflects an underlying crustal structure. Also, any extensive linear surface feature (e.g., fault lines, aligned volcanoes, and straight stream courses).

liquefaction. The transformation of loosely packed sediment into a more tightly packed fluid mass.

litharenite. A sedimentary rock, specifically sandstone, that consists of more than 25% fine-grained rock fragments, less than 10% feldspar, and less than 75% quartz, quartzite, or chert. Short for "lithic arenite."

lithic. Described a medium-grained sedimentary rock or pyroclastic deposit that contains abundant fragments of previously formed rocks.

mafic. Derived from ***ma***gnesium + ***f***err***ic*** (Fe is the chemical symbol for iron) to describe an igneous rock having abundant dark-colored, magnesium- or iron-rich minerals such as biotite, pyroxene, or olivine; also, describes those minerals.

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

matrix. The fine-grained material between coarse grains in an igneous or sedimentary rock. Also refers to rock or sediment in which a fossil is embedded.

megabreccia. A rock produced by brecciation on a very large scale; individual blocks are as much as 400 m (1,300 ft) long.

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.

mica. A group of abundant silicate (silicon + oxygen) minerals characterized by perfect cleavage, readily splitting into thin sheets. Examples include "biotite" and "muscovite."

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

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.

opal. A hydrous silicate (silcon + oxygen) mineral or mineral gel, $SiO_2 \bullet nH_2O$, consisting of packed spheres of silica and varying amounts of water (as much as 20% but usually 3%–9%).

orogeny. A mountain-building event.

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

paleontology. The study of the life and chronology of Earth's geologic past based on the fossil record.

Pangaea. A supercontinent that existed from about 300 million to about 200 million years ago and included most of the continental crust of the Earth, from which the present continents were derived by fragmentation and continental drift. During an intermediate stage of the fragmentation—between the existence of Pangaea and that of the present continents—Pangaea split into two large fragments, Laurasia in the Northern Hemisphere and Gondwana in the Southern Hemisphere.

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

pediment. A gently sloping, erosional bedrock surface at the foot of a mountain or plateau escarpment.

peperite. A breccialike material in sedimentary rocks, interpreted as a mixture of lava with sediment or as shallow intrusions of magma into wet sediment.

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

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

pluton. A deep-seated igneous intrusion.

pluvial. Describes a geologic process or feature resulting from rain.

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

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

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.

pyroxene. A group of silicate (silicon + oxygen) minerals composed of magnesium and iron with the general formula $(Mg,Fe)SiO_3$; characterized by short, stout crystals in hand specimens.

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

recharge. The addition of water to the saturated zone below the water table.

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.

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.

sanidine. A silicate (silicon + oxygen) mineral of the alkali feldspar group.

sapping. The natural process of erosion along the base of a cliff by the wearing-away of softer layers, commonly involving the weakening or rock by groundwater conducted along the contact between rock strata, and thus removing the support for the upper mass which breaks off into large blocks falling from a cliff face.

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.

seiche. An oscillation of a body of water in an enclosed or semi-enclosed basin that varies in period—depending on the physical dimensions of the basin—from a few minutes to several hours, and in height from several centimeters to a few meters; primarily caused by local changes in atmospheric pressure, aided by winds, tidal currents, and earthquakes.

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.”

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

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

silicate. A mineral group composed of silicon (Si) and oxygen (O) plus an element or elements, for example, quartz, SiO_2; olivine, $(Mg, Fe)_2SiO_4$; and pyroxene, $(Mg,Fe)SiO_3$; as well as the amphiboles, micas, and feldspars.

silicic. Describes a silica-rich igneous rock or magma.

silicic magma. Describes magma that contains more than 65% silica; generally viscous, gas-rich, and tends to erupt explosively.

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.

siltstone. A clastic sedimentary rock composed of silt-sized grains.

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.

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

sphene. A usually yellow or brown accessory mineral in granitic rocks and in calcium-rich metamorphic rocks; also called titanite.

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.

stratification. The accumulation or layering of sedimentary rocks as strata. Tabular, or planar, stratification refers to essentially parallel surfaces. Cross-stratification refers to strata inclined at an angle to the main stratification.

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 capture. The natural diversion of the headwaters of one stream into the channel of another stream having greater erosional activity. Synonymous with “stream piracy.”

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.

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.

subsidence. The sudden sinking or gradual downward settling of part of Earth’s surface.

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

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.

tuff. Consolidated or cemented volcanic ash and lapilli.

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

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.

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.

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.

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

wave base. The depth at which wave activity no longer stirs up sediments, usually at about 10 to 20 m (30 to 70 ft) below water level.

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

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

xenolith. A rock particle, formed elsewhere, entrained in magma as an inclusion.

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

Literature Cited

This section lists references cited in this report. Contact the Geologic Resources Division for assistance in obtaining these documents.

Anderson, K. M., G. J. Fenner, D. P. Morris, G. A. Teague, C. McKusick. 1986. The archeology of Gila Cliff Dwellings. Publications in Anthropology 36. Western Archeological and Conservation Center, Tucson, Arizona.

Anderson, R. S., and T. R. Van Devender. 1995. Vegetation history and paleoclimates of the coastal lowlands of Sonora, Mexico—pollen records from packrat middens. Journal of Arid Environments 30:295–306.

Bednarik, R. G. 2008. Cupules. Rock Art Research 25(1):61–100.

Bradford, J. E. 1992. Archeological survey, Gila Cliff Dwellings National Monument. Professional Papers 47. National Park Service, Division of Anthropology, Branch of Cultural Resources Management, Southwest Cultural Resources Center, Santa Fe, New Mexico.

Braile, L. W. 2009. Seismic monitoring. Pages 229–244 *in* R. Young and L. Norby, editors. Geological monitoring. Geological Society of America, Boulder, Colorado. http://www.nature.nps.gov/geology/monitoring/seismic.cfm (accessed 27 February 2012).

