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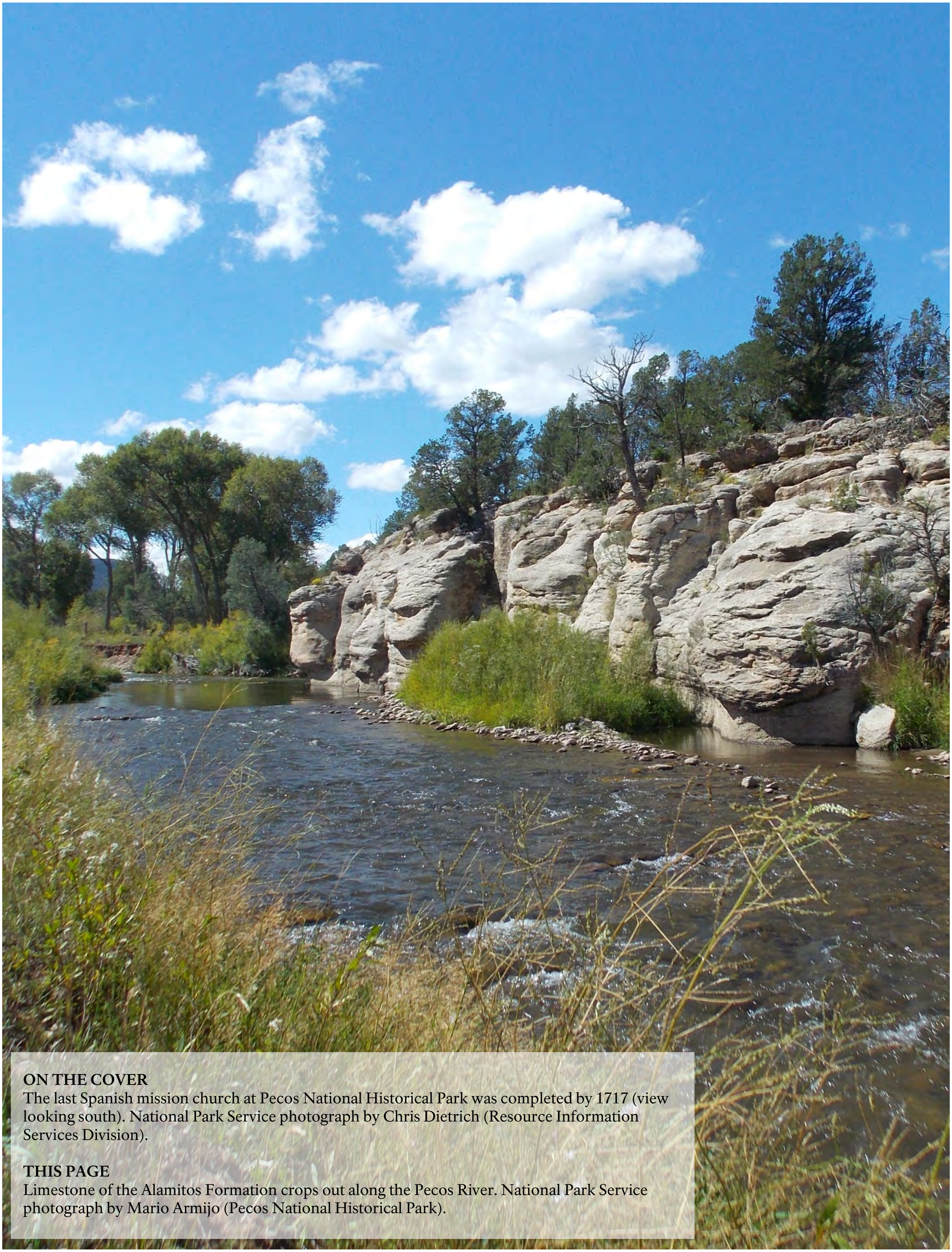
Natural Resource Stewardship and Science

Pecos National Historical Park

Geologic Resources Inventory Report

Natural Resource Report NPS/NRSS/GRD/NRR—2015/951



ON THE COVER
The last Spanish mission church at Pecos National Historical Park was completed by 1717 (view looking south). National Park Service photograph by Chris Dietrich (Resource Information Services Division).

THIS PAGE
Limestone of the Alamitos Formation crops out along the Pecos River. National Park Service photograph by Mario Armijo (Pecos National Historical Park).

Pecos National Historical Park

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Rebecca Port
National Park Service Geologic Resources Division
Geologic Resources Inventory
PO Box 25287
Denver, CO 80225

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

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

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Executive Summary

The Geologic Resources Inventory (GRI) is one of 12 inventories funded by the National Park Service (NPS) Inventory and Monitoring Program. The Geologic Resources Division of the NPS Natural Resource Stewardship and Science Directorate administers the GRI. This report synthesizes discussions from a scoping meeting for Pecos National Historical Park (New Mexico) on 28 March 2006 and a follow-up conference call on 11 April 2013, 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 Geologic Resources Inventory report was written for resource managers to support science-informed decision making, but it may also be useful for interpretation. The report was prepared using available geologic information. The NPS Geologic Resources Division did not conduct any new fieldwork in association with this report. Sections of the report discuss distinctive geologic features and processes within Pecos National Historical Park, 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 geologic map poster (in pocket) illustrates these data. The Map Unit Properties Table (in pocket) summarizes report content for each geologic map unit.

Pecos National Historical Park preserves more than 12,000 years of human history in north-central New Mexico, approximately 40 km (25 mi) southeast of Santa Fe. Within the park's roughly 2,700 ha (6,700 ac) are the remains of the Pecos Pueblo and other American Indian structures, Spanish colonial missions, a section of the Santa Fe Trail, dozens of circa-1700 Hispanic homestead sites, and the Glorieta Battlefield of the Civil War.

Today, the park consists of two units: the Pecos Unit and the Glorieta Unit. The Pecos Unit was created when the State of New Mexico set aside the ruins of the pueblo and mission as a state monument in 1935, and in 1965 President Lyndon Johnson signed a bill establishing the site as Pecos National Monument. For decades the monument occupied less than 160 ha (400 ac). In 1990 the park was renamed Pecos National Historical Park and expanded to include Forked Lightning Ranch, which completely surrounded the old monument. Later that same year, the Glorieta Unit, which includes the Cañoncito and Pigeon's Ranch subunits, was added to preserve the Civil War battlefield of Glorieta Pass.

Although primarily recognized for its cultural resources, a strong connection exists between the cultural and geologic landscapes of the park. The area now preserved as Pecos National Historical Park is on a high mountain pass (Glorieta Pass) that facilitated travel and trade between the high plains to the east and the Rio Grande valley to the west. The park is situated along the pass at an elevation of about 2,100 m (7,000 ft). To the north of the pass, near Taos for example, the Sangre de Cristo Mountains rise to 4,000 m (13,000 ft) above sea level. To the south Glorieta Mesa looms over the pass, rising to 2,304 m (7,559 ft) above sea level at its highest point. The geologic processes that formed Glorieta Pass paved the way for a rich and complex human history.

Geologic features and processes of particular significance for resource management at Pecos National Historical Park were identified during a 2006 GRI scoping meeting and a 2013 follow-up conference call. They include the following:

- Geologic Foundation. The GIS data show four major rock/deposit types: (1) Quaternary deposits (surficial units which includes artificial fill) less than 2 million years old, (2) Tertiary deposits (gravels and the Tesuque Formation) perhaps up to 10 million years old, (3) Mississippian through Triassic sedimentary rocks approximately 360 to 200 million years old, and (4) Precambrian igneous and metamorphic rocks more than 1.4 billion years old. Geologists are able to reconstruct the history of the land based on the structure and composition of these rocks and unconsolidated deposits.
- Sangre de Cristo Mountains. The Sangre de Cristo Mountains are a north–south-trending range that terminates in foothills at Pecos National Historical Park. The mountains tell a long history culminating in the most recent major geologic event of the area—the Laramide Orogeny—which raised the modern Rocky Mountains, including the Sangre de Cristo Mountains, between about 70 and 40 million years ago.
- Glorieta Pass. Glorieta Pass is a natural, high mountain pass carved through uplifted sedimentary rocks in the former location of the Pecos River. Today, tributaries of the Pecos River dissect the pass. The pass functions as a gateway between the Great Plains and the Rio Grande valley. It was critical to the cultural events that occurred in and near Pecos National Historical Park.
- Glorieta Mesa. Glorieta Mesa is an elevated, broad, flat-topped area of land on the south side of Glorieta Pass. It is a dominant feature of the park's viewshed. It showcases layer upon layer of sedimentary rocks. The steep, high escarpment of the mesa marks the boundaries of the Rocky Mountain, Great Plains, and Basin and Range provinces.

- Fluvial Features. Three streams flow through the units of the park: the Pecos River, Glorieta Creek, and Galisteo Creek. The topography of the area is largely a result of fluvial processes downcutting through uplifted land for the last 10 million years, since the late Miocene Epoch.
- Folds. Folds are curves or bends in originally flat rock strata. A series of folds occurs throughout the foothills of the Sangre de Cristo Mountains in Pecos National Historical Park.
- Faults. A fault is a fracture in rock along which movement has taken place. Four fault zones, three named faults, and nearly 400 smaller fault features were mapped in the vicinity of Pecos National Historical Park. These features are included in the GRI GIS data set. Two of the fault zones intersect the Cañoncito Subunit. Episodes of motion along the faults occurred more than a billion years ago (Proterozoic Era) and as recently as 5 million years ago (Neogene Period).
- Slope Movements. Slope movements are the downslope transfer of soil, regolith, and/or rock under the influence of gravity. Most slope movements in Pecos National Historical Park occur in relation to fluvial processes where stream erosion has created steep banks or has exposed bedrock along the Pecos River and Glorieta Creek. Slope movements may also occur on areas of disturbed land or as landslides.
- Paleontological Resources. Fossils are evidence of ancient life preserved in a geologic context. Petrified wood is the only fossil that has been documented in Pecos National Historical Park. However, discovery of more fossils is a strong possibility if field-based inventories were conducted because rock units mapped in the park are known to contain fossils in other locations.
- Caves and Karst Resources. Two caves, Baca Cave and "small cave," are in Pecos National Historical Park. Both caves are closed to the public. Most of the geologic units mapped in the park contain some amount of karst-forming carbonates such as limestone or dolomite. However, no karst topography is exposed in the park.
- Earthquakes. The area around Pecos National Historical Park has experienced some earthquakes in recent history. Since 1962—when earthquake monitoring began in the area—no earthquakes greater than a magnitude 3.5 have been recorded. Nearly 100 smaller earthquakes have been recorded.
- Geologic Resources in a Cultural Context. Geologic processes created the landscape on which cultural events played out in and near Pecos National Historical Park. Additionally, the inhabitants of Pecos Pueblo used geologic resources to produce ceramic pottery, bricks, and stone tools, and for building stone and glass.

Geologic issues of particular significance for resource management at Pecos National Historical Park were identified during a 2006 GRI scoping meeting and a 2013 follow-up conference call. They include the following:

- Fluvial Erosion. Accelerated fluvial erosion along the Pecos River and Glorieta Creek has led to narrowing of some stream channels, loss of riparian habitat, increased sediments in waterways, and threats to cultural resources.
- Water Quantity and Quality. Water quantity and quality issues in Pecos National Historical Park are related to geologic processes. In 2011, a section of Pecos River had temperature and turbidity (suspended sediment) levels that exceeded federal standards. This may be partially the result of disturbed lands with exposed surfaces from which excess sediments are eroded and transported into the river, and a lack native vegetation to provide shade to the waterways. Drought has reduced surface water quantity.
- Disturbed Land Restoration. Prior to establishment of Pecos National Historical Park, decades of livestock grazing, clearing of vegetation, and development by settlers created areas of disturbed land. These areas are especially susceptible to erosion because the naturally developed drainage has been altered and stabilizing vegetation has been removed. The National Park Service has already completed several restoration projects within the park. At the time of this report, park managers were seeking assistance to address the remaining disturbed lands.
- Abandoned Mineral Lands Hazards. Abandoned mineral lands present a variety of resource management issues such as visitor and staff safety and environmental quality of air, water, and soil. The Baca Mine, which was excavated into a natural cave—Baca Cave, is closed to the public to prevent injury to park visitors and impacts to cave resources. Remains of the Pecos Mine operation, located adjacent to the Pecos River and 26 km (16 mi) upstream from the park, may be adversely affecting water quality in the park by contributing heavy metals leached from waste piles into the Pecos River.
- Slope Movement Hazards and Risks. At the time of this report, slope movements (gravity-driven processes) were not affecting infrastructure in Pecos National Historical Park. Slumping does occur along river corridors and may be impacting backcountry areas and cultural resources.
- Paleontological Resource Inventory, Monitoring, and Protection. 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. A field-based survey could determine the source of petrified wood found in Pecos National Historical Park and the presence of additional fossils.
- Caves and Associated Landscape Management. The Federal Cave Resources Protection Act 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. Park staff monitors Baca Cave but a detailed cave management plan was not available at the time of this report.

- Land Subsidence. Subsidence has not been documented in Pecos National Historical Park but has the potential to occur. Geologic units that are mapped in the park have caused land subsidence in locations outside the park, where it occurred following the dissolution of limestone and gypsum rock.
- Earthquakes Hazards and Risks. Earthquakes have historically occurred in the area. However, the potential for damaging earthquakes is low.
- External Energy and Mineral Development. In the past, mining has taken place in and near Pecos National Historical Park, but current and future development is of limited concern to park resource managers. Based on regional seismic and exploration activities, the rock formations in the park are not believed to have commercially exploitable mineral deposits, and the various strata are not associated with oil and gas producing beds.
- Interpretation and Education. Interpreters at the park often include geology information in their talks and tours. Park staff should continue to work with local geologists and could request interpretation/education/outreach program assistance from the NPS Geologic Resources Division.

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 Geologic Resources Inventory 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/ (accessed 17 February 2015). The current status and projected completion dates of products are at http://www.nature.nps.gov/geology/GRI_DB/Scoping/Quick_Status.aspx (accessed 17 February 2015).

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Additional thanks to **Paul Varela** (Pecos National Historical Park) and **Mario Armijo** (Pecos National Historical Park) for providing photographs, **Vincent Santucci** (NPS Geologic Resources Division), **Justin Tweet** (NPS Geologic Resources Division) and **Erica Clites** (University of California Museum of Paleontology) for providing paleontological resource information, and **Katie KellerLynn** (Colorado State University) for providing the scoping summary. **Joel Wagner** (NPS Water Resources Division) provided photographs and information regarding Glorieta Creek restoration. **Trista Thornberry-Ehlrich** (Colorado State University) drafted some graphics used in this report.

Author

Rebecca Port (NPS Geologic Resources Division)

Review

Cheri Dorshak (NPS Pecos National Historical Park)
Jeremy Moss (NPS Pecos National Historical Park)
J. Michael Timmons (New Mexico Bureau of Geology and Mineral Resources)
Jason Kenworthy (NPS Geologic Resources Division)

Editing

Katie KellerLynn (Colorado State University)

Report Formatting and Distribution

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

Source Maps

New Mexico Bureau of Geology and Mineral Resources

GRI Digital Geologic Data Production

Georgia Hybels (Colorado State University)
Andrea Croskrey (NPS Geologic Resources Division)

GRI Geologic Map Poster Design

Rachel Yoder (Colorado State University)
Georgia Hybels (Colorado State University)

GRI Geologic Map Poster Review

Georgia Hybels (Colorado State University)
Rebecca Port (NPS Geologic Resources Division)
Jason Kenworthy (NPS Geologic Resources Division)

Geologic Setting and Significance

This section describes the regional geologic setting of Pecos National Historical Park, as well as summarizes connections between geologic resources and other park resources and stories.

Geologic Setting

Pecos National Historical Park is located at the junction of three major, and very different, physiographic provinces (fig. 1). Diverse geologic features occur in every direction. Most of the park is technically in the extreme southern part of the Rocky Mountain province, which extends into northern New Mexico with the Sangre de Cristo Mountains (fig. 1). They are a continuation of the Front Range, a major section of the Rocky Mountain system (Anderson 1956). The Great Plains province is to the east of the park (fig. 1). The portion of the plains adjacent to New Mexico is a remnant Tertiary landform occasionally interrupted by erosional and volcanic features (Trimble 1980). The Basin and Range province is to the south and west (fig. 1). It is a series of north–south-trending mountains separated by wide valleys. Cutting through the Basin and Range is the Rio Grande rift (fig. 1), a natural low area that native peoples and later settlers utilized (KellerLynn 2006). Spanning 1,000 km (600 mi)—from Chihuahua in northern Mexico through central New Mexico to Leadville in central Colorado —the Rio Grande rift is a major Basin-and-Range feature of crustal extension. The southern part of rift began to pull apart about 36 million year ago (Eocene Epoch; see fig. 4). In the north, rifting began in about 22 million years ago (Miocene Epoch) (Price 2010).

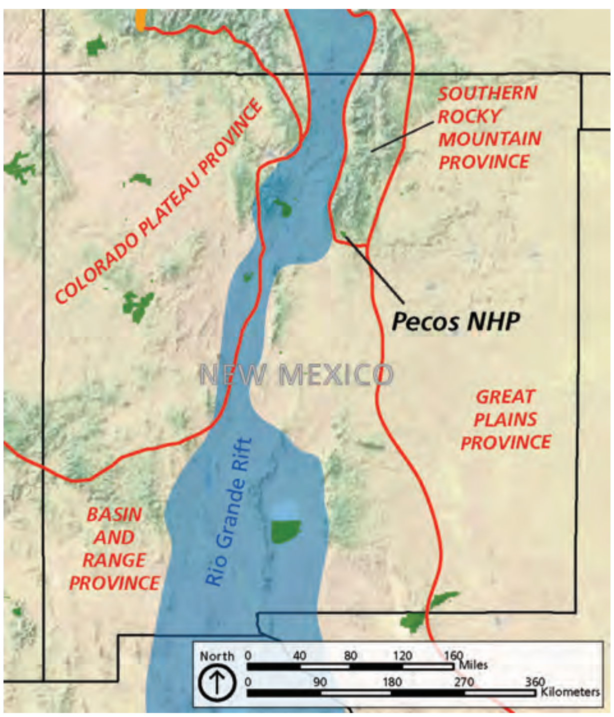

Figure 1. Physiographic province map of New Mexico. Pecos National Historical Park is at the junction of three major provinces, the Southern Rocky Mountain, Basin and Range (includes the Rio Grande Rift), and the Great Plains provinces. National Park Service graphic by Rebecca Port (NPS Geologic Resources Division).

The Pecos Unit and Pigeon's Ranch Subunit are both completely within the Rocky Mountain province. The Pecos Unit is bisected by the Pecos River (fig. 2). On the east side of the river, the Sangre de Cristo Mountains terminate in foothills. The west side of the river is broader and flatter. The Pigeon's Ranch Subunit is also in the foothills. It is bisected by ephemeral Glorieta Creek (fig. 2). The Cañoncito Subunit covers the very southern edge of the foothills and extends south over a small portion of Glorieta Mesa, which is in the Basin and Range province. The Cañoncito Subunit is bisected by ephemeral Galisteo Creek (fig. 2).

The general stratigraphy in the park is Paleozoic Era strata hundreds of millions of years old overlain by much younger alluvium (stream deposited sediment). The Paleozoic rocks of the Pecos River valley floor and Sangre de Cristo foothills consist of 320 million–270 million-year-old soft mudstones, sandstones, siltstones, limestones, and conglomerates of the Alamitos (**PNal**) and Sangre de Cristo formations (**PPNsc**) of the Pennsylvanian and early Permian (see figs. 3 and 4; and poster, in pocket). In many places the Sangre de Cristo Formation is buried up to 8 m (25 ft) beneath alluvium (**Qa**, **Qc**, **Qvf**, **Qt**, **QTg**; fig. 3). Most of the valley is covered by this Quaternary alluvial fill (see poster, in pocket), and a mantle of thick soil derived from weathering and decomposition. The pueblo, mission ruins, and visitor center are located on alluvial fill dating from when the site was occupied by the Pecos River whose channel has now migrated to the east. The underlying Pennsylvanian and Permian strata of the Alamitos and Sangre de Cristo formations crop out along the rivers, as do ancient igneous and metamorphic rocks, billions of years old (Precambrian time and/or Proterozoic Era; fig. 4).

To the southwest of the Pecos Unit and across Interstate 25 is the broad, elevated Glorieta Mesa. The mesa showcases 300 million–200 million-year-old sedimentary rocks (Permian to Triassic periods; figs. 3 and 4, and poster, in pocket). The Cañoncito Subunit is the only park unit whose boundary extends into part of the mesa.

Geologic Significance and Connections to Park Stories

Pecos Pueblo was built on a broad lowland area between the southernmost point of the Sangre de Cristo Mountains and the northern edge of the Glorieta Mesa. That this site was used by so many people and selected as

Figure 2. Pecos National Historical Park map. Pecos National Historical Park consists of two units, the Pecos Unit and the Glorieta Unit, which includes the Cañoncito and Pigeon's Ranch subunits. The Pecos Unit is bisected by the Pecos River, the Pigeon's Ranch Unit is bisected by Glorieta Creek, and The Cañoncito Unit is bisected by Galisteo Creek. National Park Service map, available at http://www.nps.gov/peco/index.htm (accessed 5 August 2014).

the location for the pueblo is due in large part to its physical setting, which resulted largely from geologic processes. The low area surrounding the pueblo served as a natural passage, or "gateway," between the Rio Grande valley and the high plains. In addition, this location receives solar heating from its southern exposure, is out of the way of cold air which commonly exits Pecos Canyon, has access to water, and has unobstructed views of the surrounding landscape. All of these qualities made the area ideal for settlement. Today, Interstate 25 traverses the pass within view of the historic pueblo and church. Together, these features "span centuries of southwest history as a testament to the role of geology and geographical location in human experience" (Bezy 1988, p. 18).

The Battle of Glorieta Pass, fought on 26–28 March 1862, has ties to the geologic landscape. It was a decisive battle of the Civil War, ultimately ending the war in the west. The purpose of the Glorieta Unit is to preserve and interpret this battle. In the valley of the Pigeon's Ranch Subunit battle lines were established, artillery was set up and skirmishing took place. On the north side of the valley, "Sharpshooter's Ridge" was utilized as a lookout (National Park Service 1993). During a skirmish, Union forces used the landscape to their advantage by traversing Glorieta Mesa and descending undetected into the Cañoncito Subunit, where they destroyed the Confederate supply camp (National Park Service 1993).

Geologic features and processes in the park are also linked to natural resources. For example, the sliding of sandstone slabs atop weathered mudstone of the Sangre de Cristo Formation creates crevices with a microclimate ideal for the growth of Douglas-fir (*Pseudotsuga menziesii*); fig. 5) (Mario Armijo, staff, Pecos National Historical Park, written communication, 24 September 2014). Also, owls have been documented near the cool, quiet, and protected cavities formed in the limestone rock of the Alamitos Formation (see "Caves and Karst Resources" section) (Mario Armijo, written communication, 24 September 2014).

