National Park Service
U.S. Department of the Interior

Natural Resource Stewardship and Science

El Malpais National Monument

Geologic Resources Inventory Report

Natural Resource Report NPS/NRSS/GRD/NRR—2012/578

ON THE COVER
The 3,900-year-old McCartys flow is juxtaposed against the 160-million-year-old Zuni Sandstone, which is capped by 100-million-year-old Dakota Sandstone at the Sandstone Bluffs Overlook. The bluffs consist of gently dipping sandstone that crops out along the eastern flank of the Cebollita Mesa on the eastern margin of El Malpais National Monument. Photograph by Katie KellerLynn (Colorado State University).

THIS PAGE
The McCartys flow is the youngest lava flow in New Mexico and still exhibits a glassy rind in many locations. Photograph by Katie KellerLynn (Colorado State University).

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National Park Service
Geologic Resources Division
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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.

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

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

Printed copies of this report are produced in a limited quantity and they are only available as long as the supply lasts. This report is available from the Geologic Resources Inventory website (http://www.nature.nps.gov/geology/inventory/gre_publications.cfm) and the Natural Resource Publications Management website (http://www.nature.nps.gov/publications/nrpm/).

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Executive Summary

This report accompanies the digital geologic map data for El Malpais 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.

El Malpais National Monument is part of the Zuni–Bandera volcanic field in west-central New Mexico. The relatively recent volcanism, combined with the arid New Mexico climate, make El Malpais an ideal place in the continental United States to see Hawaiian-style volcanic deposits, extensive lava-tube systems, and associated lava-tube caves.

The Zuni–Bandera volcanic field began erupting about 700,000 years ago, but the El Malpais episode occurred less than 60,000 years ago. The youngest lava flow at the national monument is 3,900 years old and represents the most recent volcanic eruption in New Mexico; this eruption produced the McCartys flow. El Malpais National Monument preserves a portion of this young flow, as well as its vent, the McCartys cinder cone, which is the youngest volcano in New Mexico.

Early Spanish explorers who encountered the extremely rough lava-flow surfaces named the area "El Malpais," meaning "The Badlands." The geologic importance of the area has been recognized since at least the 1930s, when El Malpais was first proposed as a national monument. El Malpais National Monument and adjacent El Malpais National Conservation Area were formally established in 1987 and are managed by the National Park Service and the Bureau of Land Management, respectively.

Maxwell (1986) is the primary source for the digital geologic map covering the area of El Malpais National Monument. The digital data set also includes Maxwell (1977), which covers the McCartys quadrangle northeast of the national monument and includes the portion of the McCartys lava flow outside the national monument boundaries.

The rock units mapped by Maxwell (1986) can be divided into three main types: (1) very old metamorphic and igneous rocks of Precambrian age (approximately 1.4 billion years old); (2) sedimentary rocks of Permian, Triassic, Jurassic, and Cretaceous ages (299 million–65.5 million years old); and (3) young volcanic rocks, most of which erupted in the past 700,000 years. The deposition of unconsolidated materials, such as alluvium, colluvium, landslide deposits, and windblown silt, is also part of recent geologic history at the national monument. A geologic time scale showing the eras, periods, and epochs of geologic time is included in this report.

The Precambrian rocks at El Malpais National Monument are fragments of oceanic and continental crust that accreted to the western edge of the North American continent. Over time, these rocks became the stable North American craton. These ancient rocks can be seen in the El Calderon area north of Highway 53.

The "middle-aged" sedimentary rocks at the national monument accumulated over millions of years as shallow seas advanced and withdrew from the area from the Permian through the Upper Cretaceous periods. Representatives of these rocks are exposed at the Sandstone Bluffs Overlook.

The young volcanic rocks, which dominate the landscape at the national monument, erupted over the last 60,000 years. Older pulses of volcanism occurred 150,000 and 700,000 years ago and cover the Chain of Craters and Hole-in-the-Wall areas, respectively.

This Geologic Resources Inventory (GRI) report was written for resource managers to assist in resource management and science-based decision making, but it may also be useful for interpretation. The report discusses geologic issues facing resource managers at El Malpais National Monument, distinctive geologic features and processes within the national monument, and the geologic history leading to the present-day landscape. The Geologic Map Overview Graphic illustrates the geologic data; the Map Unit Properties Table summarizes the main features, characteristics, and potential management issues for all rocks and unconsolidated deposits on the digital geologic map for El Malpais National Monument. This report also provides a glossary that contains explanations of technical, geologic terms, including terms on the Map Unit Properties Table. The 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.

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

- Cave Management. The top resource-management priority at El Malpais National Monument is to complete a cave management plan. The most immediate threat to cave resources at the national monument is the potential spread of white-nose syndrome, which is responsible for millions of bat deaths across the eastern and central United States. Other threats include pollution, garbage dumping, physical impacts such as trampling, and impacts to the fragile moss gardens at cave entrances and under skylights. The loss of cave ice as a result of multiannual drought is also a concern.

- Mass Wasting. Within El Malpais National Monument, the primary mass-wasting (gravity-driven) process is rockfall off the sandstone bluffs. Maxwell (1986) mapped extensive landslides east of the national monument.
- Erosion. Although erosion is a natural feature on the landscape, a legacy of grazing and other agricultural practices has exacerbated this process in parts of the national monument, particularly in the Sandstone Bluffs Overlook area.
- Flooding. Streams in El Malpais National Monument are ephemeral and flow only during flash-flooding events. Storm-water runoff is a concern for management because stream channels originating in agricultural and grazed areas outside the national monument transport pesticides, herbicides, fertilizers, and increased amounts of sediment into the lava-tube system within the national monument, thereby introducing contaminants and impacting cave biota. On the east side of the national monument, flooding causes erosion between the sandstone bluffs and the McCartys flow, affecting an area in which archeological sites are highly concentrated. Flooding on the east side also periodically washes out Highway 117.
- Disturbed Lands. Disturbances on the El Malpais landscape have resulted from channel diversions, grazing and agricultural practices, logging, mining, and military activities.
- Recent and Potential Volcanism. A 1% chance exists that some type of volcanic eruption will occur in New Mexico in the next 100 years, and a 10% chance exists that an eruption will occur in the next 1,000 years. In probabilistic terms, 100 eruptions will occur in the next 1 million years. Future eruptions are most likely to occur along the Jemez lineament and the Rio Grande rift, particularly where the Rio Grande rift intersects crosscutting lineaments, such as in the Jemez Mountains and near Socorro, New Mexico. The eruption will likely be basaltic, which has been the dominant mode of volcanism in New Mexico over the past 5 million years.
- Seismic Activity. New Mexico has a recorded history of seismic activity since 1869. This long record allows researchers to evaluate seismic hazards and make predictions concerning the likely locations and magnitudes of future earthquakes. A disproportionate number of earthquakes in New Mexico are centered in the Rio Grande Valley near Socorro, which is about 80 km (50 mi) southeast of El Malpais National Monument. The intact nature of lava flows at the national monument indicates that seismic activity has not occurred recently. The most recent "felt quake" was in the 1970s.
- Geochronology, Future Research, and Interpretation. Although a few gaps exist, the chronology of volcanic events at El Malpais National Monument has been well defined through relative and radiometric dating methods. Researchers continue to use the national monument as a field area, in particular for testing various dating techniques on volcanic rocks and applying cross-dating methods for comparative analysis. Dating of some of the older flows would give a more complete picture of the sequence of volcanic events. The quality of preservation of the volcanic features and accessible location make the national monument an ideal location for field trips and public education.

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

- Volcanic Features and Processes. Geologists have grouped the volcanic features at El Malpais National Monument into two main categories: flows and vents. Pahoehoe (smooth and "ropey") and aa (rough and "blocky") lava flows are present at El Malpais. These flows extruded from numerous vents, which are primarily cinder cones, but also shield volcanoes, at El Malpais. As part of the main El Malpais event, Maxwell (1986) mapped the McCartys flow and cinder cone (map unit symbols Qbm and Qcm); Bandera flows, crater, and cinder field (Qbb, Qcb, and Qvb); Hoya de Cibola flows and shield volcano (Qbw and Qvw); Twin Craters flows, cones, and mixed pyroclastics (Qbt, Qct, and Qvt); and El Calderon flows, crater, and cinder field (Qbc, Qcc, and Qvc). Maxwell (1977) used map symbols Qbd for the McCartys flow and Qba for the oldest Zuni basalt flow, which are mapped in the McCartys quadrangle northeast of the national monument.
- Lava Tubes. Lava tubes are conduits for molten lava flowing from a vent, which later become cavernous passages that remain after the lava has ceased flowing. The Bandera flows, with a flow length of 37 km (23 mi) contains remnants of what had been a very extensive lave tube system at El Malpais. This system today includes 28 km (17 mi) of small segments of intact lava tubes and longer segments of trenches left over from the roof collapse of the original lava tube. If all intact, this tube system would the longest known lava tube system in North America.
- Ice Caves. Seasonal and perennial accumulations of ice are present in many of the lava tubes at El Malpais National Monument. Some of the ice is more than 3,100 years old.
- Eolian Features and Processes. Eolian deposits in the El Malpais area are recent accumulations of windblown silt and sand that form sand sheets, dune fields, longitudinal dunes, and smaller deposits. The friable Zuni Sandstone and walls of kipukas, composed of sandstone and limestone, are sources of

eolian sediment. Eolian processes influence the lava flows by infilling vesicles and cracks with windblown dust. Infilling is a significant part of landscape evolution and is the first stage in soil development on the lava flows.

- Biologic and Geologic Connections. Many connections can be made between the biologic and geologic resources at El Malpais National Monument. In particular, lava flows, kipukas, cinder cones, lava tubes, tinajas, playas, and eolian deposits create special habitats. Moreover, soil crusts are an important and widespread component of the ecosystem and improve soil quality.
- Paleontological Resources. Tree molds, such as those on the surface of the Bandera flows (Qbb), are the most noteworthy paleontological resource at the national monument. Fossils, primarily marine organisms, are known from Permian and Cretaceous rocks within El Malpais National Monument. Additionally, Quaternary plant debris, packrat middens, and bones occur in lava-tube caves.
- Sandstone Features. Sandstone figures prominently in the landscape of El Malpais National Monument. Rock units of the Cretaceous Dakota and Jurassic Zuni sandstones are exposed at the national monument. The ridgetop at Sandstone Bluffs Overlook is composed of Dakota Sandstone. Zuni Sandstone lines the Highway 117 corridor on the eastern side of the national monument. Maxwell (1977, 1986) divided the Dakota Sandstone into many subunits called "tongues," which are listed in the Map Unit Properties Table. Mesas, ridges, arches, and hoodoos are characteristic landforms of these sandstone units.

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 scoping meeting in 2006, who are listed in the Appendix. In addition, Ken Mabery, former superintendent at El Malpais National Monument, provided input during a pre-scoping conference call in 2006. He is currently superintendent at Scotts Bluff National Monument. Dana Sullivan (chief ranger) and Dave Hays (resource manager) at El Malpais National Monument participated in a conference call in December 2011 and provided much post-scoping guidance on issues related to the national monument's geologic resources. Dale Dombrowski (writer/editor) at El Malpais National Monument assisted with collecting photographs used in this report. Larry Crumpler (research curator) at the New Mexico Museum of Natural History and Science provided photographs and granted permission for their use in this report. 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 Pate (Cave and Karst Program Coordinator) at the NPS Geologic Resources Division reviewed the lava tube sections of the report.

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Introduction

This section briefly describes the National Park Service Geologic Resources Inventory Program and the regional geologic setting of El Malpais 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).

Regional Geologic Setting

El Malpais National Monument (fig. 1) is part of the Zuni–Bandera volcanic field, which features more than 100 vents and associated cinder cones, shield volcanoes, and lava flows (Luedke and Smith 1979). The Zuni–Bandera volcanic field is on the southeastern edge of the Colorado Plateau in the "Four Corners" area of New Mexico, Arizona, Colorado, and Utah (fig. 2). Generally speaking, the Colorado Plateau is characterized by uplifted horizontal or slightly tilted sedimentary strata and a lack of volcanism. However, the Zuni–Bandera volcanic field and several other areas of volcanism, including Sunset Crater Volcano National Monument in Arizona (Thornberry-Ehrlich 2005), are located along the edge of the plateau. The vents of the Zuni–Bandera volcanic field erupted in a transition zone between the Colorado Plateau and the Rio Grande rift, which is characterized by crustal extension and thinning (Dunbar 2010).

The Zuni–Bandera volcanic field began erupting about 700,000 years ago, with the El Malpais event beginning less than 60,000 years ago (fig. 3). The primary El Malpais flows mapped by Maxwell (1986) are the McCartys (map unit symbol Qbm), Bandera (Qbb), Hoya de Cibola (Qbw), Twin Craters (Qbt), and El Calderon (Qbc) flows. Maxwell (1977) mapped the McCartys flow as unit Qbd. The Paxton Springs (Qbp), Zuni (Qbz and Qba), and Oso Ridge (Qbo) flows originated north of El Malpais National Monument in the Zuni Mountains, and erupted during the same period as the El Malpais flows (Maxwell 1977, 1986). Of these three, only a portion of the Oso Ridge flows occurs within the national monument. Maxwell (1986) also mapped nearby cinder cones (Qc), volcanic debris (Qv), and basalt flows (Qbu) typical of the Chain of Craters area west of the national monument (fig. 4). Old basalt flows (Qb) that represent initial volcanism of the Zuni–Bandera volcanic field also occur within the national monument. Old basalt flows underlie Hole-in-the-Wall and the area west of the national monument (figs. 4 and 16). Volcanic features at the national monument also include lava-tube caves such as the 27-km- (17-mi-) long system in the Bandera flows.

The Zuni–Bandera volcanic field is situated along a zone of crustal weakness called the Jemez lineament, which contains numerous volcanic fields (fig. 5). El Malpais National Monument lies near the center of the lineament, which extends from central Arizona to northeastern New Mexico. The major volcanic fields on the Jemez lineament in New Mexico are, from west to east, the Zuni–Bandera volcanic field, the Mount Taylor volcanic field, the Valles Caldera, the Ocaté volcanic field, and the Raton–Clayton volcanic field. The National Park System is well represented along the Jemez lineament: El Malpais and El Morro national monuments are part of 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 in the Valles Caldera (National Park Service 2005). Petroglyph National Monument lies on the Rio Grande rift (National Park Service 2006c), which was a center of volcanic activity during an earlier episode of volcanism (40 million–20 million years ago) and intersects the Jemez lineament near Valles Caldera.

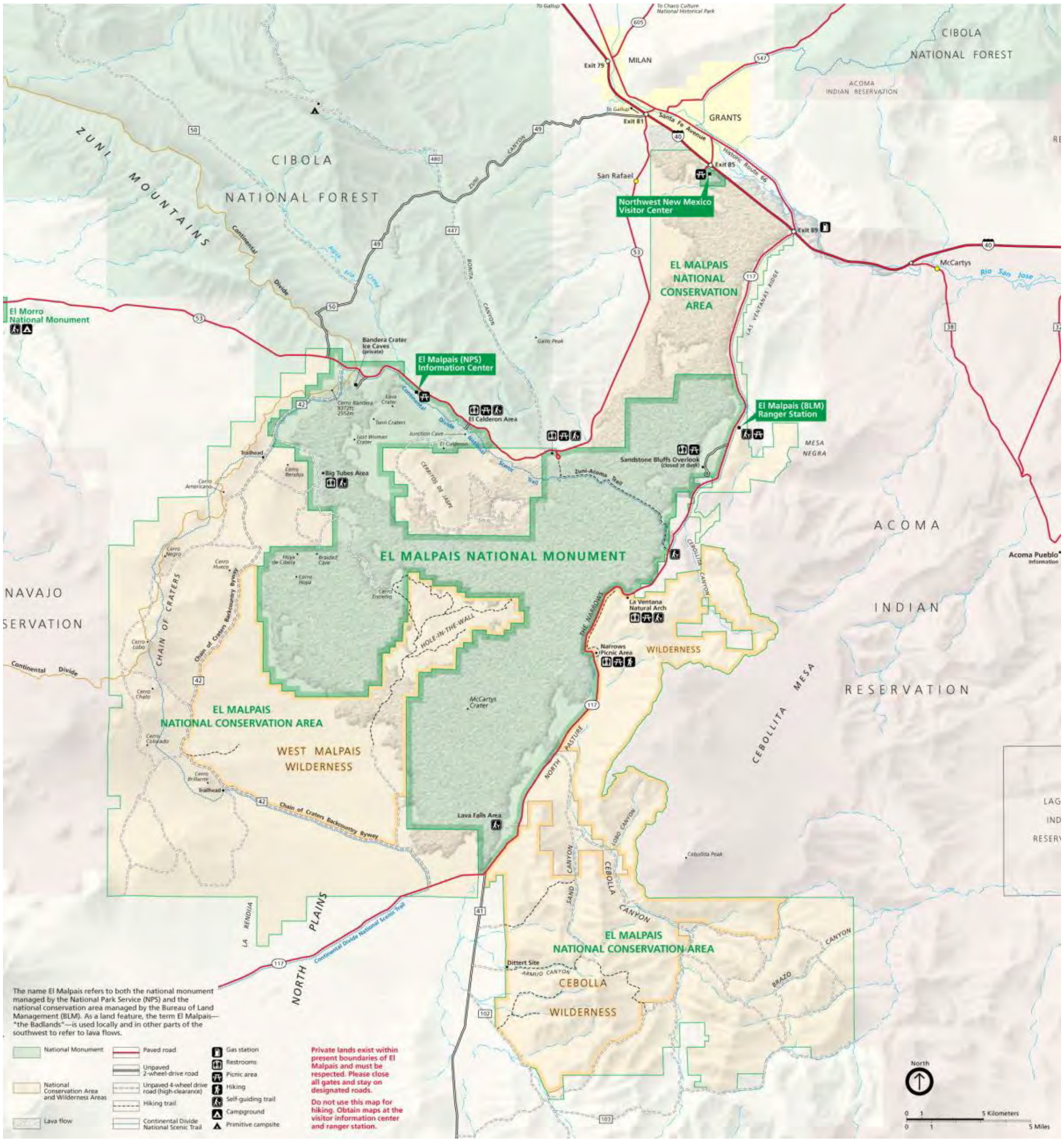

Figure 1 Map of El Malpais National Monument. Along with adjacent El Malpais National Conservation Area, administered by the Bureau of Land Management, El Malpais National Monument was established in 1987. El Malpais is situated in the Zuni–Bandera volcanic field south of Grants, New Mexico. The Chain of Craters, Hole-in-the-Wall, and Cebollita Mesa are distinctive landscape-scale features in the vicinity of the national monument. National Park Service graphic.

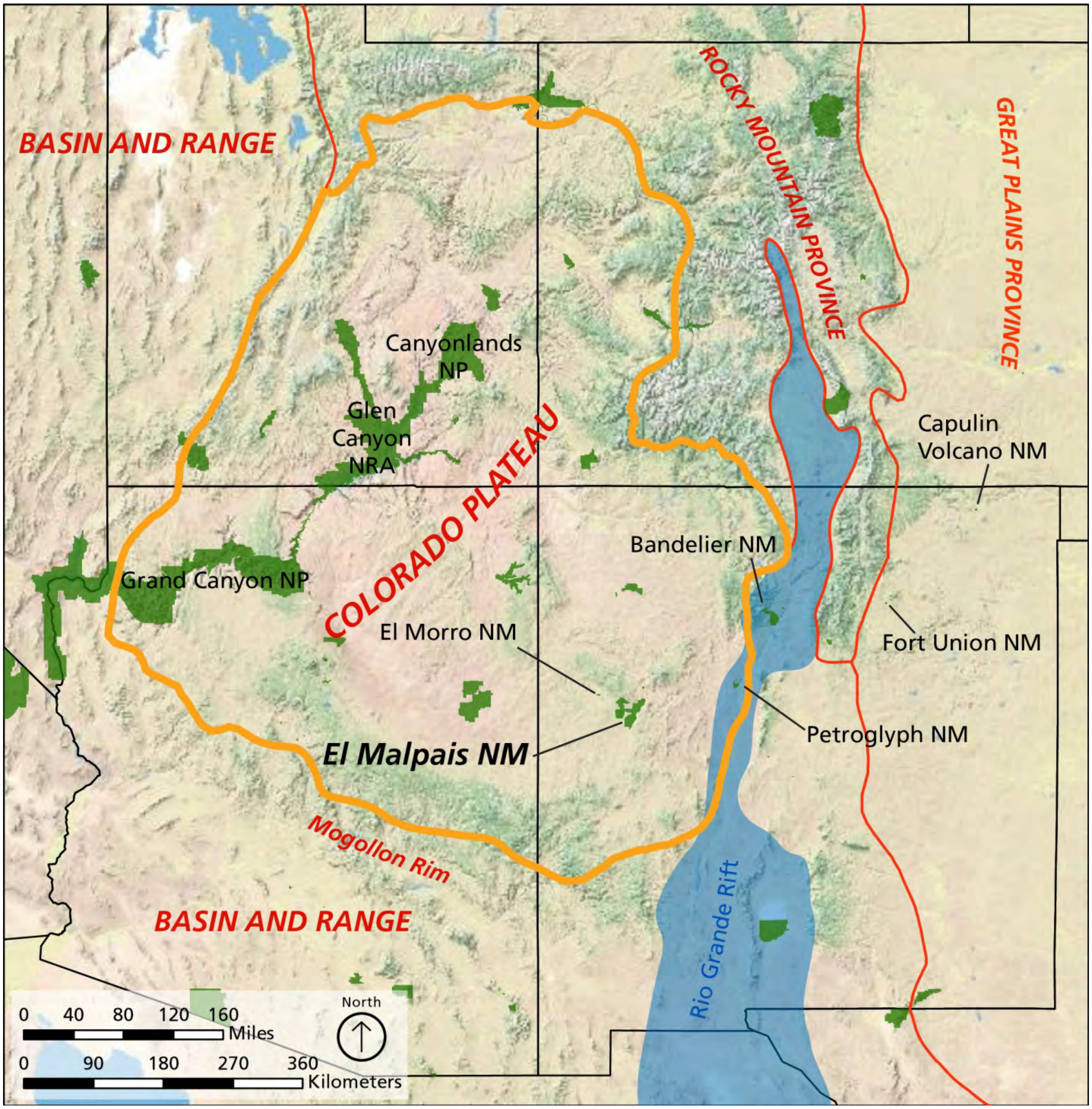

Figure 2. Colorado Plateau. The Colorado Plateau is roughly centered on the Four Corners area of Utah, Colorado, Arizona, and New Mexico. The plateau is bounded on the west by the Basin and Range physiographic province. A primary feature of the Basin and Range in New Mexico is the Rio Grande rift. Portions of the Great Plains and Rocky Mountain physiographic provinces also occur in New Mexico. Green areas on the figure represent the locations of National Park System units, some of which are labelled. Map by Philip Reiker (NPS Geologic Resources Division) and Rebecca Port (Colorado State University).

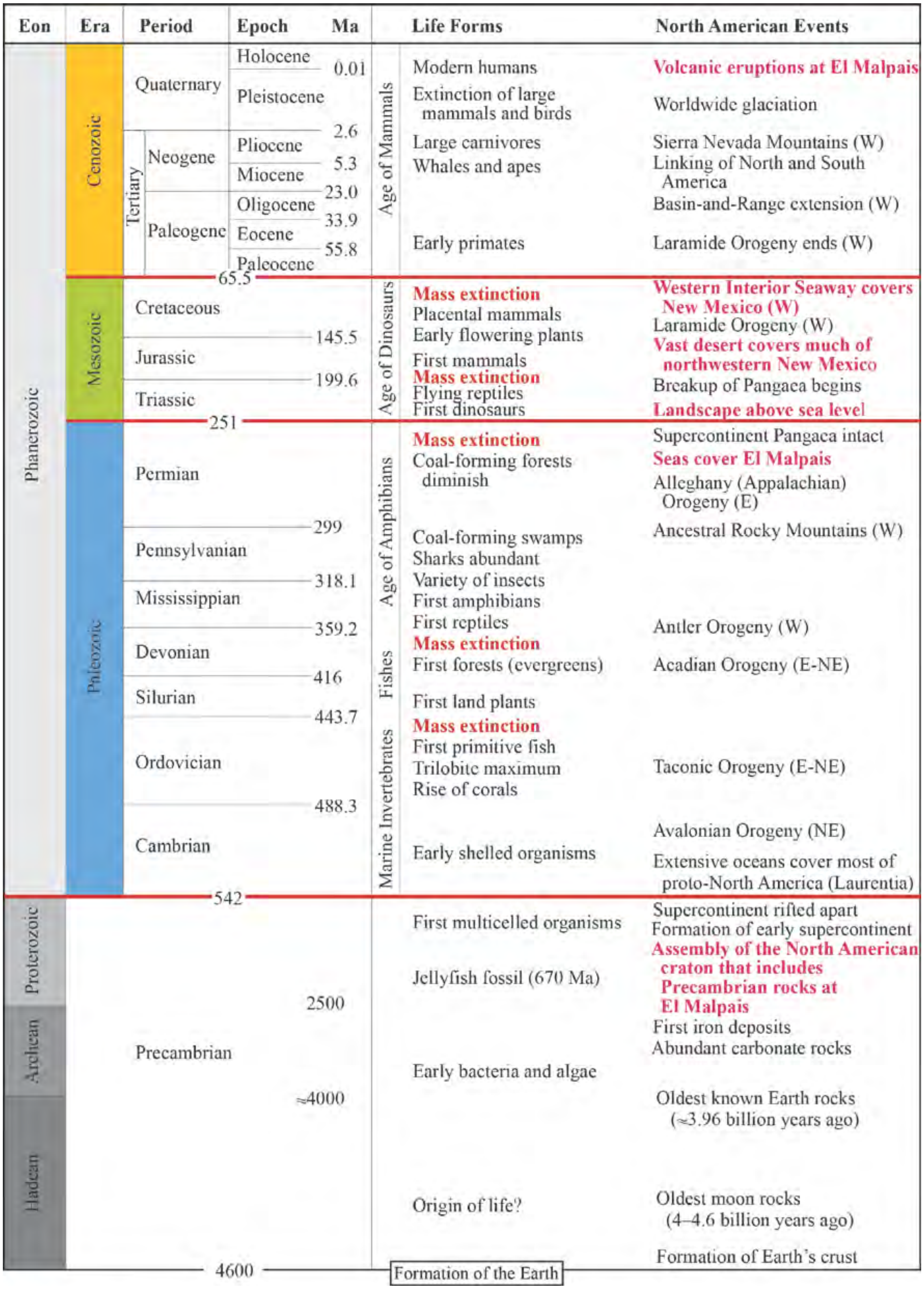

Figure 3. Geologic time scale. The divisions of the geologic time scale are organized stratigraphically, with the oldest at the bottom and youngest at the top. Boundary ages are in millions of years (Ma). Major life history and tectonic events occurring on the North American continent are included. Compass directions in parentheses indicate the regional location of individual geologic events. Red lines indicate major boundaries between eras. Graphic design by Trista Thornberry-Ehrlich (Colorado State University), 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 sand and silt
		Holocene and Pleistocene	2.6– present	Alluvium (Qal)	Sand and pebbles
				Landslide deposits (Ql)	Blocks of sandstone and shale
				Terrace alluvium and gravel ([Qtg])	Pebbles, cobbles, and boulders of volcanic and Precambrian rocks in a matrix of silt and sand
				Alluvium, colluvium, and soil (Qac)	Soil, silt, and sand
				Colluvium of McCartys Mesa ([Qc])	Colluvium, soil, caliche, terrace sand and gravel, alluvium, and windblown sand
				Pyroclastic debris and basalt flows Qbm, [Qbd], Qcm (McCartys); Qbb, Qcb, Qvb (Bandera); Qbw, Qvw (Hoya de Cibola); Qbp, Qcp, Qvp (Paxton Springs); Qbz, [Qba] (Zuni); Qbo, Qvo (Oso Ridge); Qbt, Qct, Qvt (Twin Craters); Qbc, Qcc, Qvc (El Calderon); Qbu, Qc, Qv (basalt flows, cinder cones, volcanic debris); Qb (old basalt flows)	Quaternary (Q) Middle letter in symbol: b = basalt flows c = craters/cinder cones v = volcanic debris/shield volcanoes/cinder fields
	Tertiary – Neogene	Pliocene	5.3–2.6	Basalt flows on Cebollita Mesa, Mesa Negro, and Horace Mesa (Tb)	Tertiary basalt flows
				Diabase dikes ([Td])	Intrusive igneous rock
		Miocene	65.5– 2.6	Units of this age are absent in the El Malpais National Monument area.	
	Tertiary – Paleogene	Oligocene			
		Eocene			
		Paleocene			

NOTE: Figure continues on next page. *Age is in millions of years before present and indicates the time spanned by associated epoch or period. Rock/sediment units associated with those epochs or periods may not encompass the entire age range. Map unit symbols in brackets indicate units mapped in the McCartys quadrangle by Maxwell (1977).