Buonasera, T. 2011. Final report on preliminary organic residue testing of several modified rock features at Gila Cliff Dwellings National Monument. Unpublished report. University of Arizona, School of Anthropology, Tucson, Arizona.

Cannon, S. H., and J. E. Gartner. 2005. Wildfire-related debris flow from a hazards perspective. Pages 363–385 (Chapter 15) *in* O. Hungr and J. Matthias, editors. Debris-flow hazards and related phenomena. Springer-Praxis Books in Geophysical Sciences, Chichester, UK.

Cannon, S. H., J. E. Gartner, M. G. Rupert, J. A. Michael, A. H. Rea, and C. Parrett. 2010. Predicting the probability and volume of postwildfire debris flows in the intermountain western United States. GSA Bulletin 122(1/2):127–144.

Chapin, C. E., W. C. McIntosh, and R. M. Chamberlin. 2004. The Late Eocene-Oligocene peak of Cenozoic volcanism in southwestern New Mexico. Pages 271–293 *in* G. H. Mack and K. A. Giles, editors. The geology of New Mexico: a geologic history. Special Publication 11. New Mexico Geological Society, Socorro, New Mexico.

Chapman, R. C., C. W. Gossett, and W. J. Gossett. 1985. Class II cultural resource survey, upper Gila water supply study, central Arizona project. Bureau of Reclamation, Phoenix, Arizona.

Cole, K. L. 1990. Reconstruction of past desert vegetation along the Colorado River using packrat middens. Palaeogeography, Palaeoclimatology, Palaeoecology 76:349–366.

Connell, S. C., J. W. Hawley, and D. W. Love. 2005. Late Cenozoic drainage and development in the southeastern Basin and Range of New Mexico, southeasternmost Arizona, and western Texas. Pages 125–150 *in* S. G. Lucas, G. S. Logan, and K. E. Zeigler, editors. New Mexico's ice ages. Bulletin 28. New Mexico Museum of Natural History and Science, Albuquerque, New Mexico.

Davey, C. A., K. T. Redmond, and D. B. Simeral. 2007. Weather and climate inventory, National Park Service, Sonoran Desert Network. Natural Resource Technical Report NPS/SODN/NRTR—2007/044. National Park Service, Fort Collins, Colorado. http://nature.nps.gov/publications/nrpm/nrtr.cfm#2007 (accessed 31 August 2012).

Davis, O. K., L. D. Agenbroad, P. S. Martin, and J. I Mead. 1984. The Pleistocene dung blanket of Bechan Cave, Utah. Pages 267–282 *in* H. H. Genoways and M. R. Dawson, editors. Contributions in Quaternary vertebrate paleontology: a volume in memorial of John E. Guilday. Special Publication 8. Carnegie Museum of Natural History, Pittsburgh, Pennsylvania.

Davis, J. M., and C. J. Hawkesworth. 1995. Geochemical and tectonics in the evolution of the Mogollon–Datil volcanic field, New Mexico, USA. Chemical Geology 119:31–53.

DeBano, L. F. 1981. Water repellant soils: a state-of-the-art. General Technical Report PSW-46. US Department of Agriculture, Forest Service, Pacific Southwest Forest and Range Experiment Station, Berkeley, California. http://www.fs.fed.us/psw/publications/documents/psw_gtr046/psw_gtr046.pdf (accessed 21 October 2013).

Doerr, S. H., R. A. Shakesby, and R. P. D. Walsh. 2000. Soil water repellency—its causes, characteristics and hydro-geomorphological significance. Earth-Science Reviews 15:33–65.

Douglas, M. W., R. A. Maddox, and K. Howard. 1993. The Mexican monsoon. Journal of Climate 6:1665–1677.

Elias, S. A., J. I. Mead, and L. D. Agenbroad. 1992. Late Quaternary arthropods from the Colorado Plateau, Arizona and Utah. Great Basin Naturalist 52:59–67.

Elston, W. E., M. Bikerman, and P. E. Damon. 1968. Significance of new K-Ar dates from southwestern New Mexico. Pages A-IV-1–A-IV-20 *in* Correlation and chronology of ore deposits and volcanic rocks. Annual progress report C00-689-100. US Atomic Energy Commission contract AT (11-1)–689. Arizona University, Geochronology Laboratories, Tucson, Arizona.

Elston, W. E., P. J. Coney, and R. C. Rhodes. 1970. Progress report on the Mogollon Plateau volcanic province, southwestern New Mexico: no. 2. Pages 75–86 *in* L. A Woodward, editor. Guidebook of the Tyrone–Big Hatchet Mountains–Florida Mountains region. Twenty-first field conference, October 29, 30, and 31, 1970. New Mexico Geological Society, Socorro, New Mexico.

Elston, W. E., and T. A. Netelbeek. 1965. Road log from Mimbres Valley to Silver City. Pages 167–174 *in* J. P. Fitzsimmons and C. Lochman-Balk, editors. Guidebook of southwestern New Mexico II. Sixteenth field conference, October 15, 16, and 17, 1965. New Mexico Geological Society, Socorro, New Mexico.

Elston, W. E., R. H. Weber, and F. D. Trauger. 1965. Road log from Silver City to junction of New Mexico Highways 61 and 90. Pages 45–62 *in* J. P. Fitzsimmons and C. Lochman-Balk, editors. Guidebook of southwestern New Mexico II. Sixteenth Field Conference, October 15, 16, and 17, 1965. New Mexico Geological Society, Socorro, New Mexico.

Elston, W. E., P. E. Damon, P. J. Coney, E. I. Smith, and M. Bikerman. 1973. Tertiary volcanic rocks, Mogollon-Datil province, New Mexico, and surrounding region: K-Ar dates, pattern of eruption, and periods of mineralization. Geological Society of America Bulletin 84:2259–2274.

Ferguson, H. G. 1927. Geology and ore deposits of the Mogollon mining district, New Mexico. Bulletin 787. US Geological Survey, Reston, Virginia. http://pubs.er.usgs.gov/publication/b787 (accessed 18 October 2013).

