National Park Service
U.S. Department of the Interior

Natural Resource Stewardship and Science

El Morro National Monument

Geologic Resources Inventory Report

Natural Resource Report NPS/NRSS/GRD/NRR—2012/588

ON THE COVER
Bleached horizon of Zuni Sandstone (map unit symbol Jz) along the Mesa Top Trail. Weathering processes affected the original clay and feldspar of the sandstone, altering them to well-crystallized, white kaolinite. National Park Service photograph.

THIS PAGE
Inscriptions. As travelers rested and drank from the pool at the base of the El Morro headland, they carved their names and other inscriptions into the soft Zuni Sandstone (Jz). The National Park Service has documented more than 2,000 inscriptions, and the cliffs of Zuni Sandstone have become known as “Inscription Rock.” National Park Service photograph.

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National Park Service
Geologic Resources Division
PO Box 25287
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U.S. 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 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.

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

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Executive Summary

This report accompanies the digital geologic map data for El Morro National Monument in New Mexico, produced by the Geologic Resources Division in collaboration with its partners. It contains information relevant to resource management and scientific research. This report was prepared using available published and unpublished geologic information. The Geologic Resources Division did not conduct any new fieldwork in association with this report.

This Geologic Resources Inventory (GRI) report was written for resource managers at El Morro National Monument to assist in science-based decision making and resource management. This report also may be useful for interpretation. The report discusses geologic issues at El Morro National Monument, distinctive geologic features and processes within the national monument, and the geologic history leading to the national monument's present-day landscape. The report provides a glossary, which contains explanations of technical, geologic terms, including terms on the Map Unit Properties Table (see "Geologic Map Data" section). Additionally, a geologic time scale shows the chronologic arrangement of major geologic events, with the oldest events and time units at the bottom and the youngest at the top. In the "Geologic Map Data" section, an overview graphic illustrates the geologic map of Anderson and Maxwell (1991), which served as the primary source of data for the El Morro National Monument digital geologic data set. In addition, Mapel (1985) and Mapel and Yesberger (1985) provided information for the Togeye Lake quadrangle west of the national monument, and Goat Hill quadrangle south of the national monument, respectively. The Map Unit Properties Table summarizes features, characteristics, and potential management issues associated with the rocks and unconsolidated deposits on these maps. Other significant sources of information were the 2006 scoping meeting and resulting document (National Park Service 2006) and a 2011 follow-up conference call with staff from El Morro National Monument. Scoping meeting and conference call participants are listed in the appendix.

El Morro National Monument was established as one of the nation's first national monuments under the Antiquities Act of 1906. On 8 December 1906, six months after signing the Antiquities Act into law, President Theodore Roosevelt established the national monument because of the significant role it played in early New Mexico history and the history of the American Southwest. Ancient Puebloan people, Spanish explorers and settlers, and American emigrants recognized the 70-m- (230-ft-) high monolith of El Morro—meaning "the headland" in Spanish—as a marker of a perennial pool at the base of the sandstone cliffs. At the time of Spanish and American exploration, this was the most important water source for 50 km (30 mi) in any direction. As travelers rested and drank from the pool, they carved their names and other inscriptions into the soft Zuni Sandstone (map unit symbol Jz). As a result, the sandstone cliffs of El Morro have become known as "Inscription Rock." Investigators have documented more than 2,000 inscriptions and petroglyphs, many of which were incised by ancestral Puebloan people, who built Atsinna Pueblo on top of El Morro. Notably, Atsinna means "place of writings on the rock." The ancient artisans seem to have preferred to draw on the iron-stained surfaces of the Zuni Sandstone, whereas Spanish and Anglo travelers apparently preferred the unstained, clear sandstone surfaces.

The inscriptions and ancestral Pueblo ruins at El Morro National Monument are extremely young in comparison with the rocks. The geologic history represented by these rocks spans nearly 300 million years and records the presence of a marine basin during the Permian Period (299 million–251 million years ago) and a vast desert during the Middle Jurassic Period (175 million–161 million years ago), the return of marine waters during the Cretaceous Period (145 million–65.5 million years ago), mountain building starting about 70 million years ago, and volcanism occurring about 700,000 years ago. The modern evolution of the landscape includes the wasting away of sandstone blocks from the cliffs, the eolian (windblown) deposition of sand and silt, and the transport of these materials by surface water runoff.

The headland of El Morro is a landform called a "cuesta" (tilted mesa). Cliffs bound one flank of El Morro, and the strata of the opposite flank dip into the subsurface. The northeastern point of the cuesta forms the tallest cliffs and exposes the most stratigraphy. The bulk of the inclined strata is the Middle Jurassic Zuni Sandstone (Jz). The sand grains comprising this sandstone were transported across a vast desert and deposited in sand dunes about 160 million years ago. The unit currently supplies sand for present-day eolian processes.

The cuesta is capped by Upper Cretaceous Dakota Sandstone (Kdm), which represents the initial advance of the Western Interior Seaway into New Mexico about 96 million years ago. The surface between the Zuni (Jz) and Dakota (Kdm) sandstones marks an unconformity representing at least 60 million years when rocks were deposited but later eroded away in the El Morro area. The conspicuous bleached horizon of the Zuni Sandstone—a notable zone of weathering—lies below the unconformity, and the red Dakota Sandstone lies above it.

Geologic issues of particular significance for resource management at El Morro National Monument were identified during the 2006 scoping meeting and 2011 follow-up conference call. They include the following:

- Loss of Inscriptions. The primary management issue related to the geologic resources at El Morro National Monument is the loss of inscriptions. The friable (easily crumbled, poorly cemented) Zuni Sandstone (Jz) was easy for travelers to carve, but its softness also is the main reason that the famous inscriptions are slowing weathering away. Monitoring and preservation of the inscriptions includes intensive documentation, such as photographing, sketching, and laser scanning, and selective conservation treatments to reattach and secure rock fragments when the loss of an inscription is imminent.
- Rockfall Hazards. The Zuni Sandstone (Jz) is heavily jointed, making it prone to rockfall. In addition, groundwater sapping is prevalent in the sandstone. Sapping-dominated areas commonly result in spalling (exfoliation of flakes of rock from the cliff face), which destroys the inscriptions. Investigators have identified areas of potential rockfall hazards such as Woodpecker Rock, and areas of intense spalling along the Inscription Rock Trail. The National Park Service periodically monitors these areas.
- Tinaja Pit. The southwestern limb of the Zuni Mountains near El Morro National Monument exposes the Permian San Andres Limestone (Psa), which is a valuable resource for lime, cement, building stone, and aggregate. C & E Concrete, Inc. has mined the exposed limestone along the mountain front for aggregate. A surface mine, the Tinaja Pit, is located 6 km (4 mi) east of El Morro National Monument. The primary concern for the National Park Service is that seismic vibrations from mining activities (e.g., blasting, crushing, and hauling aggregate along Highway 53, which runs through the national monument) may negatively impact the inscriptions, facilitating spalling of the friable Zuni Sandstone. Dust from quarrying operations and speeding truck traffic, hauling aggregate, are additional concerns.

Geologic features of particular significance for resource management at El Morro National Monument include the following:

- El Morro and Inscription Rock. The bulk of El Morro and the majority of Inscription Rock are composed of 160-million-year-old Zuni Sandstone (Jz). This sandstone is capped by 96-million-year-old Dakota Sandstone (Kdm). Characteristic features of Zuni Sandstone are well-rounded, well-sorted quartz sand grains; cross-beds; clay cement; parallel joints; and Liesegang banding. El Morro is an inclined mesa of tilted strata, a landform known as a "cuesta." The cliff face of El Morro has become known as "Inscription Rock" because more than 2,000 names and images are inscribed on its surface.
- Box Canyon. A box canyon has been eroded into the El Morro cuesta. This canyon is enjoyed by hikers along the Mesa Top Trail. A distinctive pinnacle of rock stands isolated near the head of the canyon. A thorough investigation of the canyon's development has not been undertaken or published in the scientific literature. However, a likely cause of its formation is groundwater sapping, a generic term for weathering and erosion of rock by groundwater flowing through the rock and emerging at the surface. The joints within the Zuni Sandstone (Jz) concentrate groundwater flow and sapping activity.
- The Pool. Situated in an alcove at the base of Inscription Rock, the pool provided water for travelers. Furthermore, ancestral Puebloans settled on top of El Morro in proximity to the pool. Over the years, the pool was dammed several times to increase the water level for human use. The historic dam, initially constructed in 1926 and repaired in 1943 after a rockfall destroyed much of it, remains today. Following drilling of a well for potable water into alluvium (Qal) in 1961, only local wildlife continues to use the pool as a source of water.
- Ephemeral Streams and Arroyos. Surrounded by a lava plain composed of basalt flows (Qb), water issuing from the Zuni Mountains quickly sinks into the porous rock and does not enter El Morro National Monument. The only streams in the national monument are ephemeral, forming during storm events as a result of surface water runoff, including runoff from the cuesta.
- Tinajas. Natural depressions called "tinajas," which are eroded into bedrock, act as catchment basins for rainwater and snowmelt. Tinajas are of special interest as a surface water resource in arid lands because they are often the only source of water for human travelers and wildlife in an area. Additionally, tinajas create microhabitats in which species develop adaptations for survival in extreme conditions. Moreover, larger tinajas are often "animal traps," serving as valuable repositories for paleontological material. No such repository has been discovered within the boundaries of El Morro National Monument, however. Tinajas in the national monument have been eroded into the topmost bleached zone and the iron-stained zone of the Zuni Sandstone (Jz) and the Dakota Sandstone (Kdm) cap rock.
- Eolian Features and Processes. The most conspicuous eolian feature at El Morro National Monument is the Zuni Sandstone (Jz), which is composed of a 160-million-year-old dune field. Today, the ancient sandstone is the primary source of modern eolian material, contributing sand grains to small dunes and sand sheets within the national monument. The area surrounding the national monument is characterized by small eolian deposits oriented east–northeast.
- Lava Flows. A 700,000-year-old lava flow of the Zuni–Bandera volcanic field covers much of the land surface within and surrounding El Morro National Monument. To the east, El Malpais National Monument is centered on this volcanic field. Today, mature vegetation grows on these basalt flows (Qb), concealing the volcanic setting.

- Unconformities. Anderson and Maxwell (1991) mapped four unconformities in the rocks/geologic record of the El Morro quadrangle. One of these is quite conspicuous and lies between the bleached horizon of the Zuni Sandstone and the red Dakota Sandstone within the national monument. It represents more than 60 million years when sediment was deposited as part of the widespread Morrison Formation, but later eroded away from the El Morro area. This unconformity occurs between the Middle Jurassic and Upper Cretaceous periods, 161 million–100 million years ago.
- Paleontological Resources. Although no fossils have been reported from the rocks within El Morro National Monument, potential for discovery exists because these rock units are known to contain fossils elsewhere. Because fossils are very rare in the Zuni Sandstone (Jz), Dakota Sandstone (Kdm), followed by Quaternary sedimentary deposits (Ql, Qac, Qal, and Qe), are the most likely units to contain fossils within El Morro National Monument. Fossil discoveries might include terrestrial plant fossils and vertebrate tracks from the Dakota Sandstone or bones of mammals as old as 2.6 million years, such as beaver, horse, camel, musk ox, bison, or mammoth, from the Quaternary sediments.

Acknowledgements

The Geologic Resources Inventory (GRI) is one of 12 inventories funded by the National Park Service Inventory and Monitoring Program. The GRI is administered by the Geologic Resources Division of the Natural Resource Stewardship and Science Directorate.

The Geologic Resources Division relies heavily on partnerships with institutions such as the U.S. Geological Survey, Colorado State University, state geologic surveys, local museums, and universities in developing GRI products.

The GRI team would like to thank the participants at the 2006 scoping meeting for their contribution. The names of these participants are listed in the appendix. In addition, Ken Mabery (Scotts Bluff National Monument, superintendent, formerly with El Malpais National Monument) provided valuable input during a pre-scoping conference call. Furthermore, during a follow-up conference call in 2011 and subsequent correspondence in 2012, Dana Sullivan and Dave Hays (El Malpais and El Morro national monuments) provided updated, post-scoping information on issues related to the national monument's geologic resources. Julia Brunner and Hal Pranger (both from the NPS Geologic Resources Division) reviewed the Tinaja Pit and Rockfall and Box Canyon sections, respectively. Gina D'Ambrosio (production editor) at the New Mexico Bureau of Geology and Mineral Resources provided graphics originally drafted for use in Bureau publications. Dale Dombrowski (El Malpais and El Morro national monuments) helped track down many photographs used in this report. Jason Kenworthy (NPS Geologic Resources Division), Rebecca Port (Colorado State University), Trista Thornberry-Ehrlich (Colorado State University), and Philip Reiker (NPS Geologic Resources Division) developed graphics used in this report.

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Introduction

This section briefly describes the National Park Service Geologic Resources Inventory Program and the regional geologic and historic setting of El Morro National Monument.

Geologic Resources Inventory Program

The Geologic Resources Inventory (GRI) is one of 12 baseline natural resource 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.

The compilation and use of natural resource information by park managers is called for in the 1998 National Parks Omnibus Management Act (section 204), the 2006 NPS Management Policies, and in the Natural Resources Inventory and Monitoring Guideline (NPS-75). Refer to the "Additional References" section for links to these and other resource management documents.

The objectives of the GRI are to provide geologic map data and pertinent geologic information to support resource management and science-based decision making in more than 270 natural resource parks throughout the National Park System. To realize these objectives, the GRI team undertakes three tasks for each natural resource park: (1) conduct a scoping meeting and provide a scoping summary, (2) provide digital geologic map data in a geographic information system (GIS) format, and (3) provide a GRI report. These products are designed and written for nongeoscientists. Scoping meetings bring together park staff and geologic experts to review available geologic maps, develop a geologic mapping plan, and discuss geologic issues, features, and processes that should be included in the GRI report. Following the scoping meeting, the GRI map team converts the geologic maps identified in the mapping plan into digital geologic map data in accordance with their data model. Refer to the "Geologic Map Data" section for additional map information. After the map is completed, the GRI report team uses these data, as well as the scoping summary and additional research, to prepare the geologic report. This geologic report assists park managers in the use of the map, and provides an overview of the park geology, including geologic resource management issues, geologic features and process, and the geologic history leading to the park's present-day landscape.

For additional information regarding the GRI, including contact information, please refer to the Geologic Resources Inventory website (http://www.nature.nps.gov/geology/inventory/). The current status and projected completion dates for GRI products are available on the GRI status website (http://www.nature.nps.gov/geology/GRI_DB/Scoping/Quick_Status.aspx).

Park Setting

El Morro National Monument is part of the Colorado Plateau physiographic province (fig. 1). The term "Colorado Plateau" conjures up images of multihued, earth-toned cliffs of flat-lying strata, broad mesas, and steep-sided canyons, as well as stark badlands sculpted by erosion (Kelley 2010). Although such landscapes generally characterize the Colorado Plateau, this physiographic province is geologically diverse and also includes the northwest-striking Zuni Mountains and the volcanic rocks of the Mount Taylor and the Zuni–Bandera volcanic fields (Kelley 2010). El Morro National Monument lies on the western edge of the Zuni–Bandera volcanic field, and the Zuni Mountains rise to the northeast.

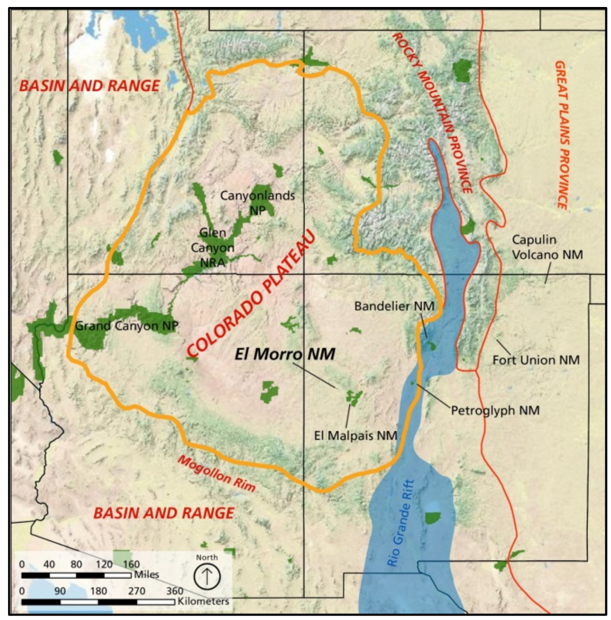

Figure 1. Colorado Plateau. El Morro National Monument and many other National Park System units are situated on the elevated Colorado Plateau. This region makes up the Four Corners area of Utah, Colorado, Arizona, and New Mexico. Green areas represent National Park System units, some of which are labeled. Graphic by Philip Reiker (NPS Geologic Resources Division).

The broad valley in which El Morro National Monument is situated has long been a natural passageway for the movement of people and goods (Anderson and Maxwell 1991). The cliffs of El Morro lie along the southern side of this east–west route through mountain, mesa, and canyon country (Anderson and Maxwell 1991). The route was called the "ancient way" by Spanish explorers who traveled through the area for 300 years, beginning with Coronado in 1540. Before Spanish exploration, Ancient Puebloan people traveled through and inhabited the area. American explorers began using the route in

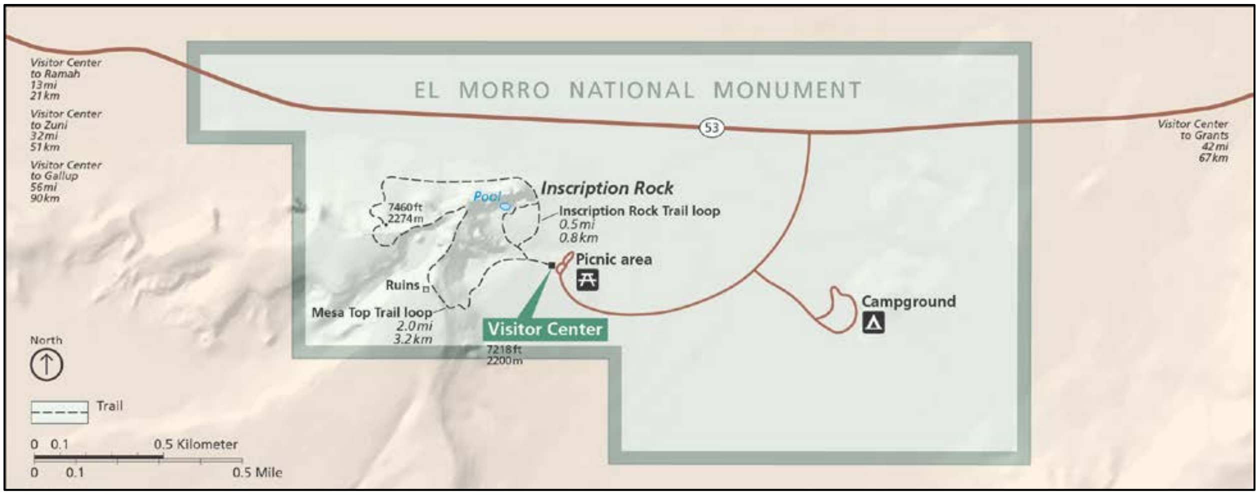

Figure 2. Map of El Morro National Monument. Highway 53 parallels an east–west route traveled by humans since 1275 CE, the "ancient way" through mountain, mesa, and canyon country. National Park Service graphic.

1849. Today, New Mexico Highway 53, which runs through the national monument, parallels segments of the ancient way, thereby continuing the long history of human movement through this region (fig. 2).

El Morro, meaning "the headland" in Spanish, is a prominent sandstone cuesta (tilted mesa) (fig. 3). Ancient Puebloan people, Spanish explorers and settlers, and American emigrants recognized this 70-m- (230-ft-) high monolith of Zuni Sandstone (geologic map unit Jz) as a marker of a perennial pool at the base of the cliffs. Until the construction of the railroad to the north reduced the necessity for this stop, El Morro was the most important water source for 50 km (30 mi) in any direction (Leach 2008). As travelers rested and drank from the pool, they carved their names and other inscriptions into the soft sandstone. As a result, the cliff face of El Morro has become known as "Inscription Rock."

Figure 3. El Morro headland. Ancient Puebloan people, Spanish explorers and settlers, and American emigrants recognized the 70-m- (230-ft-) high monolith of Zuni Sandstone (Jz) as a marker of the perennial pool at the base of the cliffs. These inhabitants and travelers inscribed the soft white (fig. 7 and inside front cover) and iron-stained (fig. 16) surfaces of the stone. National Park Service photograph by Sarah Beckwith.

The ancient people who built Atsinna Pueblo atop El Morro were part of this long tradition of carving into the stone. Notably, Atsinna means "place of writings on the rock" (National Park Service 2007). These high-desert farmers built Atsinna Pueblo between 1275 and 1350 CE (Common Era; preferred to "A.D.") by cutting locally available sandstone into slabs, which they piled to create multiple stories of interconnected rooms (National Park Service 2011a) (fig. 4). Investigators have counted 875 rooms in the pueblo, which measured about 60 × 90 m (200 × 300 ft) and housed between 1,000 and 1,500 people. The location of Atsinna Pueblo was practical, close to the only source of water for many miles, and possibly strategic, on top of a sheer bluff. The indigenous residents had vacated the pueblo by the time Spanish explorers arrived (National Park Service 2011b).