Figure 4. General stratigraphic column for El Malpais National Monument. The rocks in and around El Malpais National Monument include very old metamorphic and igneous rocks of Precambrian age (approximately 1.4 billion years old); sedimentary rocks of Permian, Triassic, Jurassic, and Cretaceous ages (299 million–65.5 million years old); and young (Quaternary) volcanic rocks, most of which erupted in the past 700,000 years. Unconsolidated deposits top the sequence. Colors are standard colors approved by the U.S. Geological Survey to indicate different time periods on geologic maps; they also correspond to the colors on the Map Unit Properties Table. See the Map Unit Properties Table for more detail. Figure continues on next page.

Era	Period	Epoch	Age*	Rock/Sediment Unit	Description
Mesozoic	Cretaceous	Upper	100–65.5	Crevasse Canyon Formation (Kcc, [Kgc, Kcd, Kcs, and Kcdi])	Sandstone, siltstone, shale, and coal beds
				Gallup Formation (Kg, [Kgm, Kgu, and Kgi])	Silty shale
				Mancos Shale (Kmd, Kmr, Kmw, [Km, Kmm, Kmwc, and Kmc])	Shale with some limestone and thin-bedded sandstone
				Tres Hermanos Sandstone (Kth)	Sandstone, shale, coal beds, and siltstone
				Dakota Sandstone (Kdt, Kdp, Kdo)	Sandstone
		Lower	145–100	Units of this age are absent in the El Malpais National Monument area.	
	Jurassic	Upper	161–145	Morrison Formation (Jm)	Mudstone, siltstone, and sandstone
		Middle	175–161	Zuni Sandstone and Wanakah Formation (Jz)	Sandstone, mudstone, and claystone
				Todilto Limestone Member of the Wanakah Formation (Jt)	Limestone
				Entrada Formation (Je)	Sandstone
		Lower	200–175	Units of this age are absent in the El Malpais National Monument area.	
	Triassic	Upper	228–200	Chinle and Moenkopi formations (TRcm)	Claystone and siltstone
		Middle	245–228		
		Lower	251–245		
Paleozoic	Permian	Lopingian (Upper)	260–251	Units of this age are absent in the El Malpais National Monument area.	
		Guadalupian (Middle)	270–260		
		Cisuralian (Lower)	299–270	San Andres Limestone (Psa)	Limestone
				Glorieta Sandstone (Pg)	Sandstone and siltstone
				Yeso Formation (Py)	Sandstone, siltstone, and gypsum beds
				Abo Formation (Pa)	Sandstone and siltstone
Precambrian	Proterozoic Eon	Mesoproterozoic Era	1,600–1,000	Igneous and metamorphic rocks (PChb, PCpa, PCap, PCpg, PCag, PCgg, PCmg, PCqt, PChg, PCig, PCsc)	Hornblendite, gabbro, intrusive basalt, aplite, granite, gneiss, quartzite, and schist

Age is in millions of years before present and indicates the time spanned by associated epoch or period. Rock/sediment units associated with those epochs or periods may not encompass the entire age range. Map unit symbols in brackets indicate units mapped in the McCartys quadrangle by Maxwell (1977).

Figure 4 (continued). General stratigraphic column for El Malpais National Monument. Caption on previous page.

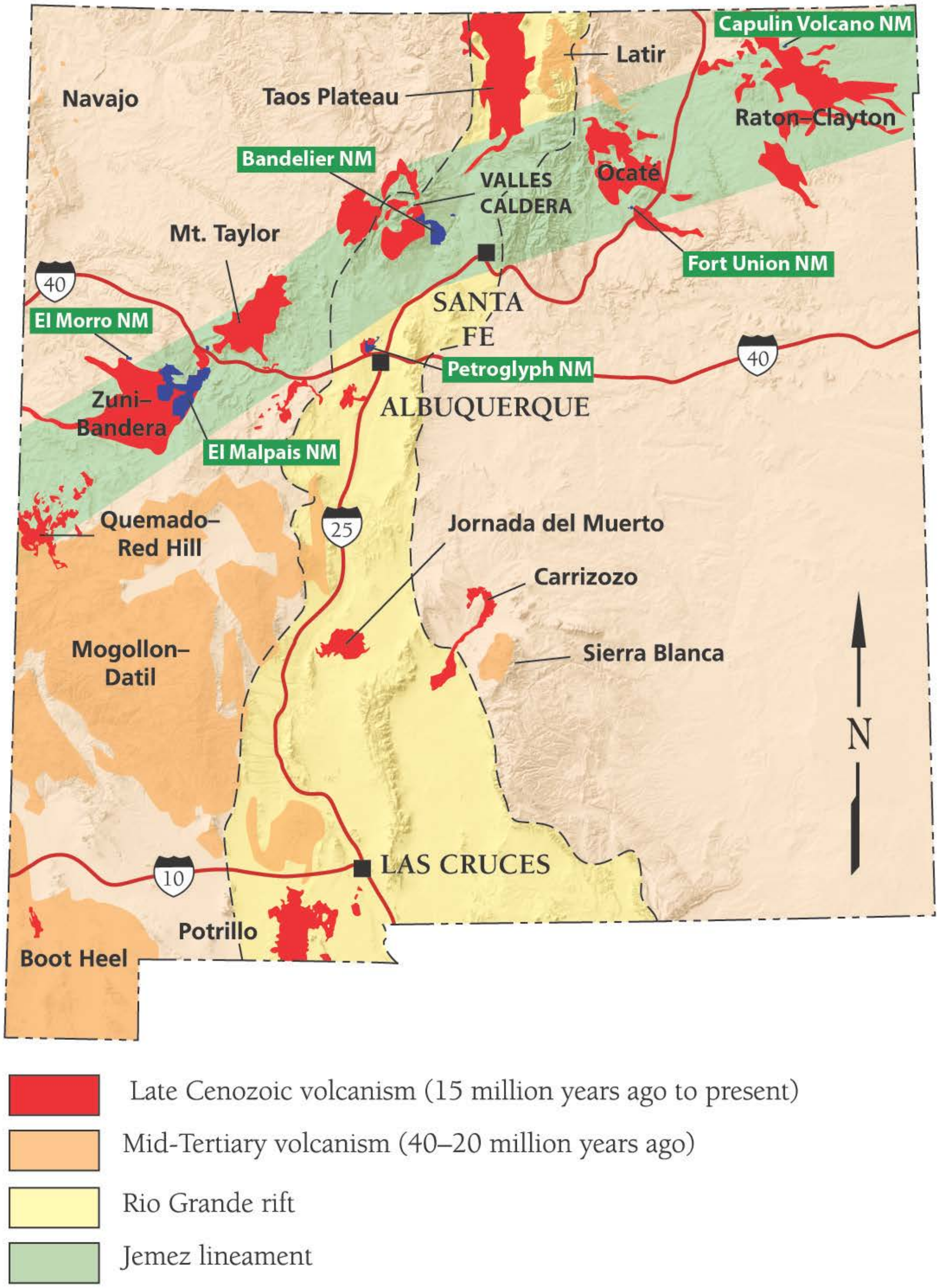

Figure 5. Major volcanic fields in New Mexico. El Malpais National Monument is part of the Zuni–Bandera volcanic field in west-central New Mexico. This and many other volcanic fields lie on the Jemez lineament, a zone of crustal weakness and concentrated volcanism that stretches from central Arizona to northeastern New Mexico. The National Park System is well represented along the Jemez lineament. El Malpais National Monument and El Morro National Monument are part of the Zuni–Bandera volcanic field. Bandelier National Monument is part of the Valles Caldera. Fort Union National Monument is surrounded by the Ocaté volcanic field. Capulin Volcano National Monument is in the Raton-Clayton volcanic field. The north–south-trending Rio Grande rift—a center of volcanic activity during an earlier episode of volcanism (40 million–20 million years ago)—intersects the Jemez lineament near Valles Caldera. Petroglyph National Monument lies on the Rio Grande rift. New Mexico Bureau of Geology and Mineral Resources graphic, modified by Philip Reiker (NPS Geologic Resources Division).

Geologic Issues

The Geologic Resources Division held a Geologic Resources Inventory scoping meeting for El Malpais National Monument on 30 March 2006 and a follow-up conference call on 9 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.

Discussions during a pre-scoping conference call (16 March 2006), the GRI scoping meeting (30 March 2006), and a post-scoping conference call (9 December 2011) identified the following geologic issues of management concern at El Malpais National Monument:

- Cave Management
- Mass Wasting
- Erosion
- Flooding
- Disturbed Lands
- Recent and Potential Volcanism
- Seismic Activity
- Geochronology, Research, and Interpretation

Resource managers may find *Geological Monitoring* (Young and Norby 2009) useful for addressing these geologic resource management issues. The manual provides guidance for monitoring vital signs—measurable parameters of the overall condition of natural resources. The NPS 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. Each chapter of the manual covers a different geologic resource and includes detailed recommendations for resource managers, including expertise, personnel, and equipment needed, as well as the approximate cost and labor intensity of each method.

Cave Management

El Malpais National Monument contains more than 290 caves in lava flows, referred to as "lava tubes" or "lava-tube caves" (see "Lava Tubes" section). The top resource management priority at the national monument is to complete a management plan for these cave resources (Dave Hays, resource manager, El Malpais NM and El Morro NM, conference call, 9 December 2011). During a conference call on 9 December 2011, staff from the Geologic Resources Division suggested that El Malpais managers contact Dale Pate (NPS cave specialist) for guidance in preparing a cave management plan.

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

As part of cave management, resource managers at El Malpais National Monument will continue to maintain a database of information about the lava-tube caves. The data include electronic files, hard-copy materials, and institutional knowledge. As part of the cave management plan, resource managers are examining and synthesizing existing information and proposing a solution for modernizing the system (Dave Hays, resource manager, El Malpais NM and El Morro NM, conference call, 9 December 2011).

Many caves at El Malpais National Monument contain seasonal or perennial accumulations of ice (see "Ice Caves" section). Compared with periodic observations made since the establishment of the national monument, present-day accumulations of perennial ice appear to be at an "all-time low" (Dana Sullivan, chief ranger, and Dave Hays, resource manager, El Malpais NM and El Morro NM, conference call, 9 December 2011). The National Park Service is not currently monitoring the ice accumulations at El Malpais National Monument. However, monitoring will likely be part of the future cave management plan (Dave Hays, resource manager, El Malpais NM and El Morro NM, conference call, 9 December 2011). Dickfoss et al. (1997) discussed the use of cave ice as a climate proxy and provided a history of ice accumulation at Ice Cave. This quantitative analysis may be useful for monitoring ice accumulations in the future. Toomey (2009) highlighted methods for monitoring permanent and seasonal ice in caves.

Investigators have studied the major lava-tube systems in El Malpais National Monument. This research is discussed in *Natural History of El Malpais National Monument* (Mabery 1997). However, the secondary cave systems have not been extensively studied (Ken Mabery, superintendent, Scotts Bluff NM, conference call, 16 March 2006). Most of what is known about the secondary systems, such as that at Hoya Volcano, has been interpreted during overflights, for instance during fires (Ken Mabery, conference call, 16 March 2006).

El Malpais National Monument has a memorandum of understanding with the Sandia Grotto—the local chapter of the National Speleological Society—for conducting basic inventory and cartography. Previously unknown locations of caves are often discovered during the inventory process. A Student Conservation Association intern found 30 new caves in 2001–2002 (National Park Service 2006b).

The 1990 El Malpais general management plan identified four caves as open to recreational use: Junction, Four Windows, Big Skylight, and Braided caves (fig. 6). In addition, the general management plan noted the special case of El Calderon Bat Cave. This cave is closed to recreational exploration, but the trail to the cave is a prime location for observing bat flights (fig. 7). As of 6 December 2010, all caves at El Malpais National Monument are closed to recreational use. The closure was prompted by the westward progression of white-nose syndrome, which is decimating bat populations in the eastern United States.

Figure 6. Entrance to Braided Cave. Braided Cave was traditionally one of five recreational caves at El Malpais National Monument, where visitors were able to obtain a "cave experience." All caves are presently closed to recreation as a result of the spread of white-nose syndrome, which has decimated bat populations in the eastern United States. National Park Service photograph.

Figure 7. Bat Cave. Even before the 2010 closure of all caves within El Malpais National Monument, Bat Cave was not open for recreation. However, the trail to the cave is a prime location for observing bat flights. National Park Service photograph.

The closure of the caves at El Malpais brought the national monument into compliance with NPS policy, much of which is derived from the Federal Cave Resources Protection Act of 1988. Guidelines for the protection of bat populations seek to limit the human-caused spread of this fungus through actions such as screening visitors and employees before they enter caves, and by restricting access if screening is not feasible. The caves at El Malpais are spread over 46,100 ha (114,000 ac), with no existing control points, such as entrance stations or visitor centers through which people must pass on their way to the caves. Hence, guidance for El Malpais National Monument and other National Park System units with similar situations recommends the closure of caves to protect bat populations until permitting and management strategies are implemented to mitigate risks to bat populations. Research is underway to determine whether the fungus is present in caves at El Malpais National Monument and whether hibernating bats already have the disease (Cook Collins 2011).

Although white-nose syndrome is the most immediate threat to cave resources at El Malpais National Monument, investigators have identified other threats (Northup and Welbourn 1997). Perhaps the most publicized threat to cave environments in general has been pollution (Northup and Welbourn 1997). Surface runoff of pesticides, nitrates, and herbicides from agricultural lands and petrochemicals from roads pose major problems for karst waters and cave biota (Northup and Welbourn 1997). Contamination of cave waters by gasoline and septic leakage can kill aquatic species. Surface modifications, such as the construction of parking lots and campgrounds, alter the input of organic matter and water from the surface and may introduce additional pollutants (Northup and Welbourn 1997). The remote locations of many caves, as well as protection as part of the National Park System, have helped to protect the lava-tube caves at El Malpais National Monument from many common threats (Northup and Welbourn 1997). However, awareness of these threats is significant for park planning and development of a cave management plan.

In addition to pollution, the physical actions of humans in caves can be detrimental to cave biota. Physical trampling by cave visitors can kill invertebrates, which are not noticed or are living under the rocks on which visitors walk. Cave entrances are especially vulnerable to physical disturbances due to the greater number and types of species and the amount of activity that occurs there. Furthermore, sunlit areas, including entrances and areas under skylights (fig. 8), are known for their moss gardens, which are important habitats. In the 1990s, El Malpais National Monument staff took steps to implement protection by installing educational signs about the importance of these gardens (Northup and Welbourn 1997).

Figure 8. Skylight and garden. Light shines through a skylight in Braided Cave. Luxuriant gardens grow beneath skylights in the lava tubes at El Malpais National Monument. National Park Service photograph.

Other potential impacts include the dumping of garbage in collapsed lava tubes (see "Lava Tubes" section), which introduces harmful substances into the cave environment (Northup and Welbourn 1997). On a lesser scale, visitors to the lava tubes occasionally leave their trash behind. Chapman (1993) noted that the composition of cave fauna changed in an area containing food trash. Northup and Welbourn (1997) documented food trash in Bat and Four Windows caves, and human feces in Big Skylight Cave. In the past, the dumping of carbide from lamps had a notable impact (Peck 1969; Lavoie 1980) because carbide is toxic to invertebrates (Northup and Welbourn 1997). Carbide lamps have been largely replaced by high-intensity LED illumination. Cigarette smoking in caves is a threat to cave biota because nicotine is an insecticide (Northup and Welbourn 1997). The introduction of foreign organic matter, such as firewood, also threatens the natural cave environment. Such materials equate to food sources in what was formerly a nutrient-poor system, potentially leading to "boom-and-bust" cycles in native invertebrates (National Park Service 1994). Additionally, fires within caves may be damaging or fatal to bats and invertebrates (Northup and Welbourn 1997).

Mass Wasting

Mass wasting—the downslope movement of soil and rock material—occurs as rockfall, slumping, debris flows, and landslides. Within El Malpais National Monument, the primary type of mass wasting is rockfall off the sandstone bluffs, most likely as a result of freeze-thaw processes (Dave Hays, resource manager, El Malpais NM and El Morro NM, conference call, 9 December 2011). Mass wasting is generally a low-priority management concern at the national monument because areas prone to rockfall do not coincide with infrastructure or trails, and thus pose minimal hazards for visitors (National Park Service 2006b).

The eastern margin of El Malpais National Monument follows cliffs composed of Zuni Sandstone (map unit symbol Jz). The steep cliffs adjacent to Highway 117 near the Sandstone Bluffs Overlook illustrate the process of mass wasting (Crumpler et al. 2003). The sandstone is being undercut, resulting in cliff retreat. The cause may be groundwater seepage from springs, which is disintegrating the sandstone near the cliff base and ultimately causing massive vertical spalls and slumps (Crumpler et al. 2003). An example of such a slump is located approximately 10 km (6 mi) south of the Sandstone Bluffs Overlook along Highway 117 (Crumpler et al. 2003) (fig. 9).

Maxwell (1986) mapped extensive landslides east of El Malpais National Monument. These deposits are composed mostly of rotational slides—referred to as "toreva-block slides"—of Tertiary basalt (Tb) and Cretaceous sandstone and shale that have slid over soft shale units (Maxwell 1986). The deposits also contain some rock and mudflow slides and talus and fan accumulations, some of which are derived from outcrops and others from landslide debris (Maxwell 1986). The landslides are generally older than the alluvium (Qal) that covers the valley floors. Flash flooding, which is characteristic of present-day arid conditions, produces deep gullies in the alluvium, sometimes exhuming older landslide blocks (Maxwell 1986).

Figure 9. Mass wasting. The steep cliffs of massive Zuni Sandstone illustrate the process of mass wasting within the Highway-117 corridor along the eastern edge of El Malpais National Monument. National Park Service photograph by Dale Dombrowski (El Malpais National Monument).

Erosion

The “deep gullies” identified by Maxwell (1986) are generally referred to as “arroyos,” the Spanish word for “stream.” In the Southwest, the term is applied to streambeds that are dry most of the time, except during flash floods. Arroyos are commonly seen as “a symptom that something is wrong” (Love and Gellis 2008). However, according to Love and Gellis (2008), the natural function of arroyos is complicated and depends on external influences, such as land use and climatic conditions, and internal adjustments in surface hydrology, stream morphology, changes in sediment availability and type, and biological response of native and invasive species (fig. 10).

Managers at El Malpais National Monument have linked arroyo formation within the national monument to past land-use practices, in particular overgrazing of sheep and cattle (Dana Sullivan, chief ranger, and Dave Hays, resource manager, El Malpais NM and El Morro NM, conference call, 9 December 2011). Within the national monument, all grazing ceased after 1997 in accordance with provisions in the 1987 enabling legislation. However, a checkerboard of lands—grazed in the past and at present—surrounds the national monument. Staff members at El Malpais survey and mend fenced areas of the national monument’s boundary to control sheep and cattle trespass (National Park Service 2006b).

In 2001, an investigator from the NPS Geologic Resources Division found that erosion rates in the area of Sandstone Bluffs Overlook have likely been exacerbated by overgrazing (Greco 2001). Erosion in this area has also been accelerated by changes in natural drainage patterns. The natural hydrology of the area has been greatly altered by channel diversion (Greco 2001). Even under natural conditions, eolian deposits (map unit symbol Qe) found in the area are highly susceptible to erosion. The wash in the upper reaches of the Sandstone Bluffs Overlook area has downcut through this surficial material into the underlying, more-resistant sandstone of the Clay Mesa Tongue of Mancos Shale and lower part of Dakota Sandstone (Kdo). Greco (2001) recommended that any approach to reducing erosional impacts to the Sandstone Bluffs Road should consider natural drainage patterns. Culverts should be configured to match the natural path of the wash. Furthermore, to prevent blockage of culverts in the event of a 100-year or greater flood, culvert pipes should be sized to carry sediment, as well as floodwaters. Moreover, culvert installation should include armoring the inlet and outlets by “keying in” (securing/fitting) riprap to dissipate energy and reduce erosional forces (Greco 2001). Another significant aspect of restoration in this area is the revegetation of heavily grazed areas, which will help stabilize the soils and retard erosion (Greco 2001).

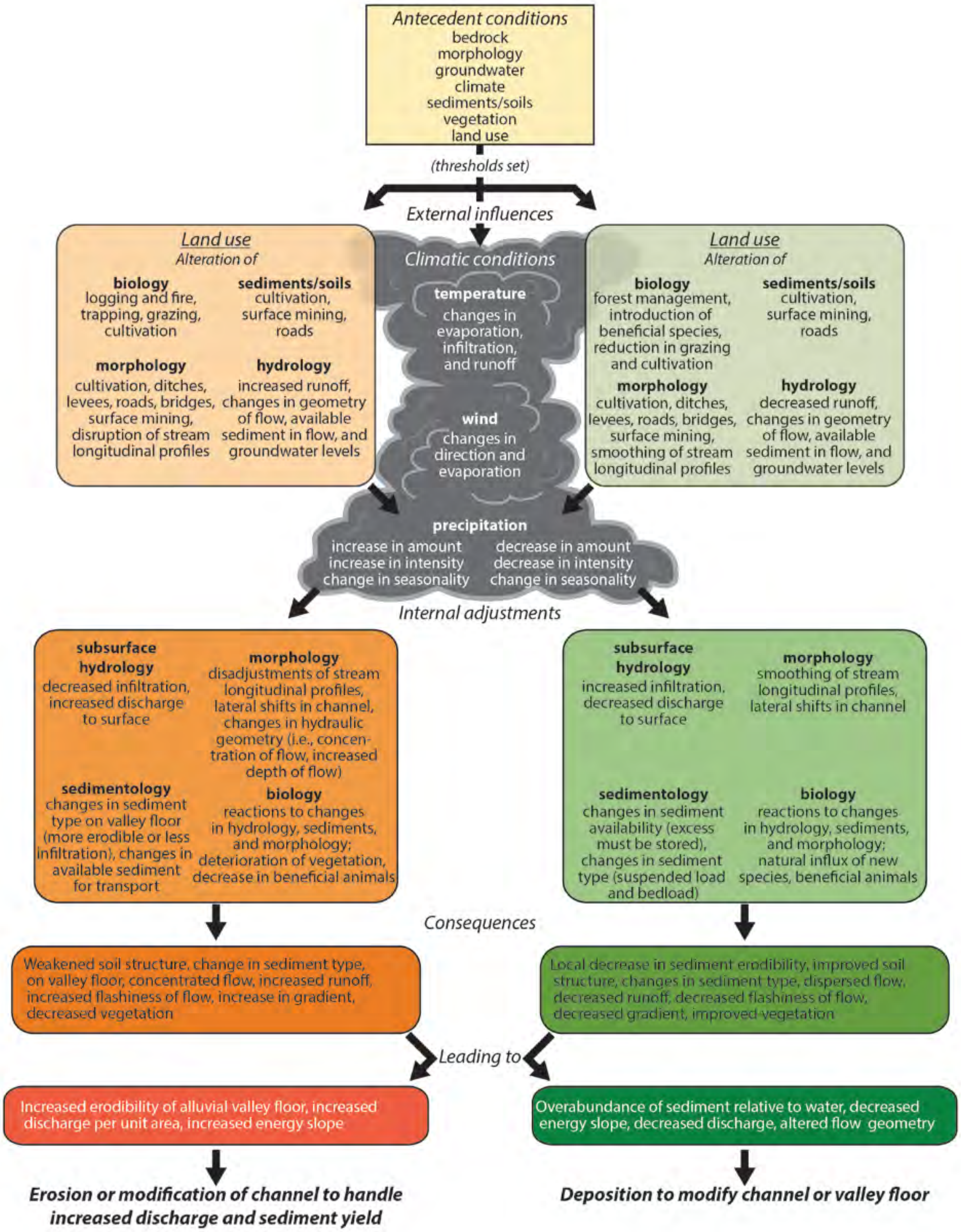

Figure 10. Variables of arroyo formation. The function of arroyos is complicated by and dependent upon antecedent conditions and external influences. Antecedent conditions at El Malpais National Monument include landscapes covered in eolian deposits (Qe). External influences include land-use practices such as cattle and sheep grazing, and changes in the natural drainage system caused by channel diversions and culverts. Graphic from Love and Gellis (2008), modified by Trista Thornberry-Ehrlich (Colorado State University).

Flooding

Streams in El Malpais National Monument are ephemeral and flow only as a result of flash-flooding events (National Park Service 2006b). In general, surface water percolates into the groundwater system within a few weeks after a flash flood. Windmills within El Malpais attest to past extraction of groundwater for livestock use. Upon establishment of the national monument, the National Park Service removed many windmills from national monument lands, but some wells were retained for their historical value and use by wildlife (National Park Service 2006b).

Storm-water runoff—and associated pesticides, herbicides, and fertilizers from agricultural lands, as well as excessive runoff and sedimentation from grazed areas—is a resource management concern at El Malpais National Monument. Stream channels originate outside the monument but flow into the lava-tube systems, potentially introducing contaminants and impacting cave biota. Source areas of concern are in the northwest corner of the national monument near Bandera Crater, and Pueblo (tribal) and Bureau of Land Management (BLM) lands on the southeast side of the national monument. In the northwest corner, pesticides are applied and grazing occurs on small ranches and other private lands adjacent to national monument lands. On the southeast, grazing occurs on Pueblo and BLM lands bordering the national monument (National Park Service 2006b).

Flooding also causes erosion between the sandstone bluffs and the McCartys flow on the east side of El Malpais National Monument, where archeological sites are highly concentrated. Furthermore, Highway 117 on the east side of the national monument is periodically washed out during flooding events (National Park Service 2006b).

Disturbed Lands

Disturbed lands within the National Park System include abandoned roads, dams, canals, railroads, grazed areas, campgrounds, mines, and other abandoned sites. Some of these features may be of historical significance, but most are not. Non-historic features can be mitigated to restore natural conditions. The NPS Geologic Resources Division assists with disturbed lands restoration, including abandoned mineral lands, within the National Park System. Disturbances at El Malpais National Monument include the following:

- Abandoned Mineral Lands
- Mining and Military Activities
- Logging
- Grazing and Agricultural Practices
- Channel Diversions

Abandoned Mineral Lands

Past mining activities impacted parts of the national monument. As of September 2012, the abandoned mineral land (AML) database maintained by the Geologic Resources Division included 28 AML features at six sites within El Malpais National Monument. "Lava rock" (basalt), cinders, sandstone, and road-base aggregate were extracted from the sites. Staff members at the national monument are aware of four additional sites for which they are collecting geographic positioning system (GPS) data that they will provide to the AML Program (Dana Sullivan, chief ranger, and Dave Hays, resource manager, El Malpais NM and El Morro NM, conference call, 9 December 2011).

Figure 11. Bandera Crater. Bandera Crater exemplifies the typical steep-sided and symmetrical form of a cinder cone. The cone exhibits a breach from which lava erupted. Today, a lava-tube system starts at the breach. Note the Bandera cinder quarry behind and to the right of the crater rim in the photograph. The Bandera cinder quarry is privately owned, but its location adjacent to the national monument and within the monument's viewshed makes it highly visible to visitors. Photograph by Larry Crumpler (New Mexico Museum of Natural History and Science).

At present, the two main mining-related issues for managers at El Malpais National Monument are (1) a highly visible cinder quarry in the northwest corner of the national monument, near Bandera Crater (fig. 11), and (2) an abandoned cinder quarry on the side of El Calderon. Cinders from the Bandera quarry were sold by the owner and used as road base by the state highway department. Although the quarry is privately owned, it is adjacent to NPS lands and within the national monument's viewshed. The most recent mining activity at this site ceased in 2010 (Dana Sullivan, chief ranger, and Dave Hays, resource manager, El Malpais NM and El Morro NM, conference call, 9 December 2011).

The El Calderon quarry site is owned by the National Park Service and is no longer used. However, the site is difficult to reclaim because re-contouring cinders is challenging. The National Park Service is considering simply leaving the site in its present state and interpreting its mining history for visitors (National Park Service 2006b). Glass bottles, tin cans, and tools are occasionally found in the loose cinders and are evidence of past mining activities (National Park Service 2004a).

In the Lava Falls area, Dakota Sandstone (Kdo) was quarried. This quarry has been reclaimed and is no longer an issue (National Park Service 2006b). The New Mexico Department of Transportation used sandstone blocks from this quarry to build culvert headwalls within the national monument and along Highway 117 between Grants and Pie Town. In 1996, the National Park Service revegetated the quarry to restore natural drainage at the site.

Finally, some evidence of guano mining remain in lava tubes. Bat guano is an excellent source of fertilizer because of its high nitrate content. Remnants of a simple mining operation are apparent in Bat Cave (National Park Service 2004a), although this activity has now ceased.

Mining and Military Activities

With the advent of World War II, fluorspar (calcium fluoride) and pumice were mined near Grants, New Mexico. The Navajo Fluorspar Company opened three mines near the commercially operated Ice Cave, which is adjacent to what is now El Malpais National Monument (Mangum 1997). Fluorspar was used in the manufacture and hardening of steel, in paints, and in acids. The fluorspar mines remained active until 1952, when foreign competition drove down the price of this material (Mangum 1997).