Findlow, F. J., and M. Bolognese. 1982. A preliminary analysis of prehistoric obsidian use within the Mogollon area. Pages 297–316 *in* P. H. Beckett and K. Silverbird, editors. Mogollon archaeology: proceedings of the 1980 Mogollon conference. Acoma Books, Ramona, California.

Forest Service. 1998. Gila National Forest, New Mexico, pocket guide; America's great outdoors. Gila National Forest, Silver City, New Mexico.

Forest Service. 2003. Geology of the Gila Cliff Dwellings with observations keyed to the sign posts of the Gila Cliff Dwellings trail guide. Version 4/20/03. Gila National Forest, Wilderness Ranger District, Mimbres, New Mexico.

Garfin, G., G. Franco, H. Blanco, A. Comrie, P. Gonzalez, T. Piechota, R. Smyth, and R. Waskom. 2014. Ch. 20: Southwest. Pages 462–486 *in* J. M. Melillo, T. C. Richmond, and G. W. Yohe, editors. Climate change impacts in the United States. The Third National Climate Assessment. US Global Change Research Program, Washington, DC. doi:10.7930/J08G8HMN. http://nca2014.globalchange.gov/downloads (accessed 26 August 2014).

Gilbert, G. K. 1875. Report on the geology of portions of New Mexico and Arizona. Pages 501–567 *in* G. M. Wheeler, editor. Report upon United States geographical surveys west of the one hundredth meridian. Volume 3. US Geological Survey, Washington, DC.

Harley, G. T. 1934. The geology and ore deposits of Sierra County, New Mexico. Bulletin 10. New Mexico School of Mines, Socorro, New Mexico.

Harp, E. L. 2000. Rock-fall hazard from cliffs above prehistoric dwellings. Memorandum to Doug Balou, site manager, Gila Cliff Dwellings National Monument, August 25, 2000. US Geological Survey, Central Geologic Hazards Team, Denver, Colorado.

Hawley, J. W. 1969. Notes on the geomorphology and late Cenozoic geology of northwestern Chihuahua. Pages 131–142 *in* D. A Cordoba, S. A. Wengerd, and J. Shomaker, editors. Guidebook of the border region. Twentieth field conference, October 23, 24, and 25, 1969. New Mexico Geological Society, Socorro, New Mexico.

Hawley, J. W., B. J. Hibbs, J. F. Kennedy, B. J. Creel, M. D. Remmenga, M. Johnson, M. M. Lee, and P. Dinterman. 2000. Trans-international boundary aquifers in southwestern New Mexico. Technical completion report–interagency contract X-996350-01-3. Prepared for US Environmental Protection Agency–Region 6 and International Boundary and Water Commission. New Mexico Water Resources Research Institute, New Mexico State University, Las Cruces, New Mexico. http://wrri.nmsu.edu/publish/otherrpt/swnm/DjVu/downl.html (accessed 8 June 2012).

Haynes, P. E. 1983. Zeolite minerals found near the Gila Cliff Dwellings National Monument. New Mexico Geology 5(4):84–85.

Highland, L. M. and P. Bobrowsky. 2008. The landslide handbook—A guide to understanding landslides. US Geological Survey, Reston, Virginia. Circular 1325. http://pubs.usgs.gov/circ/1325/ (accessed 26 August 2014).

Holmgren, C. A., M. C. Penalba, K. A. Rylander, and J. L. Betancourt. 2003. A 16,000 ^{14}C yr BP packrat midden series from the USA-Mexico borderlands. Quaternary Research 60:319–329.

Howard, A. D., and R. C. Kochel. 1988. Introduction to cuesta landforms and sapping processes on the Colorado Plateau. Pages 6–56 (Chapter 2) *in* A. D. Howard, R. C. Kochel, and H. E. Holt, editors. Sapping features of the Colorado Plateau: a comparative planetary geology field guide. Special Publication 491. National Aeronautics and Space Administration (NASA), Washington, DC.

Hunt, A. P., V. L. Santucci, J. S. Tweet, and S. G. Lucas. 2012. Vertebrate coprolites and other bromalites in National Park Service areas. Pages 343–354 *in* A. P. Hunt, S. G. Lucas, J. Milan, and J. A. Spielmann, editors. Vertebrate coprolite studies: status and prospectus. Bulletin 57. New Mexico Museum of Natural History and Science, Albuquerque, New Mexico.

Iverson, R. M. 1997. The physics of debris flows. Reviews of Geophysics 35:245–296.

KellerLynn, K. 2008. Geologic resources evaluation scoping summary, Gila Cliff Dwellings National Monument, New Mexico (June 9, 2008). National Park Service, Geologic Resources Division, Lakewood, Colorado. http://www.nature.nps.gov/geology/inventory/gre_publications.cfm (accessed 21 October 2013).

Kelley, S. A. 2012. Gila Cliff Dwellings National Monument. Online information. New Mexico Bureau of Geology and Mineral Resources, Socorro, New Mexico. http://geoinfo.nmt.edu/tour/federal/monuments/gila_cliff_dwellings/home.html (accessed 11 October 2012).

Kennedy, J. F., J. W. Hawley, and M. Johnson. 2000. The hydrogeologic framework of basin-fill aquifers and associated ground-water-flow systems in southwestern New Mexico—an overview. Pages 235–244 *in* T. F. Lawton, N. J. McMillan, and V. T. McLemore, editors. Southwest passage: a trip through the Phanerozoic. Fifty-first field conference, October 18–21, 2000. New Mexico Geological Society, Socorro, New Mexico.

King, W. E., J. W. Hawley, A. M. Taylor, and R. P. Wilson. 1971. Geology and ground-water resources of central and western Dona Ana County, New Mexico. Hydrologic Report 1. New Mexico Bureau of Mines and Mineral Resources, Socorro, New Mexico.