Era	Period	Epoch	MYA*	Rock/Sediment Unit	Description
Cenozoic	Quaternary	Holocene	0.01–present	Alluvium (**Qa**)	Unconsolidated clay, silt, sand, and gravel filling valleys.
		Pleistocene	2.6–0.01	Colluvium, valley fill, and terrace deposits (**Qc**, **Qvf**, and **Qt**)	Talus, fine grained deposits in low-relief areas, and gravel-capped deposits associated with modern streams.
	"Tertiary" Neogene	Pliocene	66.0–2.6	Gravel (**QTg**)	Rounded Paleozoic and Proterozoic clasts deposited prior to the establishment of the modern Pecos River and Glorieta Creek channels.
		Miocene		Units of this age interval are not mapped within Pecos National Historical Park.	
	"Tertiary" Paleogene	Oligocene			
		Eocene			
		Paleocene			
Mesozoic	Cretaceous	Upper	100–66.0		
		Lower	145–100		
	Jurassic	Upper	164–145		
		Middle	174–164		
		Lower	201–174		
	Triassic	Upper	237–201	Chinle Group (**TRc**)**	Light gray to grayish orange or tan, conglomeratic sandstone, and reddish brown mudstone. Mapped in the Glorieta Unit (Cañoncito).
				Santa Rosa Formation (**TRs**, **TRsu**, **TRsm**, **TRsl**)	Sandstone, mudstone, and siltstone with limestone and chert conglomerate. Some crossbedding present. Fossil wood is common in the lower member. Mapped in the Glorieta Unit (Cañoncito)
		Middle	247–237	Moenkopi Formation (**TRm**)	Grayish red to purplish red sandstones, conglomerates, mudstones, and siltstones.
		Lower	252–247		
Paleozoic	Permian	Lopingian (Upper)	260–252	Artesia Formation (**Pa**)	Reddish brown sandstones, siltstones, and gypsum.
		Guadalupian (Middle)	272–260	San Andres Formation (**Psa**)	Light gray, thin-bedded, silty limestone and calcareous sandstone.
				Glorieta Sandstone (**Pg**)	Yellow to buff, thick-bedded quartz sandstones.
		Cisuralian (Lower)	299–272	Yeso Formation (**Py**)	Red thick-bedded mudstone; fine-grained sandstone; and buff, coarse-grained arkosic sandstone.
	Pennsylvanian	Upper	307–299	Sangre de Cristo Formation (**PPNsc**)	Brownish red to purple mudstone and buff to dark brown, arkosic conglomeratic sandstone.
				Alamitos Formation (**PNal**)	Gray, fossiliferous, marine limestone; coarse-grained arkosic sandstone; and dark gray to reddish shales.

Millions of years ago.

*****Nomenclature of the "Chinle Group" has changed over time. This report follows the "Chinle Group" nomenclature as per the GRI source maps published in 1997 and 2002 (see "Geologic Map Data" section). More recently, the US Geological Survey and some state surveys prefer the "Chinle Formation" nomenclature. Refer to the US Geological Survey GEOLEX for additional information (http://ngmdb.usgs.gov/Geolex/Units/Chinle_4997.html, accessed 9 April 2015).***

Figure 3. General stratigraphic column for Pecos National Historical Park. All of the units in the column above are mapped within the park's boundaries. Colors are standard colors approved by the US Geological Survey to indicate different time periods on geologic maps; they also correspond to the colors on the Map Unit Properties Table (in pocket). Age is in millions of years before present and indicates the time spanned by associated epoch or period. Rock/sediment units associated with those epochs or periods may not encompass the entire age range.

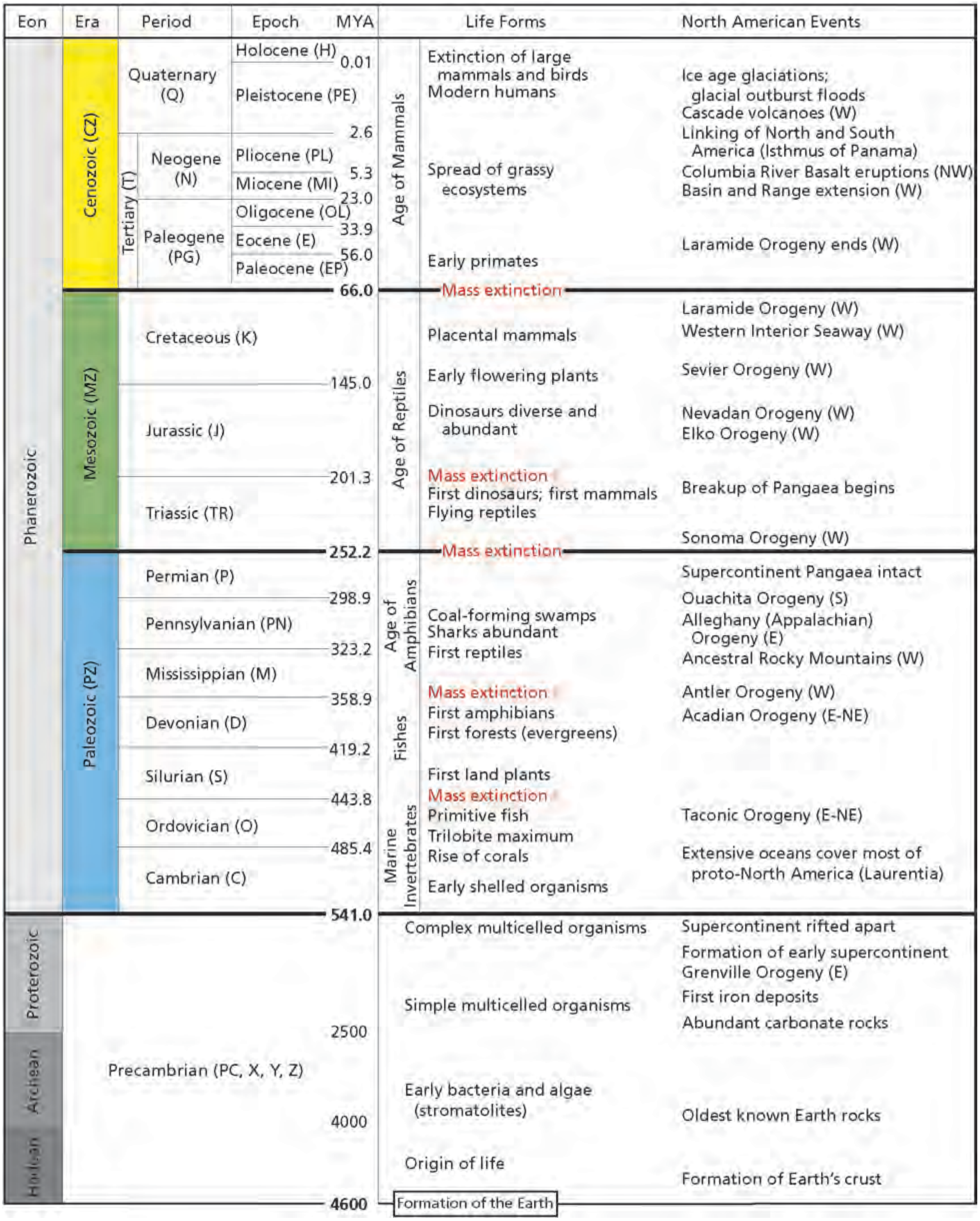

Figure 4. Geologic time scale. The divisions of the geologic time scale are organized stratigraphically, with the oldest divisions at the bottom and the youngest at the top. GRI map abbreviations for each time division are in parentheses. Compass directions in parentheses indicate the regional locations of events. Boundary ages are millions of years ago (MYA). National Park Service graphic using dates from the International Commission on Stratigraphy (http://www.stratigraphy.org/index.php/ics-chart-timescale; accessed 9 April 2015).

Figure 5. Douglas-fir microclimate. Sandstone slabs that have slid atop weathered mudstone of the Sangre de Cristo Formation (PPNsc) create cool, shaded crevices ideal for the growth of Douglas-fir. National Park Service photograph by Mario Armijo (Pecos National Historical Park).

Geologic Features and Processes

This section describes noteworthy geologic features and processes in Pecos National Historical Park.

The geologic landscape is the stage upon which episodes of natural and cultural history take place. It is important to recognize and interpret the geologic features and processes in Pecos National Historical Park because of their intrinsic value and the potential they have to impact other park resources and visitors.

During the 2006 scoping meeting (see KellerLynn 2006) and 2013 conference call, participants (see Appendix A) identified the following geologic features and processes:

- Geologic Foundation
- Sangre de Cristo Mountains
- Glorieta Pass
- Glorieta Mesa
- Fluvial Features
- Folds
- Faults
- Slope Movements
- Paleontological Resources
- Caves and Karst Resources
- Earthquakes
- Geologic Resources in a Cultural Context

Geologic Foundation

The GIS data shows four major rock/deposit types: (1) Quaternary deposits (surficial units, including artificial fill), (2) Tertiary deposits (gravels and the Tesuque Formation), (3) Mississippian through Triassic sedimentary rocks, and (4) Precambrian igneous and metamorphic rocks. Three of the four groups are composed of sedimentary rocks and deposits.

Sedimentary Rocks and Deposits

The three main types of sedimentary rocks are clastic, chemical, and organic. Clastic sedimentary rocks are the products of weathering, erosion, transportation, and deposition of rock fragments called "clasts." The clastic rocks and deposits in the GIS data were originally deposited by water in streams, seas, or lakes (Johnson 1969) or by hillslope processes.

Clastic sedimentary rocks are named after the size of clasts (table 1). Higher-energy depositional environments, such as fast-moving streams, deposit larger (heavier) clasts while transporting smaller (lighter) clasts. Where water moves slowly or is stagnant, such as in lakes, the water cannot transport even the smallest clasts and they are deposited. Wind also transports and deposits sand-sized or smaller clasts. Many clastic sedimentary rocks appear red, which is due to oxidation (rusting) of iron-bearing minerals in the sediments that make up the rock.

Clast size, types of fossils and minerals, and depositional structures within the sedimentary layers indicate the original depositional environment. Geologists can then determine the history of the land. The geologic history of the Pecos National Historical Park area is described in the "Geologic History" section of this report.

Chemical sedimentary rocks form when ions (microscopic particles of rock dissolved during chemical weathering) precipitate out of water. For example, carbonate rocks, such as limestone (calcium) or dolomite (calcium and magnesium) have a carbonate (CO_3^{2-}) ion.

Table 1. Clastic sedimentary rock classification and characteristics.

Rock Name	Clast Size	Depositional Environment	Example from GRI GIS data (unit symbol)
Conglomerate (rounded clasts, "gravel") or Breccia (angular clasts)	>2 mm (0.08 in) [larger]	Higher Energy	Gravel deposits (Qtg)
Sandstone	1/16–2 mm (0.0025–0.08 in)		Sangre de Cristo Formation (PPNsc)
Siltstone	1/256–1/16 mm (0.00015–0.0025 in)		Alluvium (Qa) and Valley Fill (Qvf) contain silt and clay, as well as other clast sizes.
Claystone	<1/256 mm (0.00015 in) [smaller]	Lower Energy	

Note: Claystones and siltstones can also be called "mudstone," or if they break into thin layers, "shale."

Organic sedimentary rocks are composed of organic remains (e.g., coal) or were produced by the physiological activities of an organism (e.g., accumulation of calcium carbonate shells of marine organisms to form limestone).

Quaternary Deposits

Quaternary deposits are the youngest units in the GRI GIS data set. They blanket the surface in a relatively thin layer of sediments that have accumulated mainly in valleys and on terraces. This category also includes artificial fill (**Qaf**), though no artificial fill is mapped in the park.

Quaternary alluvium, terrace deposits, and valley fill (**Qa**, **Qt**, and **Qvf**, respectively) line active perennial and ephemeral stream channels of the Pecos River, Glorieta Creek, and Galisteo Creek. These deposits were made by streams on river beds, flood plains, and on alluvial fans. They consist of unconsolidated clay, silt, sand, and gravel. Terrace deposits are typically capped by gravel.

Tertiary Deposits

Tertiary deposits in the GIS data include three units: the Galisteo Formation (**Tg**), gravel (**Tgv**) and the Tesuque Formation (**Tt**). These units are not mapped within the park.

The Galisteo Formation (**Tg**) tops hills north of Glorieta Pass and caps the Glorieta Mesa south of the park. It is a cross bedded sandstone interbedded with siltstone and mudstone layers.

The Tertiary gravel deposits (**Tgv**) form highs in the landscape, up to 460 m (1,500 ft) above the modern Pecos River (Read and Rawling 2002). The gravels top a ridge north of the Pigeon's Ranch Subunit and cap parts of the Glorieta Mesa, including Rowe Peak. Their colluvium mantles hillsides. The gravels consist of sedimentary, igneous, and metamorphic clasts derived from the variety of much older Precambrian and Paleozoic rocks exposed throughout the area.

The Tesuque Formation (**Tt**) is mapped in a small area southwest of the Cañoncito Subunit. It is arkosic sandstone, meaning that it is rich in feldspar (at least 25% of the rock). Arkosic sandstone forms from the weathering of feldspar-rich rocks such as granite. The weathered clasts must have been deposited rapidly under dry or cold conditions in order for the feldspar not to chemically weather into other minerals.

Mississippian through Triassic Sedimentary Rocks

The GRI GIS data set contains several types of Mississippian through Triassic sedimentary rocks representing a variety of depositional environments. The majority of the units that are mapped within Pecos National Historical Park belong to this group.

Mississippian sedimentary rocks are not mapped within the park. The Mississippian Espiritu Santo (**Mes**) and Tererro (**Mt**) formations are restricted to a small area in the southwest corner of the map area (see poster, in pocket). These units are limestones and dolomites, which were deposited in deep areas of prehistoric inland seas that once occupied the area.

Figure 6. Paleozoic arkosic sandstone. Arkosic sandstone of the Alamitos (PNal) and Sangre de Cristo (PPNsc) formations is exposed in Pecos National Historical Park. These rocks contain abundant feldspar and probably were derived from the weathering of Precambrian granite nearby. Note the red color indicating oxidation (rusting) of iron in the rock. National Park Service photograph by Mario Armijo (Pecos National Historical Park).

Two Pennsylvanian units are mapped within the park, the Alamitos (**PNal**) (inside cover) and Sangre de Cristo (**PPNsc**) formations. These units comprise the foothills of the Sangre de Cristo Mountains inside the park (see "Sangre de Cristo Mountains" section). These formations are made up of interbedded layers of limestone, mudstone, shale, and arkosic sandstone (fig. 6).

The three other Pennsylvanian units in the GRI GIS data are not mapped within the park. The La Posada Formation (**PNlp**) is limestone with banded chert along both sides of the Pecos River just north of the Lisboa Springs fault to the north of the Pecos Unit. The Sandia Formation (**PNs**) is arkosic sandstone with shale in the southwest portion of the map near the Mississippian units. It was deposited at the same time as the lower part of the La Posada Formation. Finally, the Madera Formation (**PNm**) is limestone mapped to the northwest of the park and was deposited at the same time as the Alamitos and upper part of the La Posada formations.

Permian through Triassic units comprise the layers of Glorieta Mesa. Refer to the "Glorieta Mesa" section of this chapter for more information about this landform and the geologic units.

Precambrian Igneous and Metamorphic Rocks

Precambrian igneous and metamorphic rocks are mapped mainly at higher elevations north and northwest of the park where they make up the core of the Sangre de Cristo Mountains (see poster, in pocket). The core of the mountains consists of igneous rocks such as granites, quartz monzonites, granodiorites, and metamorphic

Table 2. Simplified classification of igneous rocks.

Volcanic rock (extrusive, cooled on Earth's surface)	Relative % silica (Si/O)	Relative % mafic minerals (Fe/Mg)	Plutonic equivalent (intrusive, cooled beneath Earth's surface)	Example from GRI GIS data (unit symbol)
Rhyolite	Higher	Lower	Granite	Granite to Granitic Gneiss (Xgg)
Dacite			Granodiorite	Granodiorite (Xgr)
Andesite			Diorite	Diorite (Xd)
Basalt	Lower	Higher	Gabbro	Not present on map

"Higher" and "Lower" indicate relative percentages silica (Si/O) or mafic minerals containing iron (Fe) and magnesium (Mg).

rocks (Wilks 2005) which are approximately 1.7 billion to 1.4 billion years old (J. Michael Timmons, New Mexico Bureau of Geology and Mineral Resources, associate director for mapping programs, written communication, 24 November 2014). These core rocks are either granitic intrusions or the result of metamorphism of pre-existing sedimentary and igneous rocks (Clark 1966).

Within the park, Precambrian rocks are mapped only in the Cañoncito Subunit. Granite to granitic gneiss (**Xgg**) is the most extensively mapped of all the igneous and metamorphic rocks in the GRI GIS data (see poster, in pocket). Granite is an intrusive ("plutonic") igneous rock, which means that it formed from the cooling of molten material beneath Earth's surface. Volcanic rocks are formed when molten material cools at Earth's surface. Igneous rocks are classified by texture (grain size, shape, orientation), as well as the percentage of major minerals (quartz, alkali feldspar, and plagioclase) present in the rock (table 2). The granite in **Xgg** is medium to coarse grained and consists predominantly of the silicate minerals plagioclase, potassium feldspar, and quartz.

The gneiss in **Xgg** is metamorphosed granite. Rocks can be metamorphosed—altered—by high temperature and/or pressure to form metamorphic rocks. Metamorphism occurs mainly in two settings: contact or regional. Contact metamorphism is associated with the intrusion of molten material where rocks adjacent to the intrusion are "baked" by the high temperatures. Regional metamorphism is associated with large-scale tectonic events, such as mountain building orogenies. Gneiss forms due to regional metamorphism. The two major subdivisions of metamorphic rocks are foliated (minerals are aligned in "stripes") and non-foliated (minerals are oriented randomly). The gneiss in **Xgg** is foliated.

Sangre de Cristo Mountains

The Sangre de Cristo Mountains are the portion of the Rocky Mountains that terminates in Pecos National Historical Park. The foothills of the Sangre de Cristo Mountains cover the eastern half of the Pecos Unit, from the Pecos River east. The mountains tell the story of one of the last major geologic events to occur near the park—the Laramide Orogeny—which raised the Rocky Mountains (see "Geologic History" section).

The Sangre de Cristo Mountains are a north–south-trending range that extends from south-central Colorado to northern New Mexico. In New Mexico, the range is subdivided into the Taos Range on the west and the Cimarron Range on the east. The Taos and Cimarron ranges are separated by the high—approximately 2,510 m (8,240 ft) in elevation—and relatively flat Moreno Valley (fig. 7; Clark 1966). The park is at the southern end of the Taos Range.

The Cimarron Range is not as long as the Taos Range, extending less than 80 km (50 mi) south from the New Mexico-Colorado border. South of the Cimarron Range is the Ocate Plateau, a 23 million–3 million-year-old lava flow of the Miocene and Pliocene epochs (fig. 4; Wilks 2005).

The Taos Range continues beyond the length of the Cimarron Range and splits into two ridges separated by the Pecos River valley. The main ridge swings westward and southward to form the Santa Fe Range. The lesser, eastern leg of the split continues southward and is known as the East Range (other common names include the Las Vegas Range and Elk Mountain-Mora Range). Both ranges terminate in foothills just north of Glorieta Mesa and Interstate 25. The foothills of the East Range extend into the eastern portion of the Pecos Unit of the park and the foothills of the Santa Fe Range cross into the Pigeon's Ranch Subunit (fig. 7).

The foothills are mapped as the Pennsylvanian and Permian sedimentary Alamitos (**Pnal**) and Sangre de Cristo (**PPNsc**) formations (see poster, in pocket). They border the much higher igneous and metamorphic core of the mountain range. The layers of sedimentary rocks in the foothills dip away, to the south, from the higher mountains. Their slope is steepest north of the park, close to the core of the high mountains (Johnson 1969), and decreases to nearly horizontal as they approach the base of Glorieta Mesa.

Figure 7. Large scale physiographic map. Pecos National Historical Park is along Glorieta Pass, a naturally formed high mountain pass (white dashed line). The Pecos Unit of the park is in the Pecos River Valley. To the south of the park is the broad, elevated Glorieta Mesa and to the north of the park are the Sangre de Cristo Mountains. Note the low areas on either side of the pass—the Rio Grande valley and the high plains. For thousands of years humans traveling between these areas have passed through and inhabited the area now preserved by the park. National Park Service graphic by Rebecca Port (NPS Geologic Resources Division), using imagery by Esri, DigitalGlobe, GeoEye, i-cubed, USDA, USGS, AEX, Getmapping, Aerogrid, IGN, IGP, swisstopo, and the GIS User Community.

Glorieta Pass

Glorieta Pass is a natural, 50 km (30 mi) long, high mountain pass which parallels Interstate 25 from the Cañoncito Subunit to Starvation Peak (fig. 7). The pass separates the Sangre de Cristo Mountains from Glorieta Mesa. The elevation of the pass is at least 1,800 m (6,000 ft) in all places and reaches its highest point in Glorieta at 2,265 m (7,432 ft) above sea level (Johnson 1969). This high point marks the drainage divide between Galisteo Creek, which flows westward to join the Rio Grande at Santo Domingo Pueblo, and Glorieta Creek, which flows eastward to the Pecos River a few kilometers south of the town of Pecos (Bauer et al. 1995).

The Pecos River is responsible for carving most of Glorieta Pass by eroding relatively soft sedimentary rock between the more resistant rocks of the Sangre de Cristo Mountains to the north and Glorieta Mesa to the south (Johnson 1969; Bezy 1988).

The pass is the lowest passable route across the mountains and mesa and was critical to the cultural events that occurred in and near Pecos National Historical Park. It was a "gateway" for a great variety of people travelling between the Great Plains in the east and the Rio Grande valley in the west. Additionally, it was the site of the Civil War Battle of Glorieta Pass (see "Geologic Resources in a Cultural Context" section).

Glorieta Mesa

Glorieta Mesa is an elevated, broad, flat-topped, area of land south of Pecos National Historical Park (fig. 7). It is separated from Glorieta Pass by a steep escarpment (see "Glorieta Pass" section). Though only mapped within the Cañoncito Subunit, Glorieta Mesa is a dominant feature of the Pecos Unit's viewshed. It showcases layer upon layer of sedimentary rock formations (fig. 8). The steep, high escarpment of the mesa marks the boundary between the Rocky Mountain and the Basin and Range provinces.

Figure 8. Glorieta Mesa. The top photograph shows the rock sequence on Glorieta Mesa. This photograph was taken looking southwest from Pecos National Historical Park toward the second highest point on the mesa, Rowe Peak. The bottom photograph shows the view of the mesa taken from Old Denver Highway looking toward the highest point on the mesa, Cerro de Escobas. National Park Service photographs by Mario Armijo (Pecos National Historical Park).

The rocks of Glorieta Mesa (**PPNsc**, **Py**, **Pg**, **Psa**, **Pa**, **TRm**, **TRsl**, **TRsm**, **Trsu**, **TRs**) were originally deposited in horizontal layers between 300 million and 200 million years ago (Permian and Triassic periods; fig. 4). During the Laramide Orogeny (mountain-building event), the layers were tilted slightly—almost undiscernibly—to the south (Johnson 1969).