En route to Santa Fe in 1605, the first Spanish governor of New Mexico, Don Juan de Oñate, scratched his name into the rock face at El Morro. This inscription is the oldest authenticated "signature" at El Morro National Monument. Spanish travelers often etched *paso por aqui* ("passed by here") and their names into the rock to commemorate their exploits, including new discoveries, peace missions, and avenging the deaths of missionary priests martyred by American Indians (Leach 2008). In July 1858, the first American-emigrant wagon train to use the Santa Fe Trail stopped at El Morro, leaving 26 names carved into the rock face. Some of the last historic inscriptions on the rock were made by a Union Pacific Railroad crew surveying the Zuni-Acoma Trail for a new railroad route in 1868; a distinctive "U.P.R." appends their names (Leach 2008) (see inside front cover).

The bulk of El Morro is composed of Middle Jurassic Zuni Sandstone (figs. 5 and 6). The well-rounded, well-sorted grains of sand, and the flat-lying and cross-bedded layering of the rock, are indicative of deposition by wind. During the Middle Jurassic Period (approximately 160 million years ago), wind transported the sand across a vast desert, building dunes. Today these dunes comprise the El Morro headland.

Figure 4. Atsinna Pueblo. Between 1275 and 1350 CE, ancestral Puebloan people built Atsinna Pueblo using local sandstone, which they cut into slabs and blocks and piled into multiple stories of interconnected rooms. The pueblo presumably contains blocks of Zuni (Jz) and Dakota (Kdm) sandstones, although no geologic investigation of the materials has been conducted. Architectural features at the site included open courtyards and square and circular kivas—sunken/underground rooms that served as informal and formal gathering places. National Park Service photographs.

The top of the El Morro cuesta is capped by a thin veneer of Cretaceous Dakota Sandstone (figs. 5 and 6), which records the encroachment of the Western Interior Seaway into the area about 96 million years ago (see "Geologic History" section). This seaway extended from the Arctic to the Tropics, covering the entire west-central part of the North American continent (see fig. 28).

El Morro's significant role in early New Mexico history, and the more than 2,000 inscriptions documenting centuries of human habitation and migration, led to its designation as one of the nation's first national monuments under the Antiquities Act of 1906. Six months after signing the Antiquities Act into public law, President Theodore Roosevelt established El Morro National Monument, along with Montezuma Castle and Petrified Forest national monuments. From 1907 until the creation of the National Park Service in 1916, El Morro was administered by the General Land Office. Status as a national monument brought attention to the importance of preserving the inscriptions and preventing additional name carving. Today, visitors to the national monument can hike along two self-guided trails that begin at the visitor center (fig. 2). Inscription Rock Trail, also known as Inscription Trail, is a paved, 0.8-km (0.5-mi) loop that goes to the pool (see "The Pool" section) and passes the inscriptions. Mesa Top Trail, also known as Headland Trail, is a 3-km (2-mi) round-trip walk that continues upward from Inscription Rock Trail to the top of the El Morro mesa, leading to Atsinna Pueblo and providing views of the surrounding valley and the box canyon that formed in the cuesta (see "Box Canyon" section).

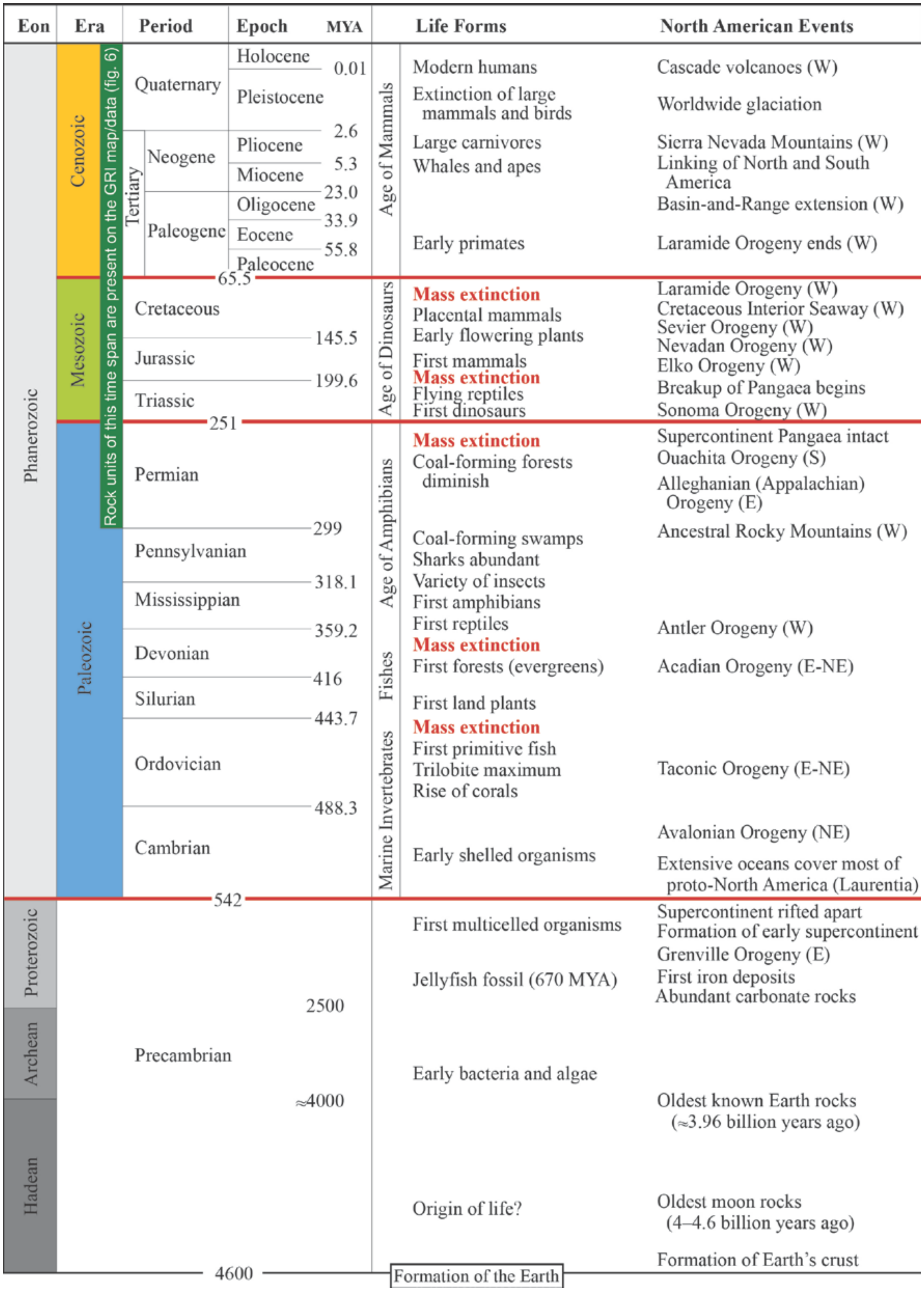

Figure 5. Geologic time scale. The divisions of the geologic time scale are organized stratigraphically, with the oldest at the bottom and youngest at the top. The green bar at left shows the time spanned by the rock units within El Morro National Monument. For more information, refer to fig. 6, the Map Unit Properties Table, and the "Geologic History" section. Boundary ages are listed as millions of years ago (MYA). Major life history and tectonic events occurring on the North American continent are included. Compass directions in parentheses indicate the regional locations of individual geologic events. Red lines indicate major boundaries between eras. Graphic designed by Trista Thornberry-Ehrlich (Colorado State University) and modified Philip Reiker (NPS Geologic Resources Division), adapted from geologic time scales published by the U.S. Geological Survey (http://pubs.usgs.gov/fs/2010/3059/) and the International Commission on Stratigraphy (http://www.stratigraphy.org/ics%20chart/09_2010/StratChart2010.pdf).

Era	Period	Epoch	Age*	Rock/Sediment Unit	Description
Cenozoic	Quaternary	Holocene	0.01–present	Eolian deposits (Qe)	Windblown silt and sand
				Alluvium (Qal)	Mostly stream-deposited silt and sand
		Holocene and Pleistocene	2.6–present	Alluvium and slopewash (Qas)	Clay, silt, and sand
				Alluvium, colluvium, and eolian deposits (Qac)	Stream-, wind-, and landslide-deposited silt, sand, and small sandstone blocks
				Landslide deposits (Ql)	Large blocks of sandstone
		Pleistocene	2.6–0.01	Basalt flows (Qb)	Basalt
	Tertiary: Neogene	Pliocene	65.5–2.6	Rocks of this age are absent in the El Morro area.	
		Miocene			
	Tertiary: Paleogene	Oligocene			
		Eocene			
		Paleocene			
Mesozoic	Cretaceous	Upper	100–65.5	Mancos Shale (Kmp)	Tongue of shale
				Tres Hermanos Formation (Kthf, Kthc, Ktha)	Tongues of sandstone
				Mancos Shale (Kmr)	Tongue of shale
				Dakota Sandstone (Kdt)	Tongue of sandstone
				Mancos Shale (Kmw)	Tongue of shale
				Dakota Sandstone (Kdm)	Sandstone and mudstone
		Lower(?)	145–100	Zuni Sandstone, reworked (Kl)	Sandstone
	Jurassic	Upper	161–145	Rocks of this age are absent in the El Morro area.	
		Middle	175–161	Zuni Sandstone (Jz)	Sandstone
		Lower	200–175	Rocks of this age are absent in the El Morro area.	
	Triassic	Upper	228–200	Chinle Formation (TRcr, TRcu)	Sandstone, siltstone, mudstone, and conglomerate
				Wingate Sandstone (TRwr)	Sandstone and siltstone
				Chinle Formation (TRcl, TRcs, TRcp)	Sandstone, siltstone, shale, mudstone, and conglomerate
		Middle	245–228	Rocks of this age are absent in the El Morro area.	
		Lower	251–245		
Paleozoic	Permian	Lopingian (Upper)	260–251		
		Guadalupian (Middle)	270–260		
		Cisuralian (Lower)	299–270	San Andres Limestone (Psa)	Limestone
				Glorieta Sandstone (Pg)	Sandstone
Older rocks are absent in the El Morro area					

Figure 6. General stratigraphy for El Morro National Monument. Zuni Sandstone (Jz) makes up the bulk of the El Morro headland and cliffs of Inscription Rock. Dakota Sandstone (Kdm) forms a cap rock. Basalt flows (Qb) cover portions of the national monument and the valley between El Morro and El Malpais national monuments. An apron of Pleistocene and Holocene deposits (e.g., unit Qac) surrounds the sandstone headland. See the Map Unit Properties Table for more detail.

Geologic Issues

The Geologic Resources Division held a Geologic Resources Inventory scoping meeting for El Morro National Monument on 30 March 2006 and a follow-up conference call on 12 December 2011 to discuss geologic resources, address the status of geologic mapping, and assess resource management issues and needs. This section synthesizes those discussions and highlights particular issues that may require attention from resource managers. Contact the Geologic Resources Division for technical assistance.

During the 2006 scoping meeting and 2011 conference call, the following geologic resource management issues were identified:

- Loss of Inscriptions
- Rockfall
- Tinaja Pit

Loss of Inscriptions

The primary management issue related to the geologic resources at El Morro National Monument is the loss of inscriptions from Inscription Rock (National Park Service 2006). Travelers easily carved images, names, dates, and messages into the surface of the friable (easily crumbled, poorly cemented) Zuni Sandstone (map unit symbol Jz). Today, the rock's friability is the main reason that the famous inscriptions are slowly eroding away (National Park Service 2008a).

Cementation, the chemical process by which unconsolidated sediments are converted into consolidated rock, is the primary lithologic factor in the disintegration of the Zuni Sandstone, and the inscriptions along with it. Common cements include carbonates, quartz, iron oxides, and clay minerals. Throughout much of the Zuni Sandstone, especially the lower portion of Inscription Rock, clay minerals—particularly kaolinite and chlorite—are the only form of cement (Cross 1996). This relatively weak, clay-mineral cement enables the easy removal of sand particles in the Zuni Sandstone (Austin 1994). The breakdown of clay cement also results in clay films that wash over and mask the surface of the Zuni Sandstone, blurring the inscriptions (Austin 1992).

Investigators (e.g., Padgett 1992; Cross 1996; Padgett and Barthuli 1996) have identified other natural factors that have resulted in the loss of inscriptions, including (1) boring of insects into the rock, which accelerates the rate of weathering; (2) physical and chemical damage to the rock surface, and obstruction of the rock art and inscriptions from view, by lichen and mosses; (3) mechanical removal of sand particles by direct moisture from pelting rain or snow and from surface water runoff over the rock face; (4) mechanical removal of sand particles by repeated freezing and thawing; (5) exfoliation of sand particles due to salt formation as a result of recurrent wetting and drying; (6) mechanical removal of sand particles by wind; and (7) erosion and spalling (flaking of surface material) as a result of moisture in the form of percolation into the rock and rising damp (also known as "wicking" or "capillary rise"). Cross (1996) identified numerous areas of spalling from the cliff face above Inscription Rock Trail, notably northeast of the pool. Spalling created the smooth rock face into which Oñate made his inscription in 1605 CE (fig. 7), and the process continues (Wachter 1978).

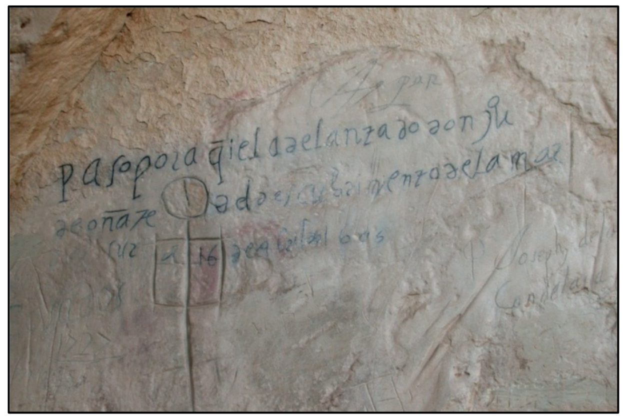

Figure 7. Oñate inscription. A form of rockfall called "spalling" created a smooth surface where Don Juan de Oñate inscribed his name in 1605. The spalling process continues and now threatens the inscription. National Park Service photograph.

Another significant factor in the loss of inscriptions is location. Comparison with photographs taken during a 1955 survey showed that the inscriptions on the northeastern point of Inscription Rock have eroded more rapidly than those at any other El Morro location (Cross 1996). This site is characterized by extreme exposure to the elements and intense disintegration of the Zuni Sandstone (Cross 1996). The northeastern point is subjected to rain and the effects of abrasion by wind-borne particles, and receives all surface drainage from the pool downward. Vegetative differences indicate that this area retains more subsurface water than do surrounding areas (Cross 1996). Moreover, this part of the outcrop is subject to "rising damp"—the upward movement of groundwater into porous sandstone. At El Morro National Monument, rising damp is probably accelerated by surface drying, driven by the region's windy conditions (Cross 1996). Rising damp also occurs near the pool at the base of Inscription Rock, where the outcrop is heavily undercut (Cross 1996) (see "The Pool" section).

In addition to these natural factors, Padgett (1992) identified anthropogenic impacts that have resulted in the loss of inscriptions. In particular, the practice of removing names incised after 1906, the year El Morro became a national monument, occurred during the 1920s, and led to the loss of many historic inscriptions, including the first Bishop of New Mexico, Jean Baptiste Lamy; and Kit Carson, a prominent figure in American history (Padgett and Barthuli 1996). At this time, "modern"/post-1906 inscriptions were considered graffiti and removed by scraping with an axe (Dalton 1971). This practice led to unintended losses by direct scraping, and associated, exacerbated exfoliation of nearly inscriptions (Padgett and Barthuli 1996).

Since the 1920s, park managers have been concerned with protecting inscriptions from the natural elements. Early efforts included covering the carvings with paraffin, chiseling grooves to reroute water flows, and darkening and deepening inscriptions with hard pencils to offset the effects of erosion. These early, well-intended attempts to preserve the inscriptions were intrusive by today's standards and ended in the 1930s. Remnants of the darkening technique used on some of Spanish carvings are visible today (National Park Service 2012b).

Present-day monitoring and preservation of the inscriptions includes intensive documentation and selective conservation treatments. The Inscription Preservation Program at El Morro National Monument began in 1997 and is ongoing. Documentation includes photographing, sketching, and laser scanning (National Park Service 2006). Park managers possess animations of the scanning process that could be incorporated into future interpretive exhibits (National Park Service 2006). Conservation treatments, which may be implemented when the loss of an inscription is imminent, include the use of cement-based grouts to fill voids (keeping water out) and to reattach fragments; consolidation of loose rock around eroded inscriptions with ethyl silicate and epoxide; securing inscription panels with pins; and treatment with calcium hypochlorite, a type of bleach, to stop lichen growth (National Park Service 2005b).

To quantify the rate of erosion, investigators have installed reference pins in several places on Inscription Rock (fig. 8). The distances from the pins to the rock surfaces are periodically measured. Monitoring showed that the rock face at these reference locations eroded about 0.8 mm (1/32 in) over a period of five years, 2000–2005 (National Park Service 2005b).

The goal of the Inscription Preservation Program at El Morro National Monument is to slow the rate of deterioration and loss of "this remarkable record of human passage" by monitoring and treating threatened inscriptions (National Park Service 2005b, p. 2). Nevertheless, whereas the treatments may be effective in the short term, the inscriptions and petroglyphs will ultimately erode away. Such an outlook poses a serious challenge to the mission of the National Park Service, which aims to preserve such features for future generations while allowing natural processes to operate. Although a record of the inscriptions has been created and preserved by laser scanning, park managers must eventually decide whether to let the natural process of erosion take its course, to remove the inscriptions and place them in a museum, or to otherwise artificially seal the rock face.

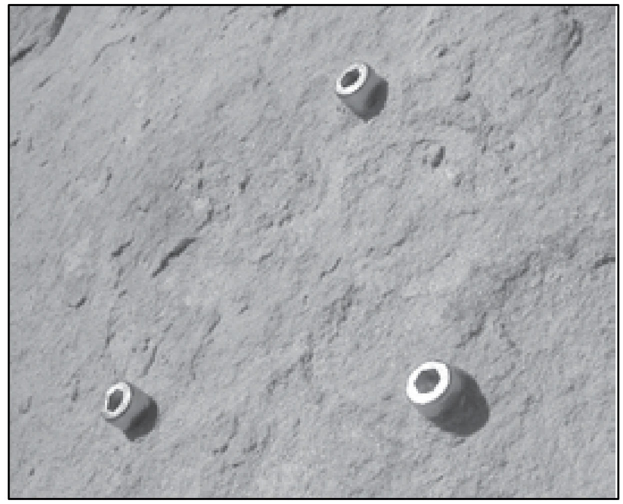

Figure 8. Monitoring loss of inscriptions. At reference locations, investigators periodically measure the distance from pins to the surface of Inscription Rock to determine the rate of erosion. National Park Service photograph.

Rockfall Hazards

Vertical joints are characteristic features of the Zuni Sandstone (see "Geologic Features and Processes" section). The joints allow water infiltration and increase surface area, enhancing weathering and erosion. As a result, large blocks of Zuni Sandstone occasionally break off the cliff face and gradually disintegrate on the adjacent valley floor (Pranger 2002). Significantly, much of the infrastructure at El Moro National Monument, such as the visitor center, picnic area, and campground, is located away from cliffs and associated rockfall hazards (National Park Service 2006). However, a notable rockfall area is the pool, and the trail leading to it, which is part of the popular Inscription Rock Trail (fig. 2). In 1942, a slab of rock broke loose from the cliffs above the pool and completely demolished the 1926 dam built to raise the pool's water level. Roughly 770 m^3 (1,000 yds^3) of rock and sand fell into the pool, filling it about halfway. Large pieces of rock, and concrete from the dam, were thrown down the trail leading to the pool (Gardner 1995). Additionally, dirt and stone filled the crevice above the pool, which had to be cleared to provide safe working conditions for dam repair below. Even with the help of local farmers, cleanup from this event took several months (Greene 1978). Workers placed most of the rock in the swale below the dam, the site of an arroyo filled in 1933 (see "The Pool" section). The potential hazard remains that slabs of rock will detach, fall, and bounce to the trail immediately below the cliffs surrounding the pool (Wachter 1978).

A geologic analysis of rock deterioration at selected NPS archeological sites identified two primary locations at El

Morro National Monument susceptible to rockfall: the northwestern face of Inscription Rock, known as "Woodpecker Rock" (fig. 9), and southeast face of Inscription Rock, which includes the cliffs above Inscription Rock Trail (figs. 10 and 11). Discussion during the 2011 conference call confirmed that these locales remain the primary areas of concern.

The northern face of El Morro is also prone to rockfall (fig. 12). However, this area of the cuesta is away from the popular Inscription Rock Trail loop, and thus is less of a concern for resource management and visitor safety. In addition, Wachter (1978) noted loose blocks of rock in the retaining wall in the switchback area along the Mesa Top Trail (fig. 2). Periodic monitoring and continued upkeep of the retaining wall will remedy this anthropogenic rockfall hazard (Wachter 1978).