Knetchel, M. M. 1936. Geologic relations of the Gila Conglomerate, southeastern Arizona. American Journal of Science 31(182):81–92.

Krohn, D. N. 1972. Gravity survey of the Mogollon Plateau volcanic province. Thesis. University of New Mexico, Socorro, New Mexico.

Kuellmer, F. J. 1954. Geologic section of the Black Range at Kingston, New Mexico. Bulletin 33. New Mexico Bureau of Mines and Mineral Resources, Socorro, New Mexico.

Lambert, S. J. 1990. Cave deposit analysis for Gila Cliff Dwellings. Pages 245–253 (Appendix 6) *in* J. E. Bradford, author (1992). Archeological survey, Gila Cliff Dwellings National Monument. Professional Papers 47. National Park Service, Division of Anthropology, Branch of Cultural Resources Management, Southwest Cultural Resources Center, Santa Fe, New Mexico.

Letey, J. 2001, Causes and consequences of fire-induced soil water repellency. Hydrological Processes 15:2867–2875.

Leopoldt, W. 1981. Neogene geology of the central Mangas graben, Cliff-Gila area, Grant County, New Mexico. Thesis. University of New Mexico, Albuquerque, New Mexico.

Lindsay, E. 1978. Late Cenozoic vertebrate faunas, southeastern Arizona. Pages 269–275 *in* J. F. Callender, J. C. Wilt, R. E. Clemons, and H. L. James, editors. Land of Cochise, southeastern Arizona. Guidebook 29. New Mexico Geological Society, Socorro, New Mexico, in cooperation with Arizona Geological Society, Tucson, Arizona.

Lindsay, E., and N. T. Tessman. 1974. Cenozoic vertebrate localities and faunas in Arizona. Journal of the Arizona Academy of Science 9(1):3–24.

Lord, M. L., D. Germanoski, and N. E. Allmendinger. 2009. Fluvial geomorphology: monitoring stream systems in response to a changing environment. Pages 69–103 *in* R. Young and L. Norby, editors. Geological monitoring. Geological Society of America, Boulder, Colorado. http://nature.nps.gov/geology/monitoring/fluvial.cfm (accessed 13 June 2012).

Marvin, R. F., C. W. Naeser, M. Bickerman, H. H. Mehnert, and J. C. Ratté. 1987. Isotopic ages of post-Paleocene igneous rocks within and bordering the Clifton 1 × 2 degree quadrangle southern Arizona-New Mexico. Bulletin 118. New Mexico Bureau of Mines and Mineral Resources, Socorro, New Mexico.

McKenna, P. J., and J. E. Bradford. 1989. The TJ Ruin, Gila Cliff Dwellings National Monument. Professional Papers 21. National Park Service, Division of Anthropology, Branch of Cultural Resources Management, Southwest Cultural Resources Center, Santa Fe, New Mexico.

Mead, J. I., and L. D. Agenbroad. 1992. Isotope dating of Pleistocene dung deposits from the Colorado Plateau, Arizona and Utah. Radiocarbon 34:1–19.

Mead, J. I., L. D. Agenbroad, O. K. Davis, and P. S. Martin. 1986. Dung of *Mammuthus* in the arid Southwest, North America. Quaternary Research 25:121–127.

Mead, J. I., and A. M. Phillips. 1981. The Late Pleistocene and Holocene fauna and flora of Vulture Cave, Grand Canyon, Arizona. Southwestern Naturalist 26:257–288.

Melillo, J. M., T. C. Richmond, and G. W. Yohe, editors. 2014. Climate change impacts in the United States. The Third National Climate Assessment. US Global Change Research Program, Washington, DC. doi:10.7930/J0Z31WJ2. http://nca2014.globalchange.gov/downloads (accessed 26 August 2014).

Meyer, G. A. 2002. Fire in western conifer forests—geomorphic and ecologic processes and climatic drivers. Geological Society of America Abstracts with Programs 34:46.

Moody, J. A., and D. A. Martin. 2001a. Hydrologic and sedimentologic response of two burned watersheds in Colorado. Water-Resources Investigations Report 01-4122. US Geological Survey, Washington, DC. http://pubs.er.usgs.gov/publication/wri014122 (accessed 18 December 2012).

Moody, J. A., and D. A. Martin. 2001b. Initial hydrologic and geomorphic response following a wildfire in the Colorado Front Range. Earth Surface Processes and Landforms 26:1049–1070.

Morgan, G. S., and S. G. Lucas. 2003. Mammalian biochronology of Blancan and Irvingtonian (Pliocene and early Pleistocene) faunas from New Mexico. Pages 269–320 *in* L. J. Flynn, editor. Vertebrate fossils and their context: contributions in honor of Richard H. Tedford. Bulletin 279. American Museum of Natural History, New York, New York.

Morgan, G. S., and P. L. Sealey. 1995. Late Miocene and Pliocene (Hemphillian and Blancan) vertebrate fossils from the Gila Group, southwestern New Mexico. New Mexico Geology 17(2):30.

Morgan, G. S., and P. L. Sealey. 1997. Latest Hemphillian and Blancan vertebrate faunas from the Gila River valley of southwestern New Mexico. Abstract. Journal of Vertebrate Paleontology 17(supplement to number 3):65A.

Morgan, G. S., P. L. Sealey, S. G. Lucas, and A. B. Heckert. 1997. Pliocene (Latest Hemphillian and Blancan) vertebrate fossils from the Mangas Basin, southwestern New Mexico. Pages 97–128 *in* S. G. Lucas, J. W. Estep, T. E. Williamson, and G. S. Morgan, editors. New Mexico's fossil record 1. Bulletin 11. New Mexico Museum of Natural History and Science, Albuquerque, New Mexico.

Morgan, G. S., and R. S. White Jr. 2005. Miocene and Pliocene vertebrates from Arizona. Pages 115–136 *in* A. B. Heckert and S. G. Lucas, editors. Vertebrate paleontology in Arizona. Bulletin 29. New Mexico Museum of Natural History and Science, Albuquerque, New Mexico.

