National Park Service
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