Woodpecker Rock

Woodpecker Rock is separated from the main body of the El Morro cliff and rests on a small pedestal of weathered sandstone (fig. 9). According to Wachter (1978), rockfall could be triggered by seismic shock; although the 1978 report does not specify, such shock could presumably be caused by vibrations from a natural earthquake, or by blasting or truck traffic (see "Tinaja Pit" section). Such an event could cause the total failure of an estimated mass of 90,000 to 900,000 kg (100 to 1,000 tons) without warning (Wachter 1978). As the Inscription Rock Trail runs below this monolith, the primary concerns are visitor safety and the destruction of the existing trail (National Park Service 2006).

During the 2011 conference call, El Morro National Monument resource management staff compared the potential failure of Woodpecker Rock at El Morro to the massive rockfall at Pueblo Bonito in Chaco Culture National Historical Park, albeit on a much smaller scale. The 1941 Pueblo Bonito rockfall was one of the most dramatic examples of such an event in a National Park System unit. "Threatening Rock," an immense slab of sandstone above Pueblo Bonito, measured 46 m (150 ft) long, 30 m (100 ft) high, and about 9 m (30 ft) thick and weighed an estimated 27 million kg (30,000 tons) (Judd 1959). On 22 January 1941, Threatening Rock collapsed and destroyed approximately 60 rooms of Pueblo Bonito.

Schumm and Chorley (1964) investigated the fall of Threatening Rock using data gathered on a monthly basis by NPS personnel. These data yielded information on the type, rate, and approximate timing of original movement, which they estimated began in 550 CE. In the last five years that Threatening Rock stood over Pueblo Bonito, the monolith moved 56 cm (22 in); the rate of movement increased steadily until the rock fell, with 25 cm (10 in) of outward movement occurring in the final month. Monthly measurements indicated that the rock was sometimes stationary for periods of several months, but would show relatively rapid and slow movements during other periods. Notably, the periods of rapid movement always occurred in winter, when snow had collected behind the rock. This may have been an important factor in its eventual failure. On the day the rock fell (also a day of regular monthly monitoring), NPS staff heard the rock popping and cracking, and the rock moved outward 0.08 cm (1/32 in) during measuring. According to eyewitness accounts, the rock fell with a combination of tilting and sliding; it initially appeared to settle and move (en masse) away from the cliff and subsequently tilted, probably due to a shift in its center of gravity beyond the shale support beneath it (Schumm and Chorley 1964).

Cliffs above Inscription Rock Trail

The cliffs above Inscription Rock Trail are another area of rockfall concern at El Morro National Monument (see fig. 10). Repeated rockfall and damage to the fence below Inscription Rock (fig. 11) demonstrate the continuous process of slabbing—the splitting of rock into slabs and falling under the force of gravity (Wachter1978; National Park Service 2006). Slabbing poses hazards to people and is a major threat to the inscriptions at El Morro National Monument (Wachter 1978).

Figure 9. Woodpecker Rock. Situated on the northwestern face of El Morro, Woodpecker Rock is separated from the main body of the cuesta and rests on a small pedestal of deteriorated sandstone. The potential for catastrophic failure of the rock is a concern for visitor safety and preservation of the trail that runs below the rock. National Park Service photographs.

Figure 10. Cliffs above Inscription Rock Trail. Areas prone to rockfall include the cliffs above Inscription Rock Trail. The trail is visible in the photograph at the base of the cliff, behind park staff. At the time the photograph was taken, the trail was closed as a result of a rockfall event on 27 June 2006. Management concerns include visitor safety, loss of inscriptions, and damage to the existing trail. Arcuate "lips" of rock with smooth rock faces below indicate areas where slabbing has occurred (arrows; see also fig. 12). National Park Service photograph.

Figure 11. Rockfall. Where designated trails run below cliff faces, such as the Inscription Rock Trail, visitor safety and the destruction of existing trails and fences are resource management concerns related to rockfall. Even small rockfall events, such as the one shown here, displace rocks sufficiently large to injure visitors and impact resources. Other rockfall events, such as the collapse of Woodpecker Rock (fig. 9), would be catastrophic. Much of the infrastructure at El Morro National Monument, such as the visitor center, picnic area, and campground, are located away from cliff faces, so rockfall is not a concern for these structures. National Park Service photograph.

Figure 12. North face of El Morro. The cliff on the northern side of El Morro is susceptible to rockfall. Smooth surfaces on the cliff face are indicative of a process called "slabbing," in which rock splits into slabs and falls under the force of gravity. The freshly spalled surfaces (bathed in light in the photograph) indicate more recent spalling, while the rougher, weathered sandstone on the left of the photograph represents older spalling events. National Park Service photograph.

Wachter (1978) noted that an estimated 200-kg (440-lb) rock fell from above the Oñate inscription (fig. 7) at the time of his geologic analysis. Notable areas of instability along the trail include an arched zone (above the Oñate inscription at trail marker #12) and undermining at the base of the cliff (below the E. Penn Long inscription at trail marker #7).

Monitoring

The National Park Service has regularly monitoring potential rockfall areas along the Inscription Rock Trail. For example, the large crack just beyond trail marker #12 is monitored and believed to be stable (National Park Service 2005b). Four bolts have been placed on opposite sides of this joint to serve as reference points, and park employees periodically measure the distances between bolts to see whether the crack has widened. This joint is also monitored using a tilt meter, which records changes in inclination in two directions. The instrument is located high on the cliff near trail marker #13. Data collected since 2000, when the current measuring devices were installed, suggest that the rock moves slightly (in the range of tenths of millimeters), particularly during freeze-thaw cycles in winter and spring (National Park Service 2005b). At present, movement is inward and outward, with no continuous outward trend (National Park Service 2005b). Monitoring of Woodpecker Rock has been less consistent than along Inscription Rock Trail, and new monitoring equipment, such as a data logger, is needed (Dave Hays and Dana Sullivan, park staff, El Morro National Monument, conference call, 12 December 2011).

Managers at El Morro National Monument may find Wieczorek and Snyder (2009)—the chapter in *Geological Monitoring* (Young and Norby 2009) about slope movement—useful for monitoring rockfall hazards at El Morro National Monunent. *Geological Monitoring* provides guidance for monitoring "vital signs"—measurable parameters of the overall condition of natural resources. The Geologic Resources Division initiated and funded the development of *Geological Monitoring* to provide guidance for resource managers seeking to establish the status and trends of geologic resources and processes within the National Park System, and to advance the understanding of how geologic processes impact ecosystem dynamics (Young and Norby 2009). Wieczorek and Snyder (2009) described the various types of slope movements and mass-wasting triggers, and suggested five vital signs for monitoring slope movements: (1) types of landslide, (2) landslide triggers and causes, (3) geologic materials in landslides, (4) measurement of landslide movement, and (5) assessing landslide hazards and risks.

Tinaja Pit

Approximately 270 million years ago, carbonate muds precipitated from shallow marine waters that spread across New Mexico and became the San Andres Limestone (Psa). During the Laramide Orogeny—a major mountain-building event that started about 70 million years ago—the limestone was raised as part of the uplift of the Zuni Mountains (see "Geologic History" section). Mountain building exposed the limestone along the northeastern and southwestern limbs of the Zuni uplift (Kottlowski 1962). The southwestern limb is in the vicinity of El Morro National Monument (fig. 13).

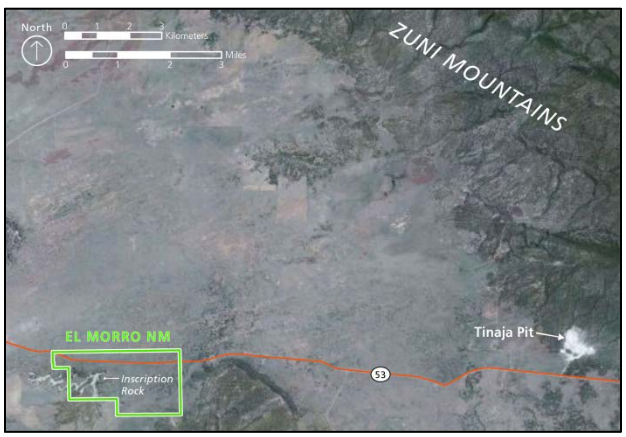

Figure 13. Zuni Mountains and Tinaja Pit. Tinaja Pit is a large aggregate mine targeting the Permian San Andres Limestone (Psa). The uplift of the Zuni Mountains brought the limestone to the surface. Although the pit is located outside El Morro National Monument, mining operations at the pit and transport of the aggregate pose safety and resource management concerns for the national monument. Graphic compiled by Jason Kenworthy (NPS Geologic Resources Division).

Figure 14. Tinaja Pit. Tinaja Pit is a surface mine located 6 km (4 mi) east of El Morro National Monument. Plumes of dust and scarring of the landscape impact the national monument's viewshed. Photograph by Elaine R. King (consultant), used by permission.

The Permian San Andres Limestone is the primary carbonate resource for lime, cement, building stone, and aggregate in the Zuni Mountains (McLemore et al. 1986). It has been mined mainly for aggregate (crushed stone) and is generally suitable for highway construction (McLemore et al. 1986). Overall, the rock formation has high resource and development potential (McLemore et al. 1986). The largest, nearest, and best-quality source of San Andreas Limestone aggregate in northwestern New Mexico is in the area around the Zuni Mountains, where the formation is transected by various highways and is near the railroad (McLemore et al. 1986). Anderson and Maxwell (1991) mapped and described the San Andres Limestone (Psa) as having an upper part composed of massive, pinkish-gray limestone, and middle and lower parts composed primarily of dolomitic limestone (see Map Unit Properties Table).

C & E Concrete, Inc. mines the exposed limestone in the Tinaja Pit, a surface mine 6 km (4 mi) east of El Morro National Monument at the base of the Zuni Mountains (figs. 13 and 14). Smaller gravel pits are scattered throughout the area; four are indicated in the GRI digital geologic map data for El Morro National Monument, but Tinaja Pit is the largest (Wade 2011). The Geologic Resources Division has assisted the staff at El Morro National Monument with analysis of permit applications submitted by C & E Concrete, Inc. to the State of New Mexico. Analysis includes identification of potential impacts to park resources and suggested mitigation measures (National Park Service 2012a). Permit applications by C & E Concrete, Inc. have requested expansion of operations, including the request for an onsite plant to make asphalt incorporating crushed limestone, and expansion of operating hours for blasting, milling, and hauling from daylight hours, 6 days per week, to 24 hours per day, 7 days per week. C & E Concrete, Inc. withdrew the permit request for the portable asphalt plant in March 2006 (Kayci Cook Collins, El Malpais and El Morro national monuments, superintendent, written communication, 20 April 2006). However, the permit request for the expansion of operating hours was under consideration at the time of writing of this GRI report (June 2012).

Figure 15. Highway 53 below Inscription Rock. Highway 53 runs through El Morro National Monument. The National Park Service is concerned about the effect of seismic vibrations on the inscriptions from traffic on Highway 53. Photograph by Elaine R. King (consultant), used by permission.

The ongoing mining operations at the Tinaja Pit affect geologic and other resources at El Morro National Monument. With respect to geologic resources, the National Park Service is concerned about the effect of seismic vibrations on the inscriptions in the friable Zuni Sandstone (Jz). Vibrations occur as a result of various mining operations, including blasting and crushing limestone at the Tinaja Pit, and hauling on Highway 53, which passes through the national monument (fig. 15). In 2003, a preliminary study was conducted to gather seismic data related to blasting at the mine and the hauling of aggregate by trucks. Given the study's short duration, the results were inconclusive (National Park Service 2012a), but the report emphasized the importance of maintaining the Highway 53 road surface to reduce vibrations (King and King 2003).

Mining operations at the Tinaja Pit also are a concern for air quality and the preservation of the national monument's viewshed and soundscape. A plume of limestone dust is emitted during each mining explosion, providing materials for eolian transport. The plume of dust is visible from the top of El Morro, and is thus a concern for viewshed preservation (National Park Service 2012a). "Fugitive dust" caused by heavy, fast-moving trucks hauling aggregate near and through the national monument is another concern related to eolian processes. Traffic stirs up the dust, which is made available for transport by wind.

The noise from hauling trucks is a concern for the preservation of the national monument's soundscape. Moreover, the speed and size of hauling trucks raise major concerns about the safety of wildlife crossing the highway and of visitors and staff traveling along it. Eringen (2003) suggested that mining operations may also impact biological resources, such as nesting prairie falcons and migrating golden eagles, bald eagles, peregrine falcons, and great horned owls, although no specifics were provided. Park managers are exploring ways to address these issues in collaboration with the state (Julia Brunner, NPS Geologic Resources Division, policy and regulatory specialist, written communication, 13 June 2012).

Geologic Features and Processes

Geologic resources underlie park ecosystems and geologic processes shape the landscape of every park. This section describes the most prominent and distinctive geologic features and processes in El Morro National Monument.

Discussions during a pre-scoping conference call (16 March 2006), the scoping meeting (30 March 2006), and a post-scoping conference call (12 December 2011) provided opportunities to develop a list of geologic features and processes at El Morro National Monument:

- El Morro and Inscription Rock
- Box Canyon
- The Pool
- Ephemeral Streams and Arroyos
- Tinajas
- Eolian Features and Processes
- Lava Flows
- Unconformities
- Paleontological Resources

El Morro and Inscription Rock

For hundreds of years, travelers recognized that the sandstone promontory known as "El Morro," meaning "the headland" in Spanish, marked a significant source of water in the region. The ancestral Puebloans referred to El Morro as Atsinna, or the "place of writings on the rock." Their petroglyphs depicting bighorn sheep, bear claws, anthropomorphs, handprints, and geometric symbols, such as zigzag lines and concentric circles, were part of the long tradition of rock carving at this location (fig. 16). As later travelers rested and drank from the pool at the base of the headland, they carved their names and other inscriptions into the surface of the soft Zuni Sandstone (map unit symbol Jz), which makes up the cliff face. As a result, the cliffs of El Morro have become known as "Inscription Rock."

Geomorphically, El Morro is a landform called a cuesta, which is an inclined mesa of tilted strata. Cliffs bound one flank of El Morro, and the rock of the opposite flank dips into the subsurface. The northeastern point of the cuesta forms the tallest cliffs and exposes the most stratigraphy. At this location, lower/older strata of the Zuni Sandstone are exposed. Walking away from this point along the northern or eastern wall, one moves "upsection" or progressively forward in geologic time (see Geologic Map Overview Graphic).

Inscription Rock, which rises 60 m (200 ft) above the valley floor, is made mostly of 160-million-year-old Zuni Sandstone (Jz) but is capped by a thin layer of 96-million-year-old Dakota Sandstone (Kdm). Although Dakota Sandstone deposits are up to 45 m (150 ft) thick elsewhere, their maximum thickness at the top of Inscription Rock (and at El Morro National Monument) is 15 m (50 ft) (Cross 1996; Lucas 2010).

Figure 16. Petroglyphs. Known as "Atsinna" or "place of writings on the rock," El Morro is the site of many images. Ancestral Puebloan artists seemed to have preferred to incise iron-stained joint surfaces, rather than unstained sandstone surfaces. Photograph by Dale Dombrowski (El Morro and El Malpais national monuments).

Zuni Sandstone

Zuni Sandstone is remarkably homogeneous, composed of 73% to 86% (by weight) fine-grained sand (Cross 1996). Most of the sand grains that compose the sandstone are quartz, with a lesser amount of feldspar (Cross 1996). Silt makes up 5% to 18% of the sandstone by weight, and clay comprises 9% to 11% (Cross 1996). Sand grains in the Zuni Sandstone are held together by clay cement.

The Zuni Sandstone exposure at Inscription Rock can be divided into an upper, middle, and lower package of rock (Cross 1996). The upper and lower parts contain large-scale cross-beds (fig. 17), whereas the middle part contains smaller cross-beds and undulating bedding. The unit's distinctive bleached zone (see front cover) lies above the upper cross-bedded section. Weathering

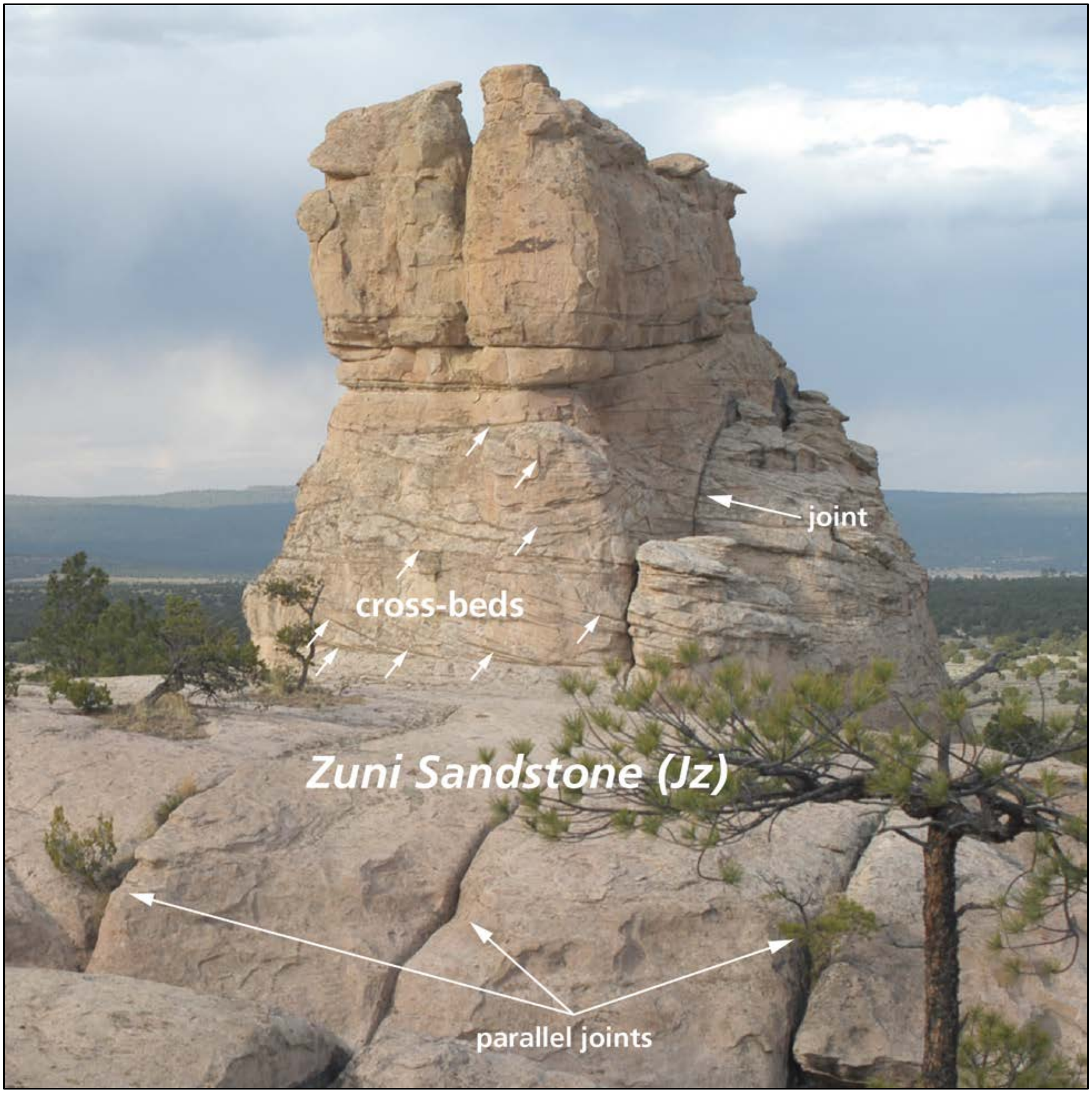

Figure 17. Cross-beds and joints in Zuni Sandstone. Cross-bedded strata of the Zuni Sandstone (Jz) are indicative of an eolian depositional setting. During the Middle Jurassic Period, the Zuni Sandstone was deposited in a dune field that covered much of the land now comprising northwestern New Mexico, northeastern Arizona, southeastern Utah, and southwestern Colorado (fig. 28). Parallel joints are also characteristic of the Zuni Sandstone (fig. 18). These joints formed as a result of confining pressure while the sandstone was buried, and uplift, probably during the rise of the Zuni Mountains. National Park Service photograph by Sarah Beckwith.

processes affected the original clay minerals and feldspar in this portion of the rock, altering them to well-crystalized, white kaolinite (Austin 1992; Spoelhof 2005). Leaching also occurred, removing soluble ions as iron oxidized (Austin 1992). Groundwater dissolved and transported the soluble iron downward along fractures in the Zuni Sandstone. The iron was then redeposited as the dark crusts and bands of color, called "Liesegang banding," that parallel the joints in the sandstone (Spoelhof 2005). Iron removal and the alteration of clay minerals and feldspars produced the white bleached horizon (Cross 1996; Spoelhof 2005). Bleaching occurred between the Middle Jurassic (175 million–161 million years ago) and Upper Cretaceous (100 million–65.5 million years ago) periods, after rocks of this age, namely the Morrison Formation, were stripped away, creating an unconformity (see "Unconformities" section).

Dakota Sandstone

The Dakota Sandstone (Kdm) rests on top of the bleached zone. In places, pieces of the underlying Zuni Sandstone were incorporated into the overlying Dakota Sandstone (Kelley 2008), which Anderson and Maxwell (1991) mapped as reworked Zuni Sandstone (Kl) of uncertain but possibly Lower Cretaceous age (145 million–100 million years ago). The reworked Zuni Sandstone is a sandy to gravelly stream deposit containing pieces of the Middle Jurassic Zuni Sandstone.