National Park Service. 1997. Geology of Cliff Dweller Canyon. Site bulletin after J. C. Ratté (1997). Geological setting of the Gila Cliff Dwellings. Unpublished Forest Service information. FShandout.jcr. Gila National Forest, Wilderness Ranger District, Mimbres, New Mexico.

National Park Service. 2008. Develop geothermal heating/heat pump cooling at Gila center. Project identification—PMIS 137913. Date created: 07/30/07. National Park Service, Project Management Information System, Washington, DC.

National Park Service. 2012a. Fire information. Online information (11 June 2012). Gila Cliff Dwellings National Monument, Silver City, New Mexico. http://www.nps.gov/gicl/fire-information.htm (accessed 13 June 2012).

National Park Service. 2012b. Seeps, springs & tinajas. Online information. Inventory and Monitoring Program, Sonoran Desert Network, Tucson, Arizona. http://science.nature.nps.gov/im/units/sodn/monitor/streams.cfm (accessed 13 June 2012).

National Park Service. 2012c. Streams. Online information. Inventory and Monitoring Program, Sonoran Desert Network, Tucson, Arizona. http://science.nature.nps.gov/im/units/sodn/monitor/streams.cfm (accessed 13 June 2012).

Nations, J. D., and J. J. Landye. 1984. Cenozoic plant and animal fossils of Arizona. Pages 7–35 *in* T. L. Smiley, J. D. Nations, T. L. Pewe, and J. P. Schafer, editors. Landscapes of Arizona: the geological story. University Press of America, Lanham, Maryland.

Neuendorf, K. K. E., J. P. Mehl Jr., and J. A. Jackson. 2005. Glossary of geology. Fifth edition. American Geological Institute, Alexandria, Virginia.

New Mexico Bureau of Mines and Mineral Resources. 1980. Pleistocene horse skull discovered. New Mexico Geology 2(1):29.

Nordby, L. V. 2011. Architecture at the Gila Cliff Dwellings: an interpretive summary. Technical Report 2011-2. Western Mapping Company, Tucson, Arizona.

Parent, L. 2004. Gila Cliff Dwellings National Monument. Western National Parks Association, Tucson, Arizona.

Pazzaglia, F. J. 2005. River responses to ice age (Quaternary) climates in New Mexico. Pages 115–124 *in* S. G. Lucas, G. S. Morgan, and K. E. Zeigler, editors. New Mexico's ice ages. Bulletin 28. New Mexico Museum of Natural History and Science, Albuquerque, New Mexico.

Pazzaglia, F. J., and J. W. Hawley. 2004. Neogene (rift-flank) and Quaternary geology and geomorphology. Pages 407–437 *in* G. H. Mack and K. A. Giles, editors. The geology of New Mexico: a geologic history. Special Publication 11. New Mexico Geological Society, Socorro, New Mexico.

Ransom, J. 2006. Hot springs near the Gila Visitor Center. Information sheet. US Department of Agriculture, Forest Service, Gila National Forest, Silver City, New Mexico.

Ratté, J. C. 1989a. Days 3 and 4: selected volcanic features of the western Mogollon–Datil volcanic field. Pages 68–85 *in* C. E. Chapin and J. Zidek, editors. Field excursions to volcanic terranes in the western United States. Memoir 46. New Mexico Bureau of Mines and Mineral Resources, Socorro, New Mexico.

Ratté, J. C. 1989b. Day 4: Bursum caldera: caldera-fill megabreccia and post-caldera magmatism at the western caldera margin in the Mogollon mining district. Pages 86–91 *in* C. E. Chapin and J. Zidek, editors. Field excursions to volcanic terranes in the western United States. Memoir 46. New Mexico Bureau of Mines and Mineral Resources, Socorro, New Mexico.

Ratté, J. C. 1997. Geological setting of the Gila Cliff Dwellings. Unpublished Forest Service information. FShandout.jcr. Gila National Forest, Wilderness Ranger District, Mimbres, New Mexico.

Ratté, J. C. 2000. Origin and development of the caves at Gila Cliff Dwellings National Monument, southwestern New Mexico. Abstract. New Mexico Geology 22(2):48–49.

Ratté, J. C. 2001. Gila Cliff Dwellings National Monument, southwestern New Mexico: origin and development of the caves; the role of exfoliation in the development of the caves. General interest publication (poster). US Geological Survey, Washington, DC. http://pubs.er.usgs.gov/publication/7000067 (accessed 21 October 2013).

Ratté, J. C. 2007. Road log: Sapillo Junction to Gila Cliff Dwellings National Monument via NM Highway 15. Unpublished draft. US Geological Survey, Denver, Colorado.

Ratté, J. C. 2008. The early Oligocene Copperas Creek volcano and geology along New Mexico Highway 15 between Sapillo Creek and Gila Cliff Dwellings National Monument, Grant and Catron counties, New Mexico. Pages 129–140 *in* G. Mack, J. Witcher, and V. W. Lueth, editors. Geology of the Gila Wilderness–Silver City area. Guidebook 59. New Mexico Geological Society, Fifty-ninth Annual Field Conference, October 23–25, 2008. New Mexico Geological Society, Socorro, New Mexico.

Ratté, J. C., and W. E. Brooks. 1983. Geologic map of the Mule Creek quadrangle, Grant County, New Mexico (scale 1:24,000). Miscellaneous Studies Map MF-1666. US Geological Survey, Washington, DC. http://ngmdb.usgs.gov/ngmsvr2/ILimagery/6000_7999/7484_1.sid (accessed 27 September 2012).

Ratté, J. C., and D. L. Gaskill. 1975 (reprinted 2002). Reconnaissance geologic map of the Gila Wilderness study area, southwestern New Mexico (scale 1:62,500). Geologic Investigations Series Map I-886. US Geological Survey, Washington, DC. http://pubs.er.usgs.gov/publication/i886 (accessed 30 September 2013).