The uppermost (youngest) rock layer on the mesa is yellow sandstone—the Santa Rosa Formation (**TRs**, **Trsu**, **TRsm**, **TRsl**; see poster, in pocket). It caps the very top of the mesa including Cerro de Escobas, the highest point at 2,503 m (8,212 ft) above sea level (Johnson 1969). Although it is as much as 140 m (450 ft) thick elsewhere in New Mexico, the Santa Rosa Formation was eroded to about 15 m (50 ft) on top of the mesa (Johnson 1969).

Beneath the Santa Rosa Formation is the grayish red Moenkopi Formation (**TRm**, sandstone), which is underlain by the orange Artesia Formation (**Pa**, siltstone). The contact between the units is a disconformity—a break in deposition where the bedding planes above and below the contact are essentially parallel—which makes the units difficult to distinguish. Additionally, both of these formations are mostly covered by vegetation and talus. Thus, the map displays the units as one (**TRm+Pa**) in some locations.

The Glorieta Sandstone (**Pg**) is extremely hard and resistant to erosion and makes up the yellow sandstone bench that covers the main escarpment of the mesa. The Glorieta Sandstone is easily visible due to its distinctive light-yellow to grayish white color (fig. 8). It takes its name from the mesa due to its prominence.

The Yeso Formation (**Py**) is a reddish brown sandstone and siltstone beneath the Glorieta Sandstone.

The lowermost (oldest) unit of the mesa is the grayish red and gray sandstone of the Sangre de Cristo Formation (**PPNsc**) (fig.8). The formation is much thicker than it appears at Glorieta Mesa. Only the top fifth of this unit is visible; the remaining 4/5ths of the unit extends beneath the mesa and valley floor. The Sangre de Cristo formation is mapped in all units of the park.

Fluvial Features

Pecos National Historical Park is in the upper Pecos River watershed. Three streams flow through the units of the park. The perennial Pecos River flows south through the Pecos Unit. Glorieta Creek flows east through the Pigeon's Ranch Subunit and into the Pecos Unit of the park where it joins the Pecos River. Galisteo Creek flows west through the Cañoncito Subunit (fig. 2). Glorieta Pass is the drainage divide between Glorieta and Galisteo creeks.

Pecos River

The drainage basin for the upper Pecos River is between the Santa Fe Range and East Range of the southernmost Sangre de Cristo Mountains (fig. 7; Anderson 1956). The Pecos River flows south from the mountains and through Pecos National Historical Park. After exiting the park, the river follows the Glorieta Mesa escarpment for approximately 24 km (15 mi) before breaching the mesa at Glorieta Pass near San Jose (Johnson 1969).

The topography of the area today is largely a result of the Pecos River downcutting through uplifted land in the last

Figure 9. Terraces and alluvial gravel deposits. Terraces and gravel deposits mark the former path of the Pecos River. In the upper photograph, the Pecos River is not visible because it is deeply incised, but a terrace marking its former elevation can be seen on the gently sloping area between the two steep cliffs. In the lower photograph, rounded gravel and cobbles next to the river are evidence of the location of the former river bed. National Park Service photographs by Paul Varela (Pecos National Historical Park).

Figure 10. Limestone cliffs confine the Pecos River. The Pecos River has downcut through limestone of the Alamitos Formation (PNal) in some locations, exposing the rock as cliffs. The erosion resistant limestone confines the river to a narrow channel and prevents meandering. National Park Service photograph by Mario Armijo (Pecos National Historical Park).

5 million years, since the Miocene Epoch (fig. 4). Deep alluvial gravel deposits and a series of terraces mark the former course of the river (fig. 9; Bezy 1988; Perkins et al. 2005; Johnson et al. 2011). Lower, younger terraces were often sites for villages or agricultural fields (Bezy 1988). The river migrated eastward to its present location. Stream erosion along the Pecos River as well as Glorieta Creek is ongoing, exposing bedrock in some locations (fig. 10; Bezy 1988; see "Fluvial Erosion" section).

Folds

Folds are curves or bends in originally flat structures, such as rock strata, bedding planes, or foliation. The two primary types of folds are anticlines which are "A-shaped" or convex and synclines which are "U-shaped" or concave (fig. 11). Both types of folds can be overturned—tilted past vertical—by continued or future tectonic forces. Folds frequently "plunge" meaning the fold axis tilts. As bedrock is compressed, anticlines and synclines form adjacent to each other. A monocline is a step-like fold where dip steepens markedly over an otherwise gently dipping area.

The southeastern part of the Sangre de Cristo Mountains is characterized by large asymmetrical folds with the steepness of the fold increasing to the north, suggesting that the forces deforming the rocks increased to the north (Baltz and Bachman 1956). The majority of the folds developed during the Laramide Orogeny between about 70 million and 40 million years ago (see "Geologic History" section).

Seven named folds—two anticlines, two synclines, and three monoclines—are included in the GRI GIS data along with several unnamed smaller folds. They are all in the eastern half of the GIS data (see poster, in pocket). Anticlines and synclines alternate across the landscape with the occasional monocline between them. From north to south the named folds are the La Cueva

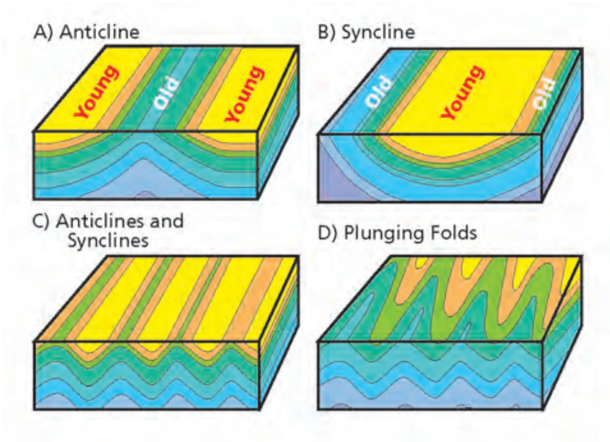

Figure 11. Block diagrams of two types of folds. The southeastern part of the Sangre de Cristo Mountains is characterized by large anticline (A) and syncline (B) folds. As bedrock is compressed, anticlines and synclines form adjacent to each other (C). Folds in the vicinity of Pecos National Historical Park frequently "plunge" (D, meaning the fold axis tilts) to the south or southwest.

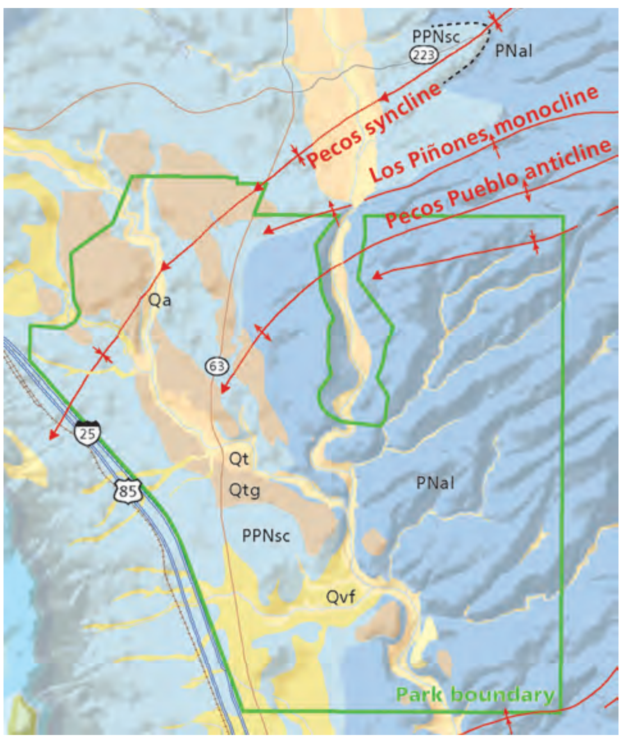

Figure 12. Map of folds in Pecos National Historical Park. Axes of the anticlines tend to be aligned with ridges whereas axes of synclines are aligned with valleys. This is especially apparent on the axis of the Pecos syncline where the contact between the Alamitos (PNal) and Sangre de Cristo (PPNsc) formations (black dashed line) in the valley is arched opposite the direction of plunge. For a description of units labeled on the map see the Map Unit Properties Table. National Park Service graphic by Rebecca Port (NPS Geologic Resources Division) using GRI GIS data. The base map was compiled from a variety of best available sources from several data providers, including the U.S. Geological Survey, National Park Service, DeLorme, NOAA, and ESRI.

anticline, Monastery monocline, Glorieta Mesa syncline, Pecos syncline, Los Piñones monocline, Pecos Pueblo anticline, and finally in the far southeast corner of the Pecos Unit, the Manzanita monocline. Several of these folds cross into the Pecos Unit, the only park unit containing mapped folds (fig. 12). The axis of the Pecos syncline crosses Glorieta Creek inside the park and goes directly through the original park boundary which includes the ruins.

The axes of the folds are generally oriented to the north or northwest, closely lining up with the ridges and valleys of the Sangre de Cristo foothills. Where the folds plunge (tilt away from horizontal), they do so to the south or southwest. Both the Alamitos (**PNal**) and Sangre de Cristo (**PPNsc**) formations are folded. The folds have some structural control over the location of valleys and ridges in the foothills. Axes of the anticlines tend to be aligned with ridges whereas axes of synclines are aligned with valleys. This is especially apparent on the axis of the Pecos syncline where the contact between the Alamitos (**PNal**) and Sangre de Cristo (**PPNsc**) formations in the valley is arched opposite the direction of plunge (fig. 12).

Faults

A fault is a fracture in rock along which movement has taken place. Faults are classified based on relative motion of rocks on either side of the fault plane. The three primary types of faults are normal, reverse, and strike-slip (lateral) (fig. 13).

All three types are mapped in the vicinity of Pecos National Historical Park, including four named fault zones (Agua Sarca, Borrego, Glorieta Mesa, and Picuris-Pecos), three named faults (Apache Canyon, Escobas, and Lisboa Springs), and nearly 400 unnamed fault features. A fault zone is a fault that is expressed as numerous small fractures and may be hundreds of meters wide. The Glorieta Mesa and Picuris-Pecos fault zones cut through the Cañoncito Subunit and intersect with the Borrego fault zone northwest of the subunit (Bauer et al. 1995). Faults are not mapped in the other two park units. As many as six or seven episodes of fault activation (and reactivation), ranging in age from Proterozoic (more than 541 million years ago) to Neogene (less than 23 million years ago), have been suggested (Bauer et al. 1995).

Agua Sarca Fault Zone

The Agua Sarca fault zone is a north–south-trending fault zone in the northwest corner of the extent of the GRI GIS data. It runs through granite and granitic gneisses (**Xgg**). Fault type and amount of displacement is not known.

Borrego Fault Zone

The Borrego fault zone parallels the Agua Sarca fault zone to the east and extends farther south crossing Interstate 25. The fault zone is primarily in granite and granitic gneiss (**Xgg**) although it bounds blocks of the Sangre de Cristo Formation (**PPNsc**) in the south section and blocks of the Madera Formation (**PNm**) in the north

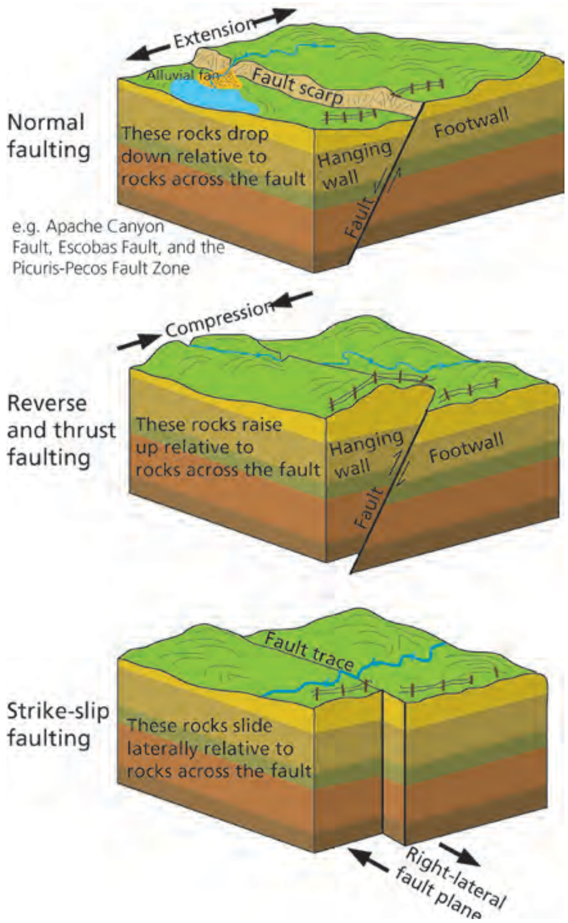

Figure 13. Schematic illustrations of fault types. Movement occurs along a fault plane. Footwalls are below the fault plane and hanging walls are above. In a normal fault, crustal extension (pulling apart) moves the hanging wall down relative to the footwall. In a reverse fault, crustal compression moves the hanging wall up relative to the footwall. A thrust fault is similar to a reverse fault, but has a dip angle of less than 45°. In a strike-slip fault, the relative direction of movement of the opposing plate is lateral. When movement across the fault is to the right, it is a right-lateral (dextral) fault, as illustrated above. When movement is to the left, it is a left-lateral (sinistral) fault. A strike-slip fault between two plate boundaries is called a transform fault. Graphic by Trista Thornberry-Ehrlich (Colorado State University).

section. Fault type and amount of displacement is not known.

Glorieta Mesa Fault Zone

The Glorieta Mesa fault zone is a north–south-trending zone where the fault type and amount of displacement is not known. It runs through the east side of the Cañoncito Subunit along the border of Glorieta Mesa where the fault's west side has moved down relative to its east side. The faults cut through all the layers of Glorieta Mesa (see "Glorieta Mesa" section).

The Picuris-Pecos Fault Zone

The Picuris-Pecos fault zone encompasses many north striking, high-angle faults that cutt rocks ranging in age from Proterozoic to Paleogene (Cather et al. 2011). The Picuris-Pecos fault is the main fault. The zone of faults has been traced for more than 84 km (52 mi), from the northern Picuris Mountains south of Taos to 24 km (15 mi) south of the Cañoncito Subunit. It may extend the entire length of the state if probable linkages to other fault zones are included (Cather et al. 2011).

The Picuris-Pecos fault zone consists of faults that exhibit both lateral (strik-slip motion) and vertical (normal motion) displacement. The Picuris-Pecos strike-slip fault exhibits 37 km (23 mi) of net right lateral (dextral) movement (Bauer and Ralser 1995; Cather et al. 2011). That is the largest displacement of any fault in the central and Southern Rocky Mountains (Cather et al. 2011) and is arguably the largest-displacement, strike-slip fault exposed in the state (Bauer and Ralser 1995). Vertical displacement is shown in the GRI GIS data north of the Cañoncito Subunit where granite and granitic gneiss (**Xgg**) has been displaced upward on the west side of the fault zone relative to the Madera Formation (**PNm**) to the east.

The timing of motion along the fault is unclear with considerable geologic evidence indicating the fault was repeatedly reactivated (Miller et al. 1963) over hundreds of millions of years from the Proterozoic Eon through the Neogene Period (fig. 4). Some movement most likely occurred during the time between the emplacement of the youngest granite about 1.4 billion years ago and the Pennsylvanian Period about 323 million years ago (Bauer and Ralser 1995; Chapin and Cather 1981). However, most of the movement occurred during the early Ancestral Rocky Mountain orogeny (beginning about 320 million years ago) and the Laramide Orogeny (between about 80 million and 40 million years ago) (Chapin and Cather 1981; Bauer and Ralser 1995; Kelley 1995; Erslev et al. 2004; Fankhauser 2005; Cather et al. 2008). Based on the age difference of rocks on opposing sides of the Picuris-Pecos fault it appears the fault was also active in the Cenozoic Era (66 million years ago to present). Later (23 million years ago to present), rift related faulting was concentrated near the Picuris-Pecos fault zone (Bauer et al. 1995). These periods of movement along the fault were determined using sedimentological evidence such as carbonate mud that filled fissures about 359 million–323 million years ago during the Mississippian Period (fig. 4; Bauer and Ralser 1995; Erslev et al. 2004; Fankhauser 2005; Cather et al. 2008).

Apache Canyon Fault

The Apache Canyon fault is an east–west striking normal fault to the north of the Cañoncito Subunit. The fault separates granite and granitic gneiss on the northern (upthrown) side of the fault from the younger Sangre de Cristo Formation (PPNsc) on the south side. The fault connects the Borrego and Picuris-Pecos fault zones.

Escobas Fault

The Escobas fault is a north-trending normal fault that runs through the east side of Glorieta Mesa and to the west of the Pecos Unit. It crosses Cerro de Escobas, the highest point on the mesa. The GIS data do not include strike and dip of the fault but it can be inferred from the map that the east side has moved up relative to the west. The Escobas fault cuts through all the layers of Glorieta Mesa (see "Glorieta Mesa" section).

Lisboa Springs Fault

The Lisboa Springs fault is an east–west-striking fault. Fault type and amount of displacement is not known. The fault runs through the Alamitos Formation (**PNal**). The north side has moved up relative to the south side. North of the Pecos Unit, the fault crosses the Pecos River. The west end of the Lisboa Springs fault lies between the El Molino Mills site and the tailings ponds to the south.

Slope Movements

Slope movements are the downslope transfer of soil, regolith, and/or rock under the influence of gravity. Soil creep, rockfalls, debris flows, and rock avalanches are common types of slope movements (fig. 14). These processes and the resultant deposits are also known as "mass wasting" and commonly grouped as "landslides."

Slope movements occur on time scales ranging from seconds to years. Slope movements create geologic hazards and associated risk in many National Park System units, including Pecos National Historical Park (see "Slope Movement Hazards and Risks" section).

Large-scale slope movements are not common in Pecos National Historical Park (KellerLynn 2006). Most slope movements in the park occur in relation to fluvial processes where stream erosion has created steep banks (fig. 15) or has exposed bedrock (fig. 16) along the Pecos River and Glorieta Creek. These movements are seldom hazardous. Slope movements may also occur on areas of disturbed land (see "Disturbed Lands Restoration" section).

Landslide deposits (**Ql**) are included on the GIS data and are predominantly composed of large sandstone blocks that moved downslope from cliffs during rockfalls. The only landslide mapped in the park extends slightly onto the north edge of the Cañoncito Subunit. The remaining landslide deposits are on Glorieta Mesa and associated with rockfalls originating from the Santa Rosa Formation (**TRs**).

Colluvium deposits (**Qc** and **Qca**) are also included on the GIS data. Colluvium refers to soil and rock fragments that were deposited at the base of gentle slopes by rainwash, sheetwash, or slow downhill movement. This

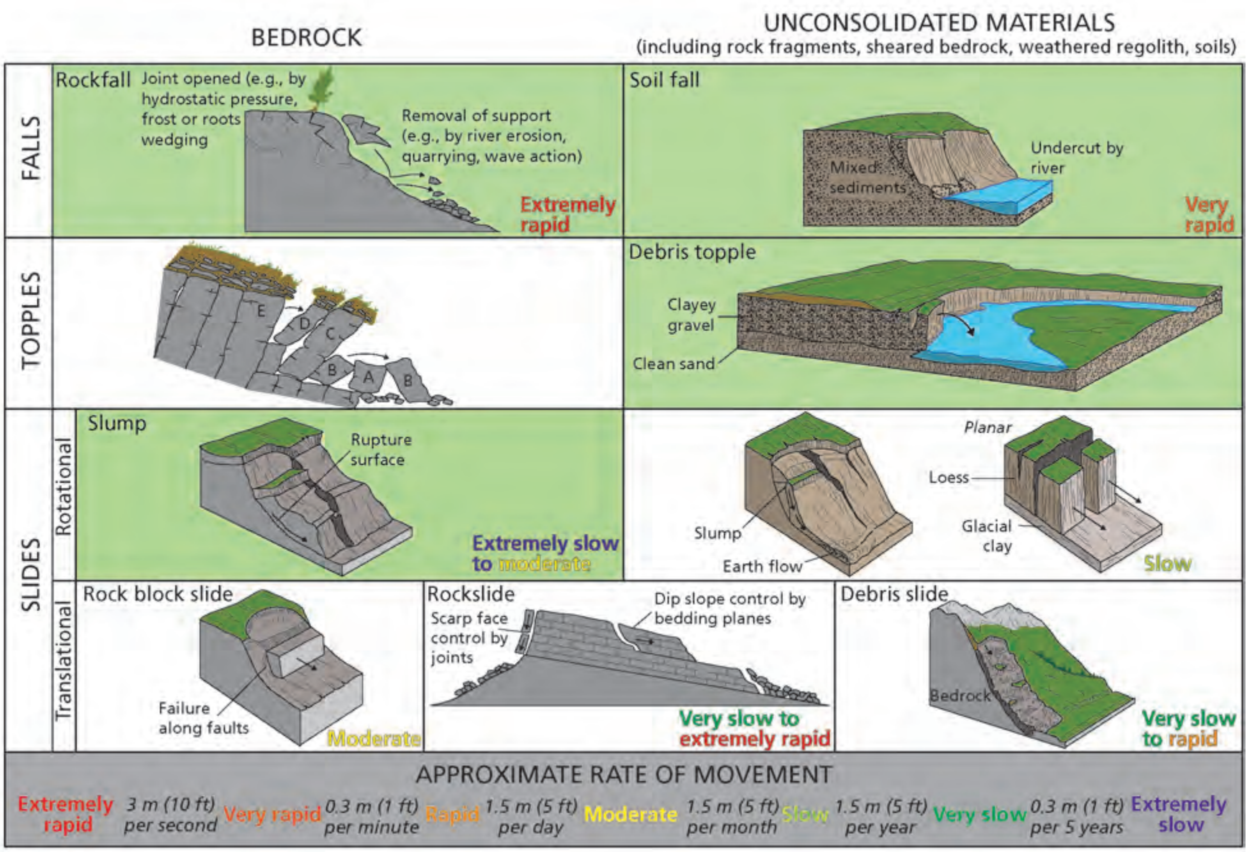

Figure 14. Schematic illustrations of selected slope movements. Different categories of slope movement are defined by material type, nature of the movement, rate of movement, and moisture content. Types of slope movements shaded in green have the potential to occur in Pecos National Historical Park. Graphic by Trista Thornberry-Ehrlich (Colorado State University) after Varnes (1978).

Figure 15. Steep banks along the Pecos River. Most slope movements in the park occur in relation to fluvial processes. A flood in September 2013 created these steep and unstable banks along the Pecos River. Slope movements such as slumps, soil fall, and debris topple occur here. National Park Service photograph by Paul Varela (Pecos National Historical Park).

Figure 16. Mudstone and sandstone cliffs. Most slope movements in the park occur in relation to fluvial processes. Where stream erosion has exposed bedrock, the rocks are susceptible to rockfalls and rockslides. In the above photos, underlying mudstone is eroding faster than overlying resistant, hard arkosic sandstone, further increasing susceptibility to slope movements. National Park Service photographs by Mario Armijo (Pecos National Historical Park).

differs from fluvial deposits which are deposited by continuously flowing water in channels like streams and rivers. Colluvium surrounds the base of Glorieta Mesa extending into both of the Glorieta Units. It also blankets some of the benches on the mesa itself. The GRI GIS data include one mapped deposit of colluvium at the southern end of the Pecos Unit on the east side of the Pecos River. This deposit consists of Tertiary gravels (**QTg**) eroded from upslope.