Typical examples occur along the trail on top of Inscription Rock (Anderson and Maxwell 1991).

The lithology of the Dakota Sandstone ranges from conglomerate to black shale. Outside of El Morro National Monument, the unit contains plant fragments, small pieces of petrified wood, and evidence of biological reworking. None of these paleontological features are found in the Zuni Sandstone (Cross 1996) (see "Paleontological Resources" section).

The lower and middle parts of the Dakota Sandstone are preserved within El Morro National Monument. The lower part is cross-bedded sandstone with lenses of conglomerate containing pebbles of chert and quartzite. The overlying middle part is gray mudstone and shale, on which the pueblo ruins were built.

Joints and Banding

Other features of Inscription Rock include vertical joints and banding. Large, vertical fractures, called "joints," split the Zuni Sandstone (Jz) (figs. 17 and 18). Joints are distinct from faults in that they lack signs of movement or slippage. Two sets of parallel joints are present at El Morro; the dominant set is oriented (strikes) N65°E and the other set strikes N10°W (Cross 1996). When erosion occurs, slabs of rock at joint surfaces fall under the force of gravity. As the outer rock falls away, the cliff remains vertical (see "Rockfall" section). Jointing likely resulted from stress imparted during burial of the sandstone and later uplift (Cross 1996). The stress may have been related to tectonic forces causing the movement of the North American continental plate, or to more local uplift of the Zuni Mountains (Spoelhof 2005).

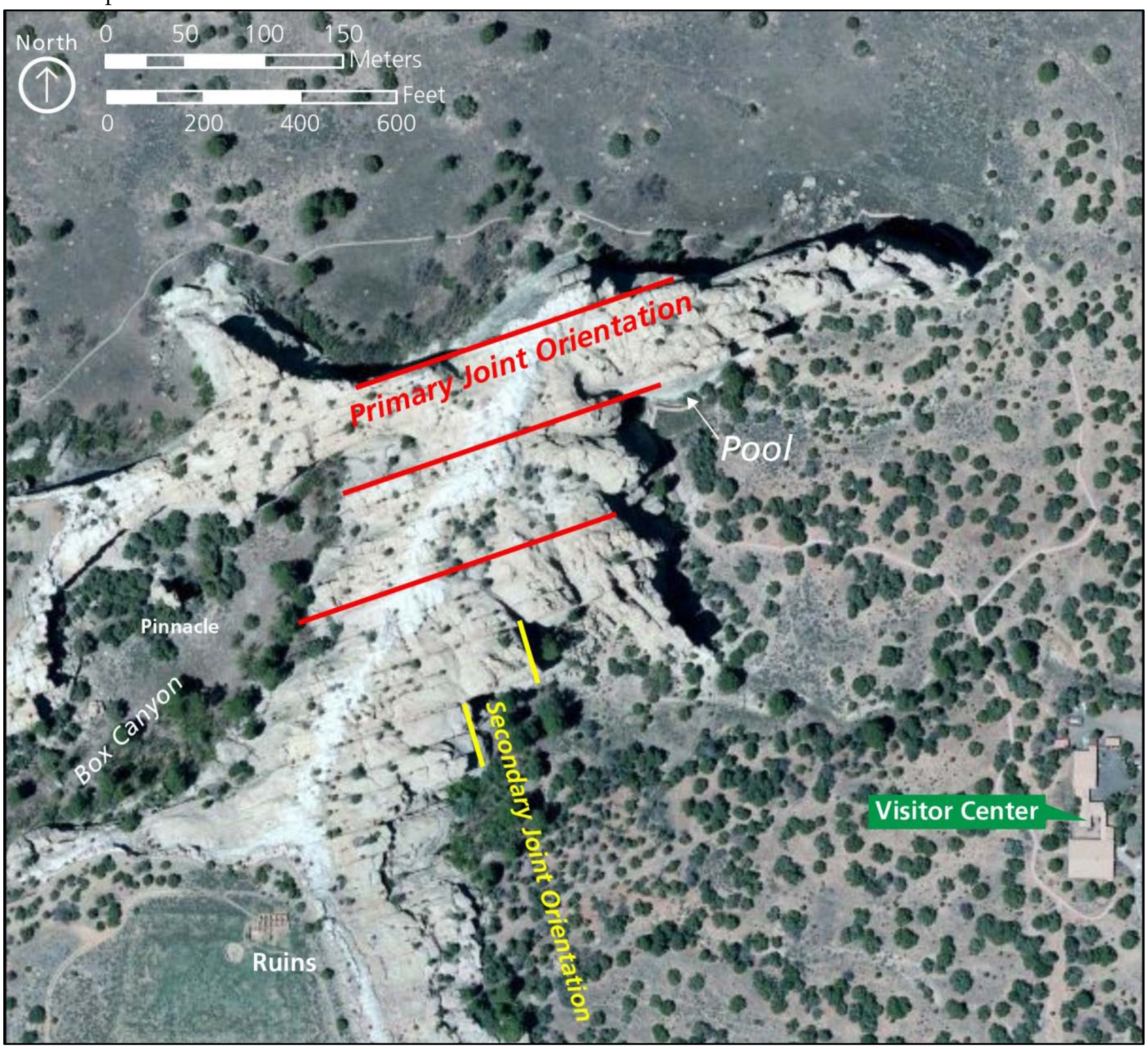

Figure 18. Aerial view of El Morro cuesta. El Morro is a tilted mesa called a "cuesta." The Zuni Sandstone (Jz) that makes up the bulk of the cuesta is heavily jointed in two directions: northeast–southwest (note fractures and cliff faces parallel to red lines), and northwest–southeast (note fractures and cliff faces parallel to yellow lines). As indicated on the figure, the joint pattern dictated the overall shape and orientation of the cuesta. The box canyon that cuts the cuesta contains a distinctive erosional pinnacle of rock. Note the location of the Atsinna Pueblo (ruins) atop the cuesta, and the pool, which is accessible by Inscription Rock Trail. Graphic compiled by Jason Kenworthy (NPS Geologic Resources Division). Imagery from ESRI Arc Map, Bing Maps aerial basemap layer.

The joints in the Zuni Sandstone are discolored and commonly coated with brown and yellow iron oxides, which appear as streaks or bands on the sandstone (see figs. 19, 21, and 22). Called "Liesegang banding," these stains formed via precipitation of iron from iron-rich groundwater along the joint surfaces (Austin 1992; Cross 1996). Staining occurred before the Dakota Sandstone (Kdm) was deposited (Austin 1992; Cross 1996). Liesegang banding occurs in and near the bleached horizon at the top of the sandstone monolith (see "Zuni Sandstone" section). Ancient Puebloan artists seem to have preferred to incise the iron-stained joint surfaces, whereas Spanish and Anglo travelers, who carved mostly letters, preferred unstained sandstone surfaces (Austin 1992).

Other streaking on Inscription Rock is likely a combination of lichen and case hardening (Pranger 2002). In contrast to Liesegang banding, case hardening is the concentration and accumulation of iron oxide and chlorite in areas of surface water (not groundwater) flow. White streaks appear to be salts produced by lichens (St. Clair and Knight 2001).

Figure 19. Alcove surrounding the pool. Inhabitants and visitors have used the pool at the base of El Morro for hundreds of years. The pool is situated in an alcove, which sheltered travelers from the sun and storms. The pool provided potable water. Note the large boulder that fell from the cliff (arrow) and the occurrence of banding on the cliffs. National Park Service photograph.

Box Canyon

The top of the El Morro headland offers stunning views of the Zuni Mountains, the volcanoes of the El Malpais area, and the surrounding valley. Hikers along the Mesa Top Trail are also rewarded by views into a box canyon that penetrates the El Morro cuesta (fig. 20). The view includes a top-down perspective of a distinctive pinnacle of rock that stands isolated near the head of the canyon. The box canyon and pinnacle of rock are distinctive geologic features at El Morro National Monument.

In 2003, Bob Spoelhof—a Geoscientist-in-the-Parks (GIP) participant at El Morro National Monument—hypothesized that the box canyon formed as a result of runoff down the gentle backside of the El Morro cuesta, which is tilted 3° southwest. This hypothesis was informally published in 2005 as part of a site bulletin, "El Morro Geology" (Spoelhof 2005). However, Pranger (2002) suggested that scour from surface water runoff during storms is a relatively insignificant erosional process on Inscription Rock. By contrast, groundwater sapping is a major erosional process at El Morro, and based on work by Cross (1996), Pranger (2002) suggested that groundwater sapping was responsible for the development of the box canyon.

Groundwater sapping is a generic term for weathering and erosion of rock by groundwater that flows through and emerges at the surface of a rock outcrop (Howard and Kochel 1988). Sapping-dominated areas commonly result in spalling and alcove development (Pranger 2002). Spalling is caused by the interplay of moisture and the formation of salts. When water percolates through permeable sandstone, it carries minerals that are brought to the rock surface. These minerals accumulate and form a surface layer that is harder and less permeable than the underlying sandstone. Salts are repeatedly deposited behind this surface and eventually cause flakes or chips of rock to spall off (Cross 1996). On a larger scale, the emergence of groundwater at cliff faces reduces the support of steep cliffs and contributes to collapse (Laity and Malin 1985). Fractures within a rock body often concentrate groundwater flow and sapping activity (Howard and Kochel 1988). Refer to the "Rockfall" section for additional information.

Studies of other box canyons on the Colorado Plateau, in particular those in the Glen Canyon region, have highlighted the role of groundwater sapping in valley evolution (Laity 1983, 1988; Howard and Kochel 1988; Kochel and Riley 1988). These studies suggested that the following factors are significant in the development of box canyons:

- Joint formation—In the case of El Morro, joint formation in the Zuni Sandstone (Jz) may have been the result of stress applied and released during uplift of the Zuni Mountains (Spoelhof 2005).
- Loss of cap rock—In the case of El Morro, Dakota Sandstone (Kdm) forms the cap rock. When the cap rock was removed by erosion, precipitation (rainwater and snowmelt) exploited the jointed rock, infiltrating the underlying Zuni Sandstone (Jz). The spire of rock in box canyon retains a cap of Dakota Sandstone, which may be the reason that it is still standing.
- Groundwater sapping—Pervasive fracturing, such as jointing in the Zuni Sandstone (Jz), greatly increases the overall permeability of the mesa surface and the contribution of precipitation to the groundwater system (fig. 18). Fractures concentrate groundwater flow. As suggested by Spoelhof (2005), an erosional notch southwest of the cuesta may have caused groundwater to converge at this point, initiating canyon formation. Increased groundwater flow enhances local weathering and initiates the sapping process.

Figure 20. Box canyon. The box canyon in the El Morro cuesta formed via groundwater sapping. Hikers along the Mesa Top Trail can look down into the canyon and see a distinctive rock pinnacle capped by Dakota Sandstone (Kdm). National Park Service photograph.

- Mass movement—Mass movement is ongoing at El Morro National Monument, as demonstrated by Woodpecker Rock (see “Rockfall” section). In this process, sandstone blocks separated by joints become detached and move away from the cliff face, in turn settling and ultimately collapsing onto the valley floor. Smaller-scale forms of mass movement, such as spalling and alcove formation, also occur as a result of groundwater sapping
- Weathering—The mechanically weak Zuni Sandstone (Jz) shatters readily upon impact and is further comminuted by active weathering processes. Boulders at cliff bases are commonly friable, rounded in situ, and surrounded by aprons of loose sand (Laity and Malin 1985).
- Transport of rock debris—Disintegrated material is removed by surface wash and wind action. Anderson and Maxwell (1991) mapped this disintegrated material as alluvium (Qal), including eolian and colluvial deposits, which covers the floor of the box canyon at El Morro National Monument (see Geologic Map Overview Graphic).

The Pool

The story of El Morro illustrates the importance of water to civilization (West and Baldwin 1965). Ancestral Puebloans settled atop the El Morro cuesta because of the pool at the base of the rock (West and Baldwin 1965). These inhabitants carved handholds and toeholds leading from the pool to the top of the mesa (Padgett and Barthuli 1996). Later, Spanish and American travelers planned stops in their journeys at Inscription Rock because the pool provided freshwater for them and their horses, and the alcove surrounding the pool provided shelter from the sun and storms (West and Baldwin 1965) (figs. 19 and 21).

When the transcontinental railroad, and later U.S. Route 66, were constructed 40 km (25 mi) north of El Morro, the route to this watering place lost its prominence for travelers. However, the pool continued to be a reliable source of potable water for local farmers and ranchers until the late 1930s, when the government prohibited water hauling because of damage to vegetation (Greene 1978). The National Park Service continued using the pool as a domestic water supply until 1961, when a well with a Quaternary alluvium (Qal) source was drilled in the northwest corner of the monument to provide water for human consumption (West and Baldwin 1965).

Figure 21. The pool. The pool provided freshwater for travelers and their horses, and was the primary reason that people stopped or settled at El Morro for centuries. Today, the pool is primarily a source of water for wildlife. Note the occurrence of black banding on the cliff face behind the pool. National Park Service photograph.

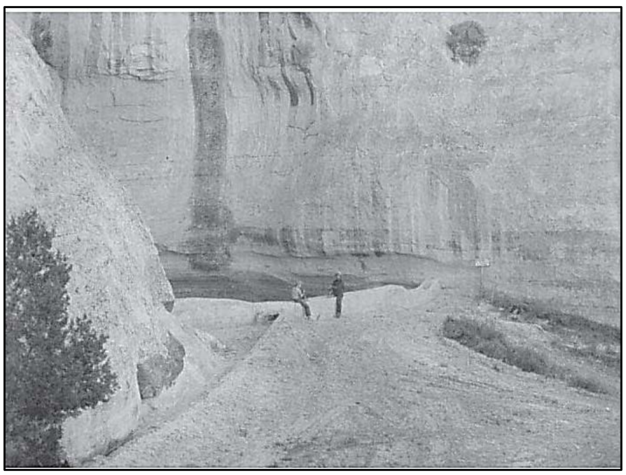

Figure 22. Concrete dam (1934). The pool at El Morro has been repeatedly modified by humans. The first concrete dam was built in 1926 and severely damaged by rockfall in 1942. In the 1970s, the National Park Service began considering removal of the dam and restoration of the pool to natural conditions. However, returning the pool to its natural state or historic appearance would require careful examination of past conditions, and the dam remains to the present day. National Park Service photograph.

Today, only local wildlife uses the pool's water (National Park Service 2008b) (fig. 21).

Over centuries, the pool formed as rain and snowmelt cascaded off Inscription Rock. Two ephemeral waterfalls empty into the pool: the northern fall drops approximately 21 m (70 ft), and the southern fall drops approximately 27 m (90 ft) (Anderson and Maxwell 1991). On top of the mesa, a limited catchment basin (a few acres in size) feeds the two waterfalls during periods of heavy precipitation (Anderson and Maxwell 1991). The splashing action of the falling water created the initial pool depression, which may have been partly in bedrock; now, the pool appears to be based in unconsolidated material that has fallen, washed, or blown into the alcove on the lee side of the mesa (Anderson and Maxwell 1991). Within the standing water of the pool, fine-grained suspended sediment settled out and sealed the bottom, increasing the effectiveness of containment. The thickness of the fine-grained material at the bottom of the pool is unknown (Anderson and Maxwell 1991).

The neutral chemistry (pH 7) of the pool's water (Austin 1992) and the geomorphic setting of intermittent waterfalls cascading into a basin suggest that the main source of water in the pool is rainfall and snowmelt. However, given the perennial presence of water in the pool, even in dry seasons, travelers and scientists have proposed that it must have a groundwater source. Although no spring has been found at El Morro National Monument, the 1963 USGS El Morro quadrangle (scale 1:24,000), which Anderson and Maxwell (1991) used as a base for geologic mapping, shows five springs north of the plain of basalt flows (Qb) that covers a portion of the national monument. Another spring is located directly east of the national monument in alluvium, colluvium, and eolian deposits (Qac).

In 1849, First Lieutenant James H. Simpson of the Corps of Topographic Engineers was the first American emigrant to describe the pool as a "spring." However, in 1885, A. F. Bandelier, F. H. Cushing, and F. W. Hodge—noted archeologists and ethnologists—explored El Morro and found no trace of a spring. At the time of their visit, the pool was nearly dry (Greene 1978). Spanish explorers' narratives refer to El Morro as a "water pool" or "tank," rather than a seep or spring. Research is seeking to determine whether the pool is fed by a spring (Spoelhof 2005). Van Dam and Hendrickx (2007) and Soles and Monroe (2012) provided more detailed information regarding the hydrology and monitoring of the pool. According to van Dam and Hendrickx (2007), additional information is needed to definitively conclude if the pool's water source is completely run-off or if there is some significant groundwater component.

Additional features of the (original) pool include a sand embankment that once surrounded the basin (Greene 1978). The presence of inscriptions on the back wall of the pool area is evidence that travelers were once able to walk around the pool on this sand bank (Slater 1961; Greene 1978). Between 1846 and 1875, at least 43 inscriptions were placed on the rock behind the basin; another was placed there in 1898 (Greene 1978). These inscriptions have since disappeared, possibly as a result of undercutting and spalling due to the higher water level in the pool after a dam was built in 1926 (Dalton 1971) (see "Loss of Inscriptions" section). Although the pool's water level and, consequently, the size of the sand bank were subject to fluctuations with the amount of precipitation, the presence of the sand bank was presumably fairly constant prior to dam construction (Greene 1978).

The first NPS caretaker of El Morro National Monument enlarged the pool with a small concrete dam in 1926 (fig. 22). While cleaning out the pool in preparation for dam erection, workers uncovered cedar posts and rock—the remains of a dam dating to the 1850s or earlier (Greene 1978). This previous dam had been constructed a short distance above the location of the new dam, suggesting that the pool was confined to a considerably smaller area in the middle of the 19th century (Greene 1978).

In 1942, rockfall destroyed the 1926 dam (see "Rockfall" section). The National Park Service rebuilt the dam in 1943. The modified dam was 15 m (50 ft) long, 4 m (13 ft) high, and approximately 36 cm (14 in) thick (Greene 1978). After these improvements, the pool was a maximum of 3.7 m (12 ft) deep and held about 760,000 L (200,000 gal) water at capacity (Baldwin and West 1965). The modified pool measures approximately 24 m (80 ft) north–south and 10 m (35 ft) east–west (Anderson and Maxwell 1991). In the 1970s, the National Park Service began to consider removal of the dam and restoration of the pool to natural conditions (Greene 1978). However, the dam remains to the present day. Returning the pool to its natural state or historic appearance would require careful examination of past conditions (Padgett and Barthuli 1996).

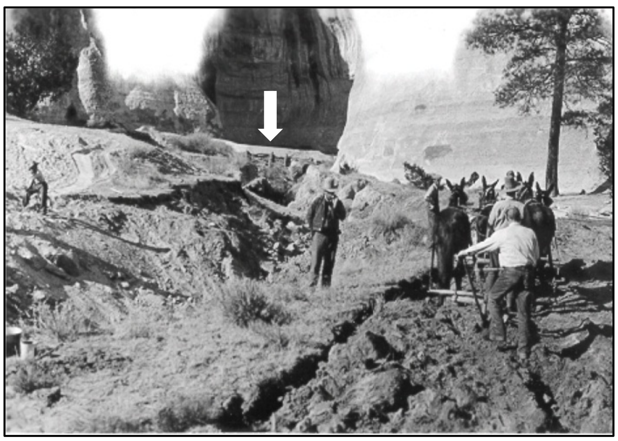

Figure 23. Arroyo filling. The most significant arroyo at El Morro National Monument emerged from the pool at the base of Inscription Rock. The arrow on the figure marks the location of the pool. In 1933, the Civil Works Administration completely filled this arroyo in an effort to restore the conditions around the pool to those existing at the time of Spanish exploration. National Park Service photograph.

An arroyo (meaning "stream" in Spanish) once led from the pool (see "Ephemeral Streams and Arroyos" section), but this feature has also been modified. In 1889, investigators from the Bureau of American Ethnology documented the existence of an arroyo just east of the pool and suggested that it had been created by runoff from the pool. At that time, the arroyo was narrow; a member of the party recalled easily stepping across the gully at its widest place (Greene 1978). Between 1889 and 1916, erosion deeply cut the arroyo to a width and depth of 5 m (15 ft) (Greene 1978). In an effort to restore the conditions around the pool to those existing at the time of Spanish exploration, the Civil Works Administration completely filled the arroyo by blasting the sides with dynamite and plowing and scraping the material into the gully in 1933 (Greene 1978) (fig. 23). Pranger (2002) discussed the possibility of reconstructing the arroyo to reduce the water table around the pool, and thereby, to improve the chance of preserving the inscriptions. Such an action could effectively reduce at least one contributing factor that affects the most actively disintegrating section of Inscription Rock (Pranger 2002). However, more investigation would be needed to determine the benefit of arroyo reconstruction (Pranger 2002).

Ephemeral Streams and Arroyos

North of El Morro National Monument, the forest-covered slopes of the Zuni Mountains rise 2,700 m (9,000 ft) above sea level. Many streams in the Zuni Mountains have carved deep canyons into the slopes. However, none of these streams crosses the lava plain—composed of basalt flows (Qb)—to flow through the national monument; all of the water sinks into the lava very quickly (West and Baldwin 1965).