The source rocks were Precambrian granites and gneisses, which contain veins of fluorite (Laughlin et al. 1993a). According to Maxwell (1986), the veins range in width from a few centimeters to 5 m (16 ft), and are filled with coarsely crystalline, bright-green fluorite that is generally brecciated and locally mixed with wall-rock fragments. The breccia is locally cemented by fine-grained, purple fluorite. Associated minerals are calcite, barite, and quartz (Maxwell 1986). Fluorite veins are indicated on the digital geologic map for El Malpais National Monument; one vein is mapped within the national monument (see "Geologic Map Data" section).

Uranium was another mineral resource that affected El Malpais National Monument. The uranium boom of the 1950s postponed establishment of a national monument until 1987, although the inclusion of the El Malpais area in the National Park System was proposed as early as the 1930s (National Park Service 2006b). Uranium was first discovered in this region in 1950 in the Jurassic Todilto Formation, which is exposed in Haystack Butte west of Grants, New Mexico. In the 1970s, the uranium boom ended and local mines closed.

Another war-effort disturbance is the use of the McCartys lava flow and cinder cone as a bombing range (Mangum 1997). The U.S. Army used the 23-km^2 (9-mi^2) area of rugged lava terrain for target practice, in particular the McCartys cinder cone (fig. 12). Although the military conducted cleanup, ordnance is periodically found on the McCartys flow (Dana Sullivan, chief ranger, and Dave Hays, resource manager, El Malpais NM and El Morro NM, conference call, 9 December 2011). El Malpais was also included on the short list for selection as the test detonation site of the first atomic bomb (Dana Sullivan and Dave Hays, conference call, 9 December 2011). Ultimately, the Trinity Site near White Sands National Monument in southern New Mexico was selected (see fig. 2). Today, the Trinity Site is a national historical landmark located on White Sands Missile Range, which surrounds White Sands National Monument (KellerLynn 2012c).

Logging

Logging activities in the 1970s altered ecosystems in what is now El Malpais National Monument. In areas not subject to logging, the lava flows support extremely old specimens of Douglas-fir (*Pseudotsuga menziesii menziesii*; see "Biologic and Geologic Connections" section).

The National Park Service is protecting some of the sawmill sites associated with past logging activities due to their value as cultural resources. Park managers do not plan to restore old logging roads within the national monument, but these roads in the wilderness area are now closed to motorized vehicles (National Park Service 2006b). Remaining slash that was cut during logging operations is now being removed during prescribed burns (National Park Service 2006b).

Figure 12. McCartys cinder cone. The McCartys vent is a small cinder cone that is approximately 8 m (26 ft) tall (note person on rim of cone for scale). The cone is approximately 90 m (295 ft) in diameter. It rests on a small shield approximately 300 m (980 ft) across. Photograph by Larry Crumpler (New Mexico Museum of Natural History and Science)

Grazing and Agricultural Practices

During the period of BLM management, cattle heavily grazed the El Malpais National Monument area, which likely amplified the effects of wind erosion and the occurrence of dust storms (National Park Service 2006b). Grazing and other agricultural practices surrounding Grants, New Mexico, probably contributed material to eolian deposits. In the 1940s and 1950s, large-scale farming developed in Grants, with carrots as the primary cash crop. Grants was known as the "carrot capitol of the world" and this carrot industry flourished until the late 1950s, when California produce put New Mexico growers out of business (Mangum 1997). In general, dust from the Grants area continues to be an issue for the national monument in the form of periodic dust storms (Dave Hays, resource manager, El Malpais NM and El Morro NM, e-mail communication, 27 December 2011).

Channel Diversions

Prior to the establishment of El Malpais National Monument, ranching practices diverted water from natural channels into ditches, dikes, and stock ponds. Diversion also occurred in conjunction with the construction of highways, such as Highway 53 near the El Calderon area. The manipulation of stream channels for ranching and highway construction has negatively impacted Junction Cave in the El Calderon area (fig. 13). During heavy rainfall, this cave becomes a storm-drain system; flooding occurred in 1987 and 1999 (National Park Service 2006b). In the 1960s, or perhaps earlier, diversion projects changed the natural flow path of Agua Fria Creek, in turn impacting Junction Cave (Pranger 2001). An artificial dike diverts water away from the native Agua Fria Creek channel into a diversion channel that passes through a stock pond and past the El Calderon parking lot. The flow splits at the El Calderon parking lot, with some high flow entering a collapsed lava tube and the rest flowing past the parking lot and into Junction Cave (Pranger 2001).

In 2001, the Geologic Resources Division responded to a technical assistance request from managers at El Malpais National Monument to assess fluvial features in relation to lava-tube caves within the Agua Fria Creek channel, and also to inspect and assess the impacts of disturbed lands along the creek resulting from the development of ditches, dikes, and stock tanks (Pranger 2001). This assessment identified specific areas that could be successfully restored and recommended the removal of two stock ponds and diversion channels and the reconstruction of a segment of the Agua Fria Creek channel (Pranger 2001). The project is currently on hold until the provenance of the diversion features is determined. These features may have been constructed as Works Progress Administration/Civilian Conservation Corps–era dams, in which case their preservation as cultural resources may be warranted (Dana Sullivan, chief ranger, and Dave Hays, resource manager, El Malpais NM and El Morro NM, conference call, 9 December 2011).

Figure 13. Junction Cave. Junction Cave is situated near the El Calderon parking lot. Approximately 49 m (160 ft) away, an eroded diversion ditch allows storm-water runoff to enter this lava-tube cave. National Park Service photograph.

Recent and Potential Volcanism

Limburg (1990) evaluated the 700 volcanic events that have occurred in New Mexico over the past 5 million years. During this time period, basaltic volcanism has been the dominant mode of volcanism in New Mexico (Limburg 1990). Basaltic volcanism is characterized by effusive, fairly continuous eruptions, with many vents erupting simultaneously within a volcanic field. If basaltic volcanism were to recur in New Mexico today, erupting basalt would change the face of the landscape, filling low-lying areas and disrupting drainages. Such modifications would take place relatively close to volcanic vents (Dunbar 2005). However, lava flowing down a river bed would affect river behavior. For instance, damming of a river by a lava flow could cause an upstream lake to form, which could result in catastrophic flooding when the natural dam fails (Fenton et al. 2004).

Limburg (1990) estimated a 1% chance that some type of volcanic eruption will occur in New Mexico by 2090, and a 10% chance that an eruption will occur in the next 1,000 years. In probabilistic terms, 100 eruptions will occur in the next 1 million years.

Future eruptions are most likely to occur along the Jemez lineament and the Rio Grande rift (Chapin et al. 2004; Dunbar 2005). The most vulnerable areas occur where the Rio Grande rift intersects crosscutting lineaments, such as in the Jemez Mountains and near Socorro, New Mexico (Chapin et al. 2004). An active magma chamber called the Socorro magma body has been recognized in the area around Bernardo, New Mexico (Sanford et al. 1977; Reilinger et al. 1980). This magma body is located 19 km (12 mi) below the surface and covers an estimated area of 3,400 km^2 (1,300 mi^2) (Balch et al. 1997). The area around the magma body has been the location of elevated levels of seismic activity (Sanford et al. 1977; Fialko and Simons 2001) (see "Seismic Activity" section), likely as a result of migration of magma, or instability, within the chamber. These combined factors suggest that the Socorro magma body is a possible source of future volcanism (Dunbar and Phillips 2004).

Although renewed volcanism at El Malpais National Monument is not imminent and resource managers are not currently monitoring volcanic activity, Walkup (2012)—an inventory of volcanic features and hazards in the National Park System—identified the following potential hazards in the event of renewed volcanism at the national monument: ash/tephra fall, earthquakes, gas, lava eruptions, and volcanic projectiles (e.g., lava bombs). Empirical observations and monitoring can be used to predict volcanic eruptions. Methods include geophysical (seismic), geodetic (tilt), and geochemical monitoring, as well as observations of readily detectible phenomena by casual observers, such as felt earthquakes, tremors, and noises; bulging or cracking of the ground surface; changes in color, temperature, and sediment content of streams; death or sickness of vegetation; and changes in usual emissions from the vents (Banks et al. 1989). Such data are qualitative, but may be useful in deciding the type and deployment location of monitoring equipment (Limburg 1990).

Two chapters in *Geological Monitoring* may be useful for anticipating future volcanic activity. Smith et al. (2009) presented the following methods and vital signs for monitoring volcanoes: (1) earthquake activity, (2) ground deformation, (3) emissions at ground level, (4) emission of gas plume and ash clouds, (4) hydrologic activity, and (5) slope instability. Braile (2009) provided information about seismic monitoring, which is discussed in the following section. Widespread seismic monitoring around New Mexico would forewarn of future volcanism and enable prediction of the potential location of an eruptive event (Dunbar 2005).

Seismic Activity

New Mexico has a recorded history of seismic activity since 1869 (Sanford et al. 2002, 2006; U.S. Geological Survey 2009b). This long record aids researchers in evaluating seismic hazards and forecasting the location and magnitude of future earthquakes (Sanford et al. 2002). The largest earthquake in New Mexico occurred on 15 November 1906 in the Socorro area. The earthquake was felt over most of New Mexico and in parts of Arizona and Texas (U.S. Geological Survey 2009a). This historic quake occurred before the Richter scale came into use and was later assigned a Modified Mercalli intensity level VII (on a scale of I to XII), indicating little damage to well-designed and well-constructed buildings, but considerable damage to poorly built or poorly designed structures, as well as breakage of some chimneys. Indeed, four chimneys were shaken off the Socorro County Courthouse, and two others were cracked severely. Plaster fell at the courthouse, and a cornice on the northwest corner of the two-story adobe Masonic Temple was thrown onto its first floor. Plaster was shaken from walls in Santa Fe, about 200 km (120 mi) from the epicenter.

A disproportionate number of earthquakes in New Mexico occurred in the Rio Grande Valley near Socorro, forming a tight cluster of earthquakes known as the Socorro seismic anomaly. Enhanced seismic activity in this region is believed to be the result of the stretching of Earth's crust over a large body of magma that exists at a depth (see "Recent and Potential Volcanism" section). This magma is associated with the Rio Grande rift, but surprisingly, with the exception of the Socorro seismic anomaly, this rift is not characterized by earthquake activity (Sanford et al. 2006). The Socorro seismic anomaly occupies less than 1% of New Mexico and bordering areas, but accounts for 23% of earthquakes of magnitude 2.0 or greater during 1962–1998 (Sanford et al. 2002), and 15% during 1999–2004 (Sanford et al. 2006).

The intact nature of the lava flows at El Malpais National Monument indicates that seismic activity has not occurred recently. The most recent "felt quake" was in the 1970s (National Park Service 2006b). However, earth cracks south of Point of Malpais in the BLM conservation area may be an indicator of seismic activity in the region (National Park Service 2006b). Maxwell (1986) mapped surface faults on the McCartys flow, but investigators have not subsequently reverified these features (National Park Service 2006b). These surface faults may line up as a series of spatter cones, indicating extrusion of lava along a fault, but this possibility has not been confirmed in the field (National Park Service 2006b).

Braile (2009)—the chapter in *Geological Monitoring* about earthquakes and seismic activity—described the following methods and vital signs for understanding earthquakes and monitoring seismic activity: (1) monitoring earthquakes, (2) analysis and statistics of earthquake activity, (3) analysis of historic and prehistoric earthquake activity, (4) earthquake risk estimation, (5) geodetic monitoring and ground deformation, and (6) geomorphic and geologic indications of active tectonics. Braile (2009) provided a summary of these methods, including the expertise, special equipment, cost, and personnel required, and the labor intensity.

Geochronology, Future Research, and Interpretation

El Malpais National Monument has served as a natural laboratory for testing various isotopic methods of dating the ages of lava flows, including potassium-argon (K-Ar), argon-argon (^{40}Ar-^{39}Ar), carbon-14 (^{14}C), helium-3 (^{3}He), chlorine-36 (^{36}Cl), and uranium (U) series. Laughlin and WoldeGabriel (1997) provided a summary of these six analytical methods, which have been applied to the basalt flows of the Zuni–Bandera volcanic field, including the very young flows in El Malpais National Monument. The national monument has been considered an ideal site for the inter-calibration of techniques because it contains a large number of well-exposed and well-mapped late-Quaternary lava flows (Laughlin et al. 1994b). The plethora of dating methods used on specific flows has provided the opportunity for cross dating and comparative analysis (National Park Service 2006b). In several cases in which multiple methods have been applied to the same flow, agreement among methods has been excellent. In other cases, however, the dates have not agreed (Laughlin and WoldeGabriel 1997). For example, the dating of very young (<100,000 years old) basalts using the K-Ar method has been problematic because the amount of argon accumulated via decay during this time period is so small and difficult to measure. Researchers continue to use the national monument as a field area (National Park Service 2006b).

Starting with Nichols (1946) and Maxwell (1986), the geochronology of El Malpais first came to light through relative dating of lava flows. Investigators used standard geologic methods of relative dating, including the principle of superposition (younger layers are on top of older layers) and morphology. More recently, work by Laughlin et al. (1993a, 1993b, 1994a, 1994b), Dunbar and Phillips (1994, 2004), McIntosh (1994), Laughlin and WoldeGabriel (1997), and Cascadden et al. (1997a, 1997b) used radiometric dating methods to refine the geochronology.

Innovations in basaltic lava flow dating continue to be developed, as shown by a recent study using gypsum crusts (Dillion et al. 2009). Gypsum crusts have been preserved in the drier parts of the lava-tube caves at El Malpais National Monument. U-series dating of this type of crust yields ages of lava tube formation, and therefore eruption ages. These gypsum crusts were likely formed by the percolation of sulfuric acid within the host basalt. Gypsum-crust speleothems have been found to form in lava tubes immediately after the cessation of cave-forming volcanic activity, making them potentially very useful for dating lava flows (Polyak 2009).

Although much is now known about the sequence of events at El Malpais National Monument (see "Volcanic Features and Processes" and "Geologic History" sections), a few gaps prohibit a full understanding of the volcanic story. In particular, the Hoya de Cibola flows (Qbw) have presented challenges in efforts to decipher the geochronology of eruptions at El Malpais. Maxwell (1986) mapped the Hoya de Cibola flows (Qbw) as younger than the Twin Craters flows (Qbt). However, investigations since 1986 have brought this interpretation into question. The difficulty arises because the Hoya de Cibola (Qbw) and Twin Craters (Qbt) flows do not come into contact; they are separated by the Bandera flows (Qbb). Hence, the principle of superposition cannot be applied in this circumstance, and no reliable ages have been produced. Confusion also arises because Maxwell (1986) used the map symbol Qbw for the Hoya de Cibola flows. Since 1986, however, the Bluewater flow west of Grants, New Mexico, which was not mapped by Maxwell (1986), has been recognized to represent a significant eruptive event in the chronology of the Zuni–Bandera volcanic field. Dunbar and Phillips (2004) used the symbol Qbw for the Bluewater flow, and substituted Qh for the Hoya de Cibola flows. In addition, the exact ages of various flows in the Zuni Mountains north of El Malpais are unknown, including the Zuni (Qbz) and Oso Ridge (Qbo) flows mapped by Maxwell (1986).

Some areas of El Malpais could benefit from more detailed mapping, for instance, the area around Lost Woman Crater in the northwestern part of the national monument, which Maxwell (1986) mapped as part of the Twin Craters cinder cones (Qct). Original mapping (from aerial photographs) missed features in this area because it is heavily forested (Ken Mabery, superintendent, Scotts Bluff NM, conference call, 16 March 2006). Preliminary ground reconnaissance revealed a cinder cone and vent that had not been mapped by Maxwell (1986). Findings of this field reconnaissance were not published (Ken Mabery, , e-mail communication, 14 May 2012), but the existence of previously unidentified features suggests that additional field work is warranted. Work by Cascadden et al. (1997b) improved the understanding of this area, but much remains unknown and new discoveries are likely.

A full understanding of the history of the Bandera flows (Qbb) also requires further research. This unit is huge, approximately 37 km (23 mi) long, and is mostly composed of aa lava, which contrasts with other pahoehoe events (e.g., Hoya de Cibola) in the national monument.

Finally, unanswered research questions remain regarding the national monument's youngest volcanic event, represented by the McCartys flow (Qbm and Qbd): Why was this flow so long, extruding from such a small vent? Why was the flow so fluid, while its chemical composition does not differ widely from those of other flows in the monument? Why did aa flows occur in a "sea" of pahoehoe?

Larry Crumpler (New Mexico Museum of Natural History) is studying the physical characteristics of the McCartys flow. Using differential GPS measurements across several transects, Crumpler will map surface textures to determine the sequences of lava inflation and flow breakouts. He is expected to complete his research in 2012. Peter Reiners (University of Arizona) submitted a still-pending grant proposal to the National Science Foundation (NSF) for a light detection and ranging (LiDAR) project across the western half of the national monument to characterize the emplacement and structure of the older flows. More recent volcanic data can be integrated into the national monument's GIS. Nelia Dunbar (New Mexico Bureau of Geology and Mineral Resources) can provide updated information and guidance.

The geologic features at El Malpais National Monument are also a valuable resource for public education. Their accessibility and level of preservation makes them ideal field-trip stops. For example, El Malpais was highlighted in the Rockin' Around New Mexico Workshop led by the New Mexico Bureau of Geology and Mineral Resources in 2000 (New Mexico Bureau of Geology and Mineral Resources 2009). Additionally, many examples of volcanic features from El Malpais are included in the popular video *Lava Flows and Lava Tubes: What They Are, How They Form* (Volcano Video Productions 2004).

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 Malpais National Monument.

Discussions during a pre-scoping conference call (16 March 2006), the GRI scoping meeting (30 March 2006), and a post-scoping conference call (9 December 2011) developed a list of distinctive geologic features and processes in El Malpais National Monument:

- Volcanic Features and Processes
- Vents
- Lava Flows
- Lava Tubes
- Ice Caves
- Eolian Features and Processes
- Biologic and Geologic Connections
- Paleontological Resources
- Sandstone Features

Volcanic Features and Processes

The Zuni–Bandera volcanic field, of which El Malpais National Monument is a part, was produced by Hawaiian-style volcanism. The field began erupting about 700,000 years ago. However, the lava flows and other volcanic features within the national monument are part of an episode of eruption that occurred within the past 60,000 years, starting with the eruption of El Calderon and ending with the McCartys flow (table 1). Tertiary basalt flows of the Mount Taylor volcanic field east of El Malpais erupted before the Zuni–Bandera volcanic field. Maxwell (1986) mapped these flows as basalt flows on Cebollita Mesa, Mesa Negro, and Horace Mesa (may unit symbol Tb). The distinctive Horace Mesa formed during this eruption (fig. 14). At the same time, diabase dikes (Td) intruded the sedimentary rocks in the area, including Gallup Sandstone and Mancos Shale (Maxwell 1977).

Characteristic features of Hawaiian-style volcanism are cinder cones, spatter cones, and lava flows. Fire fountains, which can spray molten lava 900 m (3,000 ft) into the air, likely produced many of the volcanic features at El Malpais National Monument (National Park Service 2006b; Dunbar 2010). During this type of eruption, much spatter and scoria (see descriptions below) would have piled into cones and mounds along vents (see descriptions below). In addition, great quantities of fluid, basaltic lava would have poured out of fissures.

Geologists have grouped the volcanic features at El Malpais National Monument into the two main categories of vents and lava flows. A third category is lava tubes. Each of these categories is discussed in following sections (see "Vents," "Lava Flows," and "Lava Tubes" sections). Maxwell (1986) also mapped "pyroclastic debris" as a primary volcanic feature at El Malpais. According to Maxwell (1986), pyroclastic debris is composed largely of basalt flows mixed with and covered by cinders, bombs, scoria blocks, and flow breccia (see descriptions below). Around Bandera Crater, the deposits of pyroclastic debris, most of which are cinders, cover sedimentary rocks (Maxwell 1986).

Walkup (2012) completed an inventory of volcanic features throughout the National Park System, including El Malpais National Monument. This volcanic inventory complements the broader GRI and may be of interest to resource managers at El Malpais National Monument.

Table 1. Volcanism within and near El Malpais National Monument

Flow	Age (years ago)
McCartys (Qbm and Qbd)	3,900
Bandera (Qbb)	11,000
Hoya de Cibola (Qbw)	Exact age unknown, but older than Bandera
Paxton Springs, south (Qbp)	15,000
Zuni (Qbz and Qba)	Exact age unknown, but overlie Oso Ridge flows in Zuni Canyon
Oso Ridge (Qbo)	Exact age unknown, but younger than Twin Craters
Twin Craters (Qbt)	18,000
Paxton Springs, north (Qbp)	20,700
El Calderon (Qbc)	<60,000
Basalt flows (Qbu) "Chain of Craters"	~150,000
Old basalt flows (Qb), e.g., Hole-in-the-Wall	~700,000
Basalt flows on Cebollita Mesa, Mesa Negro, and Horace Mesa (Tb) "Mount Taylor"	3.73 million to 1.57 million

Sources: Maxwell (1977, 1986), Laughlin et al. (1993b), Mabery et al. (1999), Dunbar and Phillips (2004), and Dunbar (2010).

Figure 14. Horace Mesa. Maxwell (1986) mapped the Horace Mesa as composed of Tertiary basalt flows. These flows are part of the Mount Taylor volcanic field. Horace Mesa displays distinctive columnar basalt that is broken by parallel, prismatic columns that formed as a result of contraction during cooling. The McCartys flow is in the foreground. Photograph by Larry Crumpler (New Mexico Museum of Natural History and Science).

The following terms describe volcanic features found at El Malpais National Monument. These terms were used by Maxwell (1986) and other investigators, and are used throughout this report. They are presented here for convenience and as an introduction to the geology of volcanic features. Other less frequently used terms are included in the glossary.

- Basalt—a dark-colored igneous rock, commonly extrusive, composed primarily of calcic (calcium-rich) plagioclase and pyroxene minerals.
- Bomb—rock ejected in a viscous state and shaped while in flight. By definition, a bomb is larger than 64 mm (2.5 in) in diameter, and may be vesicular (bubbly) or even hollow inside. The actual shapes of bombs vary greatly, and are used in descriptions such as "rotational bomb" or "spindle bomb" (Neuendorf et al. 2005).
- Cinder—a vitric (glassy), vesicular (bubbly) fragment of rock that falls to the ground in an essentially solid condition.
- Cinder cone—a conical hill primarily formed by the accumulation of cinders around a vent. The steepness of the cone is normally greater than 10° (Neuendorf et al. 2005) but depends on factors such as the coarseness of the ejected material, height of the eruption, and wind velocity.
- Fissures—elongated cracks that break the surface of a lava flow. During eruptions, fissures develop and serve as conduits for lava, which erupts onto the surface as spatter, cinders, and flows. Hawaiian-style fissure eruptions typically start as a curtain of fire, which may extend discontinuously for several miles (Mabery et al. 1999). Most fissure eruptions eventually become concentrated at a single vent or group of closely spaced vents (Mabery et al. 1999).
- Flow breccia—rock composed of angular, broken fragments that is formed contemporaneously with the movement of a lava flow. The cooling crust becomes fragmented while the flow is in motion (Neuendorf et al. 2005).
- Lava flow—a lateral, surficial outpouring of molten lava from a vent or a fissure. Also, the solidified body of rock that is so formed.
- Scoria—vesicular, cindery material formed by the escape of gases before solidification.
- Spatter—an accumulation of initially very fluid material that usually becomes agglutinated (welded together) and coats the surface around a vent.
- Vent—an opening in Earth's crust through which volcanic materials extrude.

Vents

The primary type of vent at El Malpais National Monument is a cinder cone, which is composed of basaltic ash, cinders, bombs, large angular blocks of scoria, and minor flows of glassy lava (Maxwell 1986). Cinder cones at the national monument range in height from 1 m (3 ft) to more than 170 m (560 ft); many are 1 km (0.6 mi) or more in diameter. A few cones are symmetrical, but most have been breached on one side by lava flows and have a crescent shape. Breaches in the cones fed the lava flows. Examples of cinder cones are El Calderon (Qcc), Lost Woman Crater (part of unit Qct), Twin Craters (Qct), Bandera Crater (Qcb), Cerro Candelaria (Qc), Cerro Bandera (Qc), and Paxton Springs Crater (Qcp; fig. 15).

The shape of a cinder cone is controlled by the wind, which directs the exploding, airborne cinders during an eruption. As such, shape is an indicator of paleowind direction. The resulting shape of a cone is often asymmetrical, making symmetrical cones like those at El Malpais distinctive. Cone morphology changes through time via erosion.

Figure 15. Paxton Springs Crater. Two eruption events separated by about 5,000 years emanated from the vent at Paxton Springs. The Paxton Springs South flow is 15,000 years old; the Paxton Springs North flow is 20,700 years old. Photograph by Larry Crumpler (New Mexico Museum of Natural History and Science).

The eruption duration of a cinder cone is relatively short, generally no more than 50 years (National Park Service 2006b). Bedding (layers of volcanic rock), which builds up during the life of the cone, documents the progression of eruptions and cone evolution.

Directly to the west of El Malpais National Monument, the Chain of Craters area displays an interesting feature of the Zuni–Bandera volcanic field; many of the cinder cones within the field are aligned (fig. 16). This alignment is a result of a zone of weakness in Earth's crust, which allowed magma to rise to the surface. This type of linear alignment is observed in many Hawaiian-style volcanic fields, including that at Hawaii Volcanoes National Park (Thornberry-Ehrlich 2009).

Shield volcanoes also occur in the vicinity of El Malpais National Monument. The characteristic feature of this type of vent is its shape, which, as the name implies, resembles a shield. The Hawaiian Islands are enormous shield volcanoes, and GRI reports have been produced for six National Park System units in Hawaii (Thornberry-Ehrlich 2009, 2010, 2011a, 2011b, 2011c, 2011d). These reports may be of interest to resource managers and interpreters at El Malpais National Monument. Shields form by progressive, very fluid lava on low-gradient slopes, building up almost entirely by lava flows, with little or no spatter or cinders. Cerro Rendija is a good example of a shield at El Malpais.

Rootless vents, such as hornitos and spatter cones, also occur in the national monument. Some good examples of spatter cones occur along the trail to Bandera Crater and near the Big Tubes Trail. The term "rootless" is used to describe a volcanic feature that formed with no direct connection to the subterranean magma reservoir feeding the eruptive event (Mabery et al. 1999). "Hornito" is the diminutive of the Spanish word "horno," meaning "oven." This volcanic form resembles the old-fashioned, wood-fired ovens used in outdoor cooking. Spatter is ejected through a hole on the surface of the flow, forming mounds that generally range from 1.5 m (5 ft) to 9 m (30 ft) high. Hornitos are common in a few places on the McCartys flow, (fig. 17) and typically formed over

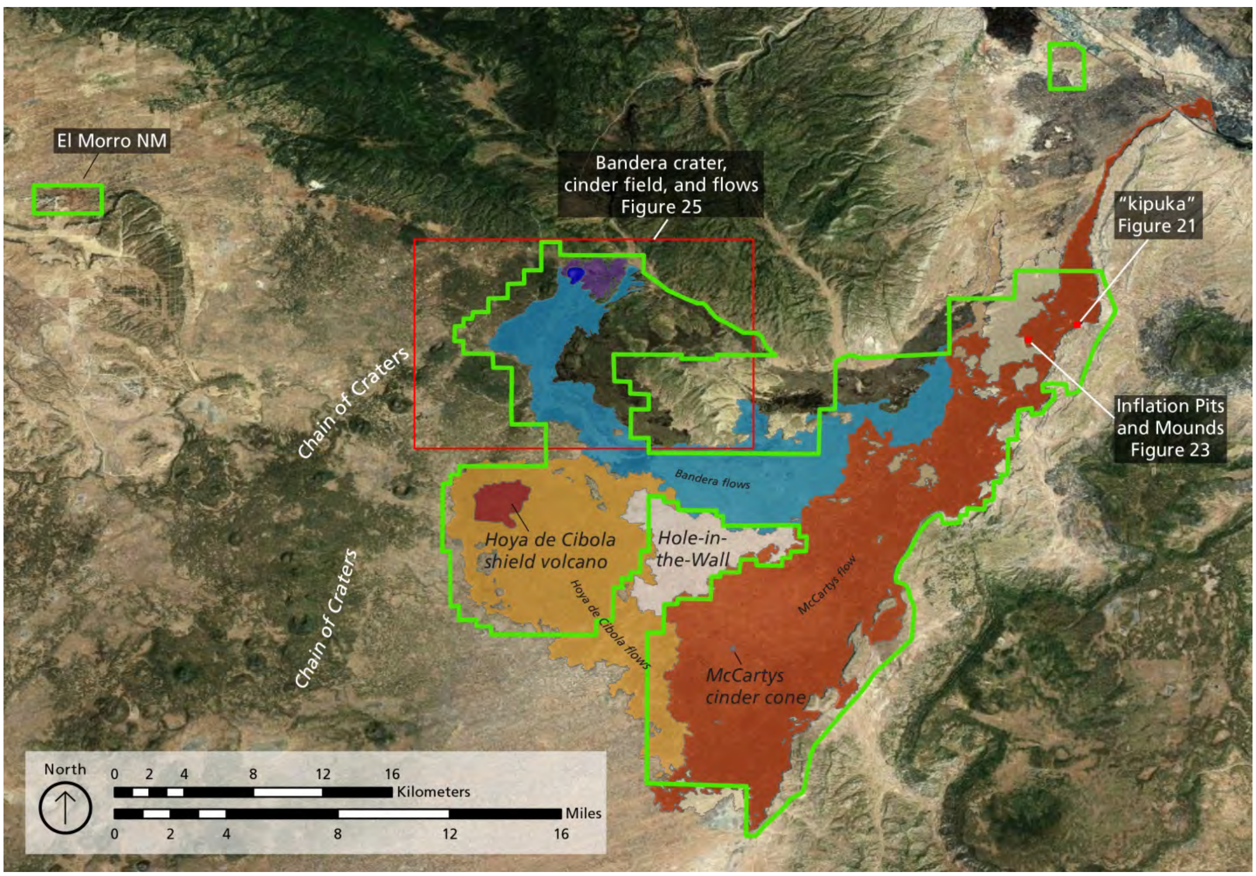

Figure 16. Aerial image of El Malpais. Aerial imagery reveals many distinctive features on the El Malpais landscape, including the long McCartys flow that spans the eastern boundary of El Malpais National Monument. The lava flow that erupted from the vent has a low gradient, but is quite long. Some of the lava flowed southward for about 8 km (5 mi), but the majority flowed northward about 40 km (25 mi) before turning eastward and flowing for 10 km (6 mi). The vent for the flow was the McCartys cinder cone in the southern part of the national monument. Another distinctive feature in aerial view is Hole-in-the-Wall, which is a kipuka—a Hawaiian term that refers to an exposure of older rock not covered by a younger lava flow (also see fig. 21). This triangular-shaped kipuka is underlain by old basalt flows (Qb) and surrounded by younger flows. The McCartys flow (Qbm) forms the lower/east wall of the kipuka, the Bandera flows (Qbb) form the upper/north wall, and the Hoya de Cibola flows (Qbw) forms the left/west wall. Also apparent in aerial view is Chain of Craters west of El Malpais National Monument. The cinder cones are aligned along a zone of crustal weakness where magma flowed to the surface. The green outlines on the figure mark National Park System areas. Graphic by Rebecca Port (Colorado State University) and Philip Reiker (NPS Geologic Resources Division).

cracks that extended to sufficient depths to tap the still-molten lava beneath the solidified surface. The molten lava rose through the cracks and spewed spatter and small flows, building these oven-shaped mounds over short periods of time (Mabery et al. 1999). A spatter cone is formed by the ejection of primarily plastic bombs of lava that fuse together after impact into a small edifice. Spatter cones may form over a fissure or vent, or may be rootless.