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 April 2015, 258 parks had documented paleontological resources in at least one of these contexts. The NPS Geologic Resources Division Paleontology website, http://www.nature.nps.gov/geology/paleontology/index.cfm (accessed 17 February 2015), provides more information.

Although fossils have been documented in only the Sangre de Cristo (**PPNsc**) and Alamitos (**PNal**) formations within Pecos National Historical Park, all of the geologic units mapped in the park, except for **Xgg**, have the potential to contain fossil resources (Vince Santucci, senior geologist, and Justin Tweet, guest scientist, NPS Geologic Resources Division, email communications, 22 January 2015). Two Pennsylvanian age geologic units mapped in the park, the Sangre de Cristo Formation (**PPNsc**) and the Madera Formation (**PNm**), are known to contain abundant fossils in locations outside of the park (Koch and Santucci 2003). Pennsylvanian strata in New Mexico include a great diversity of depositional environments and more than 1,250 reported fossil species (Kues 1982).

Staff members from Pecos National Historical Park have photographic documentation of marine invertebrate fossils from the Alamitos Formation (fig. 17). The fossils include marine bivalves, gastropods, crinoids, and ammonites.

Petrified wood was reported in the north and east sections of the Pecos Unit (Reed et al. 1999; Dand Jacobs, personal communication, cited in Johnson et al. 2011, p. 46). The geologic source of the wood was not mentioned in those publications, but it may have come from the lower member of the Triassic Santa Rosa Formation (**TRsl**) where Read and Rawling (2002) documented fossil wood. The Santa Rosa Formation is only mapped in the Cañoncito Subunit of the park. It is mapped on Glorieta Mesa where the wood may have eroded out of the rock and been brought down to the Pecos Unit by natural processes.

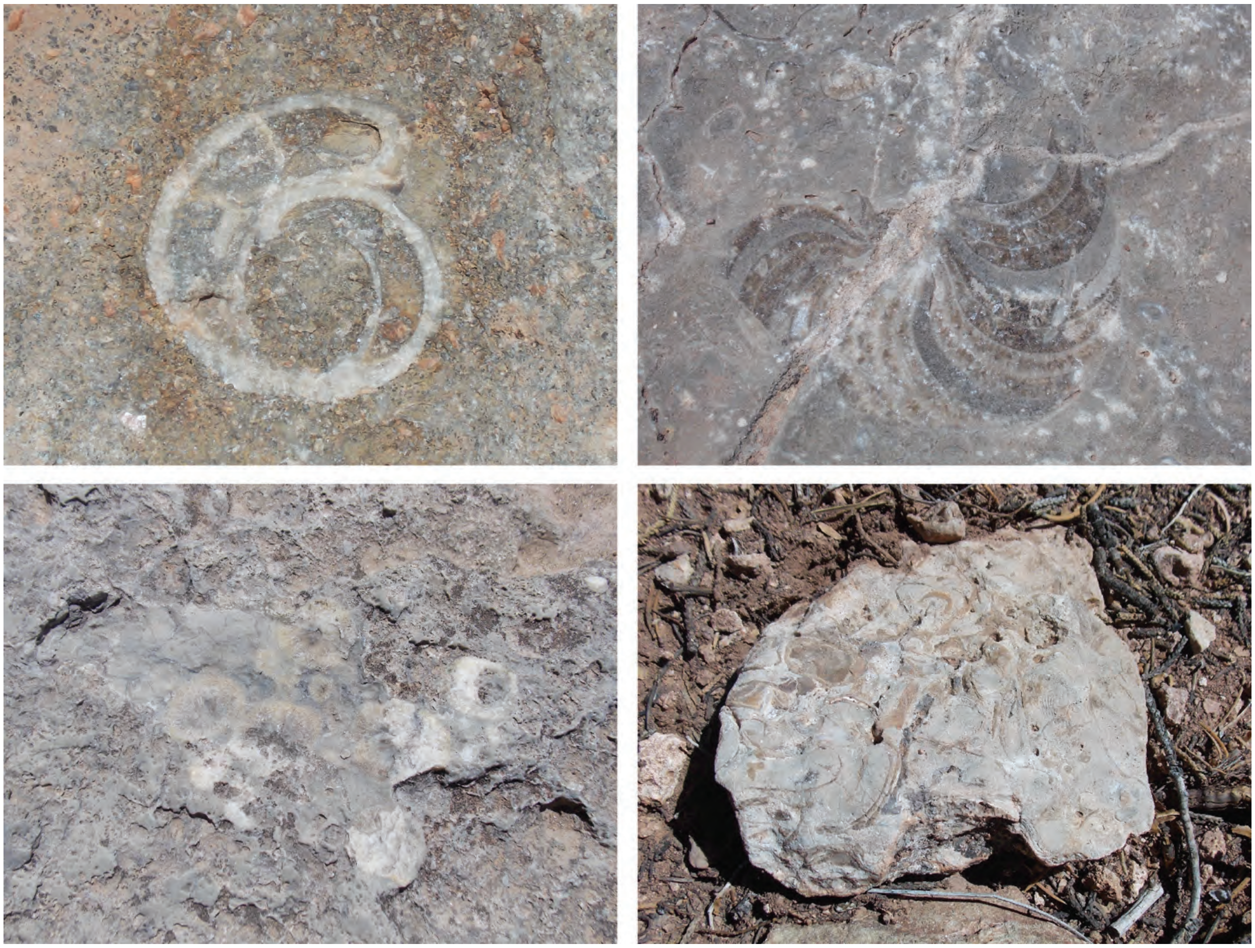

Figure 17. Fossils of the Alamitos Formation. Marine invertebrates have been documented in the Alamitos Formation (PNal) within the park. Clockwise from the top left the identifiable fossils are a gastropod, an ammonite, bivalves, and crinoids. National Park Service photographs by Mario Armijo (Pecos National Historical Park).

The Sangre de Cristo Formation (**PPNsc**) is fossiliferous within Pecos National Historical Park. During the 1930s, researchers visited the area and collected a small assemblage of vertebrate material from between 0.8 and 1.2 km (0.5 and 0.75 mi) north of the mission ruins, within the modern boundaries of the Pecos Unit. Fossils brought back to University of California Museum of Paleontology include two bone fragments attributed to the amphibian *Eryops* (fig. 18) (Erica Clites, museum scientist, University of California Museum of Paleontology, personal communication to Justin Tweet, January 2015). Romer (1960) reported that a shark tooth and bones of a diadectid (a “reptile-like amphibian”) and *Sphenacodon* (a “mammal-like reptile” similar to *Dimetrodon* but with no “sail” on its back) were found within 1.2 km (0.75 miles) of the Pecos ruins. The finds are sometimes attributed to the Abo Formation (Romer 1960) or Cutler Formation, but are now known to belong to the Sangre de Cristo Formation.

Figure 18. Fossils of the Sangre de Cristo Formation. Bone fragments attributed to *Eryops* were discovered in the 1930s near the ruins in the Pecos Unit of the park. Photograph by Erica Clites (University of California Museum of Paleontology).

Though not documented in the park, the Madera Formation contains marine inveretebrate fossils in several locations throughout New Mexico and in Colorado (Koch and Santucci 2003). Kues et al. (1997) reported them in Sandoval County. Kues (1987) described a well-preserved specimen of the large gastropod *Pharkidonotus megalius* in south-central New Mexico. Schram and Schram (1979) discovered shrimp in the Manzanita Mountains. Kues and Kietzke (1981) report a large assemblage of the eurypterid *Adelophthalmus luceroensisi* from Valencia County, in central New Mexico. A sequence of fusulinids from Huerfano Park, Colorado, helped to deduce a marine transgressional depositional environment (Tischler 1963). Conchostracans (“clam shrimp”) and brachiopods were reported in the Manzano Mountains by Huber et al.

(1989). Other invertebrates reported in the Madera Formation include fossil plants and insects in the Manzano Mountains in Bernalillo County (Huber et al. 1989).

The Madera Formation also contains vertebrate fossils. A diverse vertebrate assemblage from New Mexico was presented by Rowland et al. (1997). In addition, Berman (1973) described a new genus and species of amphibian (*Lafonius lehmani*) from the Manzano Mountains, in north-central New Mexico. Disarticulated fish were also reported from the Manzano Mountains (Huber et al. 1989). Cook and Lucas (1998) reported a locality in central New Mexico that includes various fragmentary fossils, reptiles, an amphibian, and a shark (Koch and Santucci 2003).

According to the GRI GIS data, the Madera Formation (**PNm**) is not mapped in the park. Some authors considered the Alamitos Formation (**PNal**)—which is mapped in the Pecos Unit of the park—to be equivalent to the Madera Formation (Baltz and Myers 1984, 1999). However, the Alamitos exposures in the vicinity of the park are unlike the typical Madera Formation (Kues 2001). This reduces the possibility that Madera Formation-type fossils may be found within the Alamitos Formation rocks of the park.

Caves and Karst Resources

Caves are naturally occurring underground voids. Karst is a landscape that forms through the dissolution of soluble rock, most commonly carbonates such as limestone or dolomite (Toomey 2009). Excluding Quaternary surficial units, 98.55% of the area of Pecos National Historical Park is mapped as geologic units that contain some amount of karst-forming carbonate rock such as limestone or dolomite (**PNal**, **PPNsc**, **Py**, **Pg**, **Psa**, **Pa**, **TRm**, **TRs**; see Map Unit Properties Table, in pocket; Land et al. 2013). However, no karstic features, for example sinkholes, "losing streams," springs, or internal drainage, occur in the park. As of April 2015, 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 (accessed 17 February 2015), provides more information.

In some locations the Alamitos Formation (**PNal**) crops out as cliffs along the Pecos River. In places, the limestone of the formation is dissolving and forming small dissolution caves (fig. 19). Owls have been sighted in the vicinity of these small caves and may be inhabiting the caves (Mario Armijo, Pecos National Historical Park, staff, written communication, 24 September 2014).

A karst cave located outside the park, near the Pecos mine, was used for ceremonies by Pueblo Indians (Anderson 1956). The cave extends northwest more than 1.6 km (1 mi) into a hillside composed of Magdalena limestone (Anderson 1956). Evidence of fires, arrowheads, and broken arrow shafts, suggest the cave was used by hunting parties during the 19th and early 20th centuries and may have provided shelter to local Indians into the 1940s (Anderson 1956). This cave is beyond the extent of the GRI GIS data set.

Figure 19. Limestone caves. Small caves are forming in outcrops of the Alamitos Formation (PNal, limestone). National Park Service photograph by of Mario Armijo (Pecos National Historical Park).

Non-karst Caves

Two caves, Baca Cave and "small cave," are documented in the park. Both are closed to the public. The Baca Cave is a natural opening in sandstone that prospectors expanded to create a mine (Burger and Allison 2008; see "Abandoned Mineral Lands Hazards" section). The Baca Cave is not a karst feature. It formed by the erosion of sandstone rather than through dissolution of limestone.

The cave developed between a sandstone layer and a limestone layer within the Sangre de Cristo Formation. The upper layer is grainy sandstone approximately 9 m (30 ft) thick (Burger and Allison 2008). The lower unit is a gray, limestone bed a few feet below the floor of the cave entrance and is about 8 m (26 ft) thick (Burger and Allison 2008). The east-west cave passage developed along a joint between these layers (Johnson et al. 2011). Joints are fractures in rock and provide avenues for water erosion. The joint along which the cave developed formed in response to the stress associated with normal faulting in the area (Johnson et al. 2011). The joint developed perpendicular to the normal fault plane.

The cave has a surveyed length of 73.7 m (241.8 ft), a surveyed depth of 9.14 m (30.0 ft), and a volume of approximately 283 m^3 (9,994 ft^3) (Burger and Allison 2008). The NPS Geologic Resource Division assessed the bat habitat of Baca Cave (KellerLynn 2006).

Baca Cave is currently closed to the public for safety reasons and to protect cultural resources (Johnson et al. 2011). However, Burger and Allison (2008) reported graffiti and garbage in the cave, indicating some human access (see "Caves and Associated Landscapes Management" section).

"Small cave" is another non-karst cave within the park. It is located at the base of a cliff approximately 20 m (60 ft) southeast of Baca Cave and about 5 m (15 ft) higher in

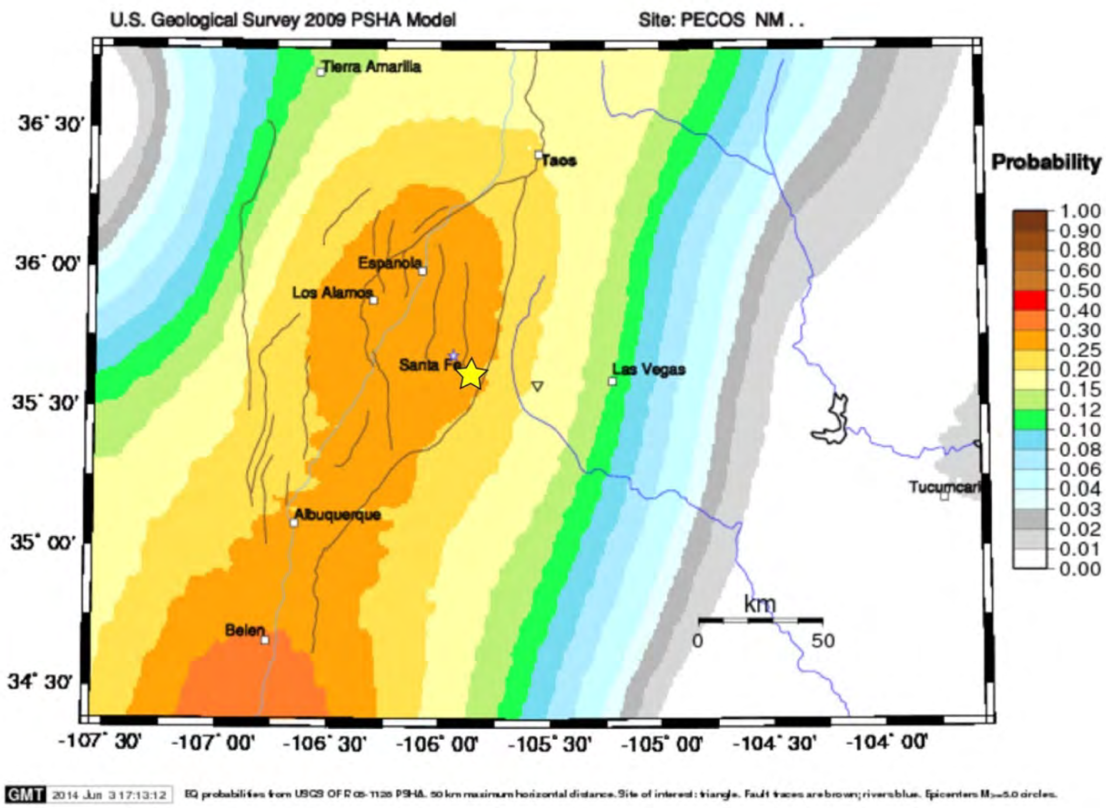

Figure 20. Earthquake probability map. The star marks the location of Pecos National Historical Park. A magnitude 5.5 earthquake has a 0.25–0.30 probability (25%–30% "chance") of a occurring within 30 mi (50 km) of the park in the next 100 years. Five earthquakes greater than magnitude 1 have occurred within 80 km (50 mi) of the Pecos Unit of the park since 1962. The area of increased probability to the south is the northern extent of the Socorro Seismic Anomaly. US Geological Survey map created at http://geohazards.usgs.gov/eqprob/2009/index.php (accessed 3 June 2014).

elevation. It appears to have formed along a joint associated with the same north–south normal fault as the Baca Cave (Burger and Allison 2008). Three passages in "small cave" can be followed for about 12 m (39 ft) before becoming too tight to traverse; it is possible that this cave is connected to Baca Cave (Burger and Allison 2008).

Earthquakes

Earthquakes are ground vibrations—shaking—that occur when rocks suddenly move along a fault, releasing accumulated energy (Braile 2009). Earthquake intensity ranges from imperceptible by humans to total destruction of developed areas and alteration of the landscape. The 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; accessed 17 February 2015), and the US Geological Survey Earthquakes Hazards website (http://earthquake.usgs.gov/; accessed 17 February 2015) provide more information. Also see the "Earthquake Hazards and Risk" section in this report.

According to the US Geological Survey Earthquake Probability map (fig. 20; http://geohazards.usgs.gov/eqprob/2009/index.php; accessed 3 June 2014), a magnitude 5.5 earthquake has a 0.25–0.30 probability (25%–30% "chance") of occurring near Pecos National Historical Park in the next 100 years. A 5.5 magnitude earthquake is considered a "moderate" earthquake.

New Mexico earthquakes have been instrumentally located since 1962 by the New Mexico Institute of Mining and Technology. During this time period, even "moderate" earthquakes have been uncommon in New Mexico, and the Rio Grande rift, a region west of the park which was seismically active during its formation roughly 30 million years ago, has remained quiet. An area of concentrated, seismic activity surrounding Socorro, referred to as the "Socorro Seismic Anomaly," is approximately 240 km (150 mi) southwest of the park. This area produces a disproportionate share of the state's earthquakes and has generated the strongest historical earthquakes (Sanford et al. 2006). Earthquake activity in this region is attributed to crustal extension (pulling apart) as molten material (magma) moves beneath the surface (Fialko and Simons 2001).

Since 1962 Pecos National Historical Park has not experienced any significant earthquakes—earthquakes greater than 3.5 magnitude. However, between 1962 and

2010, nearly 100 earthquakes with a magnitude of 3.5 or less were recorded within 80 km (50 mi) of the park, indicating that earthquakes do occur in the area, although the vast majority are minor and not felt by humans (Sanford et al. 2006; Pursley et al. 2013). The five strongest of these recorded earthquakes ranged in magnitude from 2.7 to 3.5.

Geologic Resources in a Cultural Context

The geologic history and geologic landscape of Pecos National Historical Park played a role in the history and lives of the people that have passed through and inhabited the area. The inhabitants of Pecos Pueblo used geologic resources for producing ceramic pottery, bricks, and stone tools ("lithics"), and as building stone and glass. Petroglyphs are visible on some of the gritty arkosic sandstone outcrops of the Sangre de Cristo Formation (**PPNsc**) (fig. 21).

Figure 21. Petroglyphs. Prehistoric inhabitants of the Pecos area carved petroglyphs into the arkosic sandstone of the Sangre de Cristo Formation (PPNsc). National Park Service photograph by Mario Armijo (Pecos National Historical Park).

Travel Route and Battlefield

For more than 800 years Glorieta Pass has provided travelers with a connection between the Pecos River valley in the east and the Rio Grande valley in the west. The pueblo and mission were both situated along this "gateway" corridor. In 1541, Francisco Vasquez de Coronado traversed the pass in route to explore the plains; Spanish friars followed in the 1660s, attempting to convert Plains Indian tribes; Apaches and Comanches entered the Pueblo area from the east (Bauer et al. 1995). The Santa Fe Trail crossed the pass from the 1820s to the 1880s, followed by the railroad and Interstate 25 today.

Glorieta Pass and neighboring Glorieta Mesa played significant roles in the outcome of the Battle of Glorieta Pass. This battle, fought on 26–28 March 1862, was a decisive, ending the Civil War in the far west (National Park Service 1993). The Glorieta Unit of the park interprets these stories. While the skirmishing occurred in the valley near the Pigeon's Ranch Subunit and unbeknownst to the Confederates, a detachment of Union soldiers made their way west over the top of Glorieta Mesa, out of sight from the battleground, and into the Confederate supply camp at Cañoncito, which they attacked and destroyed (James 1979).

Ceramics

Ceramic pottery is made out of clay. Most of the ceramic pottery recovered by archeologists at Pecos National Historical Park has been broken over time into small fragments—sherds (fig. 22; Powell 2002). Locally excavated minerals (see "Mining" section) may have been the materials used to make glaze paints for some Pecos glaze ware ceramics (Jeremy Moss, Pecos National Historical Park, chief of cultural resources, written communication, 5 August 2014).

Figure 22. Ceramic jar. This ceramic jar was reconstructed from 36 micaceous-clay pottery sherds recovered from Pecos National Historical Park. National Park Service photograph, and additional information, available at http://go.nps.gov/peco_jar (accessed 9 April 2015).

Lithics

Lithics, or stone tools, used by Pueblo Indians in and around the Pecos Valley include projectile points, manos, and metates (fig. 23; Kidder 1932; Kilby and Cunningham 2002). One Clovis-type projectile point has been reported from the upper Pecos Valley (Nordby 1981). In addition, the mid-section of a Folsom point was found in the Tecolate Range in the north east section of the Pecos Unit (Kilby and Cunningham 2002).
Stone was also used to craft hammer stones, pot polishers, arrow shaft straighteners, smoking pipes, and other ceremonial objects (Kidder 1932). Some lithic materials were locally available from within a 30 km (20 mi) radius of the park, such as chert and chalcedony from the Madera Formation (**PNm**) and sandstones and quartzite of the Dakota Formation (Kilby and Cunningham 2002). The Dakota Formation was not mapped in the extent of the GRI GIS data. More abundant and higher-quality lithic material such as petrified wood, lignite, flint, turquoise, fibrolite ax heads,

Figure 23. Prehistoric tools from Pecos National Historical Park. Investigators found a variety of lithics during a cultural resource inventory at the park in the mid-1990s. National Park Service photographs.

salt, obsidian, and shell was acquired from more distant regions through trade (Bezy 1988; Kilby and Cunningham 2002). Lithics derived from source rocks found in the Rocky Mountains, Basin and Range, and Great Plains have all been discovered in Pecos National Historical Park.

Rocky Mountain Lithic Materials

Some Rocky Mountain lithic materials were sourced locally. Bezy (1988) reported schists and quartzites (**Xf**) from nearby terraces that were used as hammer stones, pot polishers, arrow shaft straighteners, smoking pipes, and other ceremonial objects.

Obsidian and chert were obtained from the Jemez Mountains which surround the Valles caldera northwest of Santa Fe. The Jemez Mountains comprise a volcanic field that started erupting episodically about 14 million years ago (Miocene Epoch; fig. 4) and culminated during two caldera-forming events 1.62 million and 1.25 million years ago (Pleistocene Epoch; see GRI report about Bandelier National Monument by KellerLynn in review). Obsidian ("volcanic glass") produced during these eruptions was prized throughout the Southwest and Southern Plains as exceptional source rock for stone tools. The obsidian sources of the Jemez Mountains are located 80–100 km (50–60 mi) northwest of Pecos National Historical Park. Three locations appear to have been the most important for lithic raw material: El Rechuelos, Cerro Toledo, and Valle Grande (fig. 24), each of which has a distinctive chemical signature and can be differentiated by x-ray florescence or neutron activation (Baugh and Nelson 1987; Glascock and Neff 1993). The Rio Grande and its tributaries that drain the Jemez Mountains, such as the Chama and Jemez river systems, are potential secondary sources of the same obsidian.

Chert (flint) was acquired from Cerro Pedernal, or locally just "Pedernal," a mesa in northern New Mexico on the northern flank of the Jemez Mountains approximately 100 km (60 mi) from Pecos National Historical Park (fig. 24; Kilby and Cunningham 2002) . The name is Spanish for "flint hill." The chert was obtained from Miocene sedimentary deposits of the Tesuque Formation (**Tt**) (Wilks 2005).