All streams in the national monument are ephemeral, forming during storm events as a result of runoff from the cuesta. Runoff erodes alluvial material, producing arroyos, as well as deposits alluvial material (Qal), which covers the floor of the box canyon, spreading beyond the sandstone walls to the west.

In the Southwest, the term "arroyo" is applied to streambeds that are dry except during flash floods. Arroyos are commonly seen as "a symptom that something is wrong and that someone or something is to blame" (Love and Gellis 2008, online information). However, the natural function of arroyos is complex and depends on several independent and linked variables of landscape, climate, vegetation, and land use (Love and Gellis 2008). The most significant arroyo at El Morro National Monument emerged from the pool at the base of Inscription Rock. In 1933, the Civil Works Administration completely filled this arroyo (see "The Pool" section). Another notable arroyo runs adjacent to the present-day maintenance compound (National Park Service 2006). In an attempt to slow erosion, the National Park Service placed barricades and slash in this arroyo (National Park Service 2006), as well as deposited appliances and barrels of unknown material (Dave Hays and Dana Sullivan, park staff, El Morro National Monument, conference call, 12 December 2011). This practice has stopped, and the National Park Service is presently considering remediation strategies, although no project date has been set (Dave Hays and Dana Sullivan, conference call, 12 December 2011).

Tinajas

Natural depressions eroded into bedrock act as catchment basins for rainwater and snowmelt. The Spanish word "tinaja," meaning bowl or jar, is often used for these features in the southwestern United States. They are also referred to as "desert potholes." Tinajas are of special interest as a surface water resource in arid lands because they are often the only sources of water for human travelers and wildlife in an area. Furthermore, these features create fascinating miniature ecosystems inhabited by species that have developed extraordinary adaptations for survival in extreme conditions (Doelling et al. 2000). In addition, large depressions can serve as natural traps for animals, which fall in while trying to get water and drown or starve to death. Some “animal traps” are valuable repositories for paleontological material, such as deposits of recently extinct animals (Ives 1948).

A primary characteristic of tinajas is that they form in bedrock. In the Colorado Plateau region, bedrock is usually characterized by flat, exposed surfaces of porous eolian sandstone (Chan et al. 2005, 2006), such as the Zuni Sandstone (Jz) at El Morro National Monument. Cross (1996) documented tinajas in the topmost bleached zone and the iron-stained zone of the Zuni Sandstone (Jz), as well as within the Dakota Sandstone (Kdm) cap rock (fig. 24).

Figure 24. Tinaja. Natural depressions eroded into bedrock act as catchment basins for rainwater and snowmelt. At El Morro National Monument, tinajas occur in the topmost bleached horizon of the Zuni Sandstone (shown here), the iron-stained zone of the Zuni Sandstone (Jz), and on the cap rock Dakota Sandstone (Kdm). National Park Service photograph by Sarah Beckwith.

Another characteristic of tinajas is that they form naturally, although their origin continues to be a scientific enigma. Early attempts to explain their formation included unequal weathering of rock surfaces by glaciers, streams, dissolution, and even sea urchins (Elston 1917, 1918; Bryan 1920; Ross 1923; Alexander 1932). Recent investigations have led researchers to hypothesize that the development of tinajas has strong biological ties. Despite extreme seasonal and daily fluctuations in moisture, temperature, and pH, organisms adapt and flourish within tinajas (Chan et al. 2001). Many species become dormant when these features dry, and must endure intense heat, UV radiation, desiccation, and freezing, but flourish again upon rehydration. These life-forms appear as a complex black biofilm within tinajas, which may dissolve the cement between sandstone grains, allowing the features to enlarge, and also seal the tinajas, enabling them to retain water longer than the surrounding sandstone (Chan et al. 2001). Bryan (1923, p. 301) observed that the bases of these depressions are covered by “an effective seal composed of the slime from decayed organic matter and dust.”

Most tinajas are passive water sources, relying on direct precipitation for recharge, as opposed to active water sources such as springs (Brown and Johnson 1983). The water in tinajas can be ephemeral, intermittent, or perennial (Brown and Johnson 1983). Factors that affect the presence or longevity of water in a tinaja include the amount of protection or shade, the size of the adjacent bedrock catchment area, the amount of sediment infilling, and the permeability of the bedrock (Brown and Johnson 1983; Pate and Filippone 2006).

In many areas in the arid Southwest, humans have altered tinajas to enhance water collection for human and livestock consumption (Brown and Johnson 1983), and improve habitat for desert bighorn sheep (Monson and Sumner 1980). The inhabitants of Atsinna Pueblo collected water from many tinajas distributed across the top of the mesa (National Park Service 2007), and also enlarged these catchment basins and created channels or slopes that fed into them (Cross 1996).

Eolian Features and Processes

The most conspicuous eolian feature at El Morro National Monument is the Zuni Sandstone (Jz). During the Middle Jurassic Period (approximately 160 million years ago), El Morro was at the southern edge of a vast desert (see “Geologic History” section) where wind was the primary transporter of fine-grained sand that became well sorted and well rounded during eolian transport. The sand was piled into dunes and spread into sheets, and the cross-beds and flat-lying beds of the Zuni Sandstone are indicative of eolian deposition (Lucas 2010). Cross-beds occur where sand was deposited at an angle to the horizontal plane, such as along the advancing front of a dune. Horizontal beds and laminated sand layers in the Zuni Sandstone represent rapid sedimentation or high wind velocities (Cross 1996). Brookfield (1977) ascribed the origin of major bounding surfaces between cross-beds to dune migration over interdune areas.

The cross-bedded strata of the Zuni Sandstone dip predominantly to the southwest, indicating that the transporting winds were primarily from the northeast, although wind patterns would have been modified locally by mountains and intense heating over the continental interior (Kocurek and Dott 1983). During the Middle Jurassic Period, the land comprising what is now northern New Mexico was 800 km (500 mi) inland from the active western continental margin (Cross 1996), compared with today’s distance of more than 1,000 km (600 mi).

Today, northern New Mexico is about 35° north of the equator. However, at the time of deposition of the Zuni Sandstone, the land of northern New Mexico was situated between 12° and 15° north of the equator and moving northward (Kocurek and Dott 1983). This paleolatitude range would have been associated with the paleo-trade winds (Kocurek and Dott 1983). Then as now, that area of the globe encourages the formation of trade-wind-type deserts, and most modern hot deserts of the world occur within the trade wind belt. With respect to paleolatitude, El Morro was similar to the modern Western Sahara Desert during the Jurassic Period (Kocurek and Dott 1983).

In map view, another conspicuous feature at El Morro is the triangular apron of Quaternary (Holocene and Pleistocene) sediments, including windblown silt surrounding the sandstone cliffs. This apron of sediment (Qac) is composed of alluvium, colluvium, and eolian deposits, and readily seen on the digital geologic map of El Morro National Monument (see Geologic Map Overview Graphic). Anderson and Maxwell (1991) also mapped windblown silt and sand in small sand dunes and sand sheets (Qe) across the El Morro quadrangle. As a group, eolian deposits (Qe) are the youngest geologic deposits in the area, with the oldest dunes and sheets being only a few thousand years old (Lucas 2010). Scoping session participants noted that small sand dunes are scattered throughout El Morro National Monument (National Park Service 2006). Furthermore, the entire area surrounding the national monument is characterized by small eolian deposits oriented east–northeast (Anderson and Maxwell 1991). Blowouts, with dunes on the lee (east–northeast) sides, are common in the northern part of the El Morro quadrangle (Anderson and Maxwell 1991).

The friable Zuni Sandstone is a source of eolian sediment today. Eolian sand is accumulating at the base of Inscription Rock (Lucas 2010), highlighting the main resource-management issue concerning eolian processes at El Morro National Monument: wind erosion is contributing to deterioration of the sandstone upon which ancient and historic travelers left inscriptions (National Park Service 2006). Wind is a powerful agent of erosion, and is known to blow rocks off the top of Inscription Rock during high winds (Dave Hays and Dana Sullivan, El Morro National Monument, conference call, park staff, 12 December 2011). Also related to resource management, eolian processes may play a role in the formation of tinajas. For example, some deep tinajas contain piles of windblown sand indicative of such processes (personal communication by Netoff [2000] in Chan et al. 2005, p. 284) (see “Tinajas” section).

Finally, eolian processes are significant for landscape evolution. Eolian silt has “infilled” the vesicles, cracks, and fissures of the basalt flows (Qb) at El Morro (see “Lava Flows” section). Infilling by windblown dust, called “loess,” is the first stage in soil development on a lava flow. As a lava flow fills in and attains a smooth surface, vegetation augments sedimentation by influencing moisture content and trapping sediment. Bauman (1999) studied the influences of climate, provenance (source of sediment), and surface cover on soil formation within the Carrizozo lava flow in central New Mexico. A significant finding of this study was that the soils on the flows are of eolian origin and are not the products of basalt weathering. Eolian infilling is also a useful tool for geologists estimating the relative ages of various lava flows. For example, a clean, silt-free surface indicates a “youthful” lava flow; depressions filled with silt indicate a flow of moderate age; and removal of topographic highs by silt indicates old age (KellerLynn 2011).

Lava Flows

El Morro National Monument contains one volcanic rock unit: an aa lava flow (National Park Service 2006). Aa flows are characterized by relatively high viscosity lava with rough (blocky, rubbly, or clinkery) flow tops. Anderson and Maxwell (1991) mapped basalt across much of the northern boundary and eastern half of El Morro National Monument. The basalt flows (Qb) cover a much greater area to the north, northeast, and northwest of the national monument. The basalt is weathered and generally covered with soil, alluvium (Qac or Qal), or sand dunes (Qac or Qe), and open grasslands with small outcrops of basalt have formed (Anderson and Maxwell 1991). The road to the campground at El Morro National Monument crosses exposures of lava, and the campground is situated on a lava flow (see “Geologic Map Data” section).

The basalt flows (Qb) at El Morro erupted from the Zuni–Bandera volcanic field east of the national monument (fig. 25). El Malpais National Monument is centered on this volcanic field (KellerLynn 2012a). Flows from the volcanic field cover the area between El Morro and the Bandera Crater of El Malpais, a distance of about 40 km (25 mi) (New Mexico Bureau of Geology and Mineral Resources 2003). The Zuni–Bandera volcanic field is situated along a zone of crustal weakness called the “Jemez lineament,” which extends from central Arizona to northeastern New Mexico (fig. 26). The Jemez lineament contains numerous volcanic fields. From west to east in New Mexico, these are the Zuni–Bandera volcanic field, the Mt. Taylor volcanic field, the Valles Caldera, the Ocaté volcanic field, and the Raton–Clayton volcanic field. El Malpais and El Morro national monuments lie near the center of the lineament.

The National Park System is well represented along the Jemez lineament. In addition to El Morro and El Malpais national monuments in the Zuni–Bandera volcanic field (KellerLynn 2012a), Fort Union National Monument is surrounded by the Ocaté volcanic field (KellerLynn 2012b), Capulin Volcano National Monument is part of the Raton–Clayton volcanic field (KellerLynn 2011), and Bandelier National Monument is situated in the Valles Caldera (National Park Service 2005a). The Jemez Mountains lie at the intersection of the Jemez lineament and the Rio Grande rift. This rift runs north–south across the state and intersects the Jemez lineament at Valles Caldera. The Rio Grande rift represents an ongoing episode of east–west crustal extension. Volcanism associated with this extension brings deeper mantle materials and processes closer to the surface.

Anderson and Maxwell (1991) suggested that the basalt flows at El Morro National Monument were essentially the same flows as “Qbo” of Maxwell (1986). This map served as the source for the digital geologic data set of El Malpais National Monument (see KellerLynn 2012a). However, the basalt flows at El Morro are too old to be unit Qbo (Oso Ridge flows) of Maxwell (1986), and are correctly considered to be part of unit Qb (old basalt flows) of Maxwell (1986) (Nelia Dunbar, New Mexico

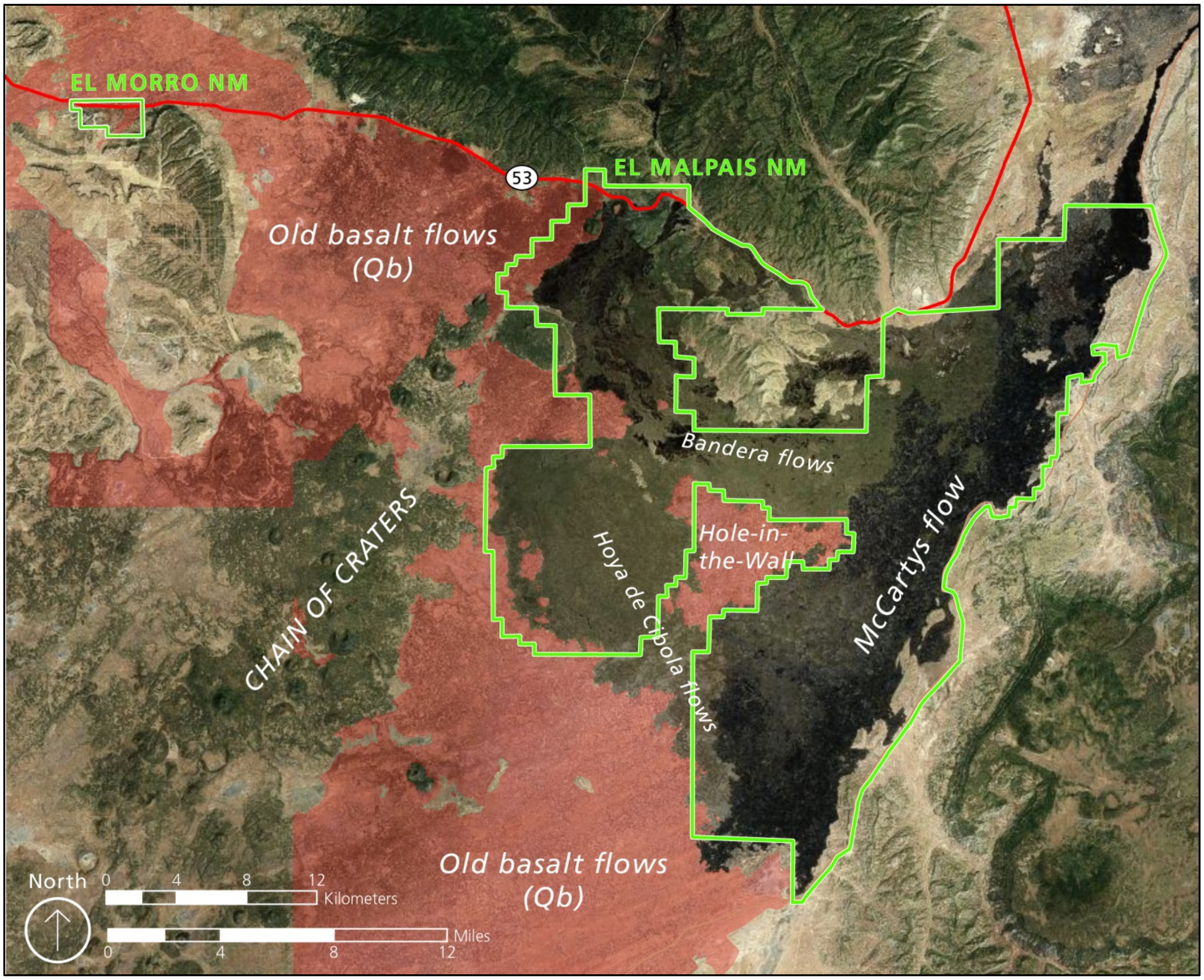

Figure 25. Basalt flows at El Morro and El Malpais national monuments. The basalt flows at El Morro National Monument erupted from the Zuni–Bandera volcanic field. To the east, El Malpais National Monument is centered on the Zuni–Bandera volcanic field. The flows between Bandera Crater (in El Malpais) and El Morro National Monument are older basalt flows of the middle to lower Pleistocene Epoch (map unit symbol Qb). All Qb units are shaded red in this image. Basalt flows of the same age continue to the southwest, but are not included in the extent of geologic data for El Morro or El Malpais. Three younger flows (Bandera, Hoya de Cibola, and McCartys) within El Malpais National Monument are much darker in this image, indicating less weathered basalt surfaces and less time for soil development and vegetation growth. Additional distinctive features shown on the figure are the Chain of Craters area between El Morro and El Malpais national monuments, which displays an alignment of multiple cinder cones. This alignment is a result of zones of weakness in Earth's crust, which allowed magma to rise to the surface, and is a characteristic feature of the Zuni–Bandera volcanic field. Such linear alignment is also observed in many Hawaiian-style volcanic fields, including those at Hawaii Volcanoes National Park (Thornberry-Ehrlich 2009). Another distinctive feature is the Hole-in-the-Wall, which is shown as a red triangular area surrounded by darker (younger) lava. Hole-in-the-Wall is a "kipuka"—a Hawaiian term that refers to an exposure of older rock not covered by an overlying lava flow. Hole-in-the-Wall and the basalt flows at El Morro National Monument are the same age. Graphic compiled by Jason Kenworthy (NPS Geologic Resources Division), using GRI map data available for El Morro and El Malpais national monuments. Imagery from ESRI Arc Map, Bing Maps aerial basemap layer.

Bureau of Geology and Mineral Resources, volcanologist, e-mail communication, 9 March 2012).

The flows at El Morro National Monument are from the first of three episodes of volcanic activity within the Zuni–Bandera volcanic field. Based on work by Luedke and Smith (1978), Anderson and Maxwell (1991) estimated that the basalt flows at El Morro were between 1.38 million and 788,000 years old. However, work since that time has interpreted the "old basalt flows" (Qb) of Maxwell (1986)—and by correlation the flows at El Morro—as part of the first episode of volcanic activity, which occurred about 700,000 years ago (Laughlin et al. 1993b). They are the same age as the lava that underlies the Hole-in-the-Wall within El Malpais National Monument (fig. 25).

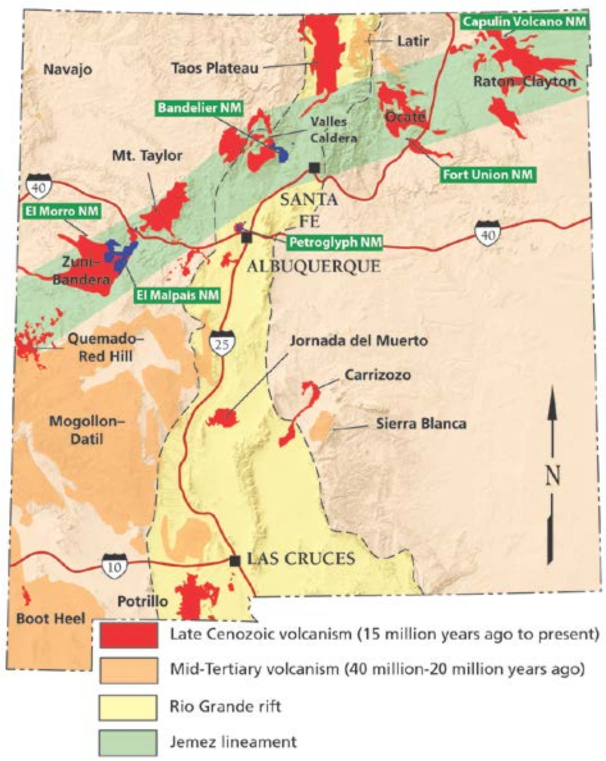

Figure 26. Major volcanic fields of New Mexico. El Morro National Monument is part of the Zuni–Bandera volcanic field in northern New Mexico. El Malpais National Monument, east of El Morro, is centered on the field. This and numerous other volcanic fields lie on the Jemez lineament, which stretches from central Arizona to northeastern New Mexico. The lineament marks a zone of crustal weakness along which volcanism has occurred for approximately 15 million years. The National Park System is well represented along the Jemez lineament: El Morro and El Malpais national monuments are part of the Zuni–Bandera volcanic field, Bandelier National Monument is situated in Valles Caldera, Fort Union National Monument is surrounded by the Ocaté volcanic field, and Capulin Volcano National Monumentis in the Raton–Clayton volcanic field. Graphic by New Mexico Bureau of Geology and Mineral Resources graphic, modified by Rebecca Port (Colorado State University).

Unconformities

Anderson and Maxwell (1991) documented four unconformities within or in the vicinity of El Morro National Monument (fig. 6 and Map Unit Properties Table). An unconformity is a gap in the rock record representing a period during which no rocks were deposited or rocks were deposited but have since eroded away. Where exposed, the physical appearance of an unconformity can be a distinct surface between two rock units of different ages, in some cases separated by millions of years. Within El Morro National Monument, the unconformity between the Middle Jurassic Period (approximately 175 million–161 million years ago) and the Upper Cretaceous Period (beginning about 100 million years ago) represents at least 60 million years of missing rock (fig. 27). In other parts of New Mexico and the Southwest, the Dakota Sandstone usually lies above the Jurassic Morrison Formation, but not at El Morro (Spoelhof 2005). Rivers likely crossed the area during this interval of time and covered the El Morro region with fluvial sediments of the Morrison Formation, a terrestrial unit known to contain dinosaur remains. This formation is the source of the spectacular fossil discoveries within Dinosaur National Monument (Graham 2006). Sediments of the Morrison Formation were later stripped away in the El Morro area (O. J. Anderson, personal communication in Cross 1996, p. 3).