Ratté, J. C., D. L. Gaskill, and J. R. Chappell. 2014. Geologic map of the Gila Hot Springs 7.5' quadrangle and the Cliff Dwellings National Monument, Catron and Grant counties, New Mexico (scale 1:24,000). Open-File Report OFR-2014–1036. US Geological Survey, Denver, Colorado. http://pubs.usgs.gov/of/2014/1036/ (accessed 7 August 2014).

Ratté, J. C., D. L. Gaskill, G. P. Eaton, D. L. Peterson, R. B. Stotelmeyer, and J. C. Meeves. 1979. Mineral resources of the Gila Primitive Area and Gila Wilderness, New Mexico. Bulletin 1451. US Geological Survey, Washington, DC. http://pubs.er.usgs.gov/publication/b1451 (accessed 21 October 2013).

Ratté, J. C., and R. B. Stotelmeyer. 1984. Gila Wilderness, New Mexico. Pages 810–813 *in* S. P. Marsh, S. J. Kropschot, and R. G. Dickinson, editors. Wilderness mineral potential: assessment of mineral-resource potential in US Forest Service lands studied in 1964–1984. Volume 2. Professional Paper 1300. US Geological Survey, Washington, DC. http://pubs.er.usgs.gov/publication/pp1300 (accessed 21 October 2013).

Reed, C. 2012. Documenting basins, mortars, and cupules, Gila Cliff Dwellings National Monument. Unpublished report. Gila Cliff Dwellings National Monument, Silver City, New Mexico.

Romkens, M. J. M., S. N. Prasad, and F. D. Whisler. 1990. Surface sealing and infiltration. Pages 127–172 (Chapter 5) *in* M. G. Anderson and T. P. Burt, editors. Process studies in hillslope hydrology. John Wiley and Sons, New York, New York.

Russell, P. 1992. Gila Cliff Dwellings National Monument: an administrative history. Professional Papers 48. National Park Service, Southwest Cultural Resources Center, Southwest Region, Division of History, Santa Fe, New Mexico. http://www.nps.gov/history/history/online_books/gicl/adhi/index.htm (accessed 14 August 2012).

Sandor, J. A. 1983. Soils at prehistoric agricultural sites in New Mexico. Dissertation. University of California, Berkeley, California.

Sandor, J. A., P. L. Gersper, and J. W. Hawley. 1986a. Soils at prehistoric agricultural terracing sites in New Mexico. I: site placement, soil morphology, and classification. Soil Science Society of America Journal 50:166–173.

Sandor, J. A., P. L. Gersper, and J. W. Hawley. 1986b. Soils at prehistoric agricultural terracing sites in New Mexico. II: organic matter and bulk density changes. Soil Science Society of America Journal 50:173–177.

Sandor, J. A., P. L. Gersper, and J. W. Hawley. 1986c. Soils at prehistoric agricultural terracing sites in New Mexico. III: phosphorus, selected micronutrients, and pH. Soil Science Society of America Journal 50:177–180.

Sanford, A. R., K. Lin, I. Tsai, and L. H. Jaksha. 2002. Earthquake catalogs for New Mexico and bordering areas: 1869–1998. Circular 210. New Mexico Bureau of Geology and Mineral Resources, Socorro, New Mexico.

Sanford, A. R., T. M. Mayeau, J. W. Schlue, R. C. Aster, and L. H. Jaksha. 2006. Earthquake catalogs for New Mexico and bordering areas II: 1999–2004. New Mexico Geology 28(4):99–109.

Santucci, V. L., J. P. Kenworthy, and A. L. Mims. 2009. Monitoring in situ paleontological resources. Pages 189–204 *in* R. Young and L. Norby, editors. Geological monitoring. Geological Society of America, Boulder, Colorado. http://www.nature.nps.gov/geology/monitoring/paleo.cfm (accessed 21 October 2013).

Schaafsma, P. 1980. Indian rock art of the Southwest. School of American Research, Santa Fe, New Mexico.

Seager, W. R. 1995. Geologic map of the southwest part of Las Cruces and northwest part of El Paso 1 × 2 degree sheets, New Mexico (scale 1:125,000). Geologic Map GM-60. New Mexico Bureau of Mines and Mineral Resources, Socorro, New Mexico.

Seager, W. R., R. E. Clemons, J. W. Hawley, and R. E. Kelley. 1982. Geology of the northwest part of Las Cruces 1 × 2 degree quadrangle (scale 1:125,000). Geologic Map GM-53. New Mexico Bureau of Geology and Mineral Resources, Socorro, New Mexico.

Shackley, M. S. 1988. Sources of archaeological obsidian in the Southwest: an archaeological, petrological, and geochemical study. American Antiquity 53(4):752–722.

Shackely, M. S. 1992. The upper Gila River gravels as an archaeological obsidian source region: implications for models of exchange and interaction. Geoarchaeology: An International Journal 7(4):315–326.

Shackley, M. S. 1995. Sources of archaeological obsidian in the greater American Southwest: an update and quantitative analysis. American Antiquity 60(3):531–551.

Shackley, M. S. 1996. An energy dispersive x-ray fluorescence (EDXRF) analysis of 15 obsidian artifacts from the adobe mound pueblo (LA 4902), a Salado site near Gila Cliff Dwellings, New Mexico. Report prepared for Centro de Investigaciones Arquelogicas, El Paso, Texas. University of California, Phoebe Hearst Museum of Anthropology and Department of Anthropology, Berkeley, California.

Smith, F. A., and J. L. Betancourt. 1998. Response of bushy-tailed woodrats (*Neotoma cinerea*) to late Quaternary climatic change on the Colorado Plateau. Quaternary Research 50:1–11.

Smith, F. A., J. L. Betancourt, and J. H. Brown. 1995. Evolution of body size in the woodrat over the past 25,000 years of climate change. Science 270:2012–2014.