Basin and Range Lithic Materials

Relative to adjacent physiographic provinces, the Basin and Range contains few important sources of lithic raw materials, although there are chert deposits in the Madera and San Andres formations similar to those found in the same formations in the Rocky Mountain province (Kilby and Cunningham 2002). The Rocky Mountain sources were more likely utilized for chert in the Pecos Valley because they were closer.

However, alluvial deposits of the Rio Grande provided a closer and important secondary source of Jemez-derived obsidian (Kilby and Cunningham 2002). Evidence of utilization of Rio Grande deposits has been document as far north as Bandelier National Monument and as far

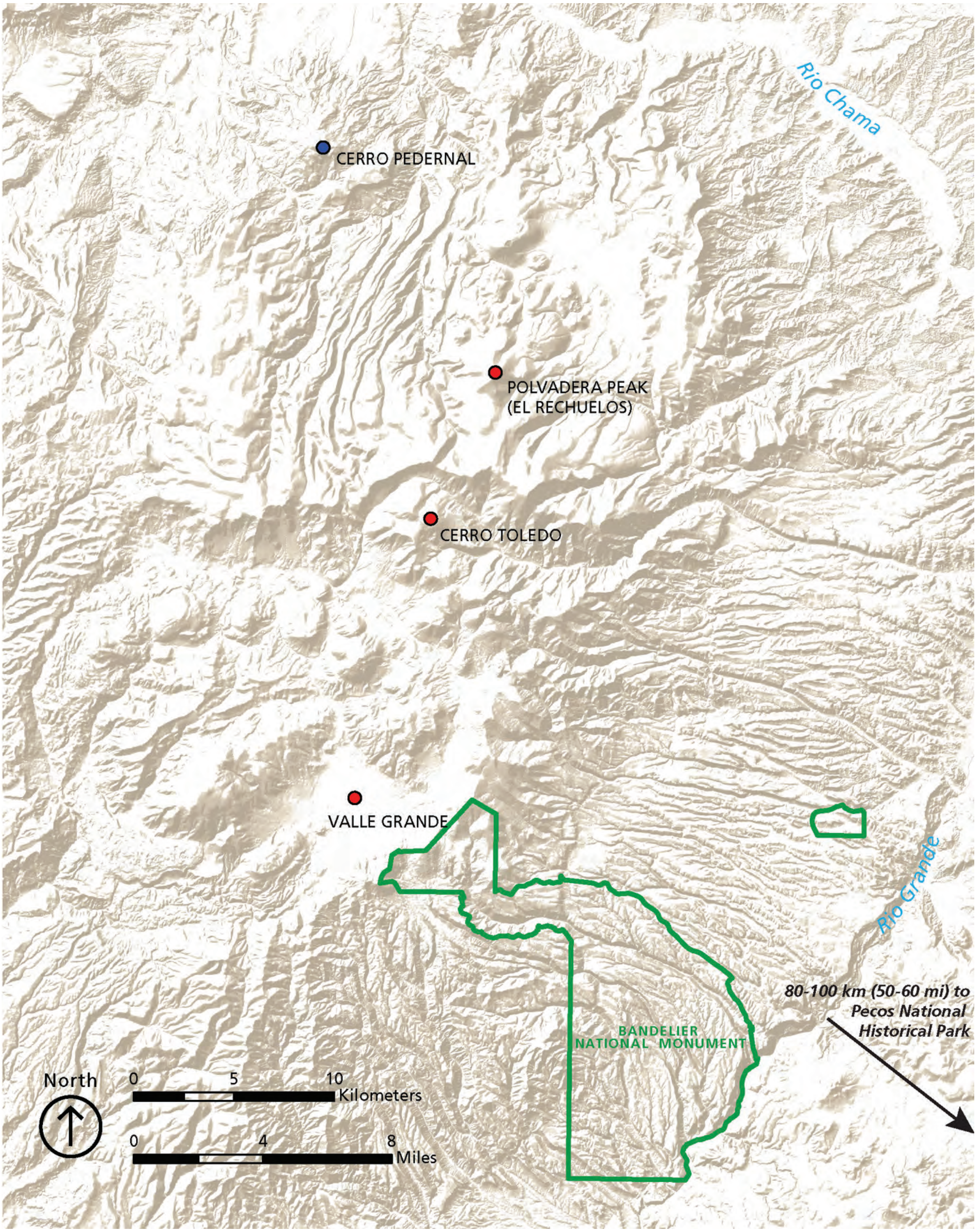

Figure 24. Obsidian and chert sources in the Jemez Mountain area. Three locations (El Rechuelos, Cerro Toledo, and Valle Grande; red dots) appear to have been the most important for obsidian used by Pueblo Indians. Cerro Pedernal (blue dot) was a source of chert. Graphic by Rebecca Port (NPS Geologic Resources Division) after information from Kilby and Cunningham (2002). The shaded relief base map was compiled from a variety of best available sources from several data providers, including the U.S. Geological Survey, NOAA, and ESRI.

south as Tularosa Basin (Head 1999). In addition, obsidian derived from Mount Taylor about 180 km (112 mi) west of Pecos was discovered in alluvial deposits within 110 km (68 mi) of the park (Kilby and Cunningham 2002). The prehistoric significance of the Mount Taylor derived obsidian is not well understood.

Great Plains Lithic Materials

Despite relatively great distances, chert or flint derived from the Great Plains is fairly common in the cultural resources of Pecos National Historical Park. Alibates flint from Alibates Flint Quarries National Monument (Texas) has been found within the park, although the quarries are more than 350 km (220 mi) east of Pecos (Kilby and Cunningham 2002). Chert from the Edwards Limestone in Texas, about 480 km (300 mi) from Pecos, has also been discovered in the park (Kilby and Cunningham 2002).

Pecos Pueblo Stone Walls

Pecos Pueblo was enclosed by a wall built with stone rather than adobe (fig. 25; Winship 1904; Nordby 1981). The inhabitants of the Pecos Valley constructed pueblo walls with igneous and metamorphic cobbles carried from nearby terraces and Glorieta Creek, as well as conglomerate and sandstone blocks of the Sangre de Cristo Formation (**PPNsc**), which underlies most of the area in the park (Johnson 1969; Bezy 1988) (see poster, in pocket). These rocks split naturally into sizes and shapes ideal for building stones (Johnson 1969).

Mission Churches

Flagstone was quarried locally from the Sangre de Cristo Formation (**PPNsc**) for walkways, steps, and shelves in Spanish mission churches (Johnson 1969). Missionaries made adobe bricks with the deep red soil from the Pecos River and Glorieta Creek valleys (Johnson 1969). Adobe bricks are made in a similar manner at the park today as part of preservation efforts (Jeremy Moss, written communication, 5 August 2014) (fig. 26).

Selenite (crystalline variety of gypsum) and white mica (muscovite) were used for window panes because they split easily into thin transparent sheets (a characteristic known as "perfect basal cleavage") (Johnson 1969; Bezy 1988). The source of the selenite was probably southwest of the Cañoncito Subunit in a large gypsum deposit in the either the San Andres (**Psa**) or Artesia (**Pa**) formations (Johnson 1969). The gypsum deposit was also used as a source of plaster of Paris to cover interior walls (Johnson 1969). The mica came from large crystals in the Precambrian muscovite schist (**Xms**) and quartz muscovite schist (**Xqms**) mountain rocks north of the park (Johnson 1969).

Mining

Though no mining of large economic value has occurred within Pecos National Historical Park (KellerLynn 2006), mines near the park have been economically viable in the past. The mining history of the park and surrounding area is primarily important from a cultural perspective and in relation to lasting environmental impacts. This section presents a brief history of mineral exploration and mines in and near the park (see also "Water Quantity and Quality" and "Abandoned Mineral Lands Hazards" sections).

Pueblo Indians were the first prospectors and miners in the area. More than 500 years ago (beginning sometime between 1100s and 1500s), they extracted minerals to be used for artifacts and pigments, such as lead ore to make glaze for pottery (Warren and Weber 1979).

Archeological remains associated with their mining activities include turquoise quarries and tunnels, lead mines, cobbing and sorting workshops, campsites, hearths, and sherd and tool scatters (Warren and Weber 1979). Prehistoric mines are not documented in the park; however, mineral artifacts belonging to Pueblo Indians

Figure 25. Pecos Pueblo stone walls. The stone walls surrounding Pecos Pueblo were constructed with igneous and metamorphic cobbles carried from nearby terraces and Glorieta Creek, as well as conglomerate and sandstone blocks of the Sangre de Cristo Formation. These rocks split naturally into sizes and shapes ideal for building stones. National Park Service photograph by Paul Varela (Pecos National Historical Park).

Figure 26. Freshly made adobe bricks at Pecos mission church. Each summer, selected areas of the mission church are restored using adobe bricks. The bricks are made in much the same manner as they were hundreds of years ago. The new adobe bricks act as a shelter or protective layer that encases the original material. National Park Service photograph.

have been discovered (Kilby and Cunningham 2002). The nearest evidence of prehistoric mining is in the Cerillos mining district, 32 km (20 mi) west of the park (Warren and Weber 1979). Warren and Weber (1979) asserted that the role and importance of prehistoric mining to Southwestern history is not well understood and deserves further study.

In 1581, Spanish explorers unsuccessfully began prospecting for silver in the land of the Pueblos (National Park Service 2014). Later, during the late 19th and early 20th centuries, European settlers began large-scale exploration for industrial and precious minerals (Bezy 1988). The GRI GIS data includes prospects and ditches located roughly 4 km (2 mi) northwest of Glorieta Pass. Several mines were subsequently opened in the area.

One mine and several small aggregate quarries existed inside the park. The nearest significant mine to operate near the park was the Pecos mine. The remains of some smaller mines have also been documented in the area (Anderson 1956).

The Old Bradley mine, 6.4 km (4.0 mi) north of the Pigeon's Ranch Subunit, briefly produced gold-silver ore from the late 1890s to 1905 (Anderson 1956). According to Anderson (1956), the gold was found between the contact of a diabase and granite body. The geologic unit that was mined was most likely Precambrian granite (**Xgg**) (Wilks 2005). The location of this mine is beyond the extent of the GRI GIS data.

Also north of the park, was a copper mine, the Fairview lode mine. The GRI GIS data includes the location of the Fairview lode mine. The mine occurs in the Sangre de Cristo Formation (**PPNsc**).

A World War I–era iron mine was located near the rim of Glorieta Mesa, south of the Pecos Unit (Kelley 1950; Anderson 1956). None of the geologic units mapped in this area (**PPNsc**, **Py**, **Pg**, **Psa**) on the GRI GIS data contain iron ore minerals. It is unclear what unit was mined at this location. The GRI GIS data includes the location of a mine feature identified as a "shaft" on the rim of Glorieta Mesa which may be the feature discussed by Kelley (1950) and Anderson (1956). The shaft is located near the contact of the Glorieta sandstone (**Pg**) and the Artesia Formation (**Pa**).

Baca Mine

According to the NPS database of Abandoned Mineral Lands, only one underground mine, the Baca mine, existed inside Pecos National Historical Park (see also Burghardt et al. 2014). The Baca mine is also a cave (see "Cave and Karst Resources" section). The cave was a natural opening that prospectors expanded into an adit and a shaft (KellerLynn 2006). Several passages appear to have been enlarged, and juniper logs used to support the roofs of the enlarged passages are still present. Local legend maintains that the cave was enlarged by treasure hunters.

The Baca mine may have been opened in search of uranium or copper; however, the cave contains no obvious valuable minerals. This finding is supported by the geology of the surrounding area which is primarily mapped as the Sangre de Cristo Formation (**PPNsc**). Lindgren et al. (1910) discussed copper deposits in the Sangre de Cristo Formation which may be a reference to the Baca mine (Virgil Leuth, New Mexico Bureau of Geology and Mineral Resources, personal communication, cited in KellerLynn 2006, p. 6). Anderson (1956) reported numerous copper showings (small particles) in sandstone on the west side of the Pecos River. Making a comparison to the GRI GIS data, Anderson (1956) may also be referring to the Sangre de Cristo Formation (**PPNsc**). To date, no ore bodies have been found in the Sangre de Cristo Formation and it has never been developed for copper mining (Anderson 1956).

Gravel Pits

More recently, probably between 1965 and 1975, gravel was extracted from pits in an area that is now within the park's boundary. The gravel was used as aggregate during construction of Interstate 25 (Dan Jacobs, personal communication, cited in Johnson et al. 2011, p. 46). Most of the pits were reclaimed prior to the expansion of the park; however, park staff reclaimed one pit in the late 1990s (KellerLynn 2006) and one gravel pit remains in the south part of the park alongside the Old Colonias Road, just before it dips into the Pecos River Valley (Dan Jacobs, personal communication, cited in Johnson et al. 2011, p. 46). The GRI GIS data set includes the location of the remaining gravel pit (see "Disturbed Lands Restoration" section).

Pecos Mine

The Pecos mine, also known as the Terrero, Willow Creek, Hamilton, or Cowles mine, is 23 km (14 mi) north of Pecos National Historical Park along the Pecos River (Anderson 1956; Bezy 1988; McLemore 1995). It was the only productive mine ever developed in the Pecos River basin (Anderson 1956). From 1927 to 1939, the Pecos mine was the largest producer of zinc, lead, gold, and silver in New Mexico (Anderson 1956; Johnson and Deeds 1995; McLemore 1995). These minerals were exported and the tailings—waste—were left near the village of Pecos (Bezy 1988).

Massive ore deposits of the sulfide minerals galena, sphalerite, and chalcopyrite contained within highly sheared Proterozoic metamorphic rocks produced the zinc, lead, copper, silver, and gold (Anderson 1956; Johnson and Deeds 1995; McLemore 1995). In the vicinity of the mine, these rocks are only exposed at the surface in a small area where the Pecos River and its tributaries have cut through the overlying limestone and shale of the Magdalena group (**PNm** and **PNs;** Anderson 1956).

Crushed ore was transported via aerial tramway 19 km (12 mi) south to the El Molino Mill (or Alamitos Canyon Mill) in Alamitos Canyon, 0.5 km (0.3 mi) west of the town of Pecos (McLemore 1995). The mill tailings were conveyed to the tailings ponds in Alamitos Canyon, downstream from the mill and immediately north of the current park boundary. The GRI GIS data include the location of the El Molino Mill and associated tailings ponds.

Pecos mine closed in 1939; the commercial ore was exhausted and mine conditions made it uneconomic to continue (Anderson 1956; McLemore 1995). Minor reprocessing of mine dumps occurred in 1943–1944 (McLemore 1995). In 1950, the surface was purchased by the State of New Mexico to become part of the Bert Clancey Fish and Wildlife Area, administered by the New Mexico Game and Fish Department. The mineral rights were transferred to a trust and periodically leased to interested mining companies (McLemore 1995). State and federal agencies used materials from the mine waste pile at the Pecos mine for road construction and as fill in various campgrounds from the 1930s through the 1970s (McLemore 1995). Since the late 1980s, the mineralized zones at the Pecos mine have been considered too deep and too limited to be mined economically (McLemore 1995).

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 Pecos National Historical Park. The NPS Geologic Resources Division provides technical and policy assistance for these issues.

During the 2006 scoping meeting (see KellerLynn 2006) and 2013 conference call, participants (see Appendix A) identified the following potential geologic resource management issues:

- Fluvial Erosion
- Water Quantity and Quality
- Disturbed Lands Restoration
- Abandoned Mineral Lands Hazards
- Slope Movement Hazards and Risks
- Paleontological Resource Inventory, Monitoring, and Protection
- Caves and Associated Landscape Management
- Land Subsidence
- Earthquakes Hazards and Risks
- External Energy and Mineral Development
- Interpretation and Education

Resource managers may find *Geological Monitoring* (Young and Norby 2009) useful for addressing some of these geologic resource management issues. This information is available at http://go.nps.gov/geomonitoring (accessed 17 February 2015). 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 Erosion

Fluvial erosion—erosion caused by rivers and streams—has changed the landscape of Pecos National Historical Park (fig. 27; KellerLynn 2006). Although some amount of erosion and change to channel morphology is within the realm of natural stream evolution, downcutting and bank erosion are proceeding at accelerated rates along some sections of the Pecos River and Glorieta Creek within the park. In addition, excessive erosion along arroyos—flat-bottomed channels where flow is intermittent—has removed soil and exposed bedrock in places.

Rapid downcutting has produced narrow and incised stream channels. This channel morphology may result in loss of riparian habitat, threats to cultural resources, and risk of slope failure (see "Slope Movement Hazards and Risks" section). In locations where the erosion-resistant

Figure 27. Fluvial erosion. Severe erosion is a concern at Pecos National Historical Park. Photographs were taken near the far northwest boundary of the Pecos Unit. Note person for scale (red circle) in top photograph. During flash floods and seasonal storms, ephemeral arroyos flood and dramatically erode their banks. The steep banks produced are at risk of slope movements. National Park Service photographs by Mario Armijo (top) and Paul Varela (bottom; Pecos National Historical Park).

Alamitos Formation (**PNal**) crops out along the waterways, it restricts lateral channel migration—meandering—and forces rapid downcutting (figs. 10, 28, and 29). In locations where arkosic sandstone and mudstone have been exposed, slabs of the hard and resistant sandstone is at risk of sliding or falling as the mudstone weathers rapidly beneath it (fig. 16).

Bank erosion can lead to increased sediment in waterways, undercut banks (see "Slope Movement Hazards and Risks" section), loss of riparian habitat, and threats to cultural resources. Staff from the NPS Water Resources Division conducted a riparian condition assessment on the Pecos River and lower Glorieta Creek in July 2010 (see Wagner and Martin 2011). A riparian area was considered in "proper functioning condition" if

Figure 28. Bedrock outcrop on the Pecos River. The Alamitos Formation (PNal**) crops out along several meanders (white arrow) along the Pecos River in the park. Bedrock outcrops restrict lateral channel migration of the Pecos River south of its confluence with Glorieta Creek. Esri, DigitalGlobe, GeoEye, i-cubed, USDA, USGS, AEX, Getmapping, Aerogrid, IGN, IGP, swisstopo, and the GIS User Community imagery, annotated by Rebeca Port (NPS Geologic Resources Division).**

streamflow forces and channel processes were in dynamic equilibrium. Excessive erosion and sediment loading indicated a "non-functional" stream system condition.

Pecos River

Three reaches along the Pecos River in the park were rated in "proper functioning condition" (the highest possible rating) by Wagner and Martin (2011). However, an earlier study of the entire Upper Pecos River Watershed by La Calandria Associates, Inc. (2007) concluded that stream bank erosion of the Upper Pecos River was contributing excessive sediments along the segment that stretches from south of the village of Pecos to the confluence with Cow Creek. According to the 2007 study, half of the banks of the 16.2 km (10.1 mi) stretch of the Pecos River from Alamitos Canyon to the confluence with Cow Creek were eroding, with an estimated 709 kg (1,563 lbs) or 182 m^3/yr (238 yd^3 or 6,416 ft^3/yr) of soil being lost each day (La Calandria Associates, Inc. 2007). This stretch includes the portion of the Pecos River that runs through the park.

Recommended remedial actions included constructing upland erosion control measures (head cut repair, check dams), repairing roads to reduce erosion (improved culverts, crossings, ditches, and road alignments), evaluating streams for possible alterations to reduce width (and facilitate formation of meanders and pools), and revegetating stream banks (La Calandria Associates, Inc. 2007). Restoring native vegetation on the banks of the Pecos River would provide shade, cooling the stream to more natural temperatures, as well as reduce bank erosion and sediment load (La Calandria Associates, Inc. 2007).

Figure 29. Potential bedrock outcrops along Glorieta Creek and the Pecos River. White arrows show the location of potential outcrops of the Alamitos Formation (PNal**) that may be inhibiting natural channel migration or are a potential source of slope movements. The red line indicates the park boundary. The top photograph shows an expanded view of the the area outlined in white on the lower photograph. Esri, DigitalGlobe, GeoEye, i-cubed, USDA, USGS, AEX, Getmapping, Aerogrid, IGN, IGP, swisstopo, and the GIS User Community imagery, annotated by Rebeca Port (NPS Geologic Resources Division).**

At the time of this report, remedial actions have not been taken because the 5-km- (3-mi-) segment of the Pecos River that flows through the park is not representative of the excessive sediments and erosion along the full stretch of the river as reported by La Calandria Associates, Inc. (Cheri Dorshak, park ranger, Pecos National Historical Park, written communication, 12 September 2014). The best available data for the park is therefore the report by

Figure 30. Artificial levee. The photograph shows a levee that impaired Glorieta creek by restricting the creek to an artificially narrow corridor. This limited the potential size, structural complexity, and habitat value of the riparian system. The National Park Service removed the levee in 2013 and the area is currently being revegetated. National Park Service photograph taken in 2011 by Joel Wagner (NPS Water Resources Division).

Wagner and Martin (2011). However, the data provided by La Calandria Associates, Inc. (2007) may be useful for understanding overall conditions of the Upper Pecos River Watershed.

Glorieta Creek

Wagner and Martin (2011) rated one reach along the lower Glorieta Creek as "functional-at risk," which indicates that the riparian area was functioning at the time but that soil, water, vegetation, or related attributes had made it susceptible to degradation. This rating was largely due to an artificial levee that was impairing the creek's natural processes (figs. 30 and 31). This was a remaining levee left in place following restoration activities along Glorieta Creek in 2000 (see "Disturbed Lands Restoration" section). The levee, constructed adjacent to the lower Glorieta Creek, constrained the channel to an artificially narrow corridor, which prevented natural stream erosion and limited the potential size, structural complexity, and habitat value of the riparian system (Wagner and Martin 2011). The artificial levee was susceptible to erosion by floods which could break through and deposit excessive sediment into the restored wetlands to the east and north of the levee, and into downstream aquatic habitats. The remaining levee was removed in November 2013 and the area is currently being restored with native vegetation (fig. 32; Cheri Dorshak, Pecos National Historical Park, park ranger, written communication, 12 September 2014).

In addition to the issues associated with the levee, accelerated erosion of Glorieta Creek has destroyed areas of bordering land that were once used for agriculture and livestock grazing by Hispanic and European settlers (Bezy 1988). Grazing coupled with timbering, which removed stabilizing vegetation, may have triggered the accelerated erosion (Bezy 1988). The former grazing areas, now devoid of soil and vegetation, consist of exposed rocks of the sedimentary Alamitos Formation (**PNal**; Johnson et al. 2011).

Figure 31. Aerial photograph of artificial levee. The levee (red dashed lines), constructed adjacent to the lower Glorieta Creek, constrained the channel to an artificially narrow corridor, which prevented natural stream erosion. Note the nearly right angle turn in the creek. The NPS Water Resources Division recommended removal of the levee in 2011. It was removed in 2013. National Agriculture Imagery Program (NAIP) photograph from 2009, annotations by Rebecca Port (NPS Geologic Resources Division).

Figure 32. Restored wetlands of Glorieta Creek. The National Park Service removed an artificial levee and planted native vegetation in an area adjacent to Glorieta Creek. This photograph shows the area in its restored condition. National Park Service photograph by Paul Varela (Pecos National Historical Park).