Anderson and Maxwell (1991) identified three other unconformities in the vicinity of El Morro National Monument: (1) between the lower Permian (Cisuralian) San Andres Limestone (Psa) and the Upper Triassic Lower Member of the Chinle Formation (TRcl)—an unconformity of at least 42 million years, (2) between the Upper Triassic Rock Point Member of the Chinle Formation (TRcr) and the Middle Jurassic Zuni Sandstone (Jz)—an unconformity of at least 24 million years, and (3) between the Upper Cretaceous Twowells Tongue of the Dakota Sandstone (Kdt) and Quaternary basalt flows (Qb) of Pleistocene age (approximately 700,000 years old)—an unconformity of at least 65 million years. Unlike the Middle Jurassic–Upper Cretaceous unconformity at the top of Inscription Rock, these three unconformities are not exposed within the national monument's boundaries. However, they mark the passing of significant amounts of geologic time and are useful for piecing together the geologic story for El Morro National Monument (see "Geologic History" section).

Paleontological Resources

Although no fossil discoveries have been reported from the rocks within El Morro National Monument, the potential for finding paleontological resources exists because geologic map units represented within the national monument contain fossils elsewhere. Because fossils are very rare in the Zuni Sandstone (Jz), Dakota Sandstone (Kdm), followed by Quaternary sedimentary deposits (Ql, Qac, Qal, and Qe), are the most likely units to contain fossils within El Morro National Monument (Tweet et al. 2009). Potential fossils include terrestrial plants and vertebrate tracks in the Dakota Sandstone, isolated bones of mammals (e.g., beaver, horse, camel, musk ox, bison, or mammoth) in Quaternary sediments, and fossil assemblages in cave sediments (Tweet et al. 2009). In addition, lava flows are known to contain fossils, in particular tree molds such as those at nearby El Malpais National Monument. Tree molds are a type of trace fossil that form when molten lava surrounds a tree and subsequently cools, creating an impression of the tree or bark in the lava.

Future field investigations within El Morro National Monument may recover fossils from one or more of these units (Tweet et al. 2009). Santucci et al. (2009) and Tweet et al. (2009), and the references therein, provide information regarding the management and monitoring of paleontological resources.

Figure 27. Views of the unconformity. The bleached zone of the Zuni Sandstone (Jz) is a conspicuous indicator of the overlying unconformity between the Middle Jurassic and Upper Cretaceous periods (arrow on upper photograph). This unconformity covers a span of at least 60 million years for which representative rocks are absent in the El Morro area. The reddish Dakota Sandstone (Kdm) rests on top of the unconformity. National Park Service photographs.

Geologic History

This section describes the rocks and unconsolidated deposits that appear on the digital geologic map of El Morro National Monument, the environment in which those units were deposited, and the timing of geologic events that formed the present landscape.

The inscriptions and ancestral Puebloan ruins at El Morro National Monument are extremely young in comparison with its rocks. The geologic story represented by these rocks involves seas inundating the area during the Permian Period (299 million–251 million years ago), a vast desert covering the region during the Middle Jurassic Period (175 million–161 million years ago), the return of marine waters during the Cretaceous Period (145 million–65.5 million years ago), mountain building starting about 70 million years ago, and volcanism about 700,000 years ago. The modern evolution of the landscape includes sandstone blocks eroding from the cliffs, and sand and silt blown by the wind and transported by surface water runoff.

Paleozoic Era: Permian Seas

The Paleozoic Era began 542 million years ago and lasted 290 million years. Only a small portion of this vast amount of time is recorded by the rocks in the vicinity of El Morro National Monument. Rocks of the Permian Period, the latest period of the Paleozoic Era, are exposed in the Zuni Mountains northeast of the national monument (see Geologic Map Overview Graphic). The Permian Period began about 299 million years ago and lasted roughly 48 million years (fig. 5). If rocks predating the Permian Period were deposited in the region, they must have been completely removed by subsequent erosion, as no evidence of them remains.

The central interior of the United States was a vast basin during the Permian Period. The El Morro region initially remained above sea level, but eventually was drowned by an advancing sea (fig. 28). Rocks of Permian age in this region have been divided into four major sedimentary units (West and Baldwin 1965). These four units are, from oldest/bottom to youngest/top, the Abo Formation, the Yeso Formation, the Glorieta Sandstone, and the San Andres Limestone. The Glorieta Sandstone (map unit symbol Pg) and the San Andres Limestone (Psa) were mapped by Anderson and Maxwell (1991) in the vicinity of El Morro National Monument.

The Glorieta Sandstone (Pg) is white to buff in color, but weathers to yellow or light brown. Composed of medium- and coarse-grained sand, this sandstone was deposited along the coast or in shallow water as the seas transgressed (advanced) across the region. This unit is the oldest of those exposed in the El Morro quadrangle (Anderson and Maxwell 1991). The Glorieta Sandstone is best exposed as the cap rock on high cliffs and on timbered slopes in the Zuni Mountains. It can be seen in the canyon walls along the mountain road between Ice Cave and Grants, New Mexico (West and Baldwin 1965).

The San Andres Limestone (Psa) overlies the Glorieta Sandstone. Anderson and Maxwell (1991) divided the San Andres Limestone into three parts: the upper part is pinkish-gray limestone; the middle part is yellowish-gray sandstone with calcitic cement, locally grading into sandy dolomitic limestone; and the lower part is mostly yellowish-gray to gray, dolomitic limestone with some calcareous shale and sandy limestone. The lower part is generally the thickest of the three and contains fossils such as seashells. The San Andres Limestone attests to marine conditions and the complete submergence of the region beneath the Permian seas. The limestone is best exposed on broad slopes on the northern, eastern, and southern sides of the Zuni Mountains. The steep, southwest-facing mountain front that can be seen from El Morro National Monument is capped with the San Andres Limestone (fig. 13). The limestone is utilized for aggregate (see "Tinaja Pit" section).

Mesozoic Era: A "Sea" of Sand and the Return of Marine Waters

The Mesozoic Era is sometimes referred to as the "Age of Reptiles" because the great dinosaurs roamed the Earth during this time. The era began about 251 million years ago and lasted about 185 million years. The El Morro area contains an incomplete record of the era's three geologic periods—Triassic, Jurassic, and Cretaceous (West and Baldwin 1965). With respect to the Triassic Period (251 million–200 million years ago), Anderson and Maxwell (1991) mapped various members of the Chinle Formation (TRcl, TRcs, TRcp, TRcr, and TRcu) within the El Morro quadrangle. Mapel (1985) and Mapel and Yesberger (1985) also mapped the Wingate Sandstone (TRwr) in the Togeye Lake quadrangle (west of El Morro) and the Goat Hill quadrangle (south of El Morro), respectively. The Chinle Formation and Wingate Sandstone were deposited during a long period when the land surface was above sea level, and rivers and streams deposited material in valleys and on broad plains (West and Baldwin 1965).

The Chinle Formation consists of a colorful sequence of red, gray, and purple mudstone, siltstone, and sandstone (Anderson and Maxwell 1991). In the El Morro area, the Chinle Formation is generally easily eroded and underlies areas of low relief in broad valleys (West and Baldwin 1965). However, some impressive exposures of the Chinle Formation occur on the flanks of the Zuni Mountains (West and Baldwin 1965). The most widely known exposures of the Chinle Formation are those within Petrified Forest National Park in Arizona (KellerLynn 2010), where petrified wood, especially the Petrified Forest Member (TRcp), is abundant. At Petrified Forest National Park, the petrified wood is

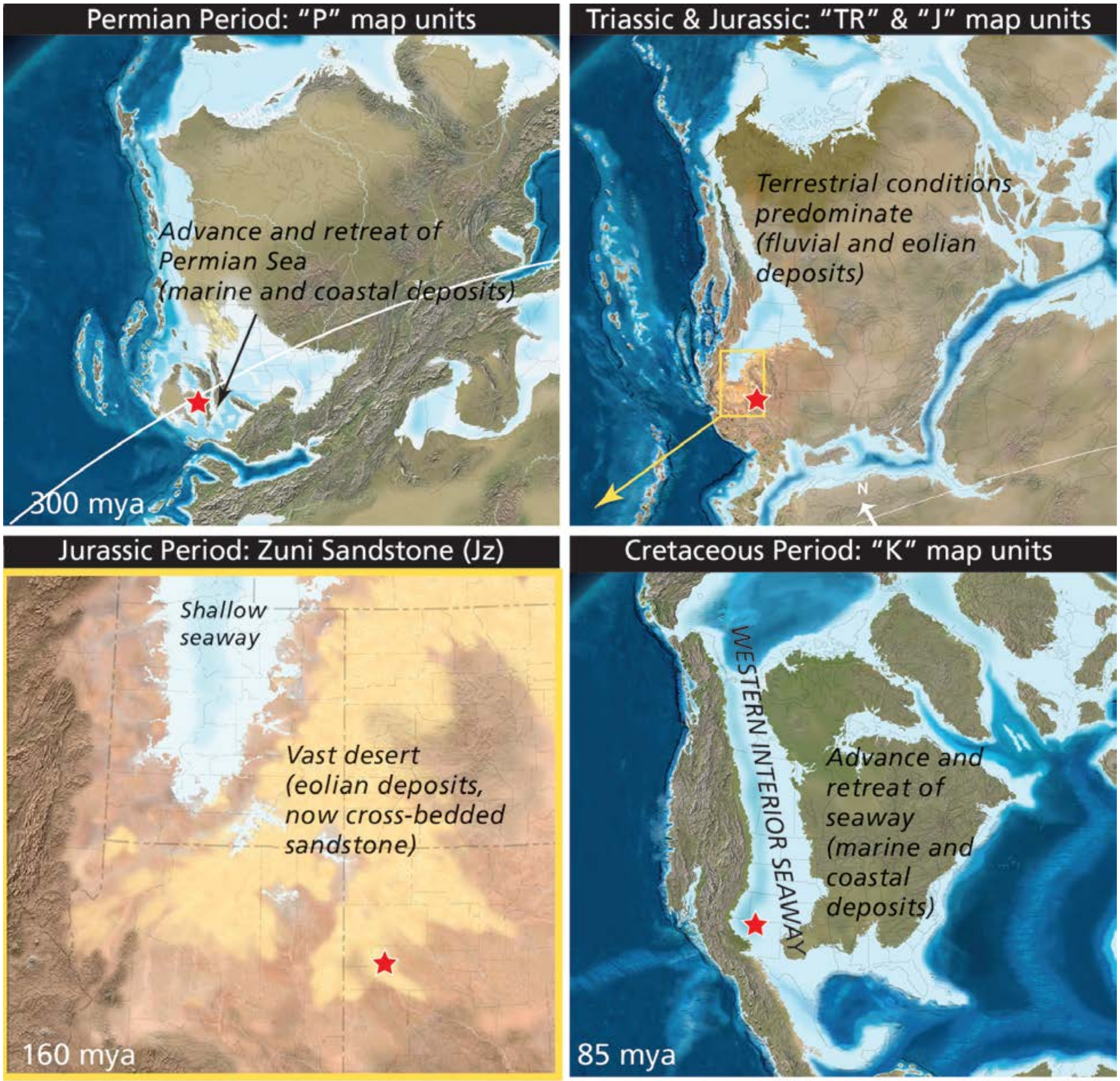

Figure 28. El Morro paleogeography. The geologic history of El Morro National Monument (approximate location indicated by stars) includes periods of inundation by marine water during the Permian (upper left graphic, 300 million years ago) and Cretaceous (lower right graphic, 85 million years ago) periods, as well as a vast desert, also called a "sand sea" or "erg." The box in the upper right graphic marks the location of this desert, which is enlarged in the lower left graphic (160 million years ago). During the Jurassic Period, wind was the primary transporter of the desert's immense supply of fine-grained quartz sand, which became well sorted and well rounded during eolian transport. The sand was piled into dunes and spread into sheets and became the Zuni Sandstone (Jz) that comprises Inscription Rock. mya = million years ago. Graphic complied by Jason Kenworthy (NPS Geologic Resources Division). Base paleogeographic maps created by Ron Blakey (Colorado Plateau Geosystems, Inc.), available at http://cpgeosystems.com/index.html (accessed 10 April 2012).

brilliantly colored. Near El Morro National Monument, the color is generally drab, although the wood grain is distinctly visible in the rock (West and Baldwin 1965).

On the northern flank of the Zuni Mountains, the Wingate Sandstone (TRwr) is exposed and was deposited as dune sand in a desert (West and Baldwin 1965). By contrast, the Wingate Sandstone south of the mountains was deposited as sand, clay, and pebbles on floodplains, and in lakes or inland basins (West and Baldwin 1965). The Wingate Sandstone consists of reddish-brown, friable, very fine-grained sandstone and siltstone; locally it is mottled greenish gray. The top 15 m (50 ft) of the unit is composed of red mudstone and grayish-white silty sandstone (Mapel 1985; Mapel and Yesberger 1985). The best exposures of Wingate Sandstone in the El Morro area are in the lower parts of cliffs on the slopes of the Zuni Mountains, and south of Highway 53 from 8 to 16 km (5 to 10 mi) east of Zuni, New Mexico. The bright-red cliffs of Wingate Sandstone east of Zuni contrast sharply with the green of juniper and piñon trees. Many of the houses in Zuni are made of stone quarried from the Wingate Sandstone (West and Baldwin 1965).

The second period of the Mesozoic Era, the Jurassic Period, began 200 million years ago and spanned 54 million years (fig. 5). The Jurassic Period is particularly significant in the geologic history of El Morro National Monument because the Zuni Sandstone (Jz)—the rock into which travelers carved inscriptions—was deposited during this time. The quartz grains that make up the yellow-gray to tan sandstone are well rounded and well sorted (Anderson and Maxwell 1991). Furthermore, large-scale cross-bedding is common in the sandstone (fig. 17). These features are characteristic of sand deposited in large eolian dunes that form in arid environments. These sand dunes were part of a dune field that covered much of the land that is now northwestern New Mexico, northeastern Arizona, southeastern Utah, and southwestern Colorado about 160 million years ago (fig. 28).

The Zuni Sandstone is stratigraphically equivalent to the Entrada Sandstone and the overlying Bluff (Cow Springs) Sandstone to the northeast (Lucas et al. 2003). Well-known Delicate Arch and the other arches in Arches National Park in Utah are made of the Entrada Sandstone. Jointing is a distinctive feature of the Zuni Sandstone (figs. 17 and 18). The joints are discolored and commonly coated with brown and yellow iron oxides, which appear as streaks or bands on the sandstone. Jointing presumably resulted from stress imparted during burial and/or uplift (Austin 1992; Cross 1996).

Overlying the Zuni Sandstone at El Morro National Monument is a unit referred to as reworked Zuni Sandstone (Kl). This unit represents fluvial erosion and redeposition of the upper part of the Zuni Sandstone. Although the exact timing is uncertain, Anderson and Maxwell (1991) suggested that reworking of the Zuni Sandstone occurred during the Lower Cretaceous Period (145 million–100 million years ago). At this time, pieces of the sandstone were incorporated into sandy and gravelly stream deposits of the Dakota Sandstone (Kdm). Cross (1996) documented a channel 1.5 m (5 ft) deep and 80 m (260 ft) wide, filled with black shale, at the contact between the Zuni and Dakota sandstones, south of the upper steps along the Mesa Top Trial (fig. 29). This feature is indicative of stream deposition. Channels cut into the top of the Zuni Sandstone represent fluvial excavating prior to the deposition of the Dakota Sandstone (Cross 1996).

In the El Morro quadrangle, Anderson and Maxwell (1991) mapped the main body (Kdm) and Twowells Tongue (Kdt) of the Dakota Sandstone. These units represent the presence of the Western Interior Seaway, which extended from the Arctic to the Tropics, covering the entire west-central part of the North American continent (fig. 28). The seaway left thick deposits of shale, siltstone, and sandstone. "Intertonguing" of the Dakota, Mancos, and Tres Hermanos rock formations is an indication of the migration of marine waters back and forth across an area. "Tongues" extend to a limited degree outward beyond the main body of a formation and ultimately disappear laterally. These strata record

Figure 29. Steps carved into Zuni Sandstone. To facilitate access to the mesa top, the Civil Works Administration carved steps into the top of the Zuni Sandstone in the 1930s. These steps cut into the bleached horizon. The steps impact natural runoff during storms, but are a significant cultural resource and preserved by the National Park Service. Note the jointed walls of the box canyon in the background. National Park Service photograph by Sarah Beckwith.

transgression (advance) and regression (retreat) of the sea in a variety of nearshore and marine settings. In general, marine waters spread across the land surface from the north/northwest in response to worldwide changes in sea level (Hunt and Kelley 2010). In the Goat Hill quadrangle south of El Morro and the Togeye Lake quadrangle west of El Morro, Mapel and Yesberger (1985) and Mapel (1985), respectively, mapped the following sequence: Dakota Sandstone (Kdm), followed by the Whitewater Arroyo Tongue of the Mancos Shale (Kmw), followed by the Twowells Tongue of the Dakota Sandstone (Kdt), followed by the Tres Hermanos Formation (Ktha, Kthc, Kthf), followed by the Pescado Tongue of the Mancos Shale (Kmp).

The Dakota Sandstone is preserved along the Mesa Top Trail within El Morro National Monument. The pueblo ruins are situated on the gray mudstone or shale part of the unit, which represents streamflow across the coastal plain along the shores of the Western Interior Seaway (Kelley 2008). Overall, the Dakota Sandstone represents coastal plain and marginal marine deposits associated with the initial advance of the Western Interior Seaway into what is now New Mexico (Cross 1996).

Cenozoic Era: Mountain Building, Volcanism, and Erosion

The withdrawal of the Western Interior Seaway was concurrent with the beginning of a mountain-building episode known as the Laramide Orogeny (Cather 2003). This mountain-building event was responsible for much of the present form of the Rocky Mountains (Aubrey 1991). Of consequence for El Morro National Monument, the uplift of the Zuni Mountains was a result of Laramide mountain building (Anderson and Maxwell 1991).

An unconformity representing about 65 million years following the Cretaceous Period is present between the Cretaceous Dakota Sandstone and Quaternary basalt flows. The unconformity documents the absence of rocks from the Paleocene, Eocene, Oligocene, Miocene, and Pliocene epochs in the El Morro area (figs. 5 and 6).

Significantly, the El Morro area escaped extensive Oligocene volcanism, the results of which dominate the landscape 60 mi (97 km) to the south (Anderson and Maxwell 1991). Recorded in the El Morro region, however, are Quaternary basalt flows (Qb) from the Pleistocene Epoch, which erupted from volcanoes in the Zuni–Bandera volcanic field about 700,000 years ago (Laughlin et al. 1993a). The flows at El Morro were from the first of three episodes of volcanic activity within the Zuni–Bandera volcanic field (Laughlin et al. 1993a).

At the time of eruption, broad valleys had developed on less resistant strata, such as the Chinle Formation. The valleys were the lowest points on the landscape and major drainage lines. Basaltic lava from volcanoes east of El Morro flowed through these low areas, covering valley floors and concealing much of the Chinle Formation (Anderson and Maxwell 1991). Mesas that were capped with resistant Dakota Sandstone, such as El Morro and the Obe Worthen Mesa to the south, were left isolated in the basin.

Pleistocene basalt flows (Qb) have subsequently undergone minor weathering, with extensive areas covered by Holocene alluvium (Qal) and windblown sand and silt (Qe). An apron of younger Quaternary colluvium (rocks eroded from cliffs; Qac), alluvium (water-lain deposits in arroyos; Qal), and windblown silt (Qe) surround the sandstone cliffs (Anderson and Maxwell 1991; Kelley 2008). Piñon and juniper have colonized areas where the soil cover is more than 1 m (3 ft) thick (Anderson and Maxwell 1991). Today, mature vegetation obscures the record of the region's volcanic setting.

Geologic Map Data

This section summarizes the geologic map data available for El Morro National Monument. The Geologic Map Overview Graphic (in pocket) displays the geologic map data draped over a shaded relief image of the national monument 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://www.nature.nps.gov/geology/inventory/gre_publications.cfm).

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, geologic maps portray the spatial distribution and relationships of rocks and unconsolidated deposits. There are two primary types of geologic maps: surficial and bedrock. Surficial geologic maps encompass deposits that are frequently unconsolidated and formed during the past 2.6 million years (the Quaternary Period). Surficial map units are differentiated by geologic process or depositional environment. Bedrock geologic maps encompass older, generally more consolidated sedimentary, metamorphic, and/or igneous rocks. Bedrock map units are differentiated based on age and/or rock type. For reference, a geologic time scale is included as figure 5. Bedrock and surficial geologic map data are provided for El Morro National Monument.

Geologic maps also may show geomorphic features, structural interpretations, and locations of past geologic hazards that may be prone to future activity. Additionally, anthropogenic features such as mines and quarries may be indicated on geologic maps.

Source Maps

The Geologic Resources Inventory (GRI) team converts digital and/or paper source maps into GIS formats that conform to the GRI GIS data model. The GRI digital geologic map product also includes essential elements of the source maps, including unit descriptions, map legend, map notes, references, and figures. The GRI team used the following source maps to produce the digital geologic data for El Morro National Monument. These source maps provided information for the "Geologic Issues," "Geologic Features and Processes," and "Geologic History" sections of this report.

Anderson, O. J., and C. H. Maxwell. 1991. Geology of El Morro quadrangle, Cibola County, New Mexico (scale 1:24,000). Geologic map 72. New Mexico Bureau of Mines and Mineral Resources, Socorro, New Mexico, USA.