Summers, W. K., and R. M. Colpitts. 1980. Preliminary appraisal of the hydrothermal-resource potential of the Gila Hot Springs area, Grant and Catron counties, New Mexico. Prepared for D. A. "Doc" and Ida Campbell, Gila Hot Springs, New Mexico. W. K. Summers and Associates, Inc., Socorro, New Mexico.

Taggart, J., and F. Baldwin. 1982. Earthquake sequence of 1938–1939 in Mogollon Mountains, New Mexico. New Mexico Geology 4(4):49–52.

Toomey, R. S. III. 2009. Geological monitoring of caves and associated landscapes. Pages 27–46 *in* R. Young and L. Norby, editors. Geological monitoring. Geological Society of America, Boulder, Colorado. http://nature.nps.gov/geology/monitoring/cavekarst.cfm (accessed 21 October 2013).

Trail of the Mountain Spirits National Scenic Byway. 2010. Geology of the Gila. Online information. Department of Transportation, Federal Highways Administration, National Scenic Byways Program, Washington, DC. http://tmsbyway.com/geology.php (accessed 11 October 2012).

Trauger, F. D. 1963. Geology and availability of ground water in the vicinity of Gila Cliff Dwellings National Monument, Catron County, New Mexico. Open-File Report 63-122 (January 1963). Prepared in cooperation with the United States National Park Service. US Geological Survey, Washington, DC. http://pubs.er.usgs.gov/publication/ofr63122 (accessed 21 October 2013).

Tweet, J. S., V. L. Santucci, and A. P. Hunt. 2012. An inventory of packrat (*Neotoma* spp.) middens in National Park Service areas. Pages 355–368 *in* A. P. Hunt, S. G. Lucas, J. Milan, and J. A. Spielmann, editors. Vertebrate coprolite studies: status and prospectus. Bulletin 57. New Mexico Museum of Natural History and Science, Albuquerque, New Mexico.

Tweet, J. S., V. L. Santucci, and J. P. Kenworthy. 2008. Paleontological resource inventory and monitoring, Sonoran Desert Network. Natural Resource Technical Report NPS/NRPC/NRTR—2008/130. National Park Service, Natural Resource Program Center, Fort Collins, Colorado.

US Geological Survey. 2004. The severity of an earthquake: the Modified Mercalli Intensity Scale. Online information. US Geological Survey, Denver, Colorado. http://pubs.usgs.gov/gip/earthq4/severitygip.html (accessed 24 October 2012).

US Geological Survey. 2009a. Online information. Earthquake glossary. US Geological Survey, Earthquake Hazards Program, Golden, Colorado. http://earthquake.usgs.gov/learn/glossary/?termID=111 (accessed 4 June 2012).

US Geological Survey. 2009b. New Mexico earthquake information. Online information. US Geological Survey, Earthquake Hazards Program, Golden, Colorado. http://earthquake.usgs.gov/earthquakes/states/index.php?regionID=31 (accessed 4 February 2011).

Van de Water, P. K., S. W. Leavitt, and J. L. Betancourt. 1994. Trends in stomatal density and $^{13}C/^{12}C$ ratios of *Pinus flexilis* needles during last glacial–interglacial cycle. Science 264:239–243.

Wachter, B. 1985. Bedrock deterioration and rockfall hazard at Gila Cliff Dwellings National Monument. Report of examination trip of September 11, 1985. Report to Ron Ice, National Park Service, Southwest Region, Santa Fe, New Mexico.

Wells, H. G. 1987. The effects of fire on the generation of debris flows in southern California. Pages 105–114 *in* J. E. Costa and G. F. Wieczorek, editors. Debris flows/avalanches—process, recognition, and mitigation. Geological Society of America Reviews in Engineering Geology 7:105–114.

Wieczorek, G. F., and J. B. Snyder. 2009. Monitoring slope movements. Pages 245–271 *in* R. Young and L. Norby, editors. Geological monitoring. Geological Society of America, Boulder, Colorado. http://nature.nps.gov/geology/monitoring/slopes.cfm (accessed 30 August 2012).

Wilks, M. E., R. M. Chamberlin, W. C. McIntosh, and R. F. Broadhead. 2005. Tectonic map. *On* side 2 of M. E. Wilks, compiler. New Mexico geologic highway map (scale 1:1,000,000). New Mexico Bureau of Geology and Mineral Resources, Socorro, New Mexico.

Witcher, J. C., and J. W. Lund. 2002. Gila Hot Springs. Geo-Heat Center (GHC) Quarterly Bulletin (December 2002) 23(4):25–29. http://geoheat.oit.edu/bulletin/bull23-4/art6.pdf (accessed 13 June 2012).

Wolberg, D. L. 1981. *Equus conversidens* from the Pleistocene of northeast Grant County, New Mexico. Pages 64–69 *in* annual report, volume 1979–80. New Mexico Bureau of Mines and Mineral Resources, Socorro, New Mexico.

Woods, S. W., A. Birkas, and R. Ahl. 2006. Spatial variability of soil hydrophobicity after wildfires in Montana and Colorado. Geomorphology 86:465–479.

Young, R., and L. Norby. 2009. Geological monitoring. Geological Society of America, Boulder, Colorado. http://nature.nps.gov/geology/monitoring/fluvial.cfm (accessed 13 June 2012).

Additional References

This section lists additional references, resources, and websites that may be of use to resource managers. Web addresses are valid as of August 2014. Refer to Appendix B for laws, regulations, and policies that apply to NPS geologic resources.

Geology of National Park Service Areas

NPS Geologic Resources Division (Lakewood, Colorado): 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/

NPS Resource Management Guidance and Documents

1998 National parks omnibus management act: http://www.gpo.gov/fdsys/pkg/PLAW-105publ391/pdf/PLAW-105publ391.pdf

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

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

NPS Natural resource management reference manual #77: http://www.nature.nps.gov/Rm77/

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.agiweb.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 Gila Cliff Dwellings National Monument, held on 14 November 2007, or the follow-up report writing conference call, held on 7 December 2011. 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.