Arroyos

Arroyos are typically dry stream beds, but may flow and even flash flood on a seasonal basis or temporarily, following thunderstorms. Arroyos, therefore, erode periodically and sometimes severely washing away soil and vegetation and exposing bedrock (fig. 33). Riparian habitat was lost along Glorieta Creek as it entrenched its channel through the former valley floor, forming a steep-walled, flat-bottomed arroyo in the upper reach of the stream where flow is intermittent (Bezy 1988). In the Cañoncito Subunit, arroyo cutting is an issue on steep slopes. Water funneled out of the interstate culverts is increasing downcutting (Staff, Pecos National Historical Park, conference call, 11 April 2013).

Figure 33. Erosion along arroyos. Arroyos that drain into the Pecos River have become so eroded that bedrock is exposed along their beds. National Park Service photographs by Mario Armijo (top) and Paul Varela (bottom; Pecos National Historical Park).

Threats to Cultural Resources

Even under natural conditions, erosion along rivers may be a concern for the preservation of cultural resources (KellerLynn 2006). As of 2011, the cultural site nearest the Pecos River was 23 m (75 ft) from the river bank with all others more than 25 m (82 ft) away (Johnson et al. 2011). This is far enough away that fluvial erosion is not likely to be a threat. These sites would only be at risk during floods (fig. 34). However, there is no evidence

Figure 34. Glorieta Creek after a rain event in September 2013. Even under natural conditions, erosion along rivers may be a concern for the preservation of cultural resources These sites would most likely only be at risk during floods. National Park Service photograph by Gary Zbel available online http://www.nps.gov/peco/planyourvisit/fishing.htm (accessed 10 April 2015).

suggests that overbank flooding occurs nearby, and these cultural sites have persisted for decades to centuries. Thus, flooding is likely not an imminent threat to these resources (Johnson et al. 2011).

The cut banks of Glorieta Creek periodically erode, most notably during times of high flow. Cultural resources are at risk of loss during these periods (staff, Pecos National Historical Park, conference call, 11 April 2013). Park staff does not regularly monitor the banks. No bank armoring or other mitigation strategies are in place (staff, Pecos National Historical Park, conference call, 11 April 2013). Major storms, which would exacerbate the problem, have not occurred since at least 2010; however, the banks are currently undercut to such a degree that slumping could occur without a storm (see “Slope Movement Hazards and Risks” section”).

Recommended Actions

Park-wide, restoration or remedial actions that aim to diminish or bring under control erosion that results in unacceptable degradation of natural and cultural is outlined as a desired condition in the park’s resource stewardship strategy (National Park Service and Colorado State University 2011). However, predicting the effects of any particular bank restoration or other remedial action on erosion is difficult. Nevertheless, remediation techniques need to be designed to function during periods of high flow because the vast majority of erosion and downstream sediment transportation happens during periods of high flow, such as spring runoff or summer thunderstorms.

In the *Geological Monitoring* chapter about fluvial geomorphology, Lord et al. (2009) described methods for inventorying and monitoring geomorphology-related vital signs, including (1) watershed landscape (vegetation, land use, surficial geology, slopes, and hydrology), (2) hydrology (frequency, magnitude, and duration of stream flow rates), (3) sediment transport (rates, modes, sources, and types of sediment), (4) channel cross section, (5) channel planform, and (6) channel longitudinal profile.

Water Quantity and Quality

In 2011, the section of Pecos River that flows through the park was classified as "impaired" due to temperature and turbidity (suspended sediment) levels that exceeded federal standards (Johnson et al. 2011). Disturbed lands adjacent to the river may be partially responsible for the river's excessive temperature and turbidity because the lands lack native vegetation that provides shade, and they are also eroding large amounts of sediments into the river valley (see "Disturbed Lands Restoration" section). The drought of the 2010s has reduced surface water quantity, which in turn exacerbates turbidity issues (Johnson et al. 2011).

Abandoned mineral lands upstream from the park may be contributing metals and other contaminants to the park's water supply and affecting water quality (see "Abandoned Mineral Lands Hazards" section).

Water quality issues not related to geologic processes are beyond the scope of this report. The NPS Water Resources Division can assist park managers with concerns about such issues (see http://nature.nps.gov/water/; accessed 19 February 2015).

Disturbed Land Restoration

Where natural processes and conditions have been impacted by human activities such as development or agriculture, disturbed land restoration (DLR) may be needed. Lands disturbed by human activity often cause unwanted and long-lasting problems that affect other resources. Many of these disturbances obliterate soil profiles, exacerbate the invasion of exotic plants, result in contamination of water and soil, and cause erosion and sedimentation. These damages, in turn, frequently impair the quality of habitats, disrupt ecosystem functions, and cause problems for managing areas as wildlands.

Prior to the park's establishment, decades of livestock grazing, clearing of vegetation, and development by settlers created areas of disturbed lands (KellerLynn 2006). These activities began in the early 1900s. By the 1940s livestock were excluded from the 26- ha (64-ac) core of the park, and in June 1967 grazing ceased. Erosion was noticed shortly thereafter. The disturbed lands are especially susceptible to erosion because the naturally developed drainage has been altered and stabilizing vegetation has been removed.

The National Park Service has completed several DLR projects in Pecos National Historical Park. In 1978, small ravines throughout the park were planted with piñon/juniper brush in an attempt to halt erosion (National Park Service 1988). Disturbed lands along the lower Glorieta Creek were restored in 2000 (fig. 32; see "Lower Glorieta Creek Restoration Project" section). At the time of this report, park managers were seeking technical assistance from the Natural Resource Stewardship and Science (NRSS) Directorate to address the remaining disturbed lands and associated erosion issues in the park.

A more recently developed area of disturbed lands involves wetlands along Glorieta Creek. Until 2011, flow in the creek was increased (albeit artificially) by well water discharge from the Glorieta Conference Center upstream from the Pecos Unit. After closure of the conference center, flow in Glorieta Creek was significantly reduced. Wetlands may be lost if the creek flow remains at the currently low level. Additionally, a beaver dam approximately three m (9 ft) high at the northern part of the Creek is currently impeding the flow of water downstream (fig. 35) (Cheri Dorshak, written communication, 12 September 2014).

Park resource managers are trying to determine what, if any, actions should be taken to restore the wetlands created by the previous "unnatural" flow levels in the creek (Pecos National Historical Park staff, conference call, 11 April 2013). Historic photographs do not indicate

Figure 35. Beaver dams on Glorieta Creek. A beaver dam at the northern part of the Glorieta Creek is currently impeding the downstream flow of water. National Park Service photographs by Mario Armijo (Pecos National Historical Park).

that wetlands are the natural condition (Pecos National Historical Park staff, conference call, 11 April 2013). Flow may resume to the area without any action taken by the National Park Service; in 2014, the conference center was purchased by new owners and it is yet to be determined if discharge has increased (Cheri Dorshak, written communication, 12 September 2014). High rainfall events during 2014 have caused the creek to flow above and over the beaver dam and all the way into the Pecos River (Cheri Dorshak, written communication, 12 September 2014).

Lower Glorieta Creek Restoration Project

In the 1980s, landowners at the time converted abandoned sand and gravel quarries into two reservoirs on the north side of Glorieta Creek approximately 0.4 km (0.25 mi) upstream from its confluence with the Pecos River (La Calandria Associates, Inc. 2007). The landowners constructed levees to hold water in the reservoirs, altering stream flow and sediment transportation in the creek (fig. 36). The NPS Water Resources Division completed a restoration project in 2000 by removing levees, re-contouring the land, and planting native vegetation to create 2 ha (5 ac) of wetland-riparian habitat (fig. 37; La Calandria Associates, Inc. 2007). The restored riparian wetlands and woodlands have clearly benefited marsh-favoring species such as red-winged blackbird (*Agelius phoenicus*) and common yellowthroat (*Geothlypys trichas*) (fig. 32; Johnson et al. 2003).

During the 2000 restoration project, a portion of the levee surrounding the "upper reservoir" was left in place as a temporary measure against erosion (Wagner and Martin 2011). In the stretch of lower Glorieta Creek that was adjacent to this remnant levee, the channel was forced to stay within an artificially narrow meander between the levee and a high terrace to the south (fig. 31; Wagner and Martin 2011). The reduced sinuosity increased the stream's gradient in that area. However, water and sediment were able to flow through the channel and onto the floodplain without excessive erosion or deposition. Furthermore, the creek appeared to function properly in large storms (Wagner and Martin 2011).

Staff at the NPS Water Resources Division and Colorado State University's Public Lands History Center strongly recommended removal of the remaining levee because a large flood could cause the creek to erode a new channel through the levee and then flow through the restored wetlands (Wagner and Martin 2011; National Park Service and Colorado State University 2011). Removal of the levee would better connect the restored riparian-wetland area to the stream corridor, allow the riparian system to reach its full potential for habitat size, diversity, and quality, and eliminate the threat of excessive sediment deposition (Wagner and Martin 2011). Because of this recommendation, NPS staff removed the last portion of the levee in December 2013, and the area is undergoing revegetation (Cheri Dorshak, written communication, 12 September 2014).

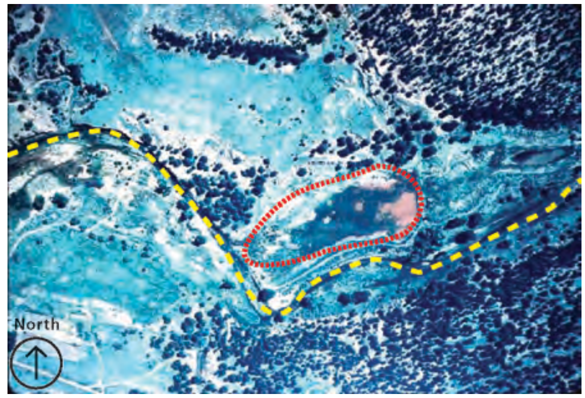

Figure 36. Lower Glorieta Creek, pre-restoration. Former landowners converted abandoned sand and gravel quarries into two reservoirs (red dashed lined) on the north side of Glorieta Creek (yellow dashed line) approximately 0.4 km (0.25 mi) upstream from its confluence with the Pecos River. Aerial image provided by Joel Wagner (NPS Water Resources Division).

Figure 37. Lower Glorieta Creek, during restoration. The NPS Water Resources Division completed a restoration project in 2000 by removing levees, re-contouring the land, and planting native vegetation to create 2 ha (5 ac) of wetland-riparian habitat. National Park Service photograph taken in 1999 by Joel Wagner (NPS Water Resources Division).

Abandoned Mineral Lands Hazards

Abandoned mineral lands (AML) are among the many types of disturbed lands in the National Park System. AML sites may be (1) underground and surface mines, (2) placer and dredge sites, (3) oil, gas, and geothermal wells, or (4) associated facilities.

AML features present a variety of resource management issues such as visitor and staff safety and environmental quality of air, water, and soil. AML features can also provide habitat for bats and other animals. Resource management of AML features requires an accurate inventory and reporting. All AML features should be recorded in the AML database (the NPS Geologic Resources Division may be able to provide assistance). An accurate inventory can identify human safety hazards, and facilitate closures, reclamation, and restoration of AML features. When appropriate for resource management and visitor safety, AML features can also present opportunities for interpretation as cultural resources.

Baca Mine

According to the NPS AML database (accessed 5 June 2014) and Burghardt et al. (2014), Pecos National Historical Park contains one AML site, the Baca mine. The Baca mine is also a cave (see "Caves and Associated Landscape Management" section). The Baca mine features an adit and a shaft, and was possibly a uranium or copper play (KellerLynn 2006). Park administrators closed the area surrounding the Baca mine with fencing and signs to address public safety concerns (KellerLynn 2006).

Pecos Mine

The remains of the Pecos mine operations, though not within the park's boundaries, still have the potential to affect water quality inside the park. Waste rock piles generated by the Pecos mine cover approximately 8 ha (19 ac) and are within 150 m (500 ft) of the east bank of the Pecos River, 26 km (16 mi) north of the park. In some places the piles are up to 14 m (45 ft) thick (Johnson and Deeds 1995). Waste rock piles are potential sources of acid mine drainage. The underlying clay and limestone bedrock may provide some buffer capacity for any acid drainage and may also limit the transport of dissolved metals in groundwater (Johnson and Deeds 1995). Wetlands may also be effective in buffering low pH and limiting the transport of dissolved metals. Nevertheless, low pH and elevated levels of cadmium, copper, lead, and zine have been measured in seeps downslope of the waste rock piles (Johnson and Deeds 1995). Elevated metal levels and low pH have also been measured in Willow Creek, which flows across a portion of the waste rock piles. The seeps and Willow Creek flow into the Pecos River and may be affecting its water quality. For example, fish die-offs at the Lisboa Springs State Fish Hatchery, 18 km (11 mi) downstream from the Pecos mine, may be related to reduced water quality in the Pecos River, the source of water for the hatchery (US Fish and Wildlife Service 1993).

Prior to 2002, some surface runoff was diverted away from the waste rock piles (Johnnie Green, Cyprus Amax Minerals Company, and Stephen Wust, New Mexico Environment Department, personal communication, cited in National Park Service 2005). The Pecos mine site was remediated in 2002 (Johnson et al. 2011). Although heavy metal concentrations have decreased post-remediation, levels are still sufficiently high to warrant limits on fish consumption (Johnson et al. 2011). Mercury is the greatest concern; its concentration has not decreased appreciably since the remediation (Johnson et al. 2011). The Upper Pecos Watershed Association may be a helpful forum for communication among the National Park Service, the Pecos valley community, and the New Mexico Environment Department about monitoring and other aspects of the Pecos mine cleanup (La Calandria Associates, Inc. 2007).

Slope Movement Hazards and Risks

Slope movements are a common type of geologic hazard—a natural or human-caused condition that may impact park resources, infrastructure, or visitor safety. Risk is the probability of occurrence combined with the expected degree of damage or loss that may result from exposure to a hazard, or the likelihood of a hazard causing losses (see Holmes et al. 2013).

Scoping meeting and conference call participants suggested that maintained infrastructure in the park was not affected by slope movements (KellerLynn 2006; Pecos National Historical Park staff, conference call, 11 April 2013). However, slumping, sliding, and rockfalls do occur along the river corridors and may be impacting backcountry areas and cultural resources (fig. 38; see "Fluvial Erosion" section). Undercut banks are especially susceptible to slope failure (fig. 39). Some abandoned roads, such as Old Colonias Road (fig. 40), are sloughing away. However, these roads are not maintained and their loss is not a concern of resource managers (KellerLynn 2006).

Figure 38. Rock slide into the Pecos River. Where limestone beds of the Alamitos Formation (PNal) dip towards the river, they are at risk of sliding or falling into the water as the river carves deeper through the strata. National Park Service photograph by Paul Varela (Pecos National Historical Park).

Figure 39. Undercut banks on the eastern side of the Pecos River. Undercut banks are especially susceptible to slope failure. National Park Service photograph by Mario Armijo.

Figure 40. Old Colonias Road. Old Colonias road sits atop limestone bedrock (Alamitos Formation). The road has sloughed away to the extent that it is barely recognizable as a roadway today. National Park Service photograph by Paul Varela (Pecos National Historical Park).

In the *Geological Monitoring* chapter about slope movements, Wieczorek and Snyder (2009) described five vital signs for understanding and monitoring slope movements: (1) types of landslide, (2) landslide causes and triggers, (3) geologic materials in landslides, (4) measurement of landslide movement, and (5) assessment of landslide hazards and risks. In addition, the following publication and websites provide detailed information about slope movements, monitoring, and mitigation options: Highland and Bobrowsky (2008), http://landslides.usgs.gov/ (accessed 17 February 2015), http://www.nature.nps.gov/geology/hazards/index.cfm (accessed 17 February 2015), and http://www.nature.nps.gov/geology/monitoring/slopes.cfm (accessed 17 February 2015).

Paleontological Resource Inventory, Monitoring, and Protection

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 April 2015, regulations associated with the act were being developed. As described in the "Paleontological Resources" section, petrified wood is the only type of fossil currently documented within Pecos National Historical Park, although Sangre de Cristo and Madera formations have potential for fossil discoveries.

A field-based paleontological resource survey can provide detailed, site-specific descriptions and resource management recommendations that are beyond the scope of this report. Although a park-specific survey has not yet been completed for Pecos National Historical Park, a brief summary of paleontological resources was completed by Koch and Santucci (2003). An updated summary report is currently being prepared (Vince Santucci, senior geologist, NPS Geologic Resources Division, email communication, 22 January 2015). A field-based survey would help determine the source of the petrified wood, as well as identify the variety of species and abundance of marine invertebrates in the Alamitos Formation and the presence of additional fossils in the remaining geologic units. The NPS Geologic Resources Division can provide assistance in conducting such a survey.

In the *Geological Monitoring* chapter about paleontological resources, Santucci et al. (2009) described five methods and vital signs for monitoring in situ paleontological resources: (1) erosion (geologic factors), (2) erosion (climatic factors), (3) catastrophic geohazards, (4) hydrology/bathymetry, and (5) human access/public use.

Caves and Associated Landscape Management

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 Appendix B). A park-specific cave management plan has not yet been completed for Pecos National Historical Park. 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.

Two caves, Baca Cave and the informally named, "small cave," are documented in the park. Both are closed to protect visitors and resources. Archeological, paleontological, and biological studies related to the cave and karst resources at Pecos National Historical Park have not been conducted, although Soto (2013) summarized the caves and associated resources in the park.

Park staff currently monitors the cave (Johnson et al. 2011). Burger and Allison (2008) noted several potential hazards, including a rockfall hazard at the southern fissure in the cave and falling hazards on climbs into a small dome and a 9-m- (30-ft-) deep shaft. Burger and Allison (2008) recommended maintaining the closure and monitoring it annually for signs of unauthorized use. They also recommended that graffiti be removed and the cave surveyed for biological and archeological resources. Installing a gate may not be practical as described in the "Abandoned Mineral Lands" section. Development of a cave management plan is recommended.

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

Land Subsidence

Scoping meeting and conference call participants (see Appendix A) did not identify land subsidence as a geologic resource management issue. However, literature on geologic hazards in New Mexico, including Haneberg (1992), describes land subsidence as a potential hazard within and near Pecos National Historical Park.

Near Santa Rosa, approximately 145 km (90 mi) southeast of the park, Sweeting (1972) described subsidence relief attributed to the dissolution of limestone and gypsum in the Permian San Andres Formation (**Psa**) and the collapse of sandstone in the overlying Santa Rosa Formation (**TRs**, **TRsu**, **TRsm**, **TRsl**). Both of these formations are present at or near the surface in the Cañoncito Subunit of the park.

Another cause of land subsidence in the Pecos River valley in the last 5 million years (Pliocene Epoch; fig. 4) has been the dissolution of Permian halite deposits and collapse of overlying strata (Bachman 1974, 1984; Gustavson and Finley 1985; Osterkamp et al. 1987). However, the geologic descriptions of the Permian units in the GRI GIS data do not mention the presence of halite.

Earthquake Hazards and Risks

Scoping meeting (see KellerLynn 2006) and conference call participants did not identify any recent earthquakes in the area of the park. The potential for damaging earthquakes in the area is low (Sanford et al. 2006, Pursley et al. 2013). According to the US Geological Survey earthquake probability map (fig. 20; http://geohazards.usgs.gov/eqprob/2009/index.php; accessed 3 June 2014), a magnitude 5.5 earthquake has a probability of 0.25–0.30 (25%–30% "chance") of occurring near Pecos National Historical Park in the next 100 years.

In the *Geological Monitoring* chapter about earthquakes and seismic activity, Braile (2009) described the following methods and vital signs for understanding earthquakes and monitoring seismic activity: (1) monitoring earthquakes, (2) analysis and statistics of earthquake activity, (3) analysis of historical and prehistoric earthquake activity, (4) earthquake risk estimation, (5) geodetic monitoring and ground deformation, and (6) geomorphic and geologic indications of active tectonics.

External Energy or Mineral Development

Although mining has taken place in and near Pecos National Historical Park at both the Baca and Pecos mines (see "Abandoned Mineral Lands Hazards" section), current and future development is of limited concern to park resource managers. Based on regional seismic and exploration activities, the rock formations in the park do not appear to have commercially exploitable mineral deposits, and the various strata are not associated with oil and gas producing beds (National Park Service 1995). The federal government owns all of the mineral rights for lands within the park boundary that are under the jurisdiction of the National Park Service (Reed et al. 1999).

The NPS Geologic Resources Division is available to provide the park with policy and technical assistance regarding minerals and energy issues. Recommendations include remaining aware of public and private mineral ownership and speculation, exploration, or drilling activity on lands in the park's vicinity. The NPS Geologic Resources Division Energy and Minerals website, http://nature.nps.gov/geology/minerals/index.cfm (accessed 17 February 2015), provides additional information.

Interpretation and Education

One of the interpretive themes in the park's foundation statement (National Park Service 2009) relates the park story to the local geology: *The natural features of the landscape, including the Pecos River and its tributaries, established the backdrop against which people (past and present) adapt their survival strategies*. Interpreters at the park often include geology information in their talks, such as during tours of the ruins.

During the 2006 scoping meeting, park staff discussed the possibility of a local geologist training interpreters and conducting field trips for visitors (KellerLynn 2006). Since the scoping meeting several local geologists have visited the park and worked with the staff (Christine Beekman, Pecos National Historical Park, chief of interpretation, personal communication, cited in Johnson et al. 2011, p. 47). Virgil Lueth of New Mexico Bureau of Geology and Mineral Resources has led one geology tour for his staff. Jennifer Lindline, geology professor at New Mexico Highlands University, presented a poster on park geology at the 2007 Pecos Conference. She has also led several field trips in the park that included park staff. A few years ago the park offered a "Geology and Human Environment" tour. Since the 2006 scoping meeting, the New Mexico Bureau of Geology and Mineral Resources published *The Geology of Northern New Mexico's Parks, Monuments, and Public Lands* (Price 2010), which may be a useful reference for park staff. Park staff should continue to work with local geologists and could request interpretation/education/outreach program assistance from the NPS Geologic Resources Division. For example, a Geoscientists-In-the-Parks (GIP) intern could assist with development of geology themed interpretation, education, and outreach products. The GIP website, http://nature.nps.gov/geology/gip/index.cfm (accessed 10 April 2015), provides additional information

Geologic History

This section describes the chronology of geologic events that formed the present landscape of Pecos National Historical Park.

The landscape at Pecos National Historical Park is an expression of hundreds of millions of years of geologic history and processes that continue to shape the land today. The rocks mapped in the park and surrounding area can be compiled into four groups, from oldest to youngest: (1) Precambrian igneous and metamorphic rocks more than 1.6 billion years old, (2) Paleozoic and early Mesozoic sedimentary rocks between about 350 million and 200 million years old, (3) Tertiary gravels about 5 million years old, and (4) surficial units less than 2 million years old. The geologic history of these rock units includes development of ancient basement rock and structure foundation, the rise and fall of the Ancestral Rocky Mountains, the assembly of the supercontinent Pangaea, subsequent uplift, erosion, and the emergence of the modern landscape.

2,500 million–542 million years ago (Proterozoic Eon): Development of the Structural Foundation

The oldest rocks in Pecos National Historical Park and surrounding area are more than 1.6 billion years old. These Proterozoic igneous and metamorphic rocks form the "basement" under all younger rocks. These ancient basement rocks are exposed at the surface where movement along faults brought them up and millions of years of erosion removed overlying rocks. Proterozoic rocks are mapped at the surface primarily in the northwest corner of the map area, which not coincidentally, is cut by many faults. A small band of granite and granitic gneiss (**Xgg**) is mapped in the Cañoncito Subunit (see poster, in pocket).