Mapel, W. J. 1985. Geologic map of the Togeye Lake quadrangle, Cibola and McKinley counties, New Mexico (scale 1:24,000). Miscellaneous field studies map MF-1726. U.S. Geological Survey, Washington, D.C., USA.

Mapel, W. J., and W. L. Yesberger. 1985. Geologic map of the Goat Hill quadrangle, Cibola County, New Mexico (scale 1:24,000). Miscellaneous field studies map MF-1727. U.S. Geological Survey, Washington, D.C., USA.

Geologic 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 online (http://science.nature.nps.gov/im/inventory/geology/GeologyGISDataModel.cfm). This data model dictates GIS data structure, including layer architecture, feature attribution, and relationships within ESRI ArcGIS software. The GRI team digitized the data for El Morro National Monument using data model version 2.1.

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

The following components and geology data layers are part of the data set:

- Data in ESRI geodatabase and shapefile GIS formats
- Layer files with feature symbology (see tables below)
- Federal Geographic Data Committee (FGDC)–compliant metadata
- A help file (.pdf) document that contains all of the ancillary map information and graphics, including geologic unit correlation tables, and map unit descriptions, legends, and other information captured from source maps
- An ESRI map document file (.mxd) that displays the digital geologic data
- A KML/KMZ version of the data viewable in Google Earth (see tables below)

Geology data layers in the El Morro National Monument GIS data

El Morro quadrangle (Anderson and Maxwell 1991)

Data Layer	Code	On Geologic Map Overview?	On Google Earth?
Geologic Cross Section Lines	ELORSEC	No	No
Geologic Attitude Observation Localities	ELORATD	No	No
Geologic Observation Localities	ELORGOL	No	No
Map Symbology	ELORSYM	Yes	No
Folds	ELORFLD	Yes	Yes
Faults	ELORFLT	No	Yes
Geologic Contacts	ELORGLGA	Yes	Yes
Geologic Units	ELORGLG	Yes	Yes

Note: El Morro National Monument is situated in the El Morro quadrangle.

Togeye Lake quadrangle (Mapel 1985)

Data Layer	Code	On Geologic Map Overview?	On Google Earth?
Mine Point Features	TOGLMIN	No	No
Geologic Contacts	TOGLGLGA	No	Yes
Geologic Units	TOGLGLG	No	Yes

Note: Togeye Lake quadrangle is west of El Morro National Monument.

Goat Hill quadrangle (Mapel and Yesberger 1985)

Data Layer	Code	On Geologic Map Overview?	On Google Earth?
Mine Point Features	GOHIATD	No	No
Geologic Contacts	GOHIGLGA	No	Yes
Geologic Units	GOHIGLG	No	Yes

Note: Goat Hill quadrangle is south of El Morro National Monument.

Geologic Map Overview Graphic

The Geologic Map Overview Graphic (in pocket) displays the GRI digital geologic data draped over a shaded relief image of El Morro National Monument and surrounding area. For graphic clarity and legibility, not all GIS feature classes are visible on the overview, as indicated in the above tables. Cartographic elements and basic geographic information have been added to the overview. Digital elevation data and geographic information, which are part of the overview graphic, are not included with the GRI digital geologic GIS data for the national monument, but are available online from a variety of sources.

Map Unit Properties Table

The geologic units listed in the Map Unit Properties Table (in pocket) correspond to the accompanying digital geologic data. Following the structure of the report, the table summarizes the geologic issues, features, and processes, and geologic history associated with each map unit. The table also lists the geologic time period, map unit symbol, and a simplified geologic description of the unit. Connections between geologic units and park stories are also summarized.

Use Constraints

Graphic and written information provided in this section is not a substitute for site-specific investigations. Ground-disturbing activities should neither be permitted nor denied based upon the information provided here. Minor inaccuracies may exist regarding the location of geologic features relative to other geologic or geographic features on the overview graphic. Based on the source map scale (1:24,000) and U.S. National Map Accuracy Standards, geologic features represented in the geologic map data are horizontally within 12 m (40 ft) of their true location.

Please contact GRI with any questions.

Glossary

This glossary contains brief definitions of geologic terms used in this report. Not all geologic terms used are listed. Definitions are based on those in the American Geological Institute Glossary of Geology *(fifth edition; 2005). Additional definitions and terms are available at: http://geomaps.wr.usgs.gov/parks/misc/glossarya.html.*

alluvium. Stream-deposited sediment.

andesite. Fine-grained volcanic rock commonly associated with subduction zone volcanoes. Named for the subduction zone volcanoes of the Andes Mountains.

arkose. A sandstone with a large percentage of feldspar minerals, commonly coarse-grained and pink or reddish.

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.

ash (volcanic). Fine material ejected from a volcano (also see "tuff").

badlands. Eroded topography characterized by steep slopes and surfaces with little or no vegetative cover, composed of unconsolidated or poorly cemented clays or silts.

basalt. A dark-colored, often low-viscosity, extrusive igneous rock.

base flow. Stream flow supported by groundwater; flow not attributed to direct runoff from precipitation or snow melt.

base level. The lowest level to which a stream can erode its channel. The ultimate base level for the land surface is sea level, but temporary base levels may exist locally.

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

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

batholith. A massive, discordant pluton, larger than 100 km^2 (40 mi^2), and often formed from multiple intrusions of magma.

bed. The smallest sedimentary strata unit, commonly ranging in thickness from one centimeter to a meter or two and distinguishable from beds above and below.

bedding. Depositional layering or stratification of sediments.

bedrock. A general term for the rock that underlies soil or other unconsolidated, surficial material.

bentonite. A soft clay or greasy claystone composed largely of smectite. Formed by the chemical alteration of glassy volcanic ash in contact with water.

bounding surface. An erosion truncation surface that separates groups of cross-beds on various scales.

calcareous. Describes rock or sediment that contains the mineral calcium carbonate ($CaCO_3$).

calcite. A common rock-forming mineral: $CaCO_3$ (calcium carbonate).

caldera. A large bowl- or cone-shaped depression at the summit of a volcano. Formed by explosion or collapse.

carbonate. A mineral that has CO_3^{-2} as its essential component (e.g., calcite and aragonite).

carbonate rock. A rock consisting chiefly of carbonate minerals (e.g., limestone, dolomite, or carbonatite).

cementation. Chemical precipitation of material into pores between grains that bind the grains into rock.

chemical sediment. A sediment precipitated directly from solution (also called nonclastic).

chemical weathering. Chemical breakdown of minerals at Earth's surface via reaction with water, air, or dissolved substances; commonly results in a change in chemical composition more stable in the current environment.

chert. A extremely hard sedimentary rock with conchoidal (smooth curved surface) fracturing. It consists chiefly of interlocking crystals of quartz Also called "flint."

cinder cone. A conical volcanic feature formed by the accumulation of cinders and other pyroclasts, normally of basaltic or andesitic composition.

clay. Can be used to refer to clay minerals or as a sedimentary fragment size classification (less than 1/256 mm [0.00015 in]).

colluvium. A general term applied to any loose, heterogeneous, and incoherent mass of rock fragments deposited by unconcentrated surface runoff or slow continuous downslope creep, usually collecting at the base of gentle slopes or hillsides.

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

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

crust. Earth's outermost compositional shell, 10 to 40 km (6 to 25 mi) thick, consisting predominantly of relatively low-density silicate minerals (also see "oceanic crust" and "continental crust").

cuesta. An asymmetric landform with one gently sloping side and one steeply sloping side. Results from erosion of gently dipping rock strata.

debris flow. A moving mass of rock fragments, soil, and mud, in which more than half the particles of which are larger than sand size.

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

dolomite. A carbonate sedimentary rock of which more than 50% by weight or by areal percentages under the microscope consists of the mineral dolomite (calcium-magnesium carbonate).

dolomitic. Describes a dolomite-bearing rock, or a rock containing dolomite.

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

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

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

ephemeral stream. A stream that flows briefly only in direct response to precipitation in the immediate locality and whose channel is at all times above the water table.

escarpment. A steep cliff or topographic step resulting from vertical displacement on a fault or by mass movement. Also called a "scarp."

exfoliation. The breakup, spalling, peeling, or flaking of layers or concentric sheets from an exposed rock mass caused by differential stresses due to thermal changes or a reduction in pressure when overlying rocks erode away.

extension. A type of strain resulting from forces "pulling apart." Opposite of compression.

extrusive. Describes molten (igneous) material that has erupted onto Earth's surface.

fault. A break in rock along which relative movement has occurred between the two sides.

feldspar. A group of abundant (more than 60% of Earth's crust), light-colored to translucent silicate minerals found in all types of rocks. Usually white and gray to pink. May contain potassium, sodium, calcium, barium, rubidium, and strontium along with aluminum, silica, and oxygen.

floodplain. The surface or strip of relatively smooth land adjacent to a river channel and formed by the river. Covered with water when the river overflows its banks.

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

fracture. Irregular breakage of a mineral. Any break in a rock (e.g., crack, joint, fault).

frost wedging. The breakup of rock due to the expansion of water freezing in fractures.

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

gully. A small channel produced by running water in earth or unconsolidated material (e.g., soil or a bare slope).

igneous. Refers to a rock or mineral that originated from molten material; one of the three main classes of rocks—igneous, metamorphic, and sedimentary.

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

interdune. Pertaining to the relatively flat surface, whether sand-free or sand-covered, between dunes.

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

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

kaolinite. A common clay mineral with a high aluminum oxide content and white color.

landslide. Any process or landform resulting from rapid, gravity-driven mass movement.

lava. Still-molten or solidified magma that has been extruded onto Earth's surface though a volcano or fissure.

leaching. The separation, selective removal, or dissolving-out of soluble constituents from a rock or orebody by the natural action of percolating water.

lenticular. Resembling in shape the cross section of a lens.

limestone. A sedimentary rock consisting chiefly of calcium carbonate, primarily in the form of the mineral calcite.

Liesgang banding. Also known as "Liesgang rings." Secondary, nested rings or bands caused by rhythmic precipitation within a fluid-saturated rock.

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

loess. Windblown silt-sized sediment, generally of glacial origin.

mantle. The zone of Earth's interior between the crust and core.

mass wasting. A general term for the downslope movement of soil and rock material under the direct influence of gravity.

mechanical weathering. The physical breakup of rocks without change in composition. Synonymous with "physical weathering."

member. A lithostratigraphic unit with definable contacts; a member subdivides a formation.

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

mica. A prominent rock-forming mineral of igneous and metamorphic rocks. It has perfect basal cleavage meaning that it forms flat sheets.

micaceous. Consisting of, containing, or pertaining to mica.

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

orogeny. A mountain-building event.

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

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

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

permeability. A measure of the relative ease with which fluids move through the pore spaces of rocks or sediments.

porosity. The proportion of void space (e.g., pores or voids) in a volume of rock or sediment deposit.

recharge. Infiltration processes that replenish groundwater.

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

rock. A solid, cohesive aggregate of one or more minerals.

rockfall. Mass wasting process where rocks are dislodged and move downslope rapidly; it is the fastest mass wasting process.

sand. A clastic particle smaller than a granule and larger than a silt grain, having a diameter in the range of 1/16 mm (0.0025 in) to 2 mm (0.08 in).

sand sheet. A large irregularly shaped plain of eolian sand, lacking the discernible slip faces that are common on dunes.

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

sapping. The undercutting of a cliff by erosion of softer underlying rock layers.

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

sedimentary rock. A consolidated and lithified rock consisting of clastic and/or chemical sediment(s). One of the three main classes of rocks—igneous, metamorphic, and sedimentary.

septarian. Said of the irregular polygonal pattern of internal cracks developed in spheroidal concretions (septarium), closely resembling the desiccation structure of the epigenetic mineral deposits that may occur as fillings of these cracks.

shale. A clastic sedimentary rock made of clay-sized particles that exhibit parallel splitting properties.

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

silicic magma. Describes magma that contains more than 63% silica and is generally viscous, gas-rich, and tends to erupt explosively.

silt. Clastic sedimentary material intermediate in size between fine-grained sand and coarse clay (1/256 to 1/16 mm [0.00015 to 0.002 in]).

siltstone. A variably lithified sedimentary rock composed of silt-sized grains.

slabbing. Rock splitting into slabs along closely spaced parallel fissures and falling under the force of gravity.

slope wash. Soil and rock material that is or has been transported down a slope by mass wasting assisted by running water not confined to channels. Also, the process by which slope-wash material is moved.

soil. Surface accumulation of weathered rock and organic matter capable of supporting plant growth and often overlying the parent material from which it formed.

spalling. Exfoliation or the process by which scales, plates, or flakes of rock, from less than a centimeter to several meters in thickness, are successively spalled or stripped from the bare surface of a large rock mass. It is caused by the physical or chemical forces producing differential stresses within the rock, as by expansion of minerals as a result of near-surface chemical weathering, or by the release of confining pressure of a once deeply buried rock as it is brought nearer to the surface by erosion.

spring. A site where water issues from the surface due to the intersection of the water table with the ground surface.

strata. Tabular or sheet-like masses or distinct layers of rock.

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.

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

tectonic. Relating to large-scale movement and deformation of Earth's crust.

tongue (stratigraphy). A member of a formation that extends and wedges out away from the main body of a formation.

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

unconformity. An erosional or non-depositional surface bounded on one or both sides by sedimentary strata. An unconformity marks a period of missing time.

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

uplift. A structurally high area in the crust, produced by movement that raises the rocks.

vesicular. Describes a volcanic rock with abundant holes that formed from the expansion of gases while the lava was still molten.

weathering. The physical, chemical, and biological processes by which rock is broken down.

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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 current as of October 2012.

Geology of National Park Service Areas

National Park Service Geologic Resources Division: (Lakewood, Colorado): http://nature.nps.gov/geology/

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

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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 wide variety of geologic parks): http://www.nature.nps.gov/views/layouts/Main.html#/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

NPS 2006 Management Policies (Chapter 4; Natural Resource Management): http://www.nps.gov/policy/mp/policies.html#_Toc157232681

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, USA.
http://nature.nps.gov/geology/monitoring/index.cfm

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

Geological Surveys and Societies

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

U.S. Geological Survey: http://www.usgs.gov/

Geological Society of America: http://www.geosociety.org/

American Geological Institute: http://www.agiweb.org/

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

U.S. Geological Survey Reference Tools

U.S. Geological Survey National Geologic Map Database (NGMDB): http://ngmdb.usgs.gov/

U.S. Geological Survey Geologic Names Lexicon (GEOLEX; geologic unit nomenclature and summary): http://ngmdb.usgs.gov/Geolex/geolex_home.html

U.S. Geological Survey Geographic Names Information System (GNIS; official listing of place names and geographic features): http://gnis.usgs.gov/

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

U.S. Geological Survey Publications Warehouse (USGS publications, many available online): http://pubs.er.usgs.gov

U.S. Geological Survey Tapestry of Time and Terrain (descriptions of physiographic provinces): http://tapestry.usgs.gov/Default.html

Appendix: Scoping Meeting Participants

The following people attended the GRI scoping meeting for El Morro National Monument, held on 30 March 2006, or the follow-up conference call during report writing, held on 12 December 2011. Discussions during these meetings supplied a foundation for this GRI report. The scoping summary document is available on the GRI publications website (http://www.nature.nps.gov/geology/inventory/gre_publications.cfm).

2006 Scoping Meeting Participants

Name	Affiliation	Position
Kayci Cook Collins	El Morro and El Malpais national monuments	Superintendent
Tim Connors	NPS Geologic Resources Division	Geologist, Mapping Coordinator
Nelia Dunbar	New Mexico Bureau of Geology and Mineral Resources	Geologist
Bruce Heise	NPS Geologic Resources Division	Geologist, Inventory Coordinator
Katie KellerLynn	Colorado State University	Geologist, Research Associate
Ron Kerbo	NPS Geologic Resources Division	Cave Specialist
*Ken Mabery	Fort Necessity National Battlefield and Friendship Hill National Historic Site (formerly with El Morro and El Malpais national monuments)	Superintendent
Greer Price	New Mexico Bureau of Geology and Mineral Resources	Geologist, Chief Editor
Peter Scholle	New Mexico Bureau of Geology and Mineral Resources	State Geologist
Herschel Schulz	El Morro and El Malpais national monuments	Chief Ranger

Participated in 16 March 2006 conference call only.

2011 Conference Call Participants

Name	Affiliation	Position
Dave Hays	El Morro and El Malpais national monuments	Resource Manager
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Dana Sullivan	El Morro and El Malpais national monuments	Chief Ranger

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National Park Service
U.S. Department of the Interior

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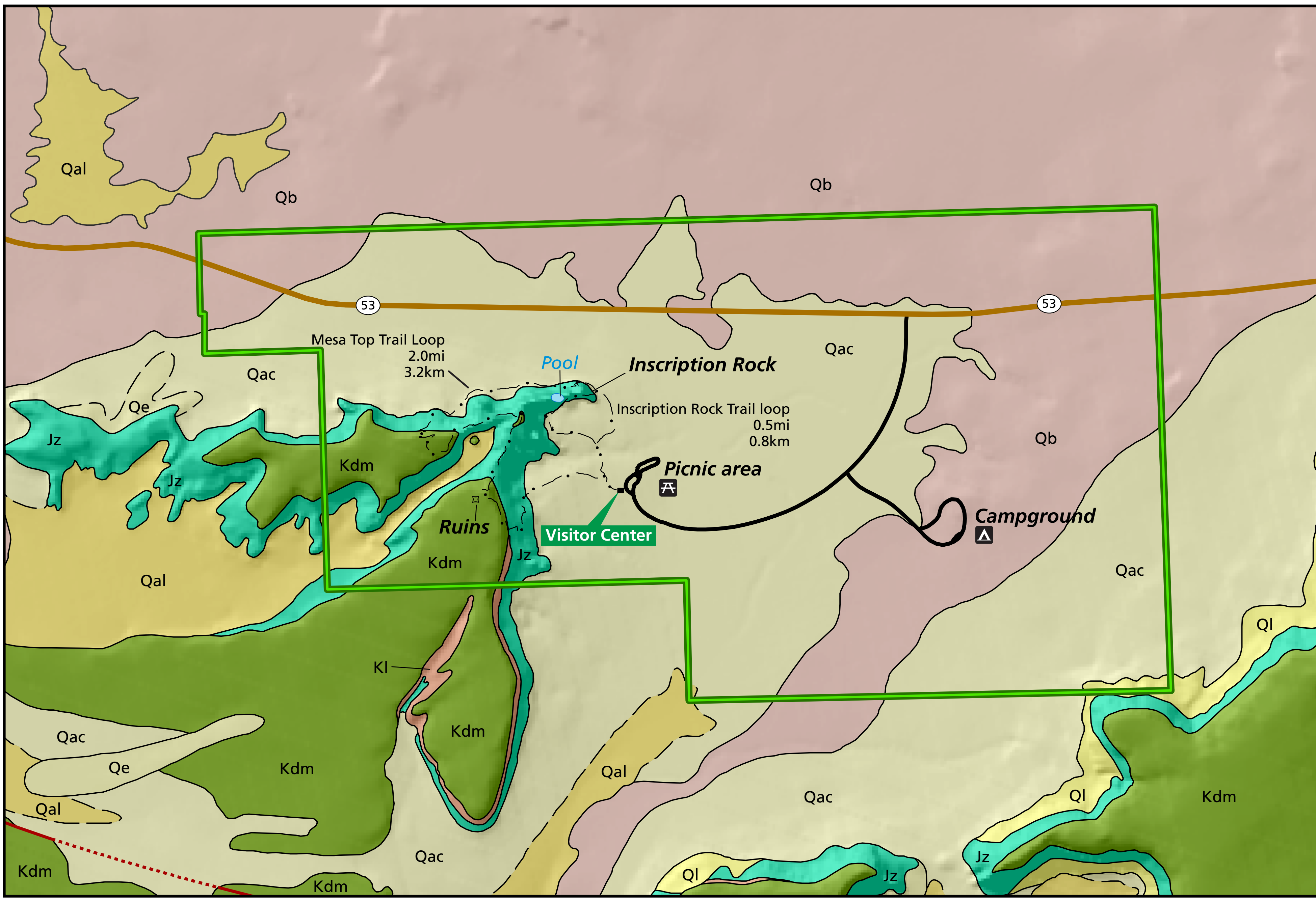
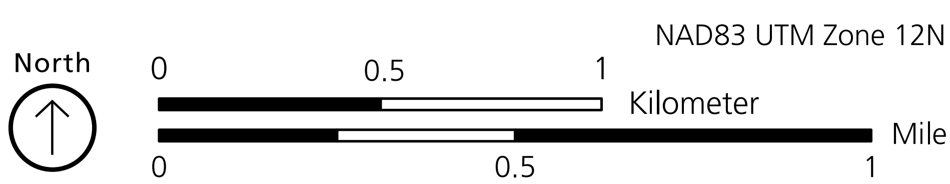
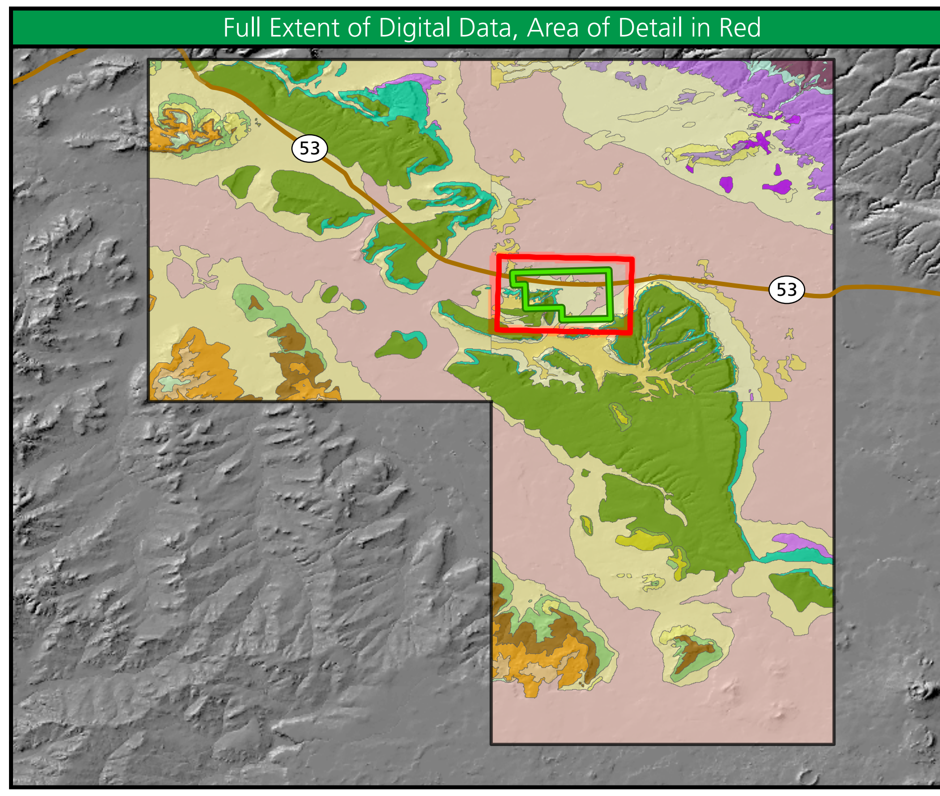
Overview of Digital Geologic Data for El Morro National Monument