Figure 17. Hornito. As lava ejected through a hole in the Bandera flows, this hornito formed from lava spatter about 11,000 years ago. National Park Service photograph.

Lava Flows

Basaltic flows at El Malpais National Monument consist of pahoehoe and aa lava. Lava flows may contain both lava types as a result of a gradient change or later pulse of different viscosity lava. Pahoehoe, a Hawaiian term pronounced "pah-hoy-hoy," produces ropey flow tops (fig. 18), with multiple ropes occurring at different scales.

Figure 18. Pahoehoe lava. Hot, fluid lava is responsible for the ropey texture of the surface of the McCartys flow. Photograph by Larry Crumpler (New Mexico Museum of Natural History and Science).

The texture is typical of low-viscosity, fluid flows. Pahoehoe flows can expand as more lava collects under a solidified crust through a process called inflation. The McCartys flow (map unit symbols Qbm and Qba) exemplifies the pahoehoe type (see "McCartys Flow" section). Aa, pronounced "ah-ah," is characterized by rough, jagged flow tops (fig. 19). Aa flows have higher viscosity than pahoehoe and move like bulldozers, creating blocky, rubbly, or clinkery deposits. Features of aa flows include rafting of lava blocks within flows.

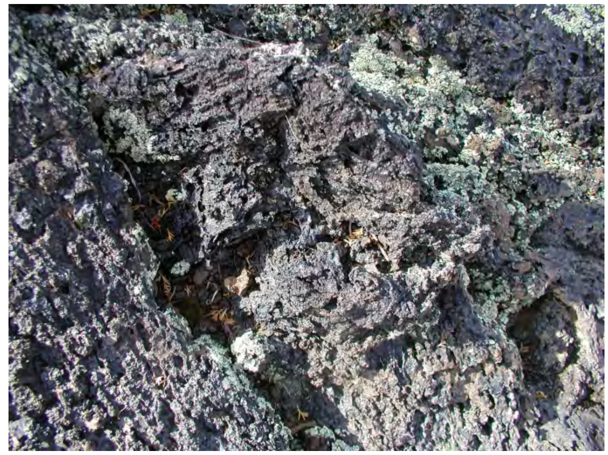

Figure 19. Aa lava. Aa lava is much more viscous than pahoehoe, creating blocky, rubbly, or clinkery deposits. The Bandera flows are known for aa, although the surface of the McCartys flow is shown in this photograph. Lava flows may contain pahoehoe and aa due to a gradient change or a later pulse of different-viscosity lava. Photograph by Katie KellerLynn (Colorado State University).

With higher viscosity than pahoehoe, aa is commonly quite vesicular, with much evidence of trapped air bubbles in solidified form (fig. 20). The Bandera flows (Qbb) exemplify the aa type (see "Bandera Crater and Flows" section).

Figure 20. Vesicular basalt. As gas bubbles escaped from the cooling McCartys flow, vesicular basalt formed. The small holes in the solidified lava are vesicles that once held volcanic gases. Photograph by Larry Crumpler (New Mexico Museum of Natural History and Science).

Maxwell (1986) divided the basalt flows of El Malpais into two informal groups: (1) the younger Malpais and (2) an older group. The older group is deeply weathered and largely covered by a more or less well-developed soil. Old basalt flows (Qb) locally are overlain by slightly younger flows (Qbu) and by pyroclastic debris (Qv) and cinder cones (Qc). Notably, old basalt flows (Qb) underlie the Hole-in-the-Wall area (fig. 16). The Hole-in-the-Wall is an example of a volcanic feature called a "kipuka," a Hawaiian term that refers to an exposure of older rock not covered by an overlying lava flow. The younger flow forms walls, enclosing the kipuka (fig. 21).

Figure 21. Kipuka. Lava surrounds an outcrop of sandstone, creating a kipuka in the McCartys flow. The outcrop is about 100 m (300 ft) long. Refer to figure 16 for location. Graphic by Philip Reiker (NPS Geologic Resources Division) utilizing ESRI Arc GIS-Bing Maps layer.

In the case of Hole-in-the-Wall, three flows surround the triangular-shaped kipuka—Bandera (Qbb) on the north, McCartys (Qbm) on the southeast, and Hoya de Cibola (Qbw) on the west (fig. 16). Hole-in-the-Wall is the largest kipuka at El Malpais National Monument, but other kipukas occur in the Hoya de Cibola (Qbw), Bandera (Qbb), and McCartys (Qbm) flows. Not all kipukas are underlain by old basalt flows (Qb).

The "younger Malpais" group of Maxwell (1986) includes the McCartys flow and cinder cone (Qbm and Qcm); Bandera flows, crater, and cinder field (Qbb, Qcb, and Qvb); Hoya de Cibola flows and shield volcano (Qbw and Qvw); Twin Craters flows, cones, and mixed pyroclastics (Qbt, Qct, and Qvt); and El Calderon flows, crater, and cinder field (Qbc, Qcc, and Qvc).

McCartys Flow

Short of a trip to Hawaii, the McCartys lava flow is one of the best places in the United States to see young, basaltic, pahoehoe volcanism. Interested visitors can view the flow from their car windows on Interstate 40, up close at several places along Highway 117, and from the Sandstone Bluffs Overlook (see "Sandstone Features" section). The McCartys flow overlies older basalts of the Zuni–Bandera volcanic field, as well as Holocene alluvium (Qal) (Laughlin et al. 1993a). Dunbar and Phillips (2004) estimated the cosmogenic chlorine-36 (^{36}Cl) age of the flow to be 3,900 years, making it the youngest lava flow in New Mexico.

The McCartys flow is beautifully preserved because of the arid conditions in the region. The flow follows topography, and although it has a low gradient, it is quite long. The source is a low shield volcano about 40 km (25 mi) south of the intersection of Interstate 40 and Highway 117 (fig. 16). A small, 8-m- (26-ft-) high cinder cone sits on top of this broad shield. Although some lava flowed southward for about 8 km (5 mi), most followed the existing drainage and flowed northward about 40 km (25 mi) before turning eastward and flowing 10 km (6 mi) down the Rio San Jose Valley (Laughlin et al. 1993a). Maxwell (1986) mapped the portion of the McCartys flow (Qbm) within El Malpais National Monument; Maxwell (1977) mapped the portion of the McCartys flow (Qbd) in the McCartys quadrangle north of the national monument.

An indicator of the youthfulness of a flow is the presence of a glassy rind, which forms on basaltic flows as they move across Earth's surface (Dunbar and Phillips 2004). The outer skin of the flow becomes quenched and forms glass (fig. 22 and inside front cover). Just-erupted basaltic flows, such as those in Hawaii, exhibit glassy rinds. The glassy part of the rind, which is very fragile compared with the rest of the flow, can be several centimeters thick on a fresh flow. The glassy rind is initially intact, but fractures develop in the glass during cooling. Because of its delicate and fractured nature, this outer rind may be stripped by mechanical weathering processes.

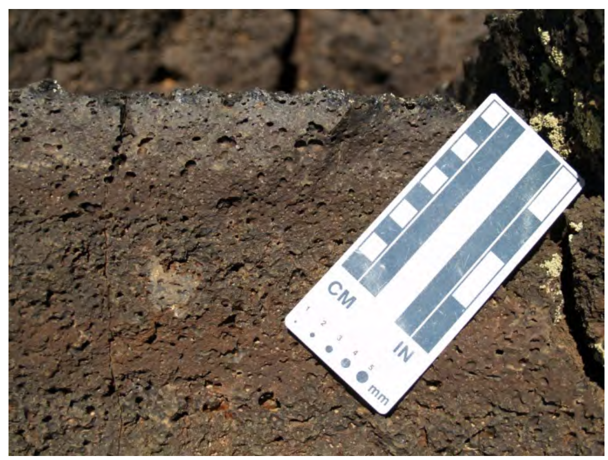

Figure 22. Crust of a basalt flow. The gray zone at the uppermost part of the vesicular basalt shown in this photograph represents the "chilled crust" of the McCartys flow. The crust of a lava flow initially exhibits a glassy rind, but weathering of the flow progressively strips away the glass over time. Some areas of the McCartys flow retain a glassy rind (see inside cover photograph). Photograph by Larry Crumpler (New Mexico Museum of Natural History and Science).

In the case of the McCartys flow, much of the glass has been stripped away in the last 3,900 years, but some rind remains. Dunbar and Phillips (2004) suggested that the glassy rind on flows is stripped progressively through time, rather than being completely removed shortly after flow emplacement.

Other features of the McCartys flow include the following:

- Inflation features—areas of pahoehoe flows that have swelled as a result of lava injection beneath the surface crust. Examples of inflation features occur along the Lava Falls Trail (Mabery et al. 1999), which crosses 2.4 km (1.5 mi) of the McCartys flow. Classic inflation features include inflation pits and mounds (fig. 23); most mounds have distinctive cracks, which formed as the brittle crust cracked as additional lava inflated the mound from below.
- Squeeze-ups and squeeze-outs—squeeze-ups form when the brittle crust of a lava flow is broken or cracked and the still-liquid lava is forced upward through the crack. Squeeze-outs form by the same process when the lava is squeezed laterally, rather than vertically. Squeeze-outs are present in the sides of inflation pits within the McCartys flow (Larry Crumpler, research curator, New Mexico Museum of Natural History and Science, telephone communication, 2 August 2012) (fig. 24).
- Vesicular basalt—vesicular basalt contains many small cavities that formed by the expansion of gas during lava solidification (fig. 20).

Figure 23. Inflation pits and mounds. Pits and mounds created through a process called inflation characterize the McCartys flow. As molten lava pushed up from beneath the hardened crust of the McCartys flow, inflation mounds formed, cracking the brittle (cooled) crust. The area in the figure is about 400 m (1200 ft) across. Refer to figure 16 for location. Graphic by Philip Reiker (NPS Geologic Resources Division) utilizing ESRI Arc GIS-Bing Maps layer.

Figure 24. Squeeze-out. Molten lava squeezed out of a crack in the walls surrounding an inflation pit on the McCartys flow. The orange field notebook rests on the squeeze-out in the photograph. Photograph by Larry Crumpler (New Mexico Museum of Natural History and Science).

Bandera Crater and Flows

The second youngest volcanic event at El Malpais yielded the Bandera flows (Qbb). Various isotopic age dates for the flows are in good agreement and cluster around 11,000 years: the carbon-14 (^{14}C) method produced an age of 10,990 years before present (Laughlin et al. 1993b), the helium-3 (^{3}He) method produced an age of 10,400 years before present (Laughlin et al. 1993b), and the chlorine-36 (^{36}Cl) method produced an age of 11,200 years before present (Dunbar and Phillips 2004).

The Bandera flows (Qbb) originated from the Bandera Crater (Qcb), a cinder cone about 1 km (0.6 mi) in diameter and 150 m (490 ft) high (Laughlin et al. 1993a). The cone is adjacent to Highway 53. The crater is privately owned and open to the public. The Ice Caves Trading Company, which owns the crater, encourages visitors to "Go climb a volcano!" in a lunar-like landscape.

Bandera Crater is an ideal example of a breached cinder cone (fig. 11). The cone has a central depression 180 m (600 ft) below the rim and 80 m (260 ft) below the breach on the southwest side (Maxwell 1986). Aa and pahoehoe surfaces are common on the Bandera flows (Laughlin et al. 1993a). These flows originated at the breach in the south wall of the cinder cone, and extend 37 km (23 mi) from the vent (fig. 25).

One of the most remarkable features of the Bandera flows is the lengthy, highly developed system of lava tubes (see "Lava Tubes" section). These tubes form the longest identified system in North America (Mabery et al. 1999). At least 27 km (17 mi) of tubes have been discovered and explored (Mabery et al. 1999).

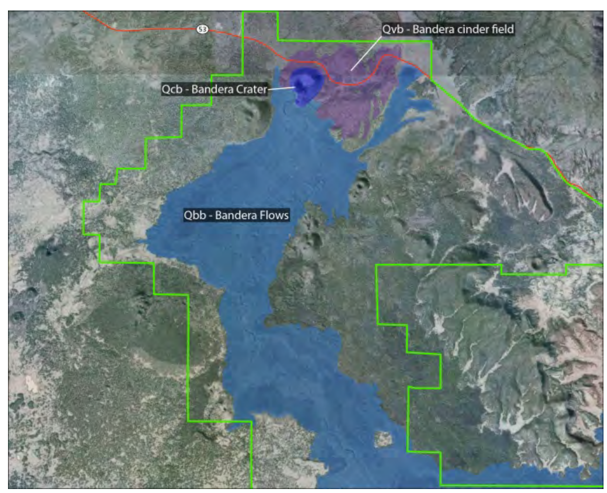

Figure 25. Bandera flows. The Bandera Crater erupted about 11,000 years ago, depositing extensive flows (Qbb) and a cinder field (Qvb). Refer to figure 16 for location. Graphic by Philip Reiker (NPS Geologic Resources Division) utilizing ESRI Arc GIS Bing Maps layer and GRI digital geologic data.

Hoya de Cibola Flows

The exact age of the Hoya de Cibola flows (Qbw) is unknown, but their relative position indicates that they are older than the Bandera flows (Qbb) (Dunbar and Philips 2004). The source of the Hoya de Cibola flows is Cerro Hoya (Qvw), a large shield volcano about 2.4 km (1.5 mi) in diameter and 90 m (300 ft) high, located near the western edge of El Malpais National Monument. Flows traveled at least 53 km (33 mi) south, east, and probably northeast from the vent. The flows are covered by the Bandera and McCartys flows (Maxwell 1986). Mabery et al. (1999) estimated that the volume of the Hoya de Cibola flows was 7.5 km^3 (1.8 mi^3). A notable feature of the Hoya de Cibola flows is the lava-tube system, which includes Braided Cave (see "Lava Tubes" section).

Paxton Springs Flows

North of El Malpais National Monument in Zuni Canyon, Maxwell (1986) mapped the Paxton Springs flows (Qbp). The flow originated from a volcanic center (fig. 15) in the Precambrian core of the Zuni Mountains (Maxwell 1986). The cone is near the historic settlement of Paxton Springs, which is about 6 km (4 mi) north-northeast of Bandera Crater (Mabery et al. 1999). According to Maxwell (1986), part of the lava flowed 3 km (2 mi) down Agua Fria Creek, and another part flowed northeast through Zuni Canyon for 27 km (17 mi) to the vicinity of Grants (Maxwell 1986).

Since the time of Maxwell's mapping, investigators have dated these two segments and determined that they actually represent two events, separated in time by about 5,000 years. Lava that flowed south comprises the younger (cosmogenic chlorine-36 dating, about 15,000 years old) Paxton Springs South flow, and lava that flowed north of the cinder cone forms the older (20,700 years old) Paxton Springs North flow (Dunbar and Phillips 2004). These flows are separated in time by the Twin Craters (Qbt) flow event, which occurred 18,000 years ago (Dunbar and Phillips 2004) (see "Twin Craters Flows" section). Morphologically, all three of these flows appear similar in age; they lack glass on their surfaces and have lost much of the ropey tops of the original pahoehoe texture (Dunbar and Phillips 2004).

Zuni Flows

The Zuni flows erupted in the Zuni Mountains, north of the "main" El Malpais flows. Maxwell (1986) mapped these flows as unit Qbz; Maxwell (1977) mapped the Zuni flows in the McCartys quadrangle as unit Qba. The Zuni flows originated from a volcanic vent about 1.7 km (1 mi) north of the El Malpais National Monument boundary (Maxwell 1986). These flows have not been dated using absolute methods. However, Laughlin and WoldeGabriel (1997) placed them in a position younger than the Oso Ridge flows (Qbo) in a relative chronology of Zuni–Bandera lava flows.

Oso Ridge Flows

Like the Zuni flows (Qbz and Qba), the Oso Ridge flows (Qbo) erupted in the Zuni Mountains, although not as far north. These flows originated from a lava cone (Qvo) on Oso Ridge about 5 km (3 mi) northwest of Bandera Crater (Qcb). The lava cone is composed largely of breccia, welded pyroclastic debris, and glassy flows (Maxwell 1986). Basalt from the Oso Ridge lava cone flowed eastward to Agua Fria Creek and southward almost to the Bandera cinder field (Qvb). A small portion of the flow is within the national monument. The exact age of these flows is not known, but Maxwell (1986) mapped them as younger than the Twin Craters flows (Qbt), which are now known to be about 18,000 years old (Dunbar and Phillips 2004).

Twin Craters Flows

The Twin Craters flows (Qbt) are composed of several overlapping flows from different vents, which Maxwell (1986) described as "difficult or impractical to separate." This map unit covers many prominent landmarks between Bandera Crater (Qcb) and El Calderon (Qcc), including La Tetra, Twin Craters, and Lost Woman. Maxwell (1986) mapped these three cinder cones (Qct) and surrounding mixed pyroclastics (Qvt) as part of this unit. The map of Dunbar and Phillips (2004) identified these flows as "flows from La Tetra area," with the map symbol Qt. Cascadden et al. (1997b) included Cerro Candelaria and Lava Crater, which are on private lands and closed to the public, within this group. Cerro Candelaria is 0.6 km (0.4 mi) east of Lava Crater, which is labeled on the park map (fig. 1).

Flows from these vents traveled at least 26 km (16 mi) east and northeast. Mabery et al. (1999) estimated that the total volume of the eruptions was 1.0 km^3 (0.25 mi^3). The similarity of the flows—for example, in abundance and size of olivine phenocrysts within the basalts—made distinguishing relative ages of the flows challenging for early workers (Mabery et al. 1999). However, since initial mapping, Cascadden et al. (1997b) analyzed paleomagnetic variations in the flows and mapped the geology around these cones in considerable detail, thereby discovering the relationships in this "family of volcanoes." Approximately 18,000 years ago (Dunbar and Phillips 2004), each of these cones erupted within a few hundred years of one another: Cerro Candelaria erupted first, followed by Twin Craters, Lost Woman Crater, and Lava Crater (Cascadden et al. 1997b). The entire eruption event lasted less than 1,000 years (Cascadden et al. 1997b).

El Calderon Flows

The El Calderon flows (Qbc)—referred to as the "Laguna flow" by some investigators (e.g., Dunbar and Phillips 2004)—issued from a volcano (Qcc) east of the Twin Craters cluster of volcanoes. Following Maxwell (1986) and the suggestion provided in Crumpler et al. (2003), this report uses "El Calderon" rather than "Laguna" because the former is more descriptive and avoids confusion with a lava flow located near Laguna, New Mexico, farther east along Interstate 40 (Crumpler et al. 2003).

Although the El Calderon volcano was once thought to have erupted about 115,000 years ago, more recent dating assigns it an age of about 54,000 years (Cascadden et al. 1997b; Laughlin and WoldeGabriel 1997). Dunbar (2010) suggested that El Calderon may have erupted between 40,000 and 30,000 years ago, but certainly less than 60,000 years ago.

Figure 26. El Calderon. The El Calderon area contains the most developed trail in El Malpais National Monument. A 5-km (3-mi) loop guides hikers past lava flows and the El Calderon volcano. National Park Service photograph.

At the time of eruption, fire fountains would have issued high into the air from the center of the cone, raining down cinders in layers that built up the conical shape (fig. 26). Original bedding (layers of cinders) is visible where erosion has cut into the cone's side (Dunbar 2010). In places, the El Calderon flows (Qbc) are covered by the Twin Craters (Qbt) and Bandera (Qbb) flows and appear small and fragmented in map view. However, investigators traced the El Calderon flows (Qbc) from the crater (Qcc) to a termination point east of the intersection of Highway 117 and Interstate 40—a distance of about 35 km (22 mi) (Mabery et al. 1999). Investigators estimated the volume of the El Calderon flows to be at least 4 km^3 (1 mi^3) (Mabery et al. 1999).

Lava Tubes

The third main category of volcanic feature at El Malpais National Monument is lava tubes. The term "lava tube" has a dual meaning. First, lava tubes are conduits for molten lava flowing from a vent to a depositional site, generally the advancing front of a lava flow. Second, the term refers to the cavernous segment of the lava conduit that remains after the lava has ceased to flow (Larson 1990). These tubular cavities are also referred to as "lava-tube caves" (Rogers and Mosch 1997a).

Lava-tube systems are the principal means by which pahoehoe flows spread widely and thinly (Larson 1990). Most lava tubes at El Malpais represent the major conduits of lava along the length of a lava flow. Smaller distributary tubes diverged downslope from these master tubes and dispersed the lava along a broad front (Rogers and Mosch 1997a). However, these smaller tubes are seldom preserved at El Malpais National Monument because of low surface gradients, relatively short eruption lengths, and low discharge rates that allowed flowing lava to slow and congeal within the tubes, thereby blocking them (Rogers and Mosch 1997a).

El Malpais National Monument contains 15 major lava tubes (Marinakis 1997). Laid end-to-end, they would stretch more than 100 km (60 mi) (Marinakis 1997). The most extensive lava tube at El Malpais—and, if it were all still intact, the longest identified system in North America (Mabery et al. 1999)—is the Bandera lava tube (Marinakis 1997). This lava tube occurs in the Bandera flows (Qbb), which are 37 km (23 mi) long and contain 28 km (17 mi) of identifiable tube, most of which is now collapsed trench (Rogers 1991a). The Bandera lava tube begins at the breach in the cinder cone (fig. 11), and its first 800-m (0.5-mi) segment is totally collapsed (Maxwell 1986). The Bandera flows contain dozens of individual caves ranging from 300 to 400 m (980 to 1,310 ft) in length and systems with lengths exceeding 1 km (0.6 mi) (Rogers 1991a, 1991b). Many tubes also contain natural bridges, which can be 50 m (164 ft) long (Rogers 1991a). Notable examples of bridges occur in the Big Tubes area of the national monument and include Natural Bridge, bridges in the Seven Bridges collapse trench, and bridges near Four Windows Cave (fig. 27).

Figure 27. Lava bridge. Lava bridges form between sections of collapsed lava tubes. The bridge shown in the photograph is located in the Big Tubes area of El Malpais National Monument. Note person for scale. National Park Service photograph.

Collapse Features

Among the common features in lava tubes at El Malpais National Monument are abundant piles of debris and rubble called breakdown (fig. 28). This material is indicative of collapse that occurred when the tube cooled and contracted. For instance, the floor of Big Skylight Cave is littered with rubble that was once part of the ceiling. Caterpillar Collapse and Seven Bridges were once lava tubes, but their roofs have subsequently collapsed. The roof of Caterpillar Collapse crumbled slowly and completely, leaving the long, winding trench seen today (National Park Service 2003a).

Figure 28. Breakdown. The floor of the entrance to Junction Cave is covered in breakdown. U.S. Geological Survey photograph, available at http://3dparks.wr.usgs.gov/elma/html2/elma0074.htm (accessed 4 May 2012).

Blocks broken from the ceiling or walls of a lava tube may be carried along with the moving lava flow. They may be partly melted and moved by rafting on top of the flow or by rolling within it. Blocks that are too large to melt are carried by the tremendous viscous drag of the moving lava. As part of the flow, blocks may become partially melted, abraded, rounded, and sometimes coated with lava; such transformed blocks are known as "lava balls." In several caves, such as Xenolith and Junction caves, blocks became jammed between the floor and ceiling and cemented in place by the still-flowing lava, nearly closing off the lava-tube passage (Rogers and Mosch 1997a).

Figure 29. Skylight on the McCartys flow. A skylight on the McCartys flow allows sunlight into the lava-tube cave below. Skylights are important during eruption because they allow atmospheric gases to mix with superheated gases in the lava tube and combust, which may assist with remelting of the basalt lining, thereby creating distinctive cave features. Photograph by Larry Crumpler (New Mexico Museum of Natural History and Science).

When the extent of collapse is large, breakdown may constrict or completely block the tube. Vertically extensive collapse may break through the ground surface to form a skylight (fig. 29). Skylights are important at the time of eruption because they allow atmospheric gases to mix with the superheated tube gases and combust. Rogers and Mosch (1997a) speculated that this burning of hydrogen-rich gas may heat the interior of the tube and thereby assist with remelting of the basalt lining it (see "Cave Features" section). Subsequent lava flows can enter the tubes through these skylights, occasionally filling them.

Cave Features

As lava tubes form, the gases within them can be hotter than the lava coursing over the floor or forming the walls (Rogers and Mosch 1997b). For example, gas temperatures of 1,150°C–1,555°C (2,102°F–2,831°F) have been measured in the tubes of Hawaii (Swanson 1973). Interior surfaces melt under these conditions, forming cave features that are often compared to the well-known speleothems (mineral deposits) found in limestone caves (Rogers and Mosch 1997b). In contrast to limestone caves, where speleothems are most commonly composed of calcite ($CaCO_3$), the El Malpais lava-tube caves contain features that are most commonly formed of basalt, and are thus some shade of black (Rogers and Mosch 1997b). Furthermore, whereas true speleothems form by the action of water and thus grow rather slowly in limestone caves, lava speleothems grow rapidly by the flowing, dripping, splashing, accreting, and pulling apart of molten or partially consolidated lava, and by the interaction of associated gases in the lava tube (Hill and Forti 1997).

Lava flows and melting lava created the following features in the lava-tube caves at El Malpais National Monument:

- Draperies and ribs—thin deposits of basalt that developed where trails of lava trickled down the walls of a lava tube. These features are fairly common in the lava tubes of El Malpais. They often have white or ochre-colored coatings of other minerals that precipitated much later in the history of the cave (Rogers and Mosch 1997b).
- Floors—where not obscured by breakdown, the floors of lava tubes often show features indicative of flow history. When all lava flowing within a tube merely stopped moving and quickly cooled, a relatively smooth floor with ropey pahoehoe textures formed. However, changes in viscosity and the rate of shear strain can cause tube-floor textures characteristic of aa. The centers of floors are often textured with ropey coils of pahoehoe, while the edges of the flow are clinkered fragments of aa. Gradations between these extremes, including cauliflower lava, are usually well displayed wherever floors are preserved and not covered by breakdown (Rogers and Mosch 1997a).
- Flowstone—masses of solidified lava that mimic calcite flowstone found in limestone caves. These features were named for their resemblance to a frozen waterfall or river.
- Helictites—deposits of lava that twist and turn in gravity-defying contortions. Lava helictites are sparingly found in lava tubes with intact ceiling or wall linings. Their stems are usually 0.2–0.5 cm (0.08–0.2 in)

in diameter. Some have beaded surfaces and may be partially hollow near their tips.