The older rocks are primarily metamorphic granitic gneiss (**Xgg**), schist and phyllite (**Xqms**, **Xf**, **Xbp**, and **Xms**),

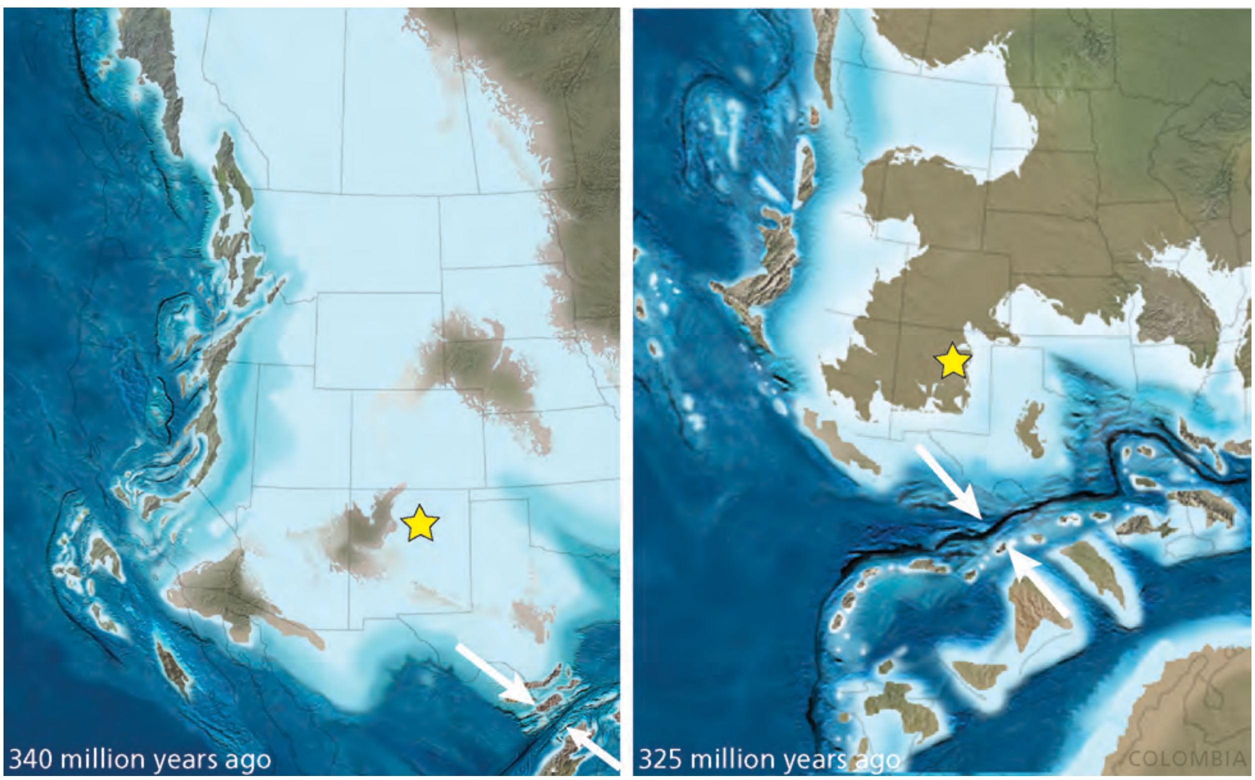

Figure 41. Mississippian Period paleogeographic maps. Western North America was inundated by a shallow sea 340 million years ago (left graphic). Dolomites and limestones were deposited in the area around Pecos National Historical Park (location marked by a star). Toward the end of the Mississippian Period (325 million years ago, right graphic) sea level fell, exposing the marine sedimentary rocks. Erosion ensued, which left only a thin sequence of limestone and dolomite behind. Throughout this time, the supercontinent Pangaea was coming together as the future South American landmass collided with the southern margin of North America (converging landmasses shown with white arrows). Base paleogeographic map by Ron Blakey (Colorado Plateau Geosystems, Inc.), available at http://cpgeosystems.com/index.html (accessed 14 July 2013), annotated by Rebecca Port (NPS Geologic Resources Division).

and amphibolite (**Xa**). These rocks originated as granite, shale, volcanic rocks, and amphibole that were changed under great heat and pressure, and in the case of amphibole, also recrystallized. As is common with basement rocks, their total thickness is unknown but may be more than 3,000 m (10,000 ft) (Baltz and Bachman 1956). Younger Proterozoic granite (**Xg** and **Xmg**), granodiorite (**Xgr**), and diorite (**Xd**) intruded into the older metamorphic rocks to form sills, dikes, and larger "bodies" of igneous rock (Baltz and Bachman 1956).

The ancient rocks were originally deposited in a sedimentary basin where moderately deep seas created thick accumulations of clay (shale) (Clark 1966). Igneous rocks (granite) interlayered with the shale are indicative of periods of tectonic activity (Baltz and Bachman 1956; Clark 1966). Later in Proterozoic Eon, compressive forces metamorphosed and tightly folded the shale and granite (Baltz and Bachman 1956; Clark 1966).

542 million–252 million years ago (Paleozoic Era): Rise and Fall of the Ancestral Rocky Mountains

Little is known about the early Paleozoic geologic history of north-central New Mexico. Early Paleozoic rocks (Devonian and older; fig. 4) are not present in the region (Baltz and Bachman 1956). During much of this time the area was elevated and deposition did not occur. Of the few rocks that were deposited, weathering and erosion later stripped them from the land creating an unconformity in the stratigraphic record. An unconformity is a horizon in the rock record separating strata of different ages. Unconformities are gaps in the rock record and strong evidence for uplift and erosion. Because of this period of erosion, late Paleozoic rocks (Missippian and younger) lie directly on Proterozoic rocks in most areas of the Sangre de Cristo Mountains (Lindsey 2010).

359 million–323 million years ago (Mississippian Period)

Approximately 340 million years ago, the landscape was subdued and seas inundated the entire southwestern half of North America (fig. 41). The supercontinent Pangaea was just beginning to form as ancestral North America moved east toward Europe and Africa. During this time period limestone and dolomites were deposited in a sea that covered much of New Mexico, including the area of Pecos National Historical Park.

Toward the end of the Mississippian Period, an interval of lowered sea level exposed the marine sedimentary rocks (fig. 41). Erosion left only a thin sequence of limestone and dolomite behind. Mississippian rocks (**Mt** and **Mes**) are mapped at the surface in the southwest corner of the extent of the GRI GIS data, which is outside of the park. Younger rocks cover Mississippian strata in most places on the map.

323 million–299 million years ago (Pennsylvanian Period)

About 320 million years ago at the beginning of the Pennsylvanian Period, the Ancestral Rocky Mountains

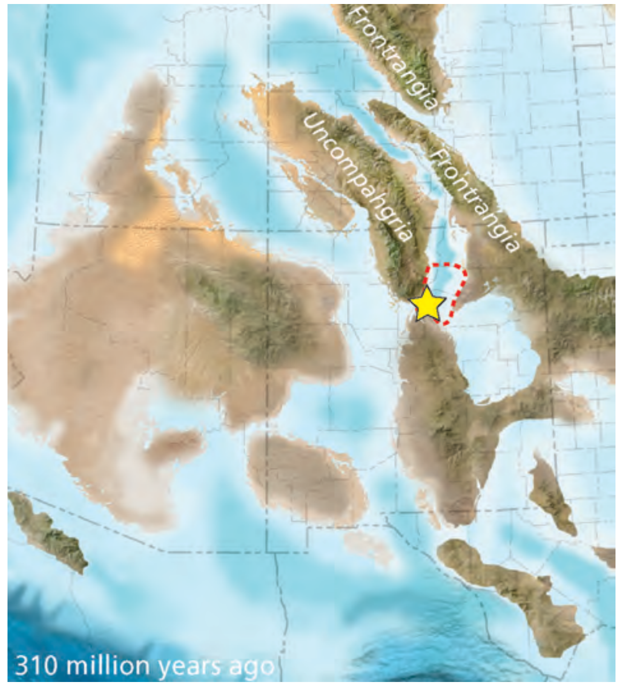

Figure 42. Pennsylvanian Period paleogeographic map. The Ancestral Rocky Mountains (Frontrangia and Uncompahgria) rose during the Pennsylvanian Period. At this time, the area of Pecos National Historical Park (location marked by a star) was situated on the southern edge of the Rowe-Mora basin (red dashed line). Both offshore-derived (calcareous ooze) and land-derived (clastic) sediments accumulated in the basin. Some of these sediments formed the limestone, shale, and sandstone of the Alamitos Formation (PNal) which underlies the eastern portion of the Pecos Unit of the park. Base paleogeographic map by Ron Blakey (Colorado Plateau Geosystems, Inc.), available at http://cpgeosystems.com/index.html (accessed 14 July 2013), annotated by Rebecca Port (NPS Geologic Resources Division).

began to rise as a result of the coming together of the supercontinent Pangaea. The ancestral Rockies consisted largely of Precambrian metamorphic rock, forced upward through layers of Mississippian limestone and dolomites. The uplift created two large ranges—Frontrangia and Uncompahgria—located roughly in the current locations of the Front Range and the San Juan Mountains (fig. 42).

The area now occupied by Pecos National Historical Park was near the southern edge of a depression—the Rowe-Mora basin or Taos trough—which occupied the valley between the southern ends of the neighboring ancestral ranges (fig. 42). A basin is a structural depression that accommodates the accumulation of sediment. The Rowe-Mora basin developed as a result of east–west compression (Baltz and Bachman 1956) and was covered in a shallow sea throughout most of Pennsylvanian Period (fig. 42; Kues 2001). Interbedded layers of offshore–derived calcareous ooze and mountain–derived clastic sediments built up in the basin and formed thick deposits of sedimentary rock (Clark 1966). Occasional retreat of the sea produced thin layers of deltaic shales and terrigenous (land-derived) mudstones and sandstones (Kues 1984).

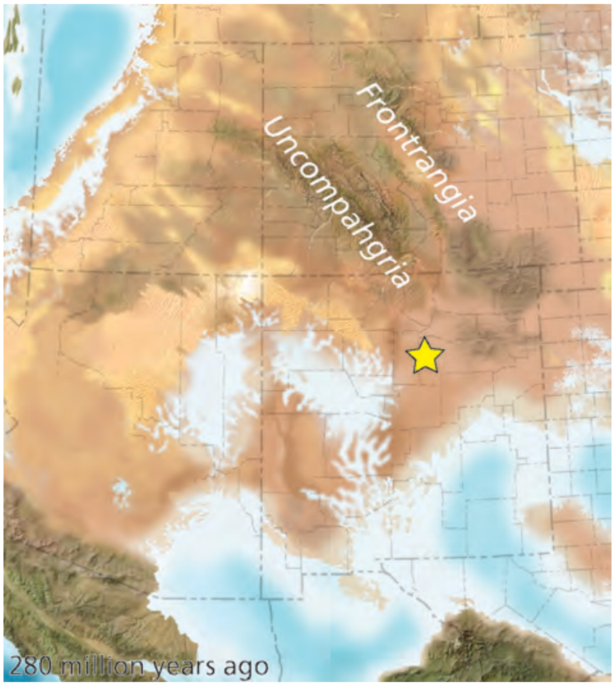

Figure 43. Permian Period paleogeographic map. By the end of the Permian Period, the Ancestral Rocky Mountains were largely word down by erosion. Land-derived sand and mud were deposited in the area of the park (location marked by a star). These sediments formed the sandstone and mudstone of the Sangre de Cristo (PPNsc), Yeso (Py), Glorieta (Pg), and Artesia (Pa) formations. During an interval of relatively higher sea level calcareous sediments were deposited to form the limestone of the San Andres Formation (Psa**).. Base paleogeographic map by Ron Blakey (Colorado Plateau Geosystems, Inc.), which is available at http://cpgeosystems.com/index.html (accessed 14 July 2013), annotated by Rebecca Port (NPS Geologic Resources Division).**

The Alamitos Formation (**PNal**) is the only unit entirely from the Pennsylvanian Period within the park. It covers the eastern half of the Pecos Unit (see poster, in pocket). The formation consists of primarily calcareous ooze, and lesser amounts of mud and sand deposited in a shallow sea, which compacted and cemented into limestone, shale, and sandstone, respectively. The limestone is known to contain fossils in exposures outside of the park (Koch and Santucci 2003).

Toward the end of the Pennsylvanian Period the sea began a gradual regression. Sediments deposited in the basin shifted from largely offshore-derived to land-derived. This transition is illustrated in the sediments of the Sangre de Cristo Formation (**PPnsc**).

299 million–252 million years ago (Permian Period)

The beginning of the Permian Period marks the completion of the transition from shallow marine to terrestrial deposition. The sea receded and the Ancestral Rocky Mountains continued to erode, filling the Rowe-Mora basin with sediments (fig. 43; Clark 1966). During its lifetime, the Rowe-Mora basin accumulated between about 300 and 900 m (1,000 and 3,000 ft) of Paleozoic sediments in the area of Pecos National Historical Park (Baltz and Bachman 1956).

Sediments of the Sangre de Cristo Formation which began accumulating in the Pennsylvanian continue to accumulate into early Permian time. The rocks formed are predominantly non-marine mudstone and sandstone with the occasional thin layer of limestone. The mudstone and sandstone are the result of a migrating, meandering stream system; the red clay represents fluvial deposition, and the white sandstone represents deltas and beaches (KellerLynn 2006).

Today, the Sangre de Cristo Formation underlies the western half of the Pecos Unit and the entire Pigeon's Ranch Subunit (see poster, in pocket). The pueblo and mission were built on a low ridge of red, maroon, and purple mudstones and tan-to-red sandstones of this formation (Johnson et al. 2011).

Throughout the rest of the Permian Period, sediments accumulated forming, from oldest (topographically lowest) to youngest (topographically highest), the Yeso Formation (**Py**), the Glorieta sandstone (**Pg**), the San Andres Formation (**Psa**), and the Artesia Formation (**Pa**). The units comprise much of Glorieta Mesa and are exposed along the base and sides of the mesa. Within the park these units are only mapped in the Cañoncito Subunit. They are primarily sandstone, with some mudstone, siltstone, and thin limestone layers, which represent periodic transgressions of the sea.

The Yeso Formation consists of mud and sand that accumulated in an intertidal environment, perhaps a coastal plain (Johnson 1969; Baars 1974). During a period of rising sea level, waves eroded some of the Yeso Formation producing quartz sand that was redeposited just offshore to become the Glorieta Sandstone (**Pg**; Johnson 1969). The high concentration of resilient quartz and lack of less stable minerals in the Glorieta Sandstone indicates that the sediments were recycled multiple times. The high concentration of quartz made the Glorieta Sandstone resistant to erosion and it therefore forms ledges on the mesa.

Following the deposition of the Glorieta Sandstone, Permian seas continued to advance and the marine limestone of the San Andres Formation (**Psa**) accumulated in slightly deeper water. A final regression of the sea occurred toward the end of the Permian Period resulting in the deposition of the Artesia Formation (**Pa**)—a quartz sandstone similar in composition to the Glorieta Sandstone. The Artesia Formation contains some gypsum, a mineral precipitated when seawater evaporates. Ripple marks are also present, indicating deposition in a coastal environment. Like the Glorieta Sandstone, the high quartz concentraiton of the Artesia Formation makes it resistant to erosion, and today it is a cliff former on Glorieta Mesa.

By the end of the Permian Period, the Ancestral Rockies were largely worn down by erosion and neighboring basins had filled with sediments shed from the eroding highlands (Lawton 1994; Lindsey 2010).

252 million–66 million years ago (Mesozoic Era): Sedimentary Basins

During the Mesozoic in the Rocky Mountain region, subsidence events triggered by tectonic plate collisions farther to the west created a succession of sedimentary basins (Baltz and Bachman 1956; Lawton 1994). Throughout the era, 1,200 to 1,500 m (4,000 to 5,000 ft) of sediments accumulated in these basins (Baltz and Bachman 1956). Most of these sediments were deposited during the Late Cretaceous Period. They are not preserved near the park today (Baltz and Bachman 1956). The stratigraphic record shows unconformities—periods of non-deposition and/or erosion—separating overlying basinal deposits (Lawton 1994).

Mesozoic strata in the extent of the digital geologic data are all from the Triassic Period (252 million–201 million years ago). They are found capping Glorieta Mesa. Within the park, Mesozoic rocks are only mapped in the Cañoncito Subunit (**TRm**, **TRsl**, **TRsm**, **TRsu**, **TRs**, **TRc**).

During the Early Triassic, the red sandstone of the Moenkopi Formation (**TRm**) was deposited by rivers and in lakes. This unit is separated from the underlying Artesia Formation (**Pa**) by an unconformity. Rocks from the Middle Triassic Period are missing on Glorieta Mesa. Johnson (1969) deduced that sedimentation did not occur during Early Triassic time in northern New Mexico and older rocks were slightly eroded.

Later in the Triassic Period, seas advanced over the land in the area around northern New Mexico and Pecos National Historical Park. Layers of sand derived from the weathering of older rocks (**TRm**) accumulated just offshore in shallow water and would eventually form the rocks of the Santa Rosa Formation (**TRsl**, **TRsm**, **TRsu**, **TRs**; Clark 1966; Johnson 1969).

Continental deposits accumulated in the Rocky Mountain region throughout much of the Jurassic Period (201 million–145 million years ago), though rock units of this age are not found in the vicinity of the park (Johnson 1969). Baltz and Bachman (1956) report evidence of some gentle folding in the Late Jurassic Period.

During the Cretaceous Period (145 million–66 million years ago), the active basin deepened considerably as Pangaea broke apart. Sea water inundated North America, creating the Western Interior Seaway that connected the Arctic Ocean to the newly formed Gulf of Mexico (fig. 44). Thick shales and limestones were deposited in New Mexico; however, these layers were removed by erosion in the area around the park. Withdrawal of the Western Interior Seaway at the end of the Cretaceous Period gave way to the most recent major mountain building event in the region—the Laramide Orogeny (Clark 1966).

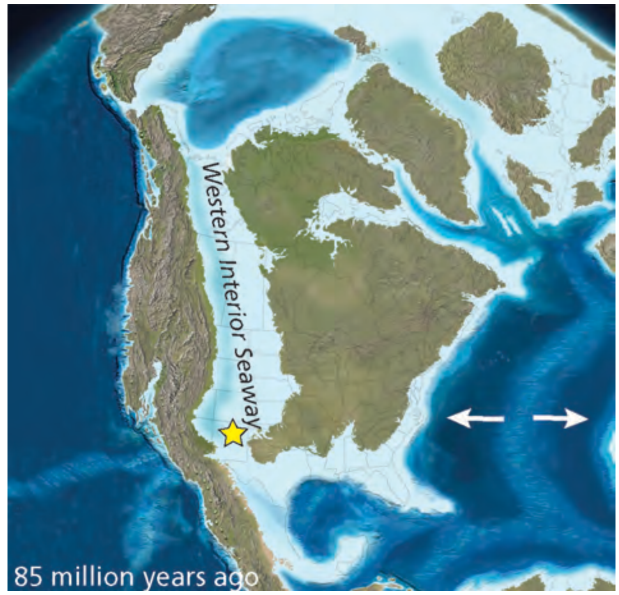

Figure 44. Cretaceous Period paleogeographic map. Toward the end of the Mesozoic Era, Pangaea had separated into the landmasses recognizable as modern-day continents. The Atlantic Ocean basin had opened considerably (diverging plates shown with white arrows), allowing a sea to bisect North America. The Western Interior Seaway connected the Arctic Ocean to the Gulf of Mexico. Thick shales and limestones were deposited near the park (location marked by a star). These layers were later removed by erosion. Graphic annotated by Rebecca Port (NPS Geologic Resources Division). Base paleogeographic map created by Ron Blakey (Colorado Plateau Geosystems, Inc.), which is available at http://cpgeosystems.com/index.html (accessed 14 July 2013).

The past 66 million years (Cenozoic Era): Mountain Building, Erosion, and Emergence of the Modern Landscape

"Laramide Orogeny" is the name given to the processes that formed the Rocky Mountains, starting about 70 million years ago and ending roughly 40 million years ago (Late Cretaceous and early Cenozoic time; fig. 4) . The Sangre de Cristo Mountains were uplifted as part of the Rocky Mountains during this time. Flat slab subduction—a shallowly subducting oceanic plate—roughly 1,100 km (700 mi) to the west caused the rise of the region much farther inland than would normally be expected for a mountain range associated with a subduction zone (fig. 45).

Laramide mountain building raised Precambrian crystalline rocks from great depths that now make up the core of the Sangre de Cristo Mountains. In the process, overlying sedimentary Paleozoic strata (**PNal**, **PPNsc**, **Py**, **Pg**, **Psa**, **Pa**) was also raised and, in the area of the park, tilted toward today's location of Glorieta Mesa. In the Pecos Unit strata are inclined to the southwest; in the Pigeon's Ranch Subunit strata dip to south; in the Canoncito Subunit strata dip primarily to the southeast except where they have been disrupted by faults. The tilt in all locations of the Paleozoic strata is steepest near the high mountains to the north and gradually decreases toward Glorieta Mesa where it becomes almost unnoticeable (Johnson 1969). These young sedimentary rocks have long been eroded away from the crest of the mountain range, but they are still present in the foothills (**PNal** and **PPNsc**).

Figure 45. Cenozoic Era paleogeographic map. By 50 million years ago, the Laramide Orogeny had raised the modern Rocky Mountains, including the Sangre de Cristo Mountains. Today, Pecos National Historical Park (location marked by a star) is on the southern foothills of the range. Base paleogeographic map by Ron Blakey (Colorado Plateau Geosystems, Inc.), available at http://cpgeosystems.com/index.html (accessed 14 July 2013), annotated by Rebecca Port (NPS Geologic Resources Division).

Faults and folds of the Laramide Orogeny can be seen throughout the Sangre de Cristo Mountains (Lindsey 2010). The faults formed by compression and uplift associated with the converging tectonic plates to the west. Folding and complex thrusting in an east–west or northeast–southwest direction affected the rocks mapped in the park (Baltz and Bachman 1956). The basement complex in the Sangre de Cristo Mountains was mildly deformed, creating folds (Baltz and Bachman 1956), which are included in the GRI GIS data. Folding and thrusting to the east continued until about 35 million–30 million years ago into the late Eocene and early Oligocene epochs (fig. 4; Clark 1966).

Lava flows and intrusive igneous features that accompanied Laramide mountain building are common in the Sangre de Cristo Mountains but are absent in the area around the park (Johnson 1969).

After mountain building commenced, nearly 40 million years of erosion shaped the land into currently recognizable features such as the Pecos River valley and Glorieta Mesa. Gravels (**Tgv** and **QTg**) derived from the Precambrian core of the Sangre de Cristo Mountains were deposited south of the mountains from about 23 million to 2 million years ago, that is, throughout the Neogene and early Quaternary periods. The Pecos River and Glorieta Creek established their valleys during this time. Underlying strata controlled the paths the rivers took. Softer rocks (**PNal** and **PPNsc**) were preferentially eroded becoming valleys, while harder rocks (**Pg** and **Pa**) resisted erosion and now stand out as cliffs and ledges.