Full Extent of Digital Data, Area of Detail in Red



NPS Boundary

Roads and Trails
- Highways
- Park Roads
- Park Trails

Folds
- anticline, known or certain
- anticline, concealed
- syncline, known or certain
- syncline, concealed

Geologic Contacts
- known or certain
- approximate
- inferred
- quadrangle boundary

Geologic Units
- Qe - Eolian deposits
- Qas - Alluvium and slopewash
- Qal - Alluvium
- Qac - Alluvium, colluvium and eolian deposits
- Ql - Landslide deposits
- Qb - Basalt flows
- Kmp - Mancos Shale, Pescado Tongue
- Kmr - Mancos Shale, Rio Salado Tongue
- Kmw - Mancos Shale, Whitewater Arroyo Tongue
- Kthf - Tres Hermanos Formation, Fite Ranch Sandstone Member
- Kthc - Tres Hermanos Formation, Carthage Member
- Ktha - Tres Hermanos Formation, Atarque Sandstone Member
- Kdt - Dakota Sandstone, Twowells Tongue
- Kdm - Dakota Sandstone, Main Body
- Kl - Zuni Sandstone, reworked
- Jz - Zuni Sandstone
- TRcu - Chinle Formation, Upper part
- TRcr - Chinle Formation, Rock Point Member
- TRcp - Chinle Formation, Petrified Forest Member
- TRcs - Chinle Formation, Sonsela Sandstone Member
- TRcl - Chinle Formation, Lower Member
- Psa - San Andres Limestone
- Pg - Glorieta Sandstone

This figure is an overview of compiled digital geologic data. It is not a substitute for site-specific investigations.

Minor inaccuracies may exist regarding the location of geologic features relative to other geologic or geographic features on the figure. Based on the source map scale (1:24,000) and U.S. National Map Accuracy Standards, geologic features represented here are within 12 meters / 40 feet (horizontally) of their true location.

The source maps used in creation of the digital geologic data product include paper U.S. Geological Survey and New Mexico Bureau of Mines and Mineral Resources publications (see Geologic Map Data section in report for specific sources).

Digital geologic data and cross sections for El Morro National Monument, and all other digital geologic data prepared as part of the Geologic Resources Inventory, are available online at the NPS Integrated Resource Management Applications Portal (IRMA): https://irma.nps.gov/App/Reference/Search. (Enter “GRI” as the search text and select El Morro National Monument from the unit list.)

Produced by the Geologic Resources Inventory

October 2012

Map Unit Properties Table: El Morro National Monument

Colored rows indicate units mapped within El Morro National Monument. Italicized text corresponds to report sections.

Age	Map Unit (Symbol)	Geologic Description	Geologic Issues	Geologic Features and Processes	Geologic History and Park Connections
QUATERNARY (Holocene)	Eolian deposits (Qe)	Windblown silt and sand in small dunes and sheets.	*Loss of Inscriptions*—eolian processes aid disintegration of inscriptions on the friable Zuni Sandstone (**Jz**), which is the source of eolian sediment today. Eolian deposits (**Qe**) are accumulating at the base of Inscription Rock. *Tinaja Pit*—eolian processes transport limestone dust produced during blasting and as a result of hauling of aggregate on roadways.	*El Morro and Inscription Rock*—**Qe** is part of apron of sediments that surrounds the El Morro cuesta. *Box Canyon*—disintegrated rock debris eroded during canyon formation is transported away via eolian processes. *Tinajas*—eolian processes may be a factor in tinaja formation. *Eolian Features and Processes*—infilling by eolian dust on basalt flows (**Qb**) is the first stage of soil development. *Paleontological Resources*—potential for mammalian fossils and other fossil assemblages.	The El Morro area is characterized by small eolian deposits (**Qe**) oriented east–northeast. Blowouts with dunes on lee (east–northeast) sides are common in the northern part of the El Morro quadrangle. Anderson and Maxwell (1991) mapped only the thickest accumulations of **Qe** within the El Morro quadrangle, but small dunes and sand sheets occur within the national monument. A cycle of eolian transport and deposition started during the Jurassic Period, when the Zuni Sandstone (**Jz**) was deposited as sand dunes. The cycle continues as the sandstone now provides sand grains for windblown transport to modern landscapes composed of **Qe**.
	Alluvium (Qal)	Mainly silt and fine-grained sand in active stream floodplains. Includes some eolian and colluvial deposits.	*Rockfall Hazards*—colluvial deposits were deposited via mass wasting (gravity-driven processes).	*El Morro and Inscription Rock*—**Qal** is part of the apron of sediment that surrounds the El Morro cuesta. *Box Canyon*—**Qal** covers the floor of box canyon, which is cut into the El Morro cuesta. *The Pool*—a well in **Qal** replaced the pool as the source of El Morro National Monument's water supply. *Lava Flows*—alluvium often covers lava flows. *Paleontological Resources*—potential for mammalian fossils and other fossil assemblages.	Records recent landscape evolution: alluvial deposits by streams, eolian deposits by wind, and colluvial deposits by mass wasting. Aquifer for current water supply at El Morro National Monument.
QUATERNARY (Holocene and Pleistocene)	Alluvium and slopewash (Qas)	Unconsolidated clay, silt, and sand.	None reported.	*Paleontological Resources*—potential for mammalian fossils and other fossil assemblages.	Mostly floodplain deposits along larger streams and slopewash on adjacent gentle slopes and broad flats. Includes eolian deposits and low stream-terrace deposits locally.
	Alluvium, colluvium, and eolian deposits (Qac)	Variable mixtures of alluvium and colluvium, small landslide blocks, and small sand dunes. Generally stabilized by vegetation.	None reported.	*El Morro and Inscription Rock*—**Qac** forms apron of sediment around the El Morro cuesta. *Paleontological Resources*—potential for mammalian fossils and other fossil assemblages.	Covers the majority of the ground surface at El Morro National Monument. A typical example of **Qac** is the slope west of the visitor center.
	Landslide deposits (Ql)	Large sandstone landslide blocks, talus, and mudslides. May be partly covered by colluvium and eolian deposits. Occur as displaced masses of shale, siltstone, and sandstone on steep slopes formed by Rio Salado Tongue of the Mancos Shale (**Kmr**).	*Rockfall Hazards*—Wieczorek and Snyder (2009) provided vital signs for monitoring.	*Paleontological Resources*—potential for mammalian fossils and other fossil assemblages.	Anderson and Maxwell (1991) mapped **Ql** in the southeastern corner of El Morro National Monument.

Colored rows indicate units mapped within El Morro National Monument. Italicized text corresponds to report sections.

Age	Map Unit (Symbol)	Geologic Description	Geologic Issues	Geologic Features and Processes	Geologic History and Park Connections
QUATERNARY (Pleistocene)	Basalt flows or volcanic rocks (Qb)	Flows of dark-gray, vesicular basalt and basaltic andesite. Weathered and generally covered with soil, alluvium, or sand dunes. Anderson and Maxwell (1991) described unit as "essentially the same flows as 'Qbo' of Maxwell (1986)" (see Anderson and Maxwell's description on map). Qbo of Maxwell (1986) is Oso Ridge lava flows, as mapped near El Malpais National Monument. However, more recent field mapping and age dating show that unit **Qb** is equivalent to Maxwell's (1986) Qb (old basalt flows), not Qbo (Nelia Dunbar, New Mexico Bureau of Geology and Mineral Resources, volcanologist, e-mail communication, 9 March 2012).	None reported.	*Ephemeral Streams and Arroyos*—no stream crosses the lava plain between the Zuni Mountains and El Morro; all water sinks very quickly into **Qb**. *Eolian Features and Processes*—eolian silt has "infilled" the vesicles, cracks, and fissures of the basalt flows (**Qb**). *Lava Flows*—composed of aa lava. *Unconformities*—at least 65 million years of the rock record are missing between the Upper Cretaceous Dakota Sandstone (**Kdm**) and **Qb**. *Paleontological Resources*—potential for tree molds on lava flows and mammalian fossils in cave sediments of lava-tube caves.	Flows are part of the Zuni–Bandera volcanic field. Forms open grasslands with small outcrops of basalt. Underlies campground at El Morro National Monument. Buried Chinle Formation (**TRc** units) in valleys. Luedke and Smith (1978) reported ages of 788,000 years near Cerro Bandera east of map area and 1.38 million years several kilometers southwest of map area; however, more recent dating and field investigation by Laughlin et al. (1993b) yielded an age of 700,000 years for the "old basalt flows" (**Qb**) of Maxwell (1986) at El Malpais National Monument and, by correlation, for the flows at El Morro National Monument.
UPPER CRETACEOUS	Mancos Shale, Pescado Tongue (Kmp)	Dark-gray shale. Contains prominent, dark-gray, brown-weathering septarian limestone concretions. A bed about 1 m (3 ft) thick of calcareous siltstone about 3 m (10 ft) above the base of the tongue caps high buttes in the northwestern part of the El Morro quadrangle. Exposed thickness 6–12 m (20–40 ft).	None reported.	None reported.	Deposited in the Western Interior Seaway. Indicative of the migration of marine waters back and forth across the area.
	Tres Hermanos Formation, Fite Ranch Sandstone Member (Kthf)	Light-gray, mostly fine-grained sandstone. Thickness 3–6 m (10–20 ft).	None reported.	None reported.	Deposited in the Western Interior Seaway. Indicative of the migration of marine waters back and forth across the area.
	Tres Hermanos Formation, Carthage Member (Kthc)	Light-gray and light-yellowish-gray, very fine to fine-grained, cross-bedded sandstone in lenticular beds. Also, light-gray siltstone, dark-gray mudstone, brown carbonaceous shale, and minor beds of coal. Thickness about 45 m (150 ft).	None reported.	None reported.	Deposited in the Western Interior Seaway. Indicative of the migration of marine waters back and forth across the area.
	Tres Hermanos Formation, Atarque Sandstone Member (Ktha)	Light- or pinkish-gray, fine-grained, flat-bedded and cross-bedded sandstone. Some interbedded, dark shale and sandy shale. Thickness 15–18 m (50–60 ft).	None reported.	None reported.	Deposited in the Western Interior Seaway. Indicative of the migration of marine waters back and forth across the area.
	Mancos Shale, Rio Salado Tongue (Kmr)	Dark-gray shale and interbeds of light-gray siltstone and very fine-gained sandstone, mostly at the top of the unit. Calcareous shale, white-weathering shaly limestone, and a few thin layers of bentonite in the basal 10–12 m (30–40 ft). Thickness about 75 m (250 ft).	None reported.	None reported.	Deposited in the Western Interior Seaway. Indicative of the migration of marine waters back and forth across the area.
	Dakota Sandstone, Twowells Tongue (Kdt)	Light-gray and light-yellowish-gray, fine- to medium-grained sandstone. Generally cross-bedded. Thickness 3–8 m (10–25 ft).	None reported.	*Paleontological Resources*—potential for terrestrial plant fossils and vertebrate tracks.	Deposited in the Western Interior Seaway. Indicative of the migration of marine waters back and forth across the area.
	Mancos Shale, Whitewater Arroyo Tongue (Kmw)	Dark-gray and yellowish-gray silty shale. Thickness 12–15 m (40–50 ft).	None reported.	None reported.	Deposited in the Western Interior Seaway. Indicative of the migration of marine waters back and forth across the area.

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Age	Map Unit (Symbol)	Geologic Description	Geologic Issues	Geologic Features and Processes	Geologic History and Park Connections
UPPER CRETACEOUS	Dakota Sandstone (Kdm)	Sandstone, mudstone, carbonaceous mudstone/shale, and conglomeratic sandstone. Upper part is light-gray to light-yellowish-gray, fine- to medium-grained, thinly bedded, locally cross-bedded sandstone. Middle part is olive-gray and light- to dark-gray mudstone and shale with fine- to coarse-grained lenticular sandstone beds that are commonly cross-bedded. Lower part consists of medium- to coarse-grained, cross-bedded sandstone and conglomeratic sandstone. Hardened with silica cement. Lower part may be absent. Locally gradational into underlying reworked Zuni Sandstone (**Kl**). Total thickness up to 45 m (150 ft).	None reported.	*El Morro and Inscription Rock*—**Kdm** rests on top of the bleached horizon of the Zuni Sandstone (**Jz**). Forms cap rock on the El Morro cuesta. *Box Canyon*—loss of **Kdm** cap rock facilitates canyon formation via groundwater sapping. *Tinajas*—occur within the **Kdm** cap rock. *Unconformities*—more than 60 million years of the rock record is missing between the bleached horizon of **Jz** and the overlying **Kdm**. *Paleontological Resources*—most likely among rock units in El Morro National Monument to contain fossils, including plants, petrified wood, or casts of burrowing and crawling organisms.	Preserved along the Mesa Top Trail. Pueblo ruins were built on the middle part (gray mudstone to shale) of the unit. Records the initial advance of the Western Interior Seaway into New Mexico from the north/northeast.
LOWER CRETACEOUS (?)	Zuni Sandstone, reworked (Kl)	Light-colored sandstone. Represents fluvial reworking of up to (30 ft) of the upper part of the Zuni Sandstone (**Jz**).	None reported.	*Paleontological Resources*—petrified wood may occur in the reworked zone.	Present at several locations in the region, notably in the southern part of El Morro National Monument and southward. The reworking involves redistribution of the eolian sand, oxidation, addition of some clay and chert grains and pebbles, and introduction of lenses of pebble conglomerate. Typical examples are found along the Mesa Top Trail.
MIDDLE JURASSIC	Zuni Sandstone (Jz)	Generally pale-yellowish-gray or tan sandstone; however, locally chalk white or pale greenish gray ("bleached zone"). Predominantly eolian and cross-bedded, but locally flat-bedded or massive. Very well-sorted, fine- to medium-sized, well-rounded grains, largely of quartz. Up to 6-m- (20-ft-) thick bed of conglomerate at base contains pebbles and cobbles with diameters up to 15 cm (6 in) of black, red, gray, and white chert and gray and brown quartzite. Total thickness ranges from 60 m (200 ft) in southeastern part of the El Morro quadrangle to as much as 110 m (350 ft) at El Morro Lookout; thickest in the northwest.	*Loss of Inscriptions*—inscriptions weathering away on friable Zuni Sandstone (**Jz**). *Rockfall*—vertical joints in the sandstone result in rockfall. Spalling of friable sandstone occurs in areas of groundwater sapping. *Tinaja Pit*—vibrations from blasting and hauling trucks on Highway 53 may exacerbate spalling of sandstone and loss of inscriptions.	*El Morro and Inscription Rock*—**Jz** makes up bulk of the El Morro cuesta and cliffs of Inscription Rock. *Box Canyon*—joints in **Jz** focus groundwater and result in sapping and box canyon development. *Tinajas*—occur in the topmost bleached zone and the iron-stained zone. *Eolian Features and Processes*—unit composed of 160-million-year-old sand dunes—the most conspicuous eolian feature in El Morro National Monument. Source of eolian sediment today. *Unconformities*—unconformities above and below **Jz**. In the El Morro area, at least 24 million years of the rock record are missing between **TRcr** and **Jz**, and at least 62 million years of the rock record are missing between **Jz** and **Kdm**. *Paleontological Resources*—fossils very rare.	Lowermost part (red sandstone and thin layers of red sandy mudstone) may be equivalent to the Entrada Sandstone (Anderson 1983). Deposited at the southern edge of a vast desert 160 million years ago.
UPPER TRIASSIC	Chinle Formation, Rock Point Member (TRcr)	Alternating red-brown, even-bedded, fine-grained, silty sandstone and chocolate-brown to red, thin-bedded, fine-grained sandstone that grades upward into a friable, well-sorted reddish-brown sandstone and chert-pebble conglomerate. *Note*: Mapel (1985) and Mapel and Yesberger (1985) mapped this unit as Rock Point Member of the Wingate Sandstone (TRwr), but the unit is now considered part of the Chinle Formation.	None reported.	*Unconformities*—at least 124 million years of the rock record are missing between **TRcr** and **Jz** in the El Morro area. *Paleontological Resources*—known to contain petrified wood elsewhere.	Deposited by rivers and streams in valleys and on broad plains. Easily eroded and underlies valleys in El Morro area. Some exposures on the flanks of the Zuni Mountains.
UPPER TRIASSIC	Upper part of Chinle Formation (TRcu)	Banded, grayish-red to pale-reddish-brown and grayish-purple mudstone, siltstone, and silty sandstone. Thickness about 30 m (100 ft).	None reported.	*Paleontological Resources*—known to contain petrified wood elsewhere.	Deposited by rivers and streams in valleys and on broad plains. Easily eroded and underlies valleys in El Morro area. Some exposures on the flanks of the Zuni Mountains.

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Age	Map Unit (Symbol)	Geologic Description	Geologic Issues	Geologic Features and Processes	Geologic History and Park Connections
UPPER TRIASSIC	Chinle Formation, Sonsela Sandstone Member (TRcs)	Yellowish-gray to grayish-red, fine- to coarse-grained sandstone with granule to pebble conglomerate. Medium to thick cross-bed sets. Thin partings of purple-gray and red siltstone and mudstone. Maximum thickness 43 m (140 ft); appears to thin westward.	None reported.	*Paleontological Resources*—known to contain petrified wood elsewhere.	Deposited by rivers and streams in valleys and on broad plains. Easily eroded and underlies valleys in El Morro area. Some exposures on the flanks of the Zuni Mountains.
UPPER TRIASSIC	Chinle Formation, Lower Member (TRcl)	Grayish-red and reddish-brown sandstone interbedded with reddish-brown siltstone. Contains medium- to coarse-grained, arkosic, micaceous sandstone beds and lenses of pebble conglomerate. Both calcitic- and silicic-cemented facies present. Thickness 30–45 m (100–150 ft).	None reported.	*Unconformities*—at least 42 million years of the rock record are missing between **Psa** and **TRcl** in the El Morro area. *Paleontological Resources*—known to contain petrified wood elsewhere.	Deposited by rivers and streams in valleys and on broad plains. Easily eroded and underlies valleys in El Morro area. Some exposures on the flanks of the Zuni Mountains.
LOWER PERMIAN	San Andres Limestone (Psa)	Upper part is massive, pinkish-gray limestone. Middle part is yellowish-gray sandstone with calcitic cement, locally grading into sandy dolomitic limestone. Lower part is mostly yellowish-gray to gray, thick-bedded, fossiliferous, dolomitic limestone with thin calcareous shale partings and thin sandy limestone lenses. Lower part is generally the thickest of the three. Total thickness 35 to 45 m (115 to 145 ft).	*Tinaja Pit*—source of aggregate. Mined by C & E Concrete, Inc. east of El Morro National Monument.	*Unconformities*—at least 42 million years of the rock record are missing between **Psa** and **TRcl** in the El Morro area.	**Psa** caps the steep, southwest-facing mountain front that can be seen from El Morro. Uplifted during the Laramide Orogeny and exposed along the Zuni Mountain front. Deposited in Permian seas.
LOWER PERMIAN	Glorieta Sandstone (Pg)	Very pure, well-sorted, white to buff, medium- to coarse-grained quartz sandstone, massively cross-bedded. Weathers yellow to light brown. Well cemented with silica or calcite. Thickness approximately 45 m (150 ft).	None reported.	None reported.	Exposed in Zuni Mountains. Deposited in Permian seas.