- Linings—relatively thin shells of lava plastered against the inside surfaces of a lava tube. Linings form in active tubes as an additional layer of lava or a melted crust (Rogers and Mosch 1997a). Where linings do not reach the ceiling of the lava tube, their upper surfaces may mark the upper limits of secondary flows. In cross section, multiple linings may look like layers of a cut onion.

  Where the entire wall has melted to a depth of about 1 cm (0.4 in), the lining may slump or partially sag down the wall. Should this sagged lining fail along a discrete crack, causing the lower panel to sag farther, the lower panel would stretch the lava apart, leaving a line of taffy-like strings and threads of basalt in the opening that often resembles whale baleen plates (Rogers and Mosch 1997a).

  Occasionally, gas pressure may build up behind patches of wall lining. When the pressure exceeds the strength of the still-plastic lining, a patch may literally explode from the wall. These ruptures have out-turned edges and highly vesicular interiors.

  When the level of lava in a tube drops quickly, highly plastic linings may curl or roll down toward the floor. In some cases, they fold back and collapse on themselves. Big Skylight Cave has excellent examples of these features.

- Shelves—horizontal banks of basalt along the walls of a lava tube. These interior forms may also be referred to as "benches" when particularly wide or as "levees" if they confined the flowing lava to a portion of the floor. Shelves are left by lava that coursed through the tubes, and mark a period of time when lava discharge remained relatively constant. Generally, wider shelves indicate a longer period of lava flow at that level.

- Stalactites—basalt deposits hanging down from the ceiling of a lava tube. Lava stalactites are commonly called "lavacicles" because of their resemblance to icicles. Lava stalactites can be conical, bulbous, cylindrical, or tear-drop shaped (Hill and Forti 1997). Some lava stalactites at El Malpais National Monument resemble shark teeth, and others resemble soda straws. Rogers and Mosch (1997b) noted globular lavacicles that look like columns of small grapes, and others that resemble golf tees.

- Stalagmites—deposits of basalt that build upward from the cave floor. Lava stalagmites form where spots on the ceiling melt and dribble blobs of lava below. They are much less numerous than lavacicles because dripping lava is often incorporated into the fluid floor or swept away from the point of origin by floor movement. Most stalagmites in El Malpais National Monument look like small-diameter columns of grapes (Rogers and Mosch 1997b). These stalagmites are commonly found along the edges of passages below cracks in linings. At other places, however, lava dripped through a central crack to spawn a series of stalagmites in the center of the passage. When a single lavacicle supplied lava to a crusted, slow-moving floor, a trail of small stalagmites may have formed along the floor (Rogers and Mosch 1997b).

Xenoliths

Some lava tubes in El Malpais National Monument, such as Junction Cave, Lava Crater, and of course Xenolith Cave, contain xenoliths. Xenoliths are inclusions in volcanic rocks that are commonly longer than 0.3 m (1.0 ft) and differ distinctly from their host rocks (Mabery et al. 1999). Xenoliths may have come from the sides of a magma chamber or the walls of an erupting lava conduit, and, thus provide clues about volcanic processes and information about rocks in the local crust or mantle. According to Mabery et al. (1999), lava flows and late-stage cinders from Bandera Crater contain xenoliths that originated in Earth's mantle. They are often found in the cinder pits at this location. Mantle-derived xenoliths were brought to the surface by fast-rising magma and encased as the lava cooled (National Park Service 2003a). These xenoliths provide rare opportunities for first-hand study of Earth's mantle, which is generally inaccessible because it lies 100–200 km (60–120 mi) below Earth's surface (Robertson 2011).

By contrast, some xenoliths may have originated at the surface as blocks of rock from bluffs and narrows that fell onto lava flows (National Park Service 2006b). According to Laughlin et al. (1971), xenoliths of sandstone, limestone, granite, gabbro, and granodiorite are present in some lava flows at El Malpais National Monument. These xenoliths provide clues about the bedrock under the lava flows and help to determine the erosive history of the valleys (National Park Service 2006b).

Cave Minerals

Using x-ray diffraction, Rogers and Mosch (1997b) identified numerous minerals with various sources in the lava tubes at El Malpais National Monument (table 2). Gypsum, epsomite, mirabilite, thenardite, calcite, trona, and burkeite appear to have drawn carbonate and sulfate from windblown dust derived from the weathering of sedimentary rocks in the area. The silica of cristobalite appears to have been leached from unstable pumice and glassy ash of the volcanic terrain (Rogers 1991b). Xenoliths within the lava flows provided raw materials for glass, opal, and malachite. These minerals form a variety of speleothems, including hairs, moonmilk, and coralloids (Marinakis 1997). Hairs are composed of single crystal fibers and resemble thin strands of hair (Hill and Forti 1997). Coralloids are nodular, globular, or coral-like in shape and form from films of water (Hill and Forti 1997). Moonmilk consists of white, finely crystalline material that feels like powder when dry and cream cheese when moist (Hill and Forti 1997).

Table 2. Cave minerals

Name	Chemical Formula	Speleothem Type	Occurrence
Amorphous silica glass	SiO_2	Bubbly, green, glass coatings on xenoliths	Rare (known only in Xenolith Cave)
Burkeite	$Na_6(CO_3)(SO_4)_2$	Crusts	Rare (known only in Outlaw Cave)
Calcite	$CaCO_3$	Flowstone, draperies, coralloids, and moonmilk	Common
αCristobalite	SiO_2	Coralloids	Uncommon
Epsomite	$MgSO_4 \bullet 7H_2O$	Hairs and crystals	Rare
Glaserite	$(K, Na)Na(SO_4)_2$	Constituent of mirabilite and thenardite "snowballs"	Rare (known only in Braided Cave)
Gypsum	$CaSO_4 \bullet 2H_2O$	Sugary crusts, stalactites, stalagmites, columns, flowstone, hairs, and powder	Common
Malachite	$Cu_2(CO_3)(OH)_2$	Green stains in xenoliths	Rare
Mirabilite	$Na_2SO_4 \bullet 10H_2O$	Hairs	Rare
Opal-A	$SiO_2 \bullet nH_2O$	Coralloids (e.g., "cave coral")	Common
Opal-CT	$SiO_2 \bullet nH_2O$	Crystals on xenoliths	Rare (known only in Xenolith Cave)
Thenardite	Na_2SO	Powder and coralloids (e.g., "snowballs")	Rare
Trona	$Na_3(CO_3)(HCO_3) \bullet 2H_2O$	Crusts	Rare (known only in Outlaw Cave)

Sources: Rogers (1991b) and Rogers and Mosch (1997b).

Ice Caves

Lava tubes that contain ice accumulations are called "ice caves." These features are abundant in El Malpais National Monument (Marinakis 1997; National Park Service 2006b). Ice forms when percolating rainwater and melting snow enter the freezing zone of a cave. Although the amount of ice varies from year to year, large amounts of ice accumulate seasonally, beginning in spring and persisting into early–middle summer (Rogers and Mosch 1997b). Much of the ice melts by later summer. Minimal amounts of ice form during the early winter because lower temperatures freeze the groundwater and the winter air contains very little moisture (Rogers and Mosch 1997b). Although most ice in caves at El Malpais is clear to white, part of the ice floor in Ice Cave (also called Candelaria Ice Cave)—the large, privately owned cave in the Bandera lava flow—is pale green. Algae apparently flourish in this part of the ice floor, which receives direct sunlight (Rogers and Mosch 1997b).

Marinakis (1997) surveyed four caves in El Malpais National Monument with massive perennial ice deposits, three caves with significant perennial ice accumulations, and dozens of other caves with smaller amounts of seasonal and perennial ice. Seasonal ice formations in caves consist of icicles and ice stalagmites, which usually reach their maximum size during March or April. Perennial accumulations of ice may contain ice flowstone, frozen ponds, ice needles, and ice crystals (figs. 30 and 31).

Ice accumulations in the ice caves are culturally and scientifically significant. For example, in the 1860s, soldiers from Fort Wingate—established on the site of what is now the town of San Rafael—used to visit Ice Cave and haul ice back to the fort (Laughlin et al. 1993a). The ice accumulations have scientific value for the study of paleoclimate. Thompson et al. (1991) extracted three ice cores from Ice and La Marchinita caves, which they dated and analyzed for pollen, microparticle concentrations, oxygen isotope ratios, and nitrate (NO^{3-}), chlorine (Cl^{-}), sulfate (SO_4^{2}), and phosphate (PO_4) contents. Results indicated that the ice laminations are not annual, but represent occasional layers between periods of melt. Thompson et al. (1991) obtained radiocarbon dates for the older ice deposits using accelerator mass spectrometry. At Ice Cave, a twig enclosed near the bottom of a 4-m- (13-ft-) thick bank of laminated ice was 3,166 ± 77 years old (Thompson et al. 1991).

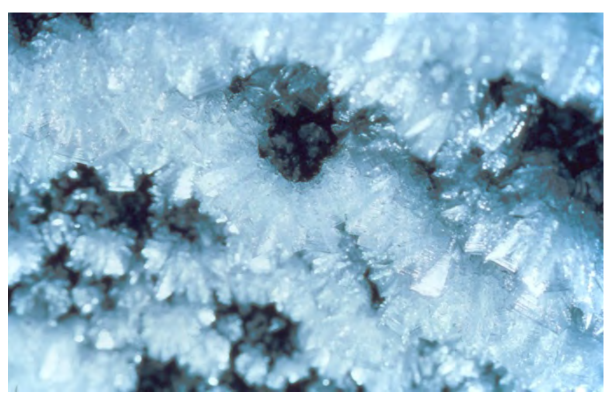

Figure 30. Ice crystals. Ice accumulates seasonally in the lava tubes at El Malpais National Monument. Seasonal ice features include icicles, ice stalagmites, and ice crystals (shown in this photograph). National Park Service photograph.

Figure 31. Perennial ice. Perennial ice accumulations produce ice flowstone, frozen ponds, and frozen floors. Some ice accumulations at El Malpais have persisted for more than 3,000 years. This photograph was taken in the Red Room of Crystal Ice Cave at Lava Beds National Monument, where similar ice accumulations occur. National Park Service photograph.

Eolian Features and Processes

Maxwell (1986) included eolian deposits (Qe) within El Malpais National Monument, and described these deposits as recent accumulations of windblown silt and sand. Maxwell (1986) only mapped the most prominent accumulations, which occur in the form of sand sheets, dune fields, longitudinal dunes, and smaller deposits. These landforms appear on aerial images (National Park Service 2006b).

At present, the friable Zuni Sandstone (Jz) supplies sediment for eolian transport. The North Pasture Ridges—a significant Cretaceous outcrop of Zuni Sandstone south of the Narrows Picnic Area—is a source area. Although usually made of basalt, some kipukas are made of sandstone (fig. 21), which serves as another source of eolian sediment (National Park Service 2006b). During the Middle Jurassic Period (175 million–161 million years ago), the Zuni and Entrada sandstones were part of a vast desert where sand was piled into dunes and spread into sheets. The crossbeds and flat-lying beds of the sandstone are indicative of eolian deposition (Lucas 2010). At nearby El Morro National Monument, 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 Entrada Sandstone (Graham 2004). Notably, La Ventana Natural Arch formed in Zuni Sandstone (see "Sandstone Features" section).

Eolian processes are significant for landscape evolution at El Malpais National Monument. They provide windblown dust, called loess, which fills in voids (vesicles and cracks) in the lava flows. Older flows generally exhibit more eolian "infilling," which smooths out a lava flow's surface over time. As a result, many older flows, such as the El Calderon flow in the Cave Junction area, are virtually flat (Dunbar 2010). By contrast, a clean, silt-free surface like that of the McCartys flow indicates that a flow is younger. In a flow of moderate age, some larger depressions are filled with silt.

Infilling of voids with loess is the first stage of soil development on the lava flows. 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, sediment source, and surface cover types on soil formation within the Carrizozo lava flow in central New Mexico. The study found that soils on the flows were of eolian origin and not the products of basalt weathering. These findings may be applicable to the lava flows at El Malpais National Monument.

Biologic and Geologic Connections

With a name meaning "The Badlands," El Malpais may seem an unlikely spot for biological diversity. Yet, the national monument hosts a variety of habitats that support a large number of plant and animal species, including some of the oldest trees in the American Southwest. Geologic features create these special habitats (Lightfoot 1997).

Lava-Flow Habitat

The McCartys (Qbm), Bandera (Qbb), Hoya de Cibola (Qbw), Twin Craters (Qbt), and El Calderon (Qbc) flows are the principal geologic features that define the lava-flow habitat at El Malpais National Monument (Lightfoot 1997). These flows constitute a "mesic island" (an area that is moister than the land around it) surrounded on all but the northwest side by drier habitats (Bleakly 1997). Investigators have hypothesized that the porous nature of the lava acts as a reservoir that traps and holds moisture from winter snowmelt and summer rainfall (Lindsey 1951; Grissino-Mayer and Swetnam 1997). This water-holding capacity allows the lava to support tree species such as aspen (*Populus tremuloides*), Douglas-fir (*Pseudotsuga menziesii menziesii*), and ponderosa pine (*Pinus ponderosa*) in a region that would otherwise be inhospitable.

The lava-flow habitat varies across an elevation gradient. Temperature and moisture conditions vary across this gradient from cooler and wetter on the upper-elevation lava flows to warmer and drier on the lower-elevation flows (Lightfoot 1997). The northwestern part of the national monument is highest, with elevations of up to 2,438 m (8,000 ft), and is contiguous with the Zuni Mountains, which are densely covered with conifers (Bleakly 1997). Mixed-conifer woodlands—composed primarily of ponderosa pine (*Pinus ponderosa*) with lesser numbers of Douglas-fir (*Pseudotsuga menziesii*), Rocky Mountain juniper (*Juniperus scopulorum*), and piñon pine (*Pinus edulis*)—blanket most of the four older flows (El Calderon, Twin Craters, Hoya de Cibola, and Bandera) and adjacent areas to the northwest. The fifth and youngest flow, the McCartys flow, is barren or sparsely vegetated with shrubs, grasses, and stunted conifers. The stunted trees, referred to as the "Pygmy Forest," are of interest to visitors and are highlighted in the Lava Falls area trail guide (National Park Service 2009). These trees occur on the eastern part of the McCartys flow, where apparently they are able to find enough water to survive, but not enough to reach the loftier heights of trees on the flows to the northwest. Other species are also affected by the elevation gradient: lichen cover is much greater on lava at higher elevations in the Bandera Crater area than at lower elevations on the McCartys flow.

The lava flows at El Malpais National Monument host some incredibly old, still-living specimens of Douglas-fir, including a tree referred to as the "Yoda Tree" by national monument staff (Dana Sullivan, chief ranger, and Dave Hays, resource manager, El Malpais NM and El Morro NM, conference call, 9 December 2011). According to the New Mexico Bureau of Mines and Mineral Resources (1993), this tree's first year of life was 719 CE (Common Era; preferred to "AD"), making it 1,293 years old in 2012. The lava also preserves some very old dead trees and pieces of wood that would have decayed under less-arid conditions (New Mexico Bureau of Mines and Mineral Resources 1993). The "Bannister Tree," named in honor of eminent dendrochronologist Dr. Bryant Bannister, has an inner tree ring dated at 200 BCE (Before Common Era; preferred to "BC") and an outer ring dated at 550 CE (Lightfoot 1997). Piecing together samples from ancient, living trees to tree-ring patterns in dead trees enabled the development of a chronology used to help decipher past climate and fire histories (New Mexico Bureau of Mines and Mineral Resources 1993).

The lava flows also affect animal species. Melantropic lizards that live on the lava are darker in color than are those that live off the flows (National Park Service 2006b). However, melanism apparently has not produced any distinct subspecies at El Malpais (Hooper 1941; Lightfoot 1997). Furthermore, certain endemic species of invertebrates are found only on lava flows or in the entrances to lava-tube caves at El Malpais (Lightfoot 1997). In the early 1990s, an extensive invertebrate inventory resulted in the discovery of 17 new species and one new genus of arthropods. Most of these species appear to be endemic (Lightfoot et al. 1994).

Kipukas

Hole-in-the-Wall is a 2,710-ha (6,700-ac) kipuka that consists of ponderosa pine parklands and grassland surrounded by lava (fig. 16). Because of their inaccessibility, several kipukas within El Malpais National Monument were never or only slightly disturbed by grazing or logging. Hence, natural vegetative assemblages remain intact in these areas (National Park Service 2006b). Kipukas host remnants of vegetation that were more widespread prior to disturbance. For example, Hidden Kipuka marks the southernmost extent of alligator juniper (*Juniperus deppeana*).

Because the "kipuka pines" have a fire regime similar to those of surrounding forests from which embers can travel and ignite, these pines have not attained the old ages of the Douglas-firs that grow on the Bandera flows (Dave Hays, resource manager, El Malpais NM and El Morro NM, e-mail communication, 16 December 2011). Nevertheless, kipukas shelter some older ponderosa pines because these areas were not logged.

Cinder-Cone Habitats

Steep-sided cinder cones are common in the western part of El Malpais National Monument (Lightfoot 1997). The loose cinders provide good places for seeds to take root. The cinders may also retain water deep below the surface, providing moisture for trees, plants, and wildflowers. Several plants in the national monument, such as bracken ferns (*Pteridium aquilinum pubescens*), cinders phacelia (*Phacelia serrata*), and limber pine (*Pinus flexilis*), grow only on cinders (National Park Service 2004a).

Lava-Tube Habitats

The sunlight that pours through skylights, for instance at Big Skylight and Four Windows caves, provides an opportunity for life to thrive where it otherwise might not. Spiders, mites, crickets, and other small creatures live beneath these sunlit openings in gardens of delicate green moss (National Park Service 2003a), which Marinakis (1997, p. 162) called "luxuriant moss gardens." Flora and fauna flourish in the cool cave air beneath most skylights. Unique assemblages of lichens and mosses grow at the mouths of caves. The cave microclimate is similar to Arctic climates, where these plants typically grow. Ferns similar to those that grow in the Pacific Northwest also grow at the mouths of caves and in collapse structures (Bleakly 1997).

Various types of organisms inhabit El Malpais caves, including those that have adapted to life in complete darkness, those that inhabit gypsum and calcium deposits, and those that inhabit ice accumulations (National Park Service 2003a) (see "Cave Minerals" and "Ice Caves" sections). Fauna include microorganisms that form "cave crusts" and "lava wall slime," as described in Northup and Welbourn (1997). Northup and Welbourn (1997) provided a list of vertebrates and invertebrates species from six caves (Bat, Big Skylight, Braided, Four Windows, Junction, and Navajo caves) in El Malpais National Monument; this inventory identified 62 species. Lightfoot (1997) described several new species of crickets from some of the national monument's more remote caves. In addition, Mexican free-tailed bats (*Tadarida brasiliensis*) inhabit the lava-tube caves. Although bighorn sheep (*Ovis canadensis*) no longer roam the area, their skeletal remains are commonly found in the caves (Marinakis 1997) (see "Paleontological Resources" section).

Sandstone and Limestone Habitats

Sandstone and limestone ridges consist of rocky slopes, as well as cliffs and bluffs, with or without vegetation. Sandstone and limestone escarpments are found in the north-central area of El Malpais National Monument, such as Cerritos de Jaspe and Oak Ridge, and along the east side of the national monument, including the Sandstone Bluffs area (Lightfoot 1997).

Some birds are associated specifically with rock habitats, regardless of surrounding vegetation (Lightfoot 1997). Such species include the band-tailed pigeon (*Columba fasciata*), rock dove (*Columba livia*), white-throated swift (*Aeronautes saxatalis*), cordilleran flycatcher (*Empidonax occidentalis*), cliff swallow (*Hirundo pyrrhonota*), rock wren (*Salpinctes obsoletus*), and canyon wren (*Catherpes mexicanus*). Of these, the cordilleran flycatcher is largely associated with lava flows and the cliff swallow with sandstone. The other birds are found on both lava and sandstone (Lightfoot 1997).

Tinajas and Playas

Natural potholes called tinajas occur in the sandstone rock units at the national monument (fig. 32), and smaller ones occur on the lava flows. These features are common in the sandstone bluffs on the east side of the national monument, Hidden Kipuka, Cerritos de Jaspe, and Oak Ridge (Lightfoot 1997). Although ephemeral, tinajas are a significant source of surface water in the national monument (National Park Service 2006b). One tinaja, Laguna Juan Garcia, may be fed by a natural (groundwater) seep (National Park Service 2006b). Tinajas provide habitats for some aquatic invertebrates and breeding pools for amphibians. Humans are known to have enhanced the natural tinajas for use in watering livestock (National Park Service 2006b). Some of the "stock tanks" are cultural features dating back to the 1200s and 1300s (Dana Sullivan, chief ranger, and Dave Hays, resource manager, El Malpais NM and El Morro NM, conference call, 9 December 2011).

Figure 32. Tinaja. Potholes called tinajas formed at Sandstone Bluffs Overlook. The pools are ephemeral and fill with rainwater during monsoonal thunderstorms. U.S. Geological Survey photograph, available at http://3dparks.wr.usgs.gov/elma/html2/elma0074.htm (accessed 4 May 2012).

Other water-related features at El Malpais National Monument are small playas that develop along the edges of lava flows. These small ephemeral lakes and associated livestock ponds are present in the southern part of El Malpais (Lightfoot 1997). When water is present, the playas provide important habitat to aquatic insects, crustaceans, amphibians, and water birds (Lightfoot 1997). When the ponds dry out partially or completely, the mud flats provide important habitats for many insects and songbirds (Lightfoot 1997). The temporary water and mud flats also provide habitat to several species of aquatic birds and shorebirds that otherwise would not occur at El Malpais, such as great blue (*Ardea herodias*) and green-backed (*Butorides striatus*) herons, white-faced ibis (*Plegadis chihi*), green-winged teal (*Anas crecca*) and northern pintail (*A. acuta*) ducks, and killdeer (*Charadrius vociferus*) and mountain (*C. montanus*) plovers. Most of these species are migrants that stop to forage on their way to or from breeding grounds (Lightfoot 1997).

Eolian Habitats

Sand dunes and sandy areas are common on the east side of El Malpais. Although a few eolian deposits (Qe) are mapped within the national monument, the majority are mapped just east of its boundary. Sand habitats are best developed between the McCartys flow and the bases of sandstone bluffs from Sandstone Bluffs Overlook to North Pasture (Lightfoot 1997). The soil mounds of pocket gophers (*Thomomys bottae* and *T. talpoides*) are evidence that these species inhabit these deposits (Lightfoot 1997).

Soil Crusts

Interpretive materials for El Malpais National Monument warn visitors about accidentally stepping on soil crusts, which can wipe out hundreds of years of growth and promote erosion (National Park Service 2004b). Soil crusts appear as knobby, black, ground coverings. A distinctive feature related to both biologic and geologic resources, they are composed of loess and weathered rocks, as well as cyanobacteria, lichens, and mosses. They are an important and widespread component of the ecosystem, benefiting soil quality in the following ways: increasing water infiltration, stabilizing soils, fixing atmospheric nitrogen for vascular plants, providing carbon to the interspaces between vegetation, secreting metals that stimulate plant growth, capturing nutrient-carrying dust, and increasing soil temperatures by decreasing surface albedo (KellerLynn 2005).

Paleontological Resources

Tweet et al. (2009) completed a paleontological resource inventory and monitoring report for the Southern Colorado Plateau Network, including El Malpais National Monument. No field-based inventory of these units has been conducted to date (Dana Sullivan, chief ranger, and Dave Hays, resource manager, El Malpais NM and El Morro NM, conference call, 9 December 2011).

The most noteworthy type of paleontological resource at El Malpais National Monument is tree molds, such as those on the surface of the Bandera flows. Tree molds form when a lava flow engulfs a forest or individual tree in its path. The tree begins to burn, but releases water and other vapors that sufficiently cool the surrounding lava, leaving an imprint of the tree in the hardening basalt. A vertical tree mold develops when lava surrounds a standing tree; a horizontal mold develops when an erect tree falls onto the surface of a flow. Both types of mold are preserved at El Malpais National Monument (fig. 33).

Investigators have begun to document these features within the national monument, and have identified four localities on the Bandera flows where they are present (Dana Sullivan, chief ranger, and Dave Hays, resource manager, El Malpais NM and El Morro NM, conference call, 9 December 2011). Tree molds are known from other National Park System units, including Craters of the Moon National Monument and Preserve in Idaho, Lava Beds National Monument in California, Puuhonua o Honaunau National Historical Park in Hawaii (Thornberry-Ehrlich 2011b), and Hawaii Volcanoes National Park in Hawaii (Thornberry-Ehrlich 2009).

Quaternary plant debris, packrat middens, and bones occur in lava tubes (Tweet et al. 2009). Bighorn sheep (*Ovis canadensis*) remains occur within Braided Cave (Ken Mabery, superintendent, Scotts Bluff NM, conference call, 16 March 2006); all that is known about the age of these remains is that they predate the 1950s. Native peoples may have used the lava tubes as traps, similar to the use of "buffalo jumps," in this case to corner bighorn sheep during hunts (Dana Sullivan, chief ranger, and Dave Hays, resource manager, El Malpais NM and El Morro NM, conference call, 9 December 2011).

The Quaternary sedimentary rocks and deposits at El Malpais National Monument include eolian deposits (Qe), alluvium (Qal), terrace gravels (Qtg), and colluvium (Qac). To date, only ancient wood has been reported from these deposits (Tweet et al. 2009). The national monument has a lengthy tree-ring record dating back to 136 BCE. (Poore et al. 2005; Stahle 2008), making the monument's resources useful for climate studies (see "Lava-Flow Habitat" section). Quaternary vertebrate fossils have not been reported from these deposits within the national monument, but fossils of proboscideans, equids, ground sloths, camels, llamas, beaver, musk oxen, and bison are known from nearby locations (Morgan and Lucas 2003, 2005). Invertebrate fossils from these nearby deposits include terrestrial gastropods, freshwater bivalves, gastropods, and ostracodes (Drakos et al. 2003). Several references list New Mexico's Quaternary fossils, including Harris (1993) and Morgan and Lucas (2000, 2003, 2005).

Paleontological resources are also known from "middle-aged" rocks at El Malpais National Monument, including the San Andres Limestone (Psa), Oak Canyon Member of the Dakota Sandstone (part of Kdo), Twowells Tongue of the Dakota Sandstone (Kdt), and Tres Hermanos Sandstone (Kth). Fossils in these units are primarily marine invertebrates. These units crop out as sandstone bluffs and limestone kipukas within the national monument.

Although the following units, which Maxwell (1986) mapped within El Malpais National Monument, have not yet yielded fossils within the national monument's boundaries, exposures of these formations outside of the national monument are known to contain fossils. Hence, future field investigations within the national monument could lead to the recovery of fossils from one or more of the following units: Abo Formation (Pa), Yeso Formation (Py), Glorieta Sandstone (Pg), Entrada Sandstone (Je), Zuni Sandstone (Jz), Clay Mesa Tongue of Mancos Shale and lower part of Dakota Sandstone (Kbo) (in addition to the Oak Canyon Member of the Dakota Sandstone, which is known to be fossiliferous within the national monument), and Paguate Tongue of Dakota Sandstone (Kdp).

Figure 33. Tree molds. Horizontal (left) and vertical (right) tree molds are notable fossils at El Malpais National Monument. Horizontal molds form when a tree falls onto the surface of a lava flow, and vertical molds form when a tree remains standing. In both cases, the tree began to burn, but released water and other vapors that sufficiently cooled the surrounding lava, leaving an imprint of the tree in the hardening basalt. Photographs by Larry Crumpler (New Mexico Museum of Natural History and Science).

Sandstone Features

The official map and guide for El Malpais National Monument describes the landscape as an area "where sharp lava meets smooth sandstone" (National Park Service 2003b). This juxtaposition of rock types is particularly notable and picturesque at Sandstone Bluffs Overlook (see cover photograph and figs. 34 and 35).

Within the national monument, two sandstone units stand out—the Jurassic Zuni Sandstone (Jz) and the Cretaceous Dakota Sandstone (Kdo). These units were deposited under very different environmental conditions. The sand grains that compose the Zuni Sandstone were transported across a vast desert and deposited as sand dunes about 160 million years ago. The Dakota Sandstone represents the initial advance of the Western Interior Seaway into New Mexico about 96 million years ago. The ridgetop at Sandstone Bluffs Overlook is composed of Dakota Sandstone. From this perch, visitors can gaze across the valley, taking in a sweeping panoramic view of the cinder cones of the Zuni–Bandera volcanic field and Mount Taylor, which rises 3,445 m (11,302 ft) above sea level, in the distance (Crumpler et al. 2003). Mount Taylor is a truncated conical composite volcano with an estimated original height of 3,960–4,270 m (13,000–14,000 ft) above sea level (Crumpler 2010).

Several lava flows are encompassed within the field of view at Sandstone Bluffs Overlook, including flows with sources at Hoya de Cibola (Qvw), Bandera Crater (Qcb), Twin Craters (Qct), and El Calderon (Qcc) (Crumpler et al. 2003). The darker flow nearest to the base of the sandstone cliffs is the McCartys flow (Qbm).

Features of the Zuni Sandstone include La Vieja ("the Old Woman") (fig. 36) and hoodoos (fig. 37). Both occur along Highway 117. La Ventana Natural Arch, located in the El Malpais National Conservation Area adjacent to the national monument and identified on the park map (fig. 1), developed in Zuni Sandstone (fig. 38). The arch is visible from the road and accessible via a short trail from the parking area on Highway 117.

Figure 34. Sandstone and lava. The contrast between light-colored sandstone and dark-colored basalt figures prominently in the El Malpais landscape. At Sandstone Bluffs Overlook, the dark lava of the McCartys flow (Qbm) and the light-colored Dakota Sandstone (Kdo) bluff are juxtaposed. Photograph by Katie KellerLynn (Colorado State University).

Figure 35. Sandstone Bluffs Overlook. Looking north from the Sandstone Bluffs Overlook, Mount Taylor looms in the distance. Part of the Mount Taylor volcanic field, the peak has an elevation of 3,445 m (11,301 ft) and formed during the same eruptive period that generated the Cebollita Mesa east of El Malpais National Monument, between 3.73 million and 1.57 million years ago. The Sandstone Bluffs consist of gently dipping Jurassic and Cretaceous sandstone that crops out along the eastern flank of the Cebollita Mesa on the eastern margin of the national monument. Forests partly mask the dark Quaternary lava flows in the valley. U.S. Geological Survey photograph, available at: http://3dparks.wr.usgs.gov/elma/html2/elma0012.htm (accessed 4 May 2012).

Figure 36. La Vieja. Along the eastern side of El Malpais National Monument, the Highway-17 corridor passes many picturesque sandstone features, including La Vieja—"the Old Woman"—eroded from Zuni Sandstone. National Park Service photograph.

Figure 37. Sandstone spires. Erosion of Zuni Sandstone created spires near Sandstone Bluffs Overlook. Some develop into pedestals with overhanging rock called "hoodoos." National Park Service photograph.

Figure 38. La Ventana Natural Arch. Adjacent to El Malpais National Monument, El Malpais National Conservation Area (administered by the Bureau of Land Management) contains La Ventana Natural Arch, which spans 41 m (135 ft). The arch is composed of Jurassic Zuni Sandstone that formed as part of a vast desert 160 million years ago. Aerial photograph by Larry Crumpler (New Mexico Museum of Natural History and Science). Inset is U.S. Geological Survey photograph, available at http://3dparks.wr.usgs.gov/elma/html2/elma0030.htm (accessed 4 May 2012).

Geologic History

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

For simplicity, and to gain a general understanding of the geologic history of El Malpais National Monument, the rocks in the area can be divided (fig. 39) into three main types: (1) very old metamorphic and igneous rocks of Precambrian age (approximately 1.4 billion years old); (2) sedimentary rocks of Permian, Triassic, Jurassic, and Cretaceous ages (299 million–65.5 million years old); and (3) young volcanic rocks, most of which erupted in the past 700,000 years. A fourth type includes unconsolidated deposits of Pleistocene or Holocene age (<2.6 million years old), including alluvium, colluvium, landslide deposits, and windblown sand and silt.

The Precambrian rocks record a complex geologic history that involved the assembly and stabilization of fragments of oceanic and continental crust, called terranes, onto the North American continent (Strickland et al. 2003; Karlstrom et al. 2004). The process of adding fragments of crust to a preexisting continent is called accretion. These ancient rocks can be seen in the El Calderon area north of Highway 53.

The “middle-aged” sedimentary rocks make up the distinctive gray, buff, and yellow ridges and cliffs that flank the national monument. These sediments accumulated over millions of years as shallow seas invaded and withdrew from the area. Some of these rocks formed in deep marine waters, some along shorelines and beaches, and some in rivers or other distributary channels leading to the sea. During terrestrial periods, when the ocean retreated, sediments were deposited in deserts and river valleys. These rocks are well displayed at the Sandstone Bluffs Overlook.

Young rocks representing Pleistocene and Holocene volcanism dominate the landscape at El Malpais National Monument. The Zuni-Acoma Trail provides a good opportunity to view and compare lava flows of different ages (Dunbar 2010). From east to west, hikers first encounter the McCartys flow (map unit symbol Qbm), which is about 3,900 years old, then the 11,000-year-old Bandera flows (Qbb), followed by the Twin Craters flows (Qbt), which are about 18,000 years old. The trail ends on the El Calderon flows (Qbc), which are less than 60,000 years old.

Precambrian Crystalline Rocks

Immediately north of El Malpais National Monument, Maxwell (1986) mapped a variety of Precambrian rocks, including schist (PCsc), gneisses (PCig, PChg, and PCmg), quartzite (PCqt), granites (PCgg, PCag, and PCpg), aplites (PCap and PCpa), and hornblende, gabbro, and intrusive basalt (PChb). Precambrian rocks in the southwestern United States, such as those exposed in the Zuni Mountains, record the accretion of comparatively young terranes onto an older (Archean and Proterozoic) craton (Strickland et al. 2003) (fig. 40). Shear zones in the rocks record periodic deformation, and dikes record subsequent magmatism (Strickland et al. 2003).

Strickland et al. (2003) proposed that the Jemez lineament is a tectonic boundary between two accreted Proterozoic terranes. The long-lived tectonic and magmatic history recorded within the Zuni Mountains is evidence that the Jemez lineament is a crustal-scale zone of weakness consistent with episodic reactivation of an accretionary boundary (Strickland et al. 2003). The Zuni Mountains on the southern edge of the Jemez lineament show evidence of repeated deformation and magmatism from Proterozoic through Cenozoic times (Strickland et al. 2003).

Sedimentary Rocks

The sedimentary rocks of El Malpais National Monument were deposited during the Permian, Triassic, Jurassic, and Cretaceous periods. These time periods span about 233 million years, from 299 million to 65.5 million years ago. Maxwell (1986) mapped rocks dating to all of these periods in the vicinity of the national monument.

Permian Period

Most of the Permian Period (299 million–251 million years ago) was characterized by marine conditions near El Malpais. However, uplift in northern New Mexico, southern Colorado, and southeastern Utah during the earliest part of this period produced a huge apron of continental sand, gravel, silt, and mud. Streams distributed these sediments southward across central New Mexico. The terrestrial Abo Formation (Pa) records this deposition of clastic material.

The Yeso Formation (Py), which overlies and thus is younger than the Abo Formation (Pa), is made up of several distinct beds of rocks that suggest a north–south transition from continental to marine conditions. The deposits include cross-stratified and horizontally stratified sandstones of eolian dune and sand-sheet origin, wavy-bedded sandstones formed in sand-dominated sabkhas, gypsiferous rocks formed in coastal sabkhas and hypersaline lagoons, ripple-laminated sandstones originating in coastal-plain and tidal settings, and carbonate rocks formed in coastal sabkha, restricted-marine, and marine-shelf environments (Stanesco 1991). On a smaller scale, vertical repetition of sediments at intervals of 1–8 m (3.3–26 ft) within the Yeso Formation (Py) indicates cyclic deposition

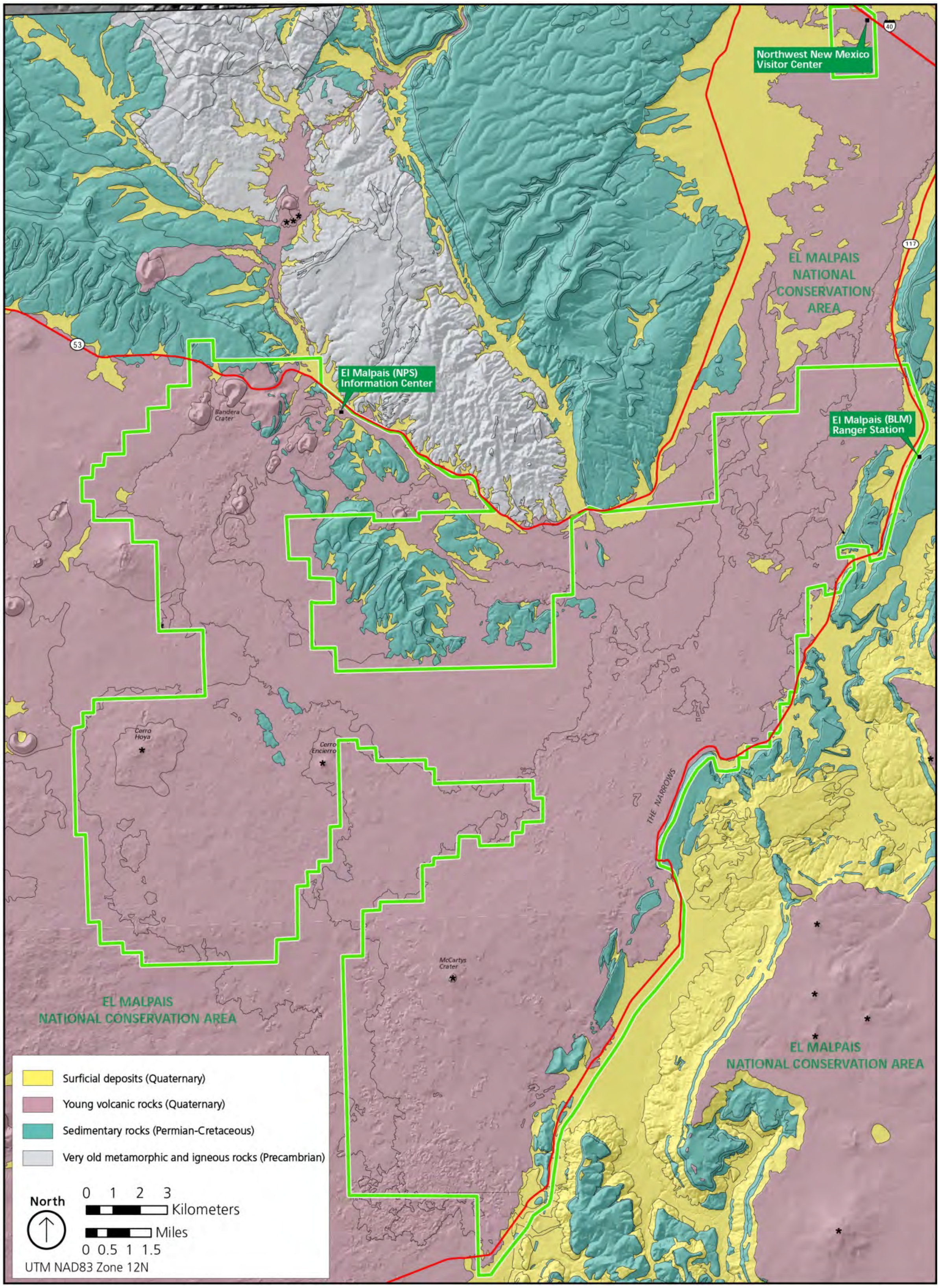

Figure 39. El Malpais rock types. The rocks in the El Malpais area can be divided into three main types: (1) very old (Precambrian) metamorphic and igneous rocks, (2) sedimentary rocks of Permian, Triassic, Jurassic, and Cretaceous ages, and (3) young volcanic rocks of mostly Quaternary age. A fourth set of geologic materials includes unconsolidated alluvium, colluvium, landslide deposits, and windblown sand and silt of Quaternary age. Map by Jason Kenworthy (NPS Geologic Resources Division) using compiled GRI digital geologic map data.

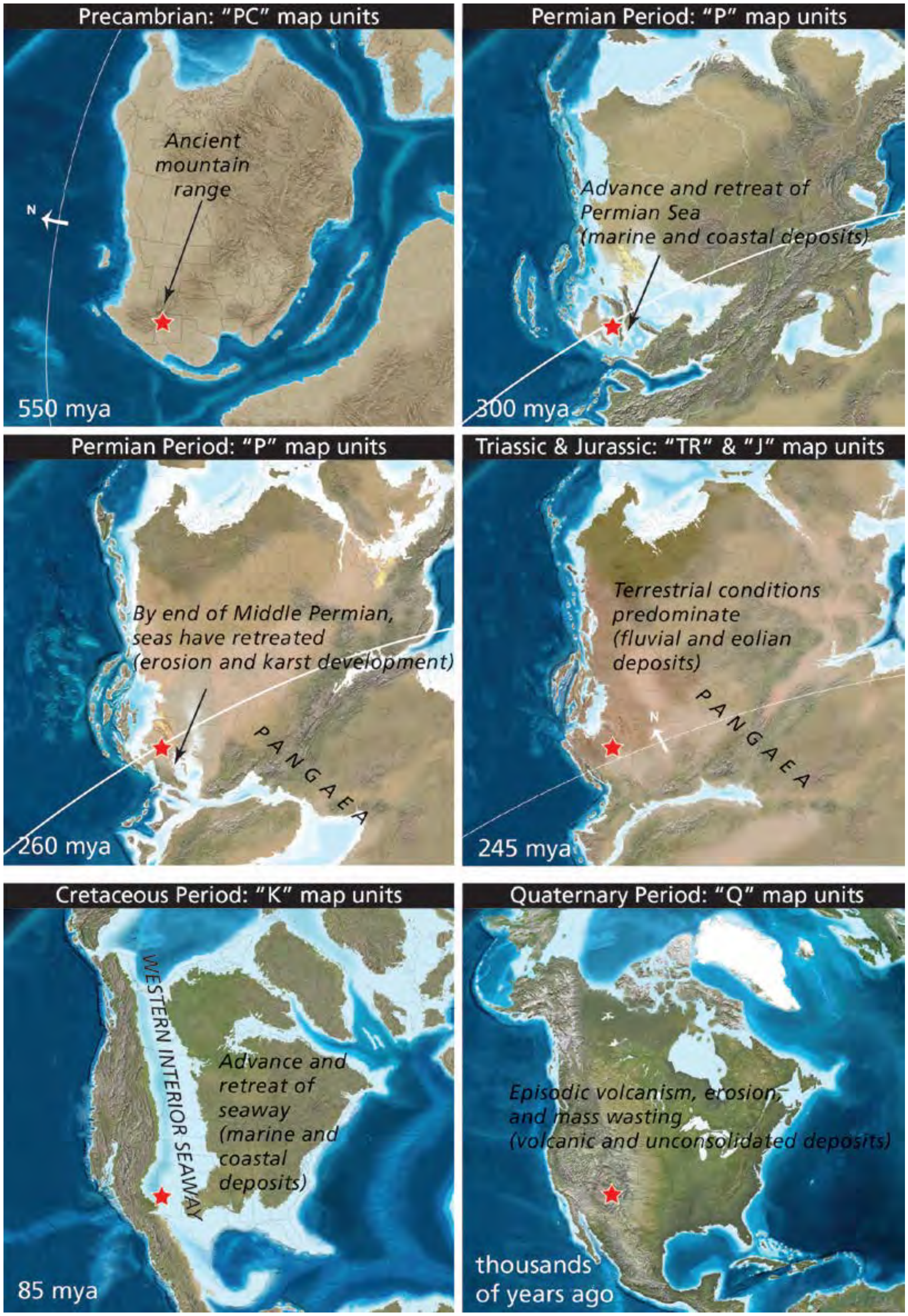

Figure 40. Paleogeographic maps for El Malpais National Monument. The images of land that became North America represent all major geologic eras—Archean and Proterozoic (combined and commonly called Precambrian), Paleozoic (Permian), Mesozoic (Triassic, Jurassic, and Cretaceous), and Cenozoic (Quaternary). The geologic history of El Malpais National Monument encompasses the formation of an ancient mountain or rift system during the Precambrian, repeated inundation by seas during the Paleozoic and Mesozoic eras, uplifting of mountains and shedding of sediments into basins during the Mesozoic and Cenozoic eras, and crustal extension (pulling apart of Earth's crust) and volcanism during the Cenozoic Era. Red stars show the approximate location of land that is now El Malpais National Monument during various points in geologic time. White lines represent the approximate location of the equator. "mya" = million years ago. Map units refer to those on the geologic map by Maxwell (1977, 1986). Graphic compiled by Jason Kenworthy (NPS Geologic Resources Division) based on paleogeographic maps created by Ron Blakey (Colorado Plateau Geosystems, Inc.), available at http://cpgeosystems.com/index.html (accessed 25 January 2012).

(Stanesco 1991). The cycles are initiated by a layer of limestone with a sharp lower contact, which probably indicates rapid marine transgression when the ocean spread across the land surface (Blakey and Middleton 1983). The cycles coarsen upward, indicating regression (fall in sea level/advance in shoreline) of a retreating sea, as well as representing the lateral migration of eolian sand-sheet and dune strata over supratidal mud-flat and coastal sabkha deposits (Stanesco 1991).

The contact between the Yeso Formation (Py) and the overlying Glorieta Sandstone (Pg) represents the slow migration of a shoreline, transitioning from the coastal sabkha of the Yeso Formation to a marginal marine setting. The Glorieta Sandstone preserves widespread beach deposits of clean quartz sand, crossed by meandering streams flowing southward toward the ocean (Rawling 2010). The Glorieta Sandstone was deposited in streams and windblown dunes on the margin of a Permian sea between 268 million and 245 million years ago (Rawling 2010).

The San Andres Limestone (Psa) overlies the Glorieta Sandstone (Pg). The fossil content and dolomitization of the limestone indicate that the depositional environment was a warm, shallow, saline sea with abundant marine life. This unit was deposited along the bottom of a shallow epicontinental seaway that covered much of New Mexico (McLemore 2010). At the end of the middle Permian Period (approximately 260 million years ago), the seas retreated and erosion occurred. During this period of exposure, karst features such as sinkholes, caves, and underground drainages formed in the limestone. However, Maxwell (1986) did not describe any such features in the San Andres Limestone near El Malpais National Monument.

Triassic and Jurassic Periods

The ocean retreated from northwestern New Mexico near the end of the Permian Period, and the area was above sea level during Triassic and Jurassic times (251 million–145 million years ago) (Kelley 2010). The Triassic fluvial Moenkopi and Chinle formations (TRcm) rest unconformably atop the San Andres Formation (Psa) (fig. 4). Jurassic rocks include the eolian Entrada Sandstone (Je); the Todilto Limestone Member of the Wanakah Formation (Jt), which was deposited in saline waters; the eolian Zuni Sandstone and Wanakah Formation (Jz); and the fluvial Morrison Formation (Jm). Some of the most famous rock formations in the western United States were deposited during the Triassic and Jurassic periods. These include the Triassic Chinle Formation (part of Maxwell's TRcm), which is known for its petrified wood and is particularly well exposed at Petrified Forest National Park in Arizona (KellerLynn 2010). The Jurassic Morrison Formation (Jm) is known for its dinosaur bones and is the source of the spectacular fossil discoveries within Dinosaur National Monument in Colorado and Utah (Graham 2006).

Cretaceous Period

An extensive seaway called the Western Interior Seaway characterizes the Cretaceous Period (145 million–65.5 million years ago) in the western United States. The Western Interior Seaway extended from the Arctic to the tropics, covering the entire west-central part of the North American continent. This sea left thick deposits of shale, siltstone, and sandstone. In the vicinity of El Malpais National Monument, Maxwell (1986) mapped the following Cretaceous rocks: Dakota Sandstone (Kdo, Kdp, and Kdt), Mancos Shale (Kdo, Kmd, Kmr, and Kmw), Tres Hermanos Sandstone (Kth), Gallup Sandstone (Kg), and Crevasse Canyon Formation (Kcc). North of El Malpais National Monument in the McCartys quadrangle, Maxwell (1977) mapped other members and tongues of the Dakota Sandstone (Kdc and Kds), Mancos Shale (Km, Kmm, Kmwc, and Kmc), Gallup Sandstone (Kgm, Kgu, and Kgl), and Crevasse Canyon Formation (Kcg, Kcd, Kcs, and Kcdi) (see Map Unit Properties Table). These strata record the 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 global changes in sea level (Hunt and Kelley 2010). Subsidence of basins facilitated the deposition of an extremely thick sequence of sediments. At least 1,555 m (5,100 ft) of relative sea-level rise or subsidence was necessary to accommodate the total Upper Cretaceous section in the southern Colorado Plateau and adjacent areas (Molenaar 1983).

Molenaar (1983) documented five major transgressive-regressive cycles that took place during the Upper Cretaceous Period in the southern Colorado Plateau and adjacent areas. Three of these are recorded in the rocks around El Malpais National Monument.

The Dakota Sandstone and lower part of the Mancos Shale were deposited during the first advance of the Western Interior Seaway (Hunt and Kelley 2010). Maxwell (1986) mapped various tongues of these units. Tongues extend outward beyond the main body of a formation, but are of limited extent and ultimately disappear laterally. Intertonguing of sediments is an indication of the migration of marine waters back and forth across an area. The Paguate (Kdp) and Twowells (Kdt) tongues of the Dakota Sandstone record a minor regression within an overall transgression, or perhaps a stillstand in shoreline when sand was spread over the shallow continental shelf (Molenaar 1983). Separating these tongues of the Dakota Sandstone are the Clay Mesa (part of unit Kdo) and Whitewater Arroyo (Kmw) tongues of the Mancos Shale, which also record transgression.

Notably, Maxwell (1986) described the Dakota Sandstone as being locally disturbed by trails and burrows. These sediments were intensely bioturbated by marine organisms living in shallow waters along the shores of the Western Interior Seaway (Hunt and Kelley 2010). In addition, Maxwell (1986) documented carbonaceous material and conglomerate within the

Dakota Sandstone, which indicate deposition in swamps and rivers. Organic-rich carbonaceous (or "coaly") material accumulated in swamps, whereas gravel consolidated into conglomerate in stream channels. These nonmarine deposits were associated with lakes, rivers, and levees within coastal areas. Regression of the initial advance of the Western Interior Seaway is recorded by the upper part of the Rio Salado Tongue of the Mancos Shale (Kmr) and the Tres Hermanos Sandstone (Kth) (Molenaar 1983).

The second major advance of the Western Interior Seaway is represented by the upper part of the Tres Hermanos Sandstone (Kth) and the D-Cross Tongues of the Mancos Shale (Kmd). The associated regression of this cycle is preserved only in rocks in New Mexico and adjacent northeastern Arizona. Widespread beach deposits of the Gallup Sandstone (Kg) document this retreat. In addition, the upper part of the D-Cross Tongue (Kmd) and lower part of the Crevasse Canyon Formation (Kcc) were deposited during this regression.

The last transgression recorded in the El Malpais area is the third advance of the Western Interior Seaway. The Gibson Coal and Dalton Sandstone members of the Crevasse Canyon Formation (Kcc) record this advance.

By the end of the Cretaceous Period, the western margin of North America was tectonically active. Oceanic crust was being subducted under North America, and active tectonism provided the compressional forces that caused the uplift of the Rocky Mountains. This mountain-building event is known as the Laramide Orogeny. Mountain building and uplift brought Precambrian rocks, such as those in the Zuni Mountains north of El Malpais National Monument, to the surface and ultimately displaced the Western Interior Seaway (Smith and Siegel 2000). Waters withdrew to the northeast.

Volcanic Rocks

Mount Taylor, which is a distinctive landmark in the El Malpais viewshed, marks the beginning of volcanic activity in the El Malpais region (fig. 41). Basalt flows from this period of volcanism cap the mesas to the east of the national monument (fig. 1). Maxwell (1986) mapped basalt flows on Cebollita Mesa, Mesa Negra, and Horace Mesa (Tb; fig. 14). This volcanic activity is not related to the Zuni–Bandera volcanic field. The Mount Taylor eruptions predate Zuni–Bandera eruptions, including the El Malpais event.

Figure 41. Mount Taylor and the McCartys lava flow. Mount Taylor, in the background, represents the beginning of volcanic activity in the El Malpais region. The McCartys lava flow, in the foreground, represents the most recent activity in the region and the youngest lava flow within the state of New Mexico. Photograph by Larry Crumpler (New Mexico Museum of Natural History and Science).

Three episodes of volcanism have occurred within the Zuni–Bandera volcanic field (Laughlin et al. 1993b), creating the landscape of El Malpais. The first episode of volcanic activity occurred about 700,000 years ago. Maxwell (1986) mapped the deposits of this event as old basalt flows (Qb), which are deeply weathered and largely covered by soil and alluvium (Qac). The old basalt flows underlie the area west of the national monument and Hole-in-the-Wall kipuka (fig. 16).

The second pulse of lava erupted about 150,000 years ago and is represented by the Chain of Craters (fig. 16). Maxwell (1986) mapped these deposits as basalt flows (Qbu), volcanic debris (Qv), and cinder cones (Qc). Although the first and second pulses of volcanic activity within the Zuni–Bandera volcanic field are part of the El Malpais landscape, generally they are not considered part of "the Malpais flows" (Maxwell 1986). The main El Malpais event occurred less than 60,000 years ago (table 1). It is the youngest pulse of volcanic activity within the Zuni–Bandera volcanic field and is represented by most of the vents within El Malpais National Monument (Laughlin et al. 1993b). This event is represented by the following units mapped by Maxwell (1986): El Calderon (Qbc, Qcc, and Qvc), Twin Craters (Qbt, Qct, and Qvt), Oso Ridge (Qbo and Qvo), Zuni (Qbz), Paxton Springs (Qbp, Qcp, and Qvp), Hoya de Cibola (Qbw and Qvw), Bandera (Qbb, Qcb, and Qvb), and McCartys (Qbm and Qcm). Maxwell (1977) mapped the McCartys flow as unit Qbd and the Zuni flows as unit Qba in the McCartys quadrangle north of El Malpais National Monument. Interestingly, each of these eruptions was monogenetic (representing a single event), except for Paxton Springs, which was polygenetic. Since mapping by Maxwell (1986), investigators have determined that the Paxton Springs vents (Qcp) produced two separate eruptions, 5,000 years apart (Laughlin et al. 1994a) (see "Paxton Springs Flows" section and table 1). This is a very unusual characteristic for a cinder cone (Dunbar 2010)

Unconsolidated Deposits

The post-volcanic geologic narrative of El Malpais National Monument includes the deposition of alluvium (Qal); alluvium, colluvium, and soil (Qac); and landslide deposits (Ql) (Maxwell 1986). Also, Maxwell (1977) mapped terrace alluvium and gravel (Qtg) and colluvium of the McCartys Mesa (Qc). Many of these deposits formed during a previous wet period in the Pleistocene Epoch (2.6 million–11,700 years ago), which was followed by progressive changes in climate to present-day arid conditions (Maxwell 1986). During periods characterized by wetter climatic conditions, large amounts of water percolated through porous basalt and sandstones and soaked and weakened underlying shales, causing large blocks of basalt and sandstone to break away from mesa edges and slide down shale slopes. As precipitation lessened, landslides occurred less frequently and less alluvial material was carried away. Eventually, slides stabilized and the valleys were choked with alluvium that covered many of the lower slides and filled valleys to form broad, flat floors (Maxwell 1986). Flash flooding, characteristic of present-day arid conditions, produced deep gullies in the alluvium, exhuming some landslide blocks (Maxwell 1986). Eolian deposits (Qe) are characteristic of drier conditions and represent the Holocene Epoch (the last 11,700 years). Windblown dust is a primary agent in landscape evolution today, filling in the vesicles and cracks of lava flows and smoothing their surfaces.

Geologic Map Data

This section summarizes the geologic map data available for El Malpais National Monument. The Geologic Map Overview Graphic displays the geologic map data draped over a shaded relief image of the park and surrounding area. The foldout Map Unit Properties Table 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 3. Bedrock and surficial geologic map data are provided for El Malpais 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 Malpais National Monument. These source maps provided information for the "Geologic Issues," "Geologic Features and Processes," and "Geologic History" sections of this report.

Maxwell, C. H. 1977. Preliminary geologic map of the McCartys quadrangle, Valencia County, New Mexico (scale 1:24,000). Open-File Report OF-77-380. U.S. Geological Survey, Washington, D.C., USA.

Maxwell, C. H. 1986. Geologic map of El Malpais lava field and surrounding area, Cibola County, New Mexico (scale 1:62,500). Miscellaneous Investigations Series Map I-1595. 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 Malpais 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 Malpais 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 table 3)
- 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. Not all data layers may be represented in the Google Earth data.

Table 3. Geology data layers in the El Malpais National Monument GIS data

Data Layer	Maxwell source map	Data Layer Code	On Overview Graphic?	Google Earth Layer?
Geologic Attitude and Observation Points	1977, 1986	ATD	No	No
Mine Point Features	1986	MIN	No	No
Geologic Point Features	1986	GPF	No	No
Volcanic Point Features	1986	VPF	Yes	No
Volcanic Line Features	1986	VLF	Yes	Yes
Faults	1977, 1986	FLT	Yes	Yes
Linear Geologic Units (fluorite vein)	1986	GLN	No	Yes
Deformation Area Boundaries	1986	DEFA	No	Yes
Deformation Areas	1986	DEF	No	Yes
Geologic Contacts	1977, 1986	GLGA	Yes	Yes
Geologic Units	1977, 1986	GLG	Yes	Yes
Map Symbology	1977	SYM	No	No

Geologic Map Overview Graphic

The Geologic Map Overview Graphic (in pocket) displays the GRI digital geologic data draped over a shaded relief image of the park and surrounding area. For graphic clarity and legibility, not all GIS feature classes may be visible on the overview, as indicated in table 3. 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 park, 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 scales—1:62,500 for Maxwell (1986) and 1:24,000 for Maxwell (1977)—and U.S. National Map Accuracy Standards, geologic features represented here are within 32 m (105 ft) at map scale 1:62,500 and 12 m (40 ft) at map scale 1:24,000 (horizontally) 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.

absolute age. The geologic age of a fossil, rock, feature, or event in years; commonly refers to radiometrically determined ages.

accretion. The gradual addition of new land to old by the deposition of sediment or emplacement of landmasses onto the edge of a continent at a convergent margin.

alluvial fan. A fan-shaped deposit of sediment that accumulates where a hydraulically confined stream flows to a hydraulically unconfined area. Commonly out of a mountainous area into an area such as a valley or plain.

alluvium. Stream-deposited sediment.

aphanitic. Describes the texture of fine-grained igneous rocks where the different components are not distinguishable with the unaided eye.

aplite. A light-colored intrusive igneous rock characterized by a fine-grained texture. Emplaced at a relatively shallow depth beneath Earth's surface.

arc. See "volcanic arc" and "magmatic arc."

arkose. A sandstone with abundant 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").

backwasting. Wasting (gradual erosion) that causes a slope to retreat without changing its declivity (gradient).

barrier island. A long, low, narrow island formed by a ridge of sand that parallels the coast.

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

beach. A gently sloping shoreline covered with sediment, commonly formed by the action of waves and tides.

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.

bedset. A relatively continuous succession of beds bounded by surfaces (called bedset surfaces, or bedset boundaries) of erosion or non-deposition.

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

bioturbation. The reworking of sediment by organisms.

bomb. A pyroclast ejected while still viscous and shaped while in flight. Commonly greater than 64 mm (2.5 in.) in diameter and often hollow or vesicular inside.

breakdown (cave). The collapse of the ceiling or walls of a cave; also, the accumulation of debris thus formed.

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

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

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

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

carbonaceous. Describes a rock or sediment with considerable carbon content, especially organics, hydrocarbons, or coal.

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).

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

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

clast. An individual grain or rock fragment in a sedimentary rock, produced by the physical disintegration of a larger rock mass.

clastic. Describes rock or sediment made of fragments of pre-existing rocks (clasts).

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

claystone. Lithified clay having the texture and composition of shale but lacking shale's fine layering and fissility (characteristic splitting into thin layers).

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

colluvium. A general term for any loose, heterogeneous, and incoherent mass of soil material and/or rock fragments deposited through the action of surface runoff (rainwash, sheetwash) or slow continuous downslope creep.

concretion. A hard, compact aggregate of mineral matter, subspherical to irregular in shape; formed by precipitation from water solution around a nucleus such as shell or bone in a sedimentary or pyroclastic rock. Concretions are generally different in composition from the rocks in which they occur.

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

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

continental crust. Crustal rocks rich in silica and alumina that underlie the continents; ranging in thickness from 35 km (22 mi) to 60 km (37 mi) under mountain ranges.

continental shelf. The shallowly submerged part of a continental margin extending from the shoreline to the continental slope with water depths less than 200 m (660 ft).

cordillera. A Spanish term for an extensive mountain range; used in North America to refer to all of the western mountain ranges of the continent.

craton. The relatively old and geologically stable interior of a continent (also see "continental shield").

cross-stratification. Arrangement of strata inclined at an angle to the main stratification.

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").

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

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.

décollement. A large-displacement (kilometers to tens of kilometers), shallowly-dipping to sub-horizontal fault or shear zone.

deformation. A general term for the processes of faulting, folding, and shearing of rocks as a result of various Earth forces such as compression (pushing together) and extension (pulling apart).

delta. A sediment wedge deposited where a stream flows into a lake or sea.

delta plain. The level or nearly level surface composing the landward part of a large or compound delta; strictly, an alluvial plain characterized by repeated channel bifurcation and divergence, multiple distributary channels, and interdistributary flood basins.

dendrochronology. The study of annual growth rings of trees for dating of the recent past.

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

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

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

dune. A low mound or ridge of sediment, usually sand, deposited by wind. Common dune types include "barchan," "longitudinal," "parabolic," and "transverse" (see respective listings).

dune field. Extensive deposits on sand in an area where the supply is abundant. As a characteristic, individual dunes somewhat resemble barchans but are highly irregular in shape and crowded.

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

epicontinental. Describes a geologic feature situated on the continental shelf or on the continental interior. An "epicontinental sea" is one example.

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

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

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

foliation. A preferred arrangement of crystal planes in minerals. In metamorphic rocks, the term commonly refers to a parallel orientation of planar minerals such as micas.

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).

friable. Said of a rock or mineral that is easily crumbled, e.g., a poorly cemented sandstone.

gabbro. A group of dark-colored, intrusive igneous rocks. The intrusive equivalent of basalt.

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

gneiss. A foliated rock formed by regional metamorphism with alternating bands of dark and light minerals.

granite. An intrusive igneous (plutonic) rock composed primarily of quartz and feldspar. Mica and amphibole minerals are also common. Intrusive equivalent of rhyolite.

granodiorite. A group of intrusive igneous (plutonic) rocks containing quartz, plagioclase, and potassium feldspar minerals with biotite, hornblende, or, more rarely, pyroxene, as the mafic components.

groundmass. The material between the large crystals in a porphyritic igneous rock. Can also refer to the matrix of a sedimentary rock.

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

gypsiferous. Gypsum-bearing.

gypsum. The most common sulfate mineral (calcium sulfate). Frequently associated with halite and anhydrite in evaporites.

hoodoo. A pillar of rock developed by erosion of horizontal strata of varying hardness. Typically found in climatic zones where most rainfall is concentrated during a short period of the year.

hornito. A small mound of spatter built on the back of a lava flow, formed by the gradual accumulation of clots of lava ejected through an opening in the roof of an underlying lava tube.

hypersaline. Excessively saline; with salinity substantially greater than that of average seawater.

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

inflation. Process by which a local area of pahoehoe lava swells as a result of injection of lava beneath its surface crust.

isotopic age. An age expressed in years and calculated from the quantitative determination of radioactive elements and their decay products; "absolute age" and "radiometric age" are often used in place of isotopic age but are less precise terms.

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

lacustrine. Pertaining to, produced by, or inhabiting a lake or lakes.

lagoon. Typically, a narrow water body that is parallel to the shore and is between the mainland and a barrier and parallel to the shore. Little or no freshwater influx and limited tidal flux cause elevated salinities.

lamination. Very thin, parallel layers.

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.

lavacicle. A general term applied to nearly anything that protrudes into a lava tube.

levee. Raised ridge lining the banks of a stream. May be natural or artificial.

levee (speleology). A retaining wall of hardened lave along the side of a lava channel, built up incrementally by overflow, overthrusting of lava crusts of blocks, or spatter; also, the freestanding cooled edge of a lava tongue of flow left after evacuation of the molten lava.

lignite. A brownish-black coal that is intermediate in coalification between peat and subbituminous coal.

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

lineament. Any relatively straight surface feature that can be identified via observation, mapping, or remote sensing, often reflects crustal structure.

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

longitudinal dune. Dune elongated parallel to the direction of wind flow.

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

magmatic arc. Zone of plutons or volcanic rocks formed at a convergent boundary.

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.

metamorphic. Describes the process of metamorphism or its results. One of the three main classes of rocks—igneous, metamorphic, and sedimentary.

mud flat. A relatively level area of fine silt along a shore (as in a sheltered estuary) or around an island, alternately covered and uncovered by the tide, or covered by shallow water; a muddy tidal flat barren of vegetation.

mudflow (mass movement). A general term for a mass-movement landform and a process characterized by a flowing mass of predominantly fine-grained earth material possessing a high degree of fluidity during movement.

oceanic crust. Earth's crust formed at spreading ridges that underlies the ocean basins. Oceanic crust is 6 to 7 km (3 to 4 miles) thick and generally of basaltic composition.

orogeny. A mountain-building event.

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

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

plastic. Describes a material capable of being deformed permanently without rupture.

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

principle of superposition. The concept that sediments are deposited in layers, one atop another, i.e., the rocks on the bottom are oldest with the overlying rocks progressively younger toward the top.

pyroclast. An individual particle ejected during a volcanic eruption.

pyroclastic. Describes clastic rock material formed by volcanic explosion or aerial expulsion from a volcanic vent; also pertaining to rock texture of explosive origin. In the plural, the term is used as a noun.

radiometric age. An age expressed in years and calculated from the quantitative determination of radioactive elements and their decay products.

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

relative dating. Determining the chronological placement of rocks, events, or fossils with respect to the geologic time scale and without reference to their numerical age.

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.

sabkha. A coastal environment in an arid climate just above high tide. Characterized by evaporate minerals, tidal-flood, and eolian deposits. Common in the Persian Gulf.

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.

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

schist. A strongly foliated metamorphic rock that can be readily be split into thick flakes or slabs. Micas are arranged in parallel, imparting a distinctive sheen, or "schistosity" to the rock.

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

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

sedimentary 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.

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

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

shear zone. A zone of rock that has been crushed and brecciated by many parallel fractures due to shear strain.

shield volcano. A volcano in the shape of a flattened dome, broad and low, built by flows of very fluid basaltic lava. The Hawaiian Mauna Loa volcano is one example.

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.

sinkhole. A circular depression in a karst area with subterranean drainage and is commonly funnel-shaped.

slope. The inclined surface of any geomorphic feature or measurement thereof. Synonymous with "gradient."

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

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

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

spatter cone. A low, steep-sided cone of spatter built up on a fissure of vent, usually composed of basaltic material.

speleothem. Any secondary mineral deposit that forms in a cave.

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

squeeze-ups. A small extrusion of viscous lava, from a fracture or opening on the solidified surface of a flow, caused by pressure. It may be marked by vertical grooves.

stalactites. Calcite deposits that form as water drips from the roof of a cave.

stalagmites. Mounds of calcite that commonly form beneath stalactites from dripping water in a cave.

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

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

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

stratovolcano. A volcano that is constructed of alternating layers of lava and pyroclastic deposits, along with abundant dikes and sills.

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

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

subduction zone. A convergent plate boundary where oceanic lithosphere descends beneath a continental or oceanic plate and is carried down into the mantle.

subsidence. The gradual sinking or depression of part of Earth's surface.

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.

tephra. A collective term used for all pyroclastic material, regardless of size, shape, or origin, ejected during an explosive volcanic eruption.

terrane. A large region or group of rocks with similar geology, age, or structural style.

terrestrial. Relating to land, Earth, or its inhabitants.

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

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

trace fossil. Tracks, trails, burrows, coprolites (dung), etc., that preserve evidence of organisms' life activities, rather than the organisms themselves.

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

ultramafic. Describes rock composed chiefly of mafic (dark-colored, iron and magnesium rich) minerals.

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

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

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

vent. An opening at Earth's surface where volcanic materials emerge.

vesicle. A void in an igneous rock formed by a gas bubble trapped when the lava solidified.

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

vitric. Describes pyroclastic material that is characteristically glassy.

volcanic. Describes anything related to volcanoes. Can refer to igneous rock crystallized at or near Earth's surface (e.g., lava).

volcanic arc. A commonly curved, linear, zone of volcanoes above a subduction zone.

wash. A term used especially in the southwestern United States for the broad, gravelly dry bed of an intermittent stream, generally in the bottom of a canyon; it is occasionally swept by a torrent of water.

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

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

Literature Cited

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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 May 2012.

Geology of National Park Service Areas

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

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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 Malpais National Monument, held on 30 March 2006, or participated in the post-scoping conference call, held on 9 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
Tim Connors	NPS Geologic Resources Division	Geologist/GRI Maps
Kayci Cook Collins	El Malpais and El Morro national monuments	Superintendent
Nelia Dunbar	New Mexico Bureau of Geology and Mineral Resources	Geologist
Bruce Heise	NPS Geologic Resources Division	Geologist
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 (at time of scoping)	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 Malpais and El Morro national monuments	Chief Ranger

Participated in 16 March 2006 conference call only. Formerly with El Morro and El Malpais national monuments; with Scotts Bluff National Monument in 2012.

2011 Conference Call Participants

Name	Affiliation	Position
Tim Connors	NPS Geologic Resources Division	Geologist/GRI Maps
David Hays	El Malpais and El Morro national monuments	Resource Manager
Katie KellerLynn	Colorado State University	Geologist/Research Associate
Jason Kenworthy	NPS Geologic Resources Division	Geologist/GRI Reports
Dana Sullivan	El Malpais and El Morro national monuments	Chief Ranger

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

NPS 103/117008, September 2012

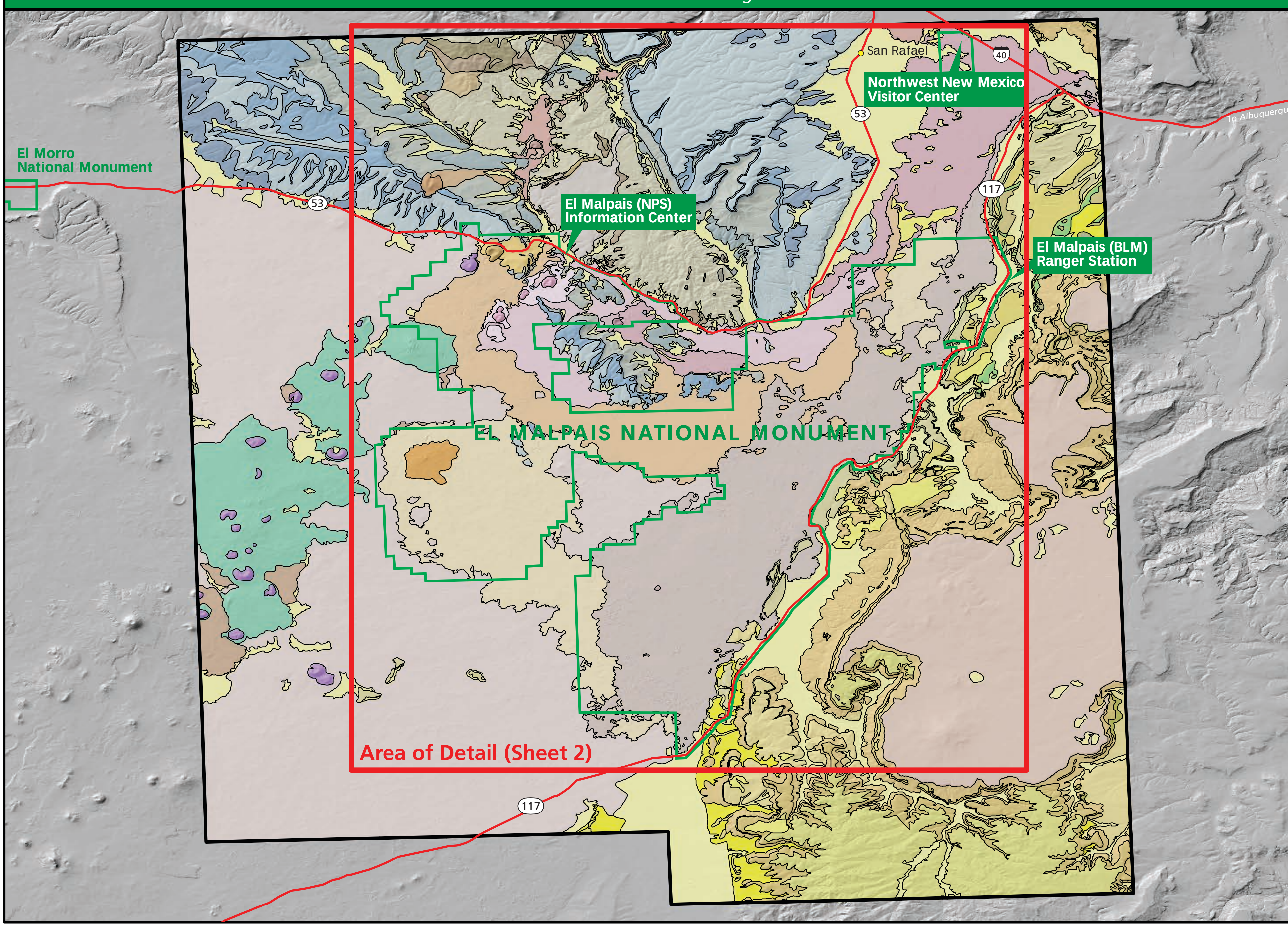
National Park Service
U.S. Department of the Interior

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

www.nature.nps.gov

Overview of Digital Geologic Data for El Malpais National Monument

Sheet 1: Full Extent of Digital Data



NPS Boundary

Infrastructure

- structures
- highways

Geologic Point Features

- ice caves

Volcanic Point Features

- lava cone

Volcanic Line Features

- crater, known or certain
- crest line of crater, known or certain
- lava tube, approximate

Faults

- unknown offset/displacement, known or certain
- unknown offset/displacement, approximate
- unknown offset/displacement, concealed
- unknown offset/displacement, queried
- unknown offset/displacement, inferred

Geologic Contacts

- known or certain
- approximate
- concealed
- queried
- map boundary

Geologic Units

Qe	Eolian deposits
Qal	Alluvium
Ql	Landslide deposits
Qac	Alluvium, colluvium, and soil
Qbm	McCartys flow
Qcm	McCartys cinder cone
Qbb	Bandera flows
Qcb	Bandera crater
Qvb	Bandera cinder field
Qbw	Hoya de Cibola flows
Qvw	Hoya de Cibola shield volcano
Qbp	Paxton Springs flows
Qcp	Paxton Springs crater
Qvp	Paxton Springs cinder field
Qbz	Zuni flows
Qbo	Oso Ridge flows
Qvo	Oso Ridge lava cone
Qbt	Twin Crater flows
Qct	Twin Crater cinder cones
Qvt	Twin Crater mixed pyroclastics and flows
Qbc	El Calderon flows
Qcc	El Calderon crater
Qvc	El Calderon cinder field
Qc	Cinder cones
Qv	Volcanic debris
Qbu	Basalt flows
Qb	Old basalt flows
Tb	Basalt flows on Cebollita Mesa, Mesa Negra, and Horace Mesa
Kcc	Crevasse Canyon Formation
Kg	Gallup Sandstone
Kmd	Mancos Shale, D-Cross Tongue
Kmr	Mancos Shale, Rio Salado Tongue
Kmw	Mancos Shale, Whitewater Arroyo Tongue
Kth	Tres Hermanos Sandstone
Kdt	Twowells Tongue of Dakota Sandstone
Kdp	Paguate Tongue of Dakota Sandstone
Kdo	Clay Mesa Tongue of Mancos Shale and Lower Part of Dakota Sandstone
Jm	Morrison Formation
Jz	Zuni Sandstone and Wanakah Formation
Jt	Todilto Limestone Member of Wanakah Formation
Je	Entrada Sandstone
TRcm	Chinle and Moenkopi (?) Formations
Psa	San Andres Limestone
Pg	Glorieta Sandstone
Py	Yeso Formation
Pa	Abo Formation
PChb	Hornblendite, gabbro, and intrusive basalt
PCpa	Porphyritic aplite
PCap	Gneissic aplite
PCpg	Porphyritic granite
PCag	Aplitic granite
PCgg	Gneissic granite
PCmg	Quartz monzonite gneiss
PCqt	Quartzite
PChg	Hornblende gneiss
PCig	Injection gneiss
PCsc	Biotite schist
sbz	Silicified breccia zone
f	Fluorite vein

0 2 4 6 8 Kilometers

0 2 4 6 8 Miles

North

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 1:62,500) and U.S. National Map Accuracy Standards, geologic features represented here are within 13 (24k) and 32 (62.5k) meters / 40 (24k) and 104 (62.5k) feet (horizontally) of their true location.

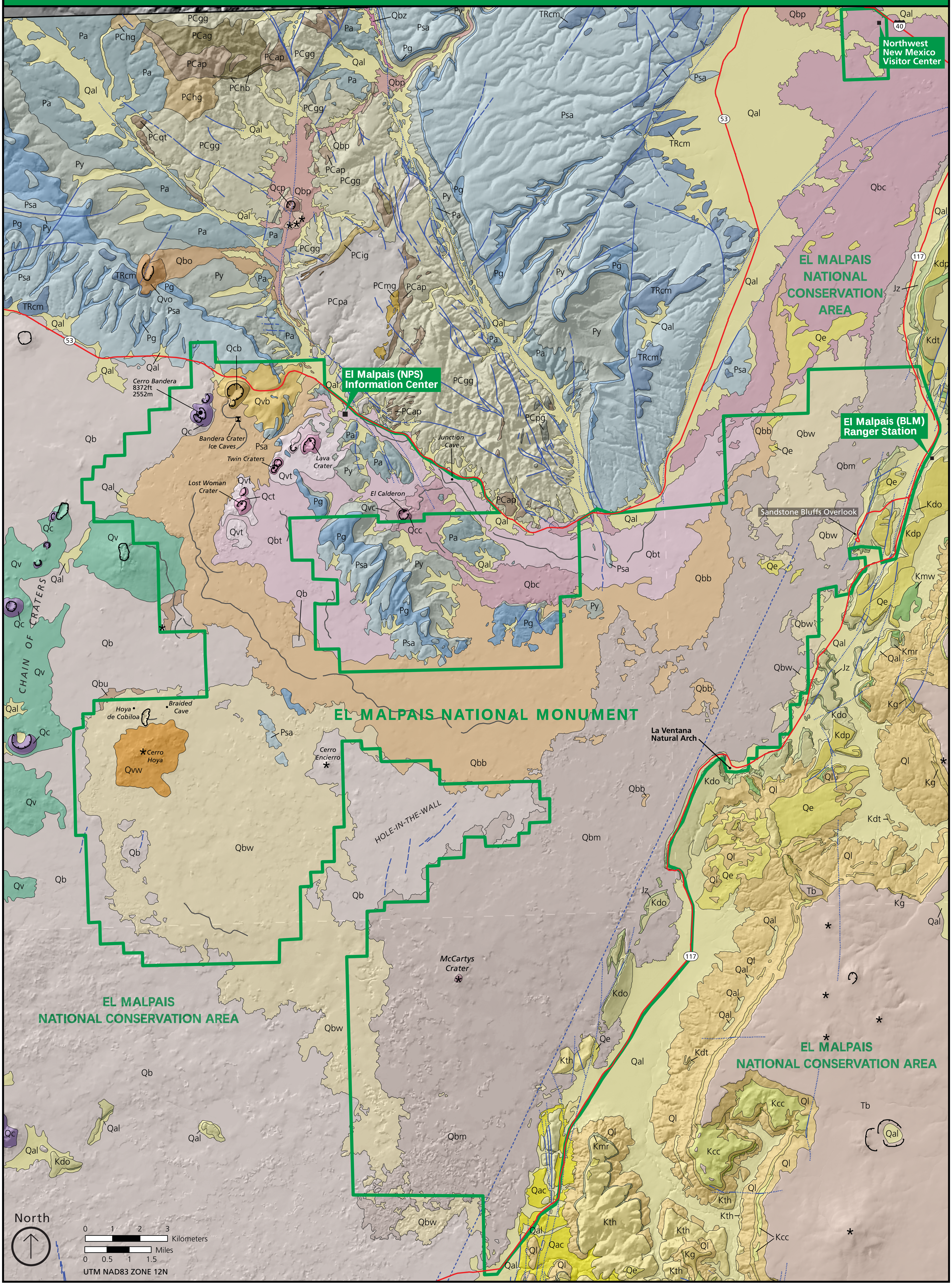
This figure was prepared as part of the NPS Geologic Resources Division's Geologic Resources Inventory. The source maps used in creation of the digital geologic data product were:

Maxwell, Charles H. 1986. Geologic Map of El Malpais Lava Field and Surrounding Area, Cibola County, New Mexico (1:62,500 scale). Miscellaneous Investigations Series Map I-1595. U.S. Geological Survey

Digital geologic data and cross sections for El Malpais 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 Malpais National Monument from the unit list.)

Overview of Digital Geologic Data for El Malpais National Monument

Sheet 2: Area of Detail



Map Unit Properties Table: El Malpais National Monument

Gray-shaded rows indicate units not mapped within El Malpais National Monument. Italicized text corresponds to report sections.

Age	Map Unit (Symbol)	Geologic Description	Geologic Issues	Geologic Features and Processes	Geologic History
QUATERNARY (Holocene)	Eolian deposits (Qe)	Recent accumulations of windblown silt and sand. Forms sand sheets, dune fields, longitudinal dunes, and smaller deposits.	*Erosion*—**Qe** is highly susceptible to erosion. Issue in the Sandstone Bluffs Overlook area. *Disturbed Lands*—**Qe** is easily disturbed by grazing. Channel diversions cut through **Qe**.	*Eolian Features and Processes*—significant for landscape evolution. Amount of "dust infilling" in lava flows provides a means of determining relative ages of lava flows. *Biologic and Geologic Connections*—eolian habitat (e.g., sand dunes). Inhabited by pocket gophers (*Thomomys bottae* and *T. talpoides*). *Paleontological Resources*—**Qe** may yield Quaternary fossils.	Maxwell (1986) mapped only the most prominent accumulations. Occur mostly to the east of El Malpais National Monument, but also on lava flows within the national monument. Characteristic of drier Holocene climatic conditions.
QUATERNARY (Holocene and Pleistocene)	Alluvium (Qal)	Mostly fine-grained, stream-deposited silt and sand. A few local lenses contain coarse sand or pebbles. As much as 15 m (50 ft) exposed in recent gullies. Includes some eolian (**Qe**) and colluvial (**Qac**) deposits.	*Mass Wasting*—landslides (**Ql**) are usually older than **Qal** that covers valley floors. *Flooding*—flash flooding produces deep gullies in **Qal**, exhuming some landslide blocks (**Ql**).	*Lava Flows*—depending on age, lava flows may cover or be covered by **Qal**. For example, McCartys flow (**Qbm**) overlies older alluvium. **Qal** covers El Calderon flows (**Qbc**) near vent. *Paleontological Resources*—**Qal** may yield Quaternary fossils.	Much of the alluvium on the valley floor today spread across during the Pleistocene wet period, but alluvium also includes material deposited during present-day flooding.
	Terrace alluvium and gravel (Qtg)	Composed largely of pebbles, cobbles, and boulders of volcanic and Precambrian rocks in a matrix of silt and sand.	Unknown.	*Paleontological Resources*—**Qtg** may yield Quaternary fossils.	Terraces represent previous floodplains that were active during the Pleistocene Epoch. Indicates erosion and transport of exposed Precambrian rocks in the Zuni Mountains.
	Landslide deposits (Ql)	Composed mostly of rotational-block slides of Tertiary basalt and Cretaceous sandstone and shale that have slid over soft shale units. Includes some rock slides and mudflows, and talus and fan accumulations, some of which are derived from outcrops and others from landslide debris.	*Mass Wasting*—extensive landslide deposits east of El Malpais National Monument. *Flooding*—**Ql** blocks become exposed during flash floods.	None reported.	Landslide deposits are generally older than alluvium (**Qal**) and formed during Pleistocene wet period, which was followed by progressive changes in climate to present-day arid conditions.
	Alluvium, colluvium, and soil (Qac)	Soil and alluvium. Locally covered by recent alluvium (**Qal**) and eolian deposits (**Qe**).	*Seismic Activity*—disturbed by recent faulting in southern part of the map area.	*Lava Flows*—**Qac** covers old basalt flows (**Qb**). *Paleontological Resources*—**Qac** may yield Quaternary fossils.	Started accumulating during Pleistocene wet period, but still being deposited. May be as young as Holocene eolian deposits (**Qe**).
	Colluvium of McCartys Mesa (Qc)	Mantling deposits composed largely of colluvial soil, caliche, terrace sand and gravel, alluvium, and windblown sand. Includes local small outcrops of Mancos Shale and Twowells Tongue. **Note**: "Qc" is used as the map symbol for both colluvium of McCartys Mesa (Maxwell 1977) and cinder cones (Maxwell 1986).	Unknown.	None reported.	Started accumulating during Pleistocene wet period, but still being deposited. Initial deposition of this colluvium predates deposition of landslide deposits (**Ql**).
	McCartys flow and cinder cone (Qbm and Qcm)	Flows (**Qbm**) and cinder cone (**Qcm**) are composed of basalt that is generally unweathered, uneroded, and relatively barren of vegetation. Contains plagioclase and olivine phenocrysts. Plagioclase phenocrysts predominant within 4 km (2.5 mi) of the crater. Olivine phenocrysts predominant in remainder of the flow. **Note**: Maxwell (1977) mapped the McCartys flow using map symbol **Qbd** in the McCartys quadrangle.	*Cave Management*—contains lava-tube caves. *Flooding*—flooding causes erosion between the sandstone bluffs and the McCartys flow. *Disturbed Lands*—military used **Qbm** as a bombing range and **Qcm** as a target. *Seismic Activity*—surface faults mapped by Maxwell (1986) have not been field verified. *Geochronology, Research, and Interpretation*—dated using ^{14}C, ^{3}He, and ^{36}Cl methods. Currently under study. Ideal field-trip location.	*Volcanic Features*—flows (notable pahoehoe) exhibit inflation pits and mounds, grooved lava, squeeze-ups and squeeze-outs, aa lava, ropes, and spatter cones. *Eolian Features and Processes*—mostly clean, silt-free surface. *Biologic and Geologic Connections*—**Qbm** and **Qcm** are part of lava-flow habitat/"mesic island." **Qbm** hosts "Pygmy Forest" and provides lava-tube habitat. Sand habitats are best developed between **Qbm** and bases of sandstone bluffs. **Qbm** forms one side of Hole-in-the-Wall kipuka. *Sandstone Features*—black basalt of **Qbm** contrasts with light-colored sandstone (**Jz** and **Kdo**) at Sandstone Bluffs Overlook.	Part of El Malpais event. Approximately 3,900 years old. Flow originated at a small cinder cone (**Qcm**). Some lava flowed to the south. More flowed to the north, extending to Rio San Jose, and eastward along Interstate 40.

Gray-shaded rows indicate units not mapped within El Malpais National Monument. Italicized text corresponds to report sections.

Age	Map Unit (Symbol)	Geologic Description	Geologic Issues	Geologic Features and Processes	Geologic History
QUATERNARY (Holocene and Pleistocene)	Bandera flows, crater, and cinder field (Qbb, Qcb, and Qvb)	Rock of flows (**Qbb**) and crater (**Qcb**) is similar to that of the McCartys flow (**Qbm**). Ultramafic inclusions in final tephra eruptions. Fine cinders of cinder field (**Qvb**) surround north, east, and west sides of crater (**Qcb**), and cover sedimentary rocks and older basalt flows.	*Cave Management*—contains extensive lava-tube system and ice caves. *Flooding*—near agricultural source area of pollutants that enter lava-tube system during flash floods. *Disturbed Lands*—past mining produced highly visible cinder quarry. *Geochronology, Research, and Interpretation*—dated using ^{14}C, ^{3}He, ^{36}Cl, and Ar-Ar methods. U-series dating of gypsum crusts in lava tubes. Currently under study. Ideal field-trip location.	*Volcanic Features*—lava flows (notable aa), crater, and cinder field. Ideal example of breached cinder cone; symmetrical and distinctive. Flows host spatter cones. *Lava Tubes*—hosts longest lava-tube system in El Malpais National Monument, in the continental United States. Contains xenoliths. *Ice Caves*—ice caves in flows, including privately owned/commercially operated Ice Caves. *Biologic and Geologic Connections*—part of lava-flow habitat/"mesic island." Hosts mixed-conifer woodlands. Provides lava-tube cave habitat. Notable lichen cover. **Qbb** forms one side of Hole-in-the-Wall kipuka. *Paleontological Resources*—tree molds.	Part of El Malpais event. Approximately 11,000 years old. **Qbb** originated at Bandera Crater (**Qcb**) adjacent to Highway 53.
	Hoya de Cibola flows and shield volcano (Qbw and Qvw)	Basalt of **Qbw** and **Qvw** is similar to that of the McCartys flow (**Qbm**) but slightly higher in Al_2O_3 and alkalis, and lower in MgO.	*Cave Management*—lava-tube caves (e.g., Braided Cave). *Geochronology, Research, and Interpretation*—dated using Ar-Ar method, but results seem "too old." Exact (absolute) age still under consideration.	*Volcanic Features*—lava flows and shield volcano. *Biologic and Geologic Connections*—part of lava-flow habitat/"mesic island." Hosts mixed-conifer woodlands. Provides lava-tube cave habitat. **Qbw** forms one side of Hole-in-the-Wall kipuka.	Part of El Malpais event. Dunbar and Phillips (2004) used map symbol "**Qh**" for Hoya de Cibola flows, and "**Qbw**" for Bluewater flows west of Grants, which were not mapped by Maxwell (1986). Western flows originated from Hoya de Cibola crater and shield volcano (**Qvw**) in western part of El Malpais National Monument. Lava flowed south, east, and probably northeast.
	Paxton Springs flows, crater, and cinder field (Qbp, Qcp, and Qvp)	Flows (**Qbp**), crater (**Qcp**), and cinder field (**Qvp**) composed of vesicular basalt. Contains olivine phenocrysts. Consists of volcanic material from two separate eruptions; the only polygenetic cinder cone vent known from the Zuni–Bandera volcanic field.	*Geochronology, Research, and Interpretation*—dated using ^{36}Cl method. Separated into northern flow (20,700 years old) and southern flow (15,000 years old) by Dunbar and Phillips (2004).	*Volcanic Features*—lava flows, crater, and cinder field. Cinder field (**Qvp**) includes three small cinder cones.	Originated from a volcanic center in the Precambrian core of the Zuni Mountains and flowed 3 km (2 mi) down Agua Fria Creek, and 27 km (17 mi) northeast down Zuni Canyon to the area between Grants and San Rafael.
	Zuni flows (Qbz)	Basalt flows. **Note**: Maxwell (1977) mapped the oldest Zuni basalt flow (**Qba**) in the McCartys quadrangle.	*Geochronology*—exact age unknown.	*Volcanic Features*—lava flows.	Lava flows from Zuni Mountains, north of El Malpais National Monument. Originated from volcanic centers about 1.7 km (1 mi) north of boundary.
	Oso Ridge flows and lava cone (Qbo and Qvo)	Basalt flows (**Qbo**) from Oso Ridge (northwest of Bandera Crater). Lava cone (**Qvo**) composed largely of breccia, welded pyroclastic debris, and glassy flows.	*Geochronology*—exact age unknown.	*Volcanic Features*—lava flows and cone.	Lava flows in the Zuni Mountains, north of El Malpais National Monument. Originated from a lava cone (**Qvo**) on Oso Ridge. Basalt flows (**Qbo**) extended eastward to Agua Fria Creek and southward almost to Malpais flows. Overlain by the Paxton Springs flows (**Qcb**).
	Twin Craters flows, cones, and mixed pyroclastics (Qbt, Qct, and Qvt)	Basalt flows (**Qbt**) from Twin Craters cinder cones (**Qct**). Mixed pyroclastics (**Qvt**) surround the cinder cones (**Qct**) and partially bury sedimentary rocks in the area. Flows (**Qbt**) originated from complex of cinder cones (**Qct**), which extends in northeast-trending line with Twin Craters at the approximate center of the line, Lost Woman center to southwest, and La Tetra center to northeast.	*Geochronology, Research, and Interpretation*—consists of several overlapping flows from different vents, which made them difficult to delineate for early investigators, including Maxwell (1986). Recently dated using ^{14}C, ^{3}He, and ^{36}Cl methods.	*Volcanic Features*—lava flows, cones, and mixed pyroclastics. *Biologic and Geologic Connections*—part of lava-flow habitat/"mesic island." Hosts mixed-conifer woodlands. Provides lava-tube cave habitat.	Part of El Malpais event. Approximately 18,000 years old. Includes many prominent El Malpais features such as Twin Craters, Lost Woman, La Tetra, Lava Crater, and Cerro Candelaria. Includes most flows under or adjacent to Highway 53.

Gray-shaded rows indicate units not mapped within El Malpais National Monument. Italicized text corresponds to report sections.

Age	Map Unit (Symbol)	Geologic Description	Geologic Issues	Geologic Features and Processes	Geologic History
QUATERNARY (Holocene and Pleistocene)	El Calderon flows, crater, and cinder field (Qbc, Qcc, and Qvc)	El Calderon crater (**Qcc**), cinder field (**Qvc**), and flows (**Qbc**) are composed of coarse-grained, porous basalt. **Qbc** largely covered by alluvium (**Qal**) or younger flows near source. Some rocks included with the old basalt flows (**Qb**), notably Cerro Bandera and Cerro Rendija, are similar and may correlate with El Calderon.	*Cave Management*—trail to El Calderon Bat Cave is prime location for observing bat flights. *Disturbed Lands*—abandoned cinder quarry on the side of El Calderon crater (**Qcc**). *Geochronology, Research, and Interpretation*—flows dated using ^{36}Cl and K-Ar methods.	*Volcanic Features*—lava flows, crater, and cinder field. *Eolian Features and Processes*—El Calderon flows noticeably infilled with loess. *Biologic and Geologic Connections*—part of lava-flow habitat/"mesic island." Hosts mixed-conifer woodlands. Provides lava-tube cave habitat.	Represents first eruption of El Malpais episode of Zuni–Bandera volcanic field. Less than 60,000 years old. Flows (**Qbc**) originated from El Calderon crater (**Qcc**) below and northeast of Cerritos de Jaspe.
QUATERNARY (Holocene and Pleistocene)	Basalt flows (Qbu), cinder cones (Qc), and volcanic debris (Qv)	Basalt flows, cinder cones, and volcanic debris west of El Malpais National Monument. Maxwell (1986) found these flows, cones, and volcanic debris to be stratigraphically related. **Qv** composed largely of weathered lava covered with coarse lava blocks and scoria. **Note**: "**Qc**" is used as the map symbol for both colluvium of McCartys Mesa (Maxwell 1977) and cinder cones (Maxwell 1986).	*Disturbed Lands*—cinders difficult to restore. *Geochronology, Research, and Interpretation*—currently under study.	*Volcanic Features*—lava flows, cinder cones, and volcanic debris (lava, lava blocks, and scoria).	Represent second episode of volcanism in Zuni–Bandera volcanic field. Approximately 150,000 years old. West of El Malpais flows. Represented by Chain of Craters area. Volcanic debris associated with cinder cones and with a few older flows.
QUATERNARY (Holocene and Pleistocene)	Old basalt flows (Qb)	Deeply weathered. Largely covered with soil and alluvium (**Qac**).	None reported.	*Biologic and Geologic Connections*—underlie many kipukas (e.g., Hole-in-the-Wall). Deeply weathered and covered by **Qac**. Produce open grasslands with small outcrops of basalt.	Represent first episode of volcanism in Zuni–Bandera volcanic field. Approximately 700,000 years old. Cover much of western half of map area. Same as flows at nearby El Morro National Monument.
TERTIARY (Pliocene)	Basalt flows on Cebollita Mesa, Mesa Negra, and Horace Mesa (Tb)	Generally aphanitic and vesicular olivine basalt and associated scoria. Flows generally 20–30 m (65–100 ft) thick, 100 m (300 ft) or more near smaller centers of eruption, and 300 m (1,000 ft) or more at Cebollita Peak. **Note**: Maxwell (1977) mapped basalt on Horace Mesa as **Tb** in the McCartys quadrangle.	*Mass Wasting*—part of rotational slide (**Ql**).	*Volcanic Features*—lava flows cap mesas seen from El Malpais National Monument. *Biologic and Geologic Connections*—largely covered with soil, alluvium, and pine trees.	Part of Mount Taylor volcanic field, and not related to Zuni–Bandera activity. About 3.73 million to 1.57 million years old. East of El Malpais National Monument.
TERTIARY (Pliocene)	Diabase dikes (Td)	Very fine-grained diabase with grains of plagioclase, augite, magnetite, and apatite. Contacts with the enclosing rock are generally marked by a thin aphanitic chill border in the dike and a hardened or silicified zone in the enclosing sandstone or shale. Range in thickness from a few decimeters to slightly more than 6 m (20 ft).	Unknown.	*Volcanic Features*—igneous rock intruded "middle-aged rocks" such as Gallup Sandstone and Mancos Shale.	Intruded at the time of Mount Taylor volcanism.
UPPER CRETACEOUS	Crevasse Canyon Formation (Kcc)	Comprises an 80–100-m- (260–330-ft-) thick sequence of nonmarine sandstone, siltstone, carbonaceous shale, and coal beds. Members are (from youngest to oldest) Gibson Coal Member, Dalton Sandstone Member, and Dilco Coal Member. **Note**: Maxwell (1977) mapped the Gibson Coal Member (**Kcg**), Dalton Sandstone Member (**Kcd**), Stray Sandstone Member (**Kcs**), and Dilco Coal Member (**Kcdi**) in the McCartys quadrangle.	*Disturbed Lands*—coal present, but not an abandoned mineral land (AML) issue.	None reported.	Marine setting. Records retreat and advance of Western Interior Seaway.
UPPER CRETACEOUS	Gallup Sandstone (Kg)	Composed of an upper sandstone member, a middle silty shale unit, and a lower silty unit. Total thickness 80–100 m (260–330 ft). **Note**: Maxwell (1977) mapped the upper tongue (**Kgu**) and lower tongue (**Kgl**), as well as a main body (**Kgm**), in the McCartys quadrangle.	*Disturbed Lands*—lower silty unit contains coaly lenses, but not an AML issue.	None reported.	Marine and sandy beach settings. Records an entire transgression–regression cycle of Western Interior Seaway. Recorded regression is unique to New Mexico and adjacent northeastern Arizona.
UPPER CRETACEOUS	Mancos Shale, D-Cross Tongue (Kmd)	Light- to dark-gray shale containing local lenses and concretionary zones of sandy fossiliferous limestone, and thin-bedded sandstone in southeastern part of map area. Outcrops are sparse and generally confined to small areas under cliffs with overlying sandstones.	*Mass Wasting*—weathers to steep, soft slopes almost entirely covered by landslides, talus, or colluvium.	*Paleontological Resources*—marine invertebrates.	Marine setting. Records advance and subsequent retreat of Western Interior Seaway.

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Age	Map Unit (Symbol)	Geologic Description	Geologic Issues	Geologic Features and Processes	Geologic History
UPPER CRETACEOUS	Tres Hermanos Sandstone (Kth)	Composed of three units—sandstone at top, highly variable middle unit (see description below), and light-yellowish-gray sandstone at base. Middle unit around Mesa Negra is similar to the D-Cross (**Kmd**) or Rio Salado (**Kmr**) tongues, but grades southward to interbedded carbonaceous shale and sandstone containing lenticular coal beds. Locally grades into predominantly thin-bedded shaley sandstone and siltstone. In southern part of map area, grades into dark-gray, fossiliferous shale and light-gray and brown, thin-bedded, calcareous sandstone.	*Disturbed Lands*—coal present, but not an AML issue.	*Paleontological Resources*—shells.	Open-marine, shoreline, fluvial and marsh, barrier-island, coastal-plain, and delta-plain settings. Records mostly retreat of the Western Interior Seaway, with upper part showing advance along with overlying D-Cross Tongue (**Kmd**).
UPPER CRETACEOUS	Mancos Shale, Rio Salado Tongue (Kmr)	Light- to dark-gray friable shale and silty shale containing local lenses of calcareous, siliceous, and sandy siltstone, and fine-grained sandstone in upper part. Thickness 70–90 m (230–300 ft). **Note**: Maxwell (1977) mapped the Mulatto Tongue (**Kmm**); main body (**Km**); Whitewater Arroyo and Clay Mesa Shale Tongues, undivided (**Kmwc**); and Clay Mesa Shale (**Kcdi**) in the McCartys quadrangle.	*Mass Wasting*—friable. Weathers to steep, soft slopes almost entirely covered by landslides, talus, or colluvium.	None reported.	Marine setting. Records retreat of Western Interior Seaway.
UPPER CRETACEOUS	Twowells Tongue of Dakota Sandstone (Kdt)	Fine- to very fine-grained, silty, local, thin lenses of medium- to coarse-grained sandstone. Light gray, weathers to grayish orange, light brown and tan. Thin to medium bedded. Resistant, slabby beds at top grade downward to silty sandstone containing thin interbeds of siltstone. Thickness 1–25 m (3–80 ft).	*Mass Wasting*—resistant beds at top. *Disturbed Lands*—provided material in old sandstone quarry in Lava Falls area, which has been restored.	*Paleontological Resources*—uppermost part and overlying shale contain the extinct oyster (*Pycnodonte newberryi* Stanton). Also contains trace fossils, including many imprints, burrows, trails, and disturbed bedding.	Nearshore and marine settings. Records minor retreat of Western Interior Seaway within an overall advance, or perhaps a stillstand of shoreline.
UPPER CRETACEOUS	Mancos Shale, Whitewater Arroyo Tongue (Kmw)	Dark-gray shale, weathers to light gray and grayish tan. Uppermost part is silty shale and siltstone that is transitional into Twowells Tongue (**Kdt**).	*Mass Wasting*—weathers to steep, soft slopes almost entirely covered by landslides, talus, or colluvium.	None reported.	Marine and nearshore settings. Records retreat of Western Interior Seaway.
UPPER CRETACEOUS	Paguate Tongue of Dakota Sandstone (Kdp)	Light-brown and tan, fine- to very fine-grained sandstone. Local lenses medium to coarse grained, thin to medium bedded. Thickness 10–30 m (30–100 ft).	*Mass Wasting*—forms prominent cliffs along northeast side of El Malpais National Monument.	*Paleontological Resources*—potential for fossils such as marine invertebrates and trace fossils (burrows and bioturbation).	Nearshore and marine settings. Records minor retreat of Western Interior Seaway within an overall advance, or perhaps a stillstand of shoreline.
UPPER CRETACEOUS	Clay Mesa Tongue of Mancos Shale and lower part of Dakota Sandstone (Kdo)	Includes, from top to bottom, the Clay Mesa Tongue of Mancos Shale (dark-gray, fissile shale), Cubero Tongue of Dakota Sandstone (similar lithology to Twowells Tongue, **Kdt**), the Oak Canyon Member (calcareous or carbonaceous sandstone and siltstone), and a basal sandstone and conglomerate unit of Dakota Sandstone. Total thickness 30–70 m (90–200 ft). **Note**: Maxwell (1977) mapped the Cubero Sandstone Tongue (**Kdc**), Oak Canyon Member (**Kdo**), and basal sandstone unit of the Oak Canyon Member (**Kds**) in the McCartys quadrangle. "**Kdo**" is used as the map symbol for both the Oak Canyon Member of Dakota Sandstone (Maxwell 1977) and Clay Mesa Tongue of Mancos Shale and lower part of Dakota Sandstone (Maxwell 1986).	*Mass Wasting*—Clay Mesa Tongue is fissile and weathers to steep, soft slopes almost entirely covered by landslides, talus, or colluvium. *Erosion*—erosion of overlying eolian sediments (**Qe**) to **Kdo** of Maxwell (1986) in Sandstone Bluffs Overlook area. *Disturbed Lands*—provided material in old sandstone quarry in Lava Falls area, which has been restored. Carbonaceous material (coal) present, but not an AML issue.	*Paleontological Resources*—potential for fossils in Clay Mesa Tongue. Oak Canyon Member has fossils (marine invertebrates) in limestone lenses within El Malpais National Monument. Basal sandstone unit has trace fossils (trails and burrows).	Records first advance (transgression) of Western Interior Seaway into New Mexico. Mancos Shale—shallow marine setting. Dakota Sandstone—nearshore and marine settings. Also, swamps and rivers adjacent to seaway.
UPPER JURASSIC	Morrison Formation (Jm)	Grayish-green mudstone and siltstone and lenticular yellowish- and reddish-gray fine- to medium-grained sandstone. Lenticular, pale-brown to white, cross-bedded pebble conglomerate and sandstone at base. Pinches out about 5 km (3 mi) south of Interstate 40. Thickness up to 30 m (100 ft).	None reported.	*Paleontological Resources*—known for dinosaur bones in places such as Dinosaur National Monument (Utah and Colorado).	Fluvial setting.
MIDDLE JURASSIC	Zuni Sandstone and Wanakah Formation (Jz)	Zuni Sandstone: variably colored, generally yellowish-gray or tan, locally chalk white, fine- to medium-grained sandstone. Well-rounded grains largely of quartz. Conspicuous bleached zone at tip of unit. Wanakah Formation: white to pale-brown, thin- to medium-bedded, very fine-grained, silty sandstone interbedded with thin, dark-brown mudstone and claystone. Grades into thin-bedded, fluviatile sandstone at base of Zuni Sandstone. Combined thickness 110–180 m (360–600 ft).	*Erosion*—friable sandstone.	*Eolian Features and Processes*—160-million-year-old sand dunes with very well-sorted, large-scale eolian cross-beds. Source of eolian sediment today.	Eolian setting. Conspicuous bleached zone is remarkable at nearby El Morro National Monument.

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Age	Map Unit (Symbol)	Geologic Description	Geologic Issues	Geologic Features and Processes	Geologic History
MIDDLE JURASSIC	Todilto Limestone Member of Wanakah Formation (Jt)	Composed of 3–12 m (10–40 ft) of pale-olive-gray, pale-olive-brown, and pale-yellow limestone. Thickly bedded, coarsely crystalline in top part. Crinkly bedded in middle part. Platy bedded at base.	*Disturbed Lands*—contains uranium.	*Paleontological Resources*—potential for dinosaur tracks, algal structures, fish scales, ostracodes, and worm burrows.	Deposited in a restricted marine embayment with an ephemeral connection to the sea.
MIDDLE JURASSIC	Entrada Sandstone (Je)	Reddish-orange to reddish-brown, fine- to medium-grained, eolian, cross-bedded, silty sandstone.	None reported.	*Eolian Features and Processes*—ancient sand dunes. *Paleontological Resources*—potential for trace fossils.	Eolian setting. **Jz** and **Je** stratigraphically correlated at nearby El Morro National Monument. Makes up arches in Arches National Park in Utah.
TRIASSIC	Chinle (Upper Triassic) and Moenkopi(?) (Middle and Lower Triassic) formations (TRcm)	Chinle Formation is 360–460 m (1,180–1,500 ft) thick in the region but only lowermost part, which is predominantly reddish-brown claystone and siltstone, is exposed in map area. Basal part of map unit is tentatively correlated with the Moenkopi Formation, which is composed of pale-reddish-brown and grayish-red sandstone interbedded with pebble conglomerate and reddish-brown, lenticular siltstone and mudstone. Thickness up to 15 m (50 ft).	None reported.	*Paleontological Resources*—Chinle Formation is known for petrified wood and other fossils outside of El Malpais National Monument, such as at Petrified Forest National Park in Arizona.	Terrestrial (fluvial) setting.
PERMIAN (Cisuralian or Early)	San Andres Limestone (Psa)	Mostly gray to yellow, thick-bedded, fossiliferous dolomitic limestone with thin, calcareous, shale partings and thin, sandy limestone lenses. A yellowish-gray sandstone bed about 6 m (20 ft) thick locally present in lower part. Total thickness 35–44 m (115–145 ft).	*Mass Wasting*—forms cliffs or persistent dip slopes.	*Paleontological Resources*—marine invertebrates in dolomitic limestone.	Marine setting. Deposited in Permian seas.
PERMIAN (Cisuralian or Early)	Glorieta Sandstone (Pg)	White to buff, very pure, well-sorted, medium-grained, cross-bedded quartz sandstone and siltstone. Weathers yellow to light brown. Well cemented with silica or calcite. Thickness 45–50 m (150–165 ft).	*Mass Wasting*—forms cliffs, ridges, or dip slopes.	*Paleontological Resources*—potential for plant debris and trace fossils.	Marginal marine setting. Widespread beach deposits crossed by meandering streams.
PERMIAN (Cisuralian or Early)	Yeso Formation (Py)	Pale-reddish-brown, medium- to fine-grained, thick- to thin-bedded, locally cross-bedded sandstone and siltstone. Grades upward into pink, white, and yellow alternating layers of friable sandstone. Three dense, fine-grained, light- to medium-gray limestone beds 3–4 m (10–13 ft) thick are present in upper part of formation. Locally overlain by 4–5 m (13–16 ft) of white to light-gray, poorly exposed gypsum beds. Total thickness about 400 m (1,300 ft).	*Mass Wasting*—friable sandstone.	*Lava Tubes*—**Py** may be a source of gypsum in cave minerals. *Paleontological Resources*—potential for marine invertebrates and trace fossils.	Coastal sabkha. Records transition from continental to marine conditions.
PERMIAN (Cisuralian or Early)	Abo Formation (Pa)	Moderate-brick-red to dusky-red, medium- to fine-grained sandstone and siltstone. Locally cross bedded. At base is 1–3 m (3–10 ft) of arkosic conglomerate containing white quartz pebbles, overlain by about 10 m (30 ft) of dusky-red arkose containing thin, medium-gray, limestone beds. Thickness about 400 m (1,300 ft).	*Mass Wasting*—forms cliffs and steep slopes.	*Paleontological Resources*—potential for trace fossils, marine and terrestrial invertebrate fossils, and vertebrate fossils.	Thick wedge of terrestrial/continental material. Fluvial setting. Deposited on an eroded, undulating surface of Precambrian rocks.
PRECAMBRIAN	Hornblendite, gabbro, and intrusive basalt (PChb)	Hornblendite, gabbro, and intrusive basalt (dikes and small irregular bodies).	None reported.	*Lava Tubes*—**PChb** gabbro is a source of xenoliths in lava tubes and flows.	Records subsequent intrusion into sutured terranes of volcanic arc and oceanic crust. Uplifted and exposed in Zuni Mountains during Laramide Orogeny.
PRECAMBRIAN	Porphyritic aplite (PCpa)	Moderate-orange-pink, slightly gneissic, porphyritic aplite composed of scattered microcline phenocrysts in medium-grained groundmass of quartz, orthoclase, and minor biotite. Occurs as stocks and dikes that intrude gneissic granite (**PCgg**) and gneissic aplite (**PCap**).	None reported.	None reported.	Records subsequent intrusion into sutured terranes of volcanic arc and oceanic crust. Uplifted and exposed in Zuni Mountains during Laramide Orogeny.
PRECAMBRIAN	Gneissic aplite (PCap)	Grayish- to moderate-orange-pink, sugary, well-foliated aplite. Consists of microcline, quartz, and some orthoclase and oligoclase. Contains minor amounts of muscovite and biotite. Occurs as irregular masses and dikes intruding or locally gradational into gneissic granite (**PCgg**).	None reported.	None reported.	Records subsequent intrusion into sutured terranes of volcanic arc and oceanic crust. Uplifted and exposed in Zuni Mountains during Laramide Orogeny.

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Age	Map Unit (Symbol)	Geologic Description	Geologic Issues	Geologic Features and Processes	Geologic History
PRECAMBRIAN	Porphyritic granite (PCpg)	Light-brownish-gray, porphyritic granite. Large, white orthoclase and small bluish quartz phenocrysts in fine-grained groundmass of quartz, orthoclase, hornblende, and biotite; slightly gneissic. Occurs as dikes that intrude gneissic granite (**PCgg**).	*Disturbed Lands*—**PCpg** contains veins of fluorite that were mined during World War II.	*Lava Tubes*—**PCpg** is a source of xenoliths in lava tubes and flows.	Records subsequent intrusion into sutured terranes of volcanic arc and oceanic crust. Uplifted and exposed in Zuni Mountains during Laramide Orogeny.
	Aplitic granite (PCag)	Grayish to pink, gneissic, fine to medium grained, composed of potassium feldspar, quartz, and small amounts of oligoclase, biotite, and muscovite. Gradational with gneissic granite (**PCgg**).	*Disturbed Lands*—**PCag** contains veins of fluorite that were mined during World War II.	*Lava Tubes*—**PCag** is a source of xenoliths in lava tubes and flows.	Records accretion of terranes to older craton. Uplifted and exposed in Zuni Mountains during Laramide Orogeny.
	Gneissic granite (PCgg)	Pinkish- to medium-gray, fine- to coarse-grained, locally porphyritic, gneissic granite composed of orthoclase, quartz oligoclase, and abundant hornblende and biotite.	*Disturbed Lands*—**PCgg** contains veins of fluorite that were minded during World War II. Contains fluorite vein within El Malpais National Monument.	*Lava Tubes*—**PCgg** is a source of xenoliths in lava tubes and flows.	Records accretion of terranes to older craton. Uplifted and exposed in Zuni Mountains during Laramide Orogeny.
	Quartz monzonite gneiss (PCmg)	Medium to dark gray, medium grained, strongly gneissic, slightly banded. Composed of oligoclase, biotite, quartz, and some orthoclase. Occurs as xenolithic masses in gneissic granite (**PCgg**).	*Disturbed Lands*—**PCmg** contains veins of fluorite that were mined during World War II.	None reported.	Records accretion of terranes to older craton. Uplifted and exposed in Zuni Mountains during Laramide Orogeny.
	Quartzite (PCqt)	Brown, fine to medium grained, locally contains phyllite beds.	None reported.	None reported.	Records accretion of terranes to older craton. Uplifted and exposed in Zuni Mountains during Laramide Orogeny.
	Hornblende gneiss (PChg)	Dark-green gneiss. Contains lenses of gneissic gabbro and layers of aplite.	*Disturbed Lands*—**PChg** contains veins of fluorite that were mined during World War II.	None reported.	Records accretion of terranes to older craton. Uplifted and exposed in Zuni Mountains during Laramide Orogeny.
	Injection gneiss (PCig)	Quartz biotite gneiss.	*Disturbed Lands*—**PCig** contains veins of fluorite that were mined during World War II.	None reported.	Records accretion of terranes to older craton. Uplifted and exposed in Zuni Mountains during Laramide Orogeny.
	Biotite schist (PCsc)	Biotite schist.	None reported.	None reported.	Records accretion of terranes to older craton. Uplifted and exposed in Zuni Mountains during Laramide Orogeny.