2007 Scoping Meeting Participants

Name	Affiliation	Position
Sonya Berger	Gila Cliff Dwellings National Monument	Chief of Interpretation
Rick Harris	Chamizal and Gila Cliff Dwellings National Monuments	Superintendent
Bruce Heise	NPS Geologic Resources Division	Geologist
Katie KellerLynn	Colorado State University	Geologist/Research Associate
Dave Love	New Mexico Bureau of Geology and Mineral Resources	Geologist
James C. Ratté	US Geological Survey	Emeritus Geologist
Steve Riley	Gila Cliff Dwellings National Monument	Superintendent

2011 Conference Call Participants

Name	Affiliation	Position
Tim Connors	NPS Geologic Resources Division	Geologist/GRI Maps Coordinator
Bruce Heise	NPS Geologic Resources Division	Geologist/GRI Program Coordinator
Katie KellerLynn	Colorado State University	Geologist/Research Associate
Jason Kenworthy	NPS Geologic Resources Division	Geologist/GRI Reports Coordinator
James C. Ratté	US Geological Survey	Emeritus Geologist
Steve Riley	Gila Cliff Dwellings National Monument	Superintendent
Rod Sauter	Gila Cliff Dwellings National Monument	Chief of Interpretation

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 2014. Contact the NPS Geologic Resources Division for detailed guidance.

Resource	Resource-specific Laws	Resource-specific Regulations	2006 Management Policies
Caves and Karst Systems	**Federal Cave Resources Protection Act of 1988, 16 USC §§ 4301 – 4309** requires Interior/Agriculture to identify "significant caves" on Federal lands, regulate/restrict use of those caves as appropriate, and include significant caves in land management planning efforts. Imposes civil and criminal penalties for harming a cave or cave resources. Authorizes Secretaries to withhold information about specific location of a significant cave from a Freedom of Information Act (FOIA) requester. **National Parks Omnibus Management Act of 1998, 16 USC § 5937** protects the confidentiality of the nature and specific location of cave and karst resources. **Lechuguilla Cave Protection Act of 1993, Public Law 103-169** created a cave protection zone (CPZ) around Lechuguilla Cave in Carlsbad Caverns National Park. Within the CPZ, access and the removal of cave resources may be limited or prohibited; existing leases may be cancelled with appropriate compensation; and lands are withdrawn from mineral entry.	**36 CFR § 2.1** prohibits possessing/ destroying/disturbing…cave resources…in park units. **43 CFR Part 37** states that all NPS caves are "significant" and sets forth procedures for determining/releasing confidential information about specific cave locations to a FOIA requester.	**Section 4.8.1.2** requires NPS to maintain karst integrity, minimize impacts. **Section 4.8.2** requires NPS to protect geologic features from adverse effects of human activity. **Section 4.8.2.2** requires NPS to protect caves, allow new development in or on caves if it will not impact cave environment, and to remove existing developments if they impair caves. **Section 6.3.11.2** explains how to manage caves in/adjacent to wilderness.

Resource	Resource-specific Laws	Resource-specific Regulations	2006 Management Policies
Paleontology	**National Parks Omnibus Management Act of 1998, 16 USC § 5937** protects the confidentiality of the nature and specific location of paleontological resources and objects. **Paleontological Resources Preservation Act of 2009**, **16 USC § 470aaa *et seq.*** provides for the management and protection of paleontological resources on federal lands.	**36 CFR § 2.1(a)(1)(iii)** prohibits destroying, injuring, defacing, removing, digging or disturbing paleontological specimens or parts thereof. **Prohibition in 36 CFR § 13.35** applies even in Alaska parks, where the surface collection of other geologic resources is permitted. Regulations in association with 2009 PRPA are being finalized (May 2014).	**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. **Exception: 16 USC § 445c (c) – Pipestone National Monument enabling statute**. Authorizes American Indian collection of catlinite (red pipestone).	**36 CFR § 2.1** prohibits possessing, destroying, disturbing mineral resources…in park units. **Exception: 36 CFR § 7.91** allows limited gold panning in Whiskeytown. **Exception: 36 CFR § 13.35** allows some surface collection of rocks and minerals in some Alaska parks (not Klondike Gold Rush, Sitka, Denali, Glacier Bay, or Katmai) by non-disturbing methods (e.g., no pickaxes), which can be stopped by superintendent if collection causes significant adverse effects on park resources and visitor enjoyment.	**Section 4.8.2** requires NPS to protect geologic features from adverse effects of human activity.
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.

Resource	Resource-specific Laws	Resource-specific Regulations	2006 Management Policies
Park Use of Sand and Gravel	**Materials Act of 1947, 30 USC § 601** does not authorize the NPS to dispose of mineral materials outside of park units. **Exception:** 16 USC §90c 1(b) the non-wilderness portion of Lake Chelan National Recreation Area, where sand, rock and gravel may be made available for sale to the residents of Stehekin for local use as long as such sale and disposal does not have significant adverse effects on the administration of the National Recreation Area.	None applicable.	**Section 9.1.3.3** clarifies that only the NPS or its agent can extract park-owned common variety minerals (e.g., sand and gravel), and: -only for park administrative uses; -after compliance with NEPA and other federal, state, and local laws, and a finding of non-impairment; -after finding the use is park's most reasonable alternative based on environment and economics; -parks should use existing pits and create new pits only in accordance with park-wide borrow management plan; -spoil areas must comply with **Part 6** standards; and -NPS must evaluate use of external quarries. Any deviation from this policy requires a written waiver from the Secretary, Assistant Secretary, or Director.
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).

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.

NPS 349/126226, August 2014

National Park Service
US Department of the Interior

Natural Resource Stewardship and Science
1201 Oakridge Drive, Suite 150
Fort Collins, CO 80525

www.nature.nps.gov

EXPERIENCE YOUR AMERICA™