Geologic Map Data

This section summarizes the geologic map data available for Pecos National Historical Park. The Geologic Map Poster (in pocket) displays the map data draped over imagery of the park and surrounding area. The Map Unit Properties Table (in pocket) summarizes 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 (accessed 17 February 2015).

Geologic Maps

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

Geologic maps often depict geomorphic features, structural interpretations (such as faults or folds), and locations of past geologic hazards that may be susceptible to future activity. Anthropogenic features such as mines or quarries, as well as observation or collection locations, may be indicated on geologic maps. The American Geosciences Institute website, http://www.americangeosciences.org/environment/publications/mapping (accessed 17 February 2015), provides more information about geologic maps and their uses.

Source Maps

The GRI team digitizes paper maps and converts digital data to conform to the GRI GIS data model. 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 Pecos National Historical Park. These sources also provided information for this report.

Ilg, B., P. W. Bauer, S. Ralser, J. Rogers, and S. Kelley. 1997. Preliminary geologic map of the Glorieta 7.5-min quadrangle, Santa Fe County, New Mexico (scale 1:12,000). Open-File Geologic Map OF-GM-11. New Mexico Bureau of Geology and Mineral Resources, Socorro, New Mexico.

Read, A., and G. Rawling. 2002. Preliminary geologic map of the Pecos 7.5-min quadrangle, San Miguel and Santa Fe counties, New Mexico (scale 1:24,000). Open-File Geologic Map OF-GM-52. New Mexico Bureau of Geology and Mineral Resources, Socorro, New Mexico.

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 (accessed 17 February 2015). 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 Pecos National Historical Park using data model version 2.1. The GRI Geologic Maps website, http://www.nature.nps.gov/geology/inventory/geo_maps.cfm (accessed 17 February 2015), 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; accessed 17 February 2015). 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 (peco_gis_readme.pdf) that describes the GRI data formats, naming conventions, extraction instructions, use constraints, and contact information
- Data in ESRI geodatabase GIS format
- Layer files with feature symbology (table 3)
- Federal Geographic Data Committee (FGDC)–compliant metadata
- An ancillary map information document (peco_geology.pdf) that contains information captured from source maps such as map unit descriptions, geologic unit correlation tables, legends, cross-sections, and figures.
- An ESRI map document (peco_geology.mxd) that displays the digital geologic data

Table 3. Geology data layers in the Pecos National Historical Park GRI GIS data.

Data Layer	On Poster?
Geologic Cross Section Lines	No
Geologic Attitude and Observation Localities	No
Alteration and Metamorphic Feature Points	No
Geologic Point Features (springs)	No
Mine Point Features	No
Mine Feature Lines	No
Geologic Line Features (arkose beds and calcite veins)	Yes
Map Symbology	Yes
Folds	Yes
Faults	Yes
Mine Area Feature Boundaries	No
Mine Area Features	No
Geologic Contacts	Yes
Geologic Units	Yes

Geologic Map Poster

The Geologic Map Poster displays the GRI digital geologic data draped over an aerial photograph of the park and surrounding area. Not all GIS feature classes are included on the poster (table 3). Geographic information and selected park features have been added to the graphic. 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 Table

The Map Unit Properties Table lists the geologic time division, symbol, and a simplified description for each of the geologic map units in the GRI GIS data. 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 Geologic Map Poster. Based on the source maps scales and US National Map Accuracy Standards, geologic features represented in the geologic map data are horizontally within 6 m (20 ft) on the 1:12,000-scale source map (Ilg et al. 1997) or 12 m (40 ft) on the 1:24,000-scale source map (Read and Rawling 2002) of their true locations.

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 (accessed 17 February 2015).*

active margin. A tectonically active plate boundary where lithospheric plates are converging, diverging, or sliding past one another. Compare with "passive margin."

adit. A horizontal passage from the surface into a mine.

alluvium. Stream-deposited sediment.

amphibolite. A rock consisting mainly of amphibole and plagioclase minerals with little to no quartz.

anticline. A fold, generally convex upward ("A"-shaped) whose core contains the stratigraphically older rocks. Compare with "syncline."

arkose. A commonly coarse-grained, pink or reddish sandstone consisting of abundant feldspar minerals.

arroyo. A small, deep, flat-floored channel or gully of an ephemeral or intermittent stream in the arid and semiarid regions of the southwestern United States.

axis. A straight-line approximation of the trend of a fold along the boundary between its two limbs. "Hinge line" is a preferred term.

basement. The undifferentiated rocks, commonly igneous and metamorphic, that underlie rocks exposed at the surface, commonly sedimentary. In many regions the basement is of Precambrian age, but it may be much younger. Also, Earth's crust below sedimentary deposits that extends down to the Mohorovicic discontinuity.

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

bedding. Depositional layering or stratification of sediments.

bedrock. Solid rock that underlies unconsolidated, superficial material and soil.

biotite. A generally dark colored rock-forming mineral of the mica group.

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

calcareous. Describes a substance that contains calcium carbonate. When applied to a rock name it implies that as much as 50% of the rock is calcium carbonate.

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

carbonate. A mineral group composed of carbon and oxygen plus an element or elements; for example calcite, $CaCO_3$; and dolomite, $CaMg(CO_3)_2$.

cement (sedimentary). Mineral material, usually chemically precipitated, that occurs in the spaces among the individual grains of sedimentary rocks, thus binding the grains together.

chalcedony. A cryptocrystalline variety of quartz.

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

chronology. The arrangement of events in their proper sequence in time.

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.

clastic. Describes rocks or sediments made of fragments of preexisting rocks.

coastal plain. Any lowland area bordering a sea or ocean, extending inland to the nearest elevated land, and sloping very gently seaward; may result from the accumulation of material along a coast.

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.

compaction. The process whereby fine-grained sediment is converted to consolidated rock.

compression. A type of deformation where Earth's crust is pulled apart.

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

contact. The surface between two types or ages of rocks.

convergent plate boundary. A boundary between two plates that are moving toward each other. Essentially synonymous with "subduction zone" but used in different contexts.

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

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

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

cuesta. A hill or ridge with a gentle slope on one side and a steep slope on the other.

cutbank. A steep, bare slope formed by lateral erosion of a stream.

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

delta. The low, nearly flat, alluvial tract of land at or near the mouth of a river, commonly forming a triangular or fan-shaped plain of considerable area; resulting from the accumulation of sediment supplied by the river in such quantities that it is not removed by tides, waves, and currents.

diabase. An intrusive igneous rock consisting primarily of the minerals labradorite and pyroxene.

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

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

diorite. A coarse-grained, intrusive (plutonic) igneous rock characteristically containing plagioclase, as well as dark-colored amphibole (especially hornblende), pyroxene, and sometimes a small amount of quartz; diorite grades into monzodiorite with the addition of alkali feldspar.

dip. The angle between a bed or other geologic surface and the horizontal plane.

dip-slip fault. A fault with measurable offset where the relative movement is parallel to the dip of the fault.

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

disconformity. An unconformity in which the bedding planes above and below are parallel and usually separated by an uneven erosion surface indicating an interruption in the orderly sequence of sedimentary strata.

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

divergent plate boundary. A boundary between two plates that are moving apart, characterized by mid-ocean ridges at which sea-floor spreading occurs.

dolomite (rock). A carbonate sedimentary rock containing more than 50% of the mineral dolomite (calcium-magnesium carbonate).

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

downwarping. Subsidence of Earth's crust on a regional scale as a result of crustal loading by ice, water, sediments, or lava flows. Compare to "upwarping."

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

drainage basin. The total area from which a stream system receives or drains precipitation runoff.

emergence. A change in the levels of water and land such that the land is relatively higher and areas formerly under water are exposed; results from either an uplift of land or fall of water level. Compare to "submergence."

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

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

eustatic. Describes a worldwide rise or fall in sea level.

evaporite. A sedimentary rock composed primarily of minerals produced from a saline solution as a result of extensive or total evaporation of the solvent (usually water).

extension. A type of deformation where Earth's crust is pulled apart.

extrusive. Describes igneous rock that has been erupted onto the surface of the Earth.

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

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.

fissile. Capable of being easily split along closely spaced planes.

flagstone. A hard, fine grained, often micaceous sandstone that occurs in extensive thin beds and splits uniformly along bedding planes for use in terrace floors, retaining walls, and the like.

flat slab subduction. Refers to the subduction of one tectonic plate beneath another at a relatively shallow angle.

flint. The homogeneous, dark-gray or black variety of chert.

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

fluvial. Of or pertaining to a river or rivers.

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

foliation. A preferred arrangement of crystal planes in minerals. Primary foliation develops during the formation of a rock and includes bedding in sedimentary rocks and flow layering in igneous rocks. In metamorphic rocks, the term commonly refers to a parallel orientation of planar minerals such as micas. Secondary foliation develops during deformation and/or metamorphism and includes cleavage, schistosity, and gneissic banding.

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

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

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

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

Gondwana. The late Paleozoic continent of the Southern Hemisphere and counterpart of Laurasia of the Northern Hemisphere; both were derived from the supercontinent Pangaea.

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

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

granitic. Pertaining to or composed of granite.

granitoid. A general term for all coarse-grained igneous rocks dominated by quartz and feldspar minerals.

granodiorite. A coarse-grained intrusive (plutonic) igneous rock intermediate in composition between quartz diorite and quartz monzonite, containing quartz, plagioclase, and potassium feldspar as the felsic ("light-colored") components, with biotite, hornblende, or, more rarely, pyroxene, as the mafic ("dark-colored") components.

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

graywacke. A dark gray, firmly indurated, coarse-grained sandstone that consists of poorly sorted angular to subangular grains of quartz and feldspar, with a variety of dark rock and mineral fragments embedded in a compact clayey matrix.

gypsum. A sulfate (sulfur + oxygen) mineral of calcium and water, $CaSO_4 \bullet 2H_2O$.

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.

intertidal. Pertaining to the benthic ocean environment or depth zone between high water and low water; also, pertaining to the organisms of that environment. Synonymous with "littoral."

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

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

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

karst topography. Topography characterized by abundant sinkholes and caverns formed by the dissolution of calcareous rocks.

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.

Laurasia. The late Paleozoic continent of the Northern Hemisphere and counterpart of Gonwana of the Southern Hemisphere; both were derived from the supercontinent Pangaea.

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

law of original horizontality. A general law of geology: Water-laid sediments are deposited in strata that are horizontal or nearly horizontal, and parallel or nearly parallel to the Earth's surface. The law was first clearly stated by Steno in 1669.

law of superposition. A general law upon which all geologic chronology is based: In any sequence of layered rocks—sedimentary or extrusive (volcanic) igneous—that has not been overturned, the youngest stratum is at the top and the oldest at the base; that is, each bed is younger that the bed beneath, but older than the bed above it. The law was first clearly stated by Steno in 1669.

left-lateral fault. A strike-slip fault on which the side opposite the observer has been displaced to the left. Synonymous with "sinistral fault."

limb. One side of a structural fold.

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

lithic reduction. The process of detaching lithic flakes from a lump of stone, often using a hammerstone, wood, or bone.

lithification. The conversion of sediment into solid rock.

lithology. The physical description or classification of a rock or rock unit based on characteristics such as color, mineral composition, and grain size.

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

mass wasting. Dislodgement and downslope transport of a mass of rock and/or unconsolidated material under the direct influence of gravity. In contrast to "erosion," the debris removed is not carried within, on, or under another medium. Synonymous with "slope movement."

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

meander. One of a series of sinuous curves, bends, loops, turns, or windings in the course of a stream, produced by a mature stream swinging from side to side as it flows across its floodplain or shifts its course laterally toward the convex side of an original curve.

megacryst. Any crystal or grain in an igneous or metamorphic rock that is significantly larger than the surrounding groundmass or matrix.

megacrystic. A rock which contains megacrysts.

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

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

metamorphic rock. Any rock derived from preexisting rocks that was altered in response to marked changes in temperature, pressure, shearing stress, and chemical environment. One of the three main classes of rock—igneous, metamorphic, and sedimentary.

metamorphism. The mineralogical, chemical, and structural changes of solid rocks, generally imposed at depth below the surface zones of weathering and cementation.

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.

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

monzonite. An intrusive (plutonic) igneous rock, intermediate in composition between syenite and diorite, containing approximately equal amounts of alkali feldspar and plagioclase and very little quartz. Monzonite contains less quartz and more plagioclase than granite.

muscovite. A light-colored silicate (silicon + oxygen) mineral of the mica group, $KAl_3Si_3O_{10}(OH)_2$, characterized by perfect cleavage in one direction and the ability to split into thin, clear sheets.

nonconformity. A type of unconformity developed between sedimentary rocks and older rocks (plutonic igneous or massive metamorphic rocks) that had been exposed to erosion before the overlying sediments covered them.

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. An extrusive (volcanic) igneous rock, specifically a black or dark-colored volcanic glass, usually composed of rhyolite, and characterized by conchoidal fracture.

ooze. A pelagic sediment consisting of at least 30% skeletal remains of pelagic organisms, the rest being clay minerals.

orogeny. A mountain-building event.

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

oxidation. The process of combining with oxygen.

paleogeography. The study, description, and reconstruction of the physical landscape in past geologic periods.

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

Pangea. A supercontinent that existed from about 300 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 Pangea and that of the present continents—Pangea split into two large fragments, Laurasia on the north and Gondwana on the south.

parent material. The unconsolidated organic and mineral material from which soil forms.

parent rock. Rock from which soil, sediment, or other rock is derived.

parting. A plane or surface along which a rock readily separates.

passive margin. A continental plate boundary where no plate-scale tectonism is taking place; plates are not converging, diverging, or sliding past one another.

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

pegmatite. An intrusive igneous rock consisting of exceptionally coarse-grained, interlocking crystals, generally granitic in composition and commonly in irregular dikes, lenses, and veins, especially at the margins of batholiths.

pelagic. Said of marine organisms whose environment is the open ocean.

pelitic. A sedimentary rock composed of clay, representing a consolidated volcanic ash deposit of clay-sized particles.

phyllite. A metamorphic rock, intermediate between slate and mica schist, with minute crystals of graphite, sericite, or chlorite that impart a silky sheen ("schistosity").

plate boundary. A zone of seismic and tectonic activity along the edges of lithospheric plates, resulting from the relative motion between plates.

plate tectonics. A theory of global tectonics in which the lithosphere is divided into about 20 rigid plates that interact with one another at their boundaries, causing seismic and tectonic activity along these boundaries.

point bar. A low ridge of sand and gravel deposited in a stream channel on the inside of a meander, where flow velocity slows.

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

principle of uniformity. The assumption of uniformity of causes or processes throughout time and space; the uniformity of natural laws. Not synonymous with "uniformitarianism."

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

quartz monzonite. An intrusive (plutonic) igneous rock of granitic composition but with about as much plagioclase as alkali feldspar.

regolith. The layer of unconsolidated rock material that forms the surface of the land and overlies or covers bedrock; includes rock debris of all kinds, volcanic ash, glacial drift, alluvium, loess, and aeolian deposits, vegetal accumulations, and soil. Etymology: Greek "rhegos" (blanket) + "lithos" (stone).

regression. Long-term seaward retreat of the shoreline or relative fall of sea level.

reverse fault. A contractional high-angle (greater than 45°) dip-slip fault in which the hanging wall moves up relative to the footwall.

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

right-lateral fault. A strike-slip fault on which the side opposite the observer has been displaced to the right.

ripple marks. The undulating, approximately parallel and usually small-scale pattern of ridges formed in sediment by the flow of wind or water.

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.

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

schist. A medium- to coarse-grained, strongly foliated, metamorphic rock with eminently visible mineral grains, particularly mica, which are arranged parallel, imparting a distinctive sheen, or "schistosity," to the rock.

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

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.

sequence. A rock-stratigraphic unit that is traceable over large areas and defined by sediment associated with a major sea level transgression–regression.

shale. A clastic sedimentary rock made of clay-sized particles and characterized by fissility.

shear. Deformation resulting from stresses that cause contiguous parts of a body to slide relatively to each other in a direction parallel to their plane of contact.

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

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

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

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

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

sorting. The dynamic process by which sedimentary particles having some particular characteristic (such as similarity of size, shape, or specific gravity) are naturally selected and separated from associated but dissimilar particles by the agents of transportation.

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

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

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

stream channel. A long, narrow depression shaped by the concentrated flow of a stream and covered continuously or periodically by water.

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

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

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

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

subduction. The process of one lithospheric plate descending beneath another.

subduction zone. A long, narrow belt in which subduction takes place.

submergence. A rise of water level in relation to land, so that areas of formerly dry land become inundated; results from either a sinking of the land or rise of water level. Compare to "emergence."

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

syncline. A generally concave upward fold of which the core contains the stratigraphically younger rocks. Compare with "anticline."

tailings. The portions of milled ore that are regarded as too poor to be treated further.

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

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

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.

terrestrial. Describes a feature, process, or organism related to land, Earth, or its inhabitants.

terrigenous. Describes material or a feature derived from the land or a continent.

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

transform fault. A strike-slip fault that links two other faults or plate boundaries such as two segments of a mid-ocean ridge.

transform plate boundary. A type of plate boundary at which lithosphere is neither created nor destroyed, and plates slide past each other on a strike-slip fault.

transgression. Landward migration of the sea as a result of a relative rise in sea level.

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

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.

uniformitarianism. The assumption that "the geological forces of the past differ neither in kind nor in energy from those now in operation," which was the basis advocated by Charles Lyell for interpreting past phenomena by analogy with modern ones. Thus the cliché, "the present is the key to the past."

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

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

wash. A broad, gravelly, dry stream bed, generally in the bottom of a canyon that is periodically swept by a torrent of water. The term is used especially in the southwestern United States.

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

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Additional References

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

Geology of National Park Service Areas

NPS Geologic Resources Division (Lakewood, Colorado)
Energy and Minerals; Active Processes and Hazards; Geologic Heritage:
http://nature.nps.gov/geology/

NPS Geologic Resources Inventory:
http://www.nature.nps.gov/geology/inventory/index.cfm.

NPS Geoscientist-In-the-Parks (GIP) internship and guest scientist program:
http://www.nature.nps.gov/geology/gip/index.cfm

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

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.americangeosciences.org/

Association of American State Geologists:
http://www.stategeologists.org/

US Geological Survey Reference Tools

National geologic map database (NGMDB):
http://ngmdb.usgs.gov/

Geologic names lexicon (GEOLEX; geologic unit nomenclature and summary):
http://ngmdb.usgs.gov/Geolex/geolex_home.html

Geographic names information system (GNIS; official listing of place names and geographic features):
http://gnis.usgs.gov/

GeoPDFs (download searchable PDFs of any topographic map in the United States):
http://store.usgs.gov (click on "Map Locator")

Publications warehouse (many publications available online): http://pubs.er.usgs.gov

Tapestry of time and terrain (descriptions of physiographic provinces):
http://tapestry.usgs.gov/Default.html

Appendix A: Scoping Participants

The following people attended the GRI scoping meeting for Pecos National Historical Park, held on 28 March 2006, or the follow-up report writing conference call, held on 11 April 2013. 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 (accessed 23 February 2015).

2006 Scoping Meeting Participants

Name	Affiliation	Position
Doug Bland	New Mexico Bureau of Geology and Mineral Resources	Geologist
Tim Connors	NPS Geologic Resources Division	Geologist
Dennis Ditmanson	Fort Union National Monument and Pecos National Historical Park	Superintendent
Bruce Heise	NPS Geologic Resources Division	Geologist
Dan Jacobs	Pecos National Historical Park	Chief Ranger
Katie KellerLynn	Colorado State University	Research Associate
Ron Kerbo	NPS Geologic Resources Division	Cave Specialist
Virgil Leuth	New Mexico Bureau of Geology and Mineral Resources	Geologist

2013 Conference Call Participants

Name	Affiliation	Position
Jason Kenworthy	NPS Geologic Resources Division	Geologist, GRI Reports Coordinator
Rebecca Port	NPS Geologic Resources Division	Geologist, Technical Writer
Dennis Carruth	Pecos National Historical Park	Superintendent
Greer Price	New Mexico Bureau of Geology and Mineral Resources	Director and State Geologist
Michael Timmons	New Mexico Bureau of Geology and Mineral Resources	Associate Director for Mapping Programs
Regina Carrico	Pecos National Historical Park	Chief Ranger
Sue Eininger	Pecos National Historical Park	Archeologist

Appendix B: Geologic Resource Laws, Regulations, and Policies

The NPS Geologic Resources Division developed this table to summarize laws, regulations, and policies that specifically apply to 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 April 2015. 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 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 C.F.R. § 2.1** prohibits possessing/ destroying/disturbing…cave resources…in park units. **43 C.F.R Part 37** states that all NPS caves are "significant" and set 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 C.F.R. § 2.1(a)(1)(iii)** prohibits destroying, injuring, defacing, removing, digging or disturbing paleontological specimens or parts thereof. **36 C.F.R. § 13.35** prohibition applies even in Alaska parks where the surface collection of other geologic resources is permitted. Regulations in association with 2009 PRPA are still being finalized (April 2015).	**Section 4.8.2** requires NPS to protect geologic features from adverse effects of human activity. **Section 4.8.2.1** emphasizes Inventory and Monitoring, encourages scientific research, directs parks to maintain confidentiality of paleontological information, and allows parks to buy fossils only in accordance with certain criteria.
Rocks and Minerals	**NPS Organic Act**, **16 USC. § 1 *et seq.*** directs the NPS to conserve all resources in parks (which includes 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 C.F.R. § 2.1** prohibits possessing, destroying, disturbing mineral resources…in park units. **Exception: 36 C.F.R. § 7.91** allows limited gold panning in Whiskeytown. **Exception: 36 C.F.R. § 13.35** allows some surface collection of rocks and minerals in some Alaska parks (not Klondike Gold Rush, Sitka, Denali, Glacier Bay, and Katmai) by non-disturbing methods (e.g., no pickaxes), which can be stopped by superintendent if collection causes significant adverse effects on park resources and visitor enjoyment.	**Section 4.8.2** requires NPS to protect geologic features from adverse effects of human activity.
Park Use of Sand and Gravel	**Materials Act of 1947, 30 USC. § 601** does not authorize the NPS to dispose of mineral materials outside of park units. **Exception:** 16 USC. §90c 1(b) the non-wilderness portion of Lake Chelan National Recreation Area, where sand, rock and gravel may be made available for sale to the residents of Stehekin for local use as long as such sale and disposal does not have significant adverse effects on the administration of the National Recreation Area.	None applicable.	**Section 9.1.3.3** clarifies that only the NPS or its agent can extract park-owned common variety minerals (e.g., sand and gravel), and -Only for park administrative uses. -After compliance with NEPA and other federal, state, and local laws, and a finding of non-impairment. -After finding the use is park's most reasonable alternative based on environment and economics. -Parks should use existing pits and create new pits only in accordance with park-wide borrow management plan. -Spoil areas must comply with Part 6 standards -NPS must evaluate use of external quarries. Any deviations from this policy require written waiver from the Secretary, Assistant Secretary, or Director.

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

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

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National Park Service
U.S. Department of the Interior

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

www.nature.nps.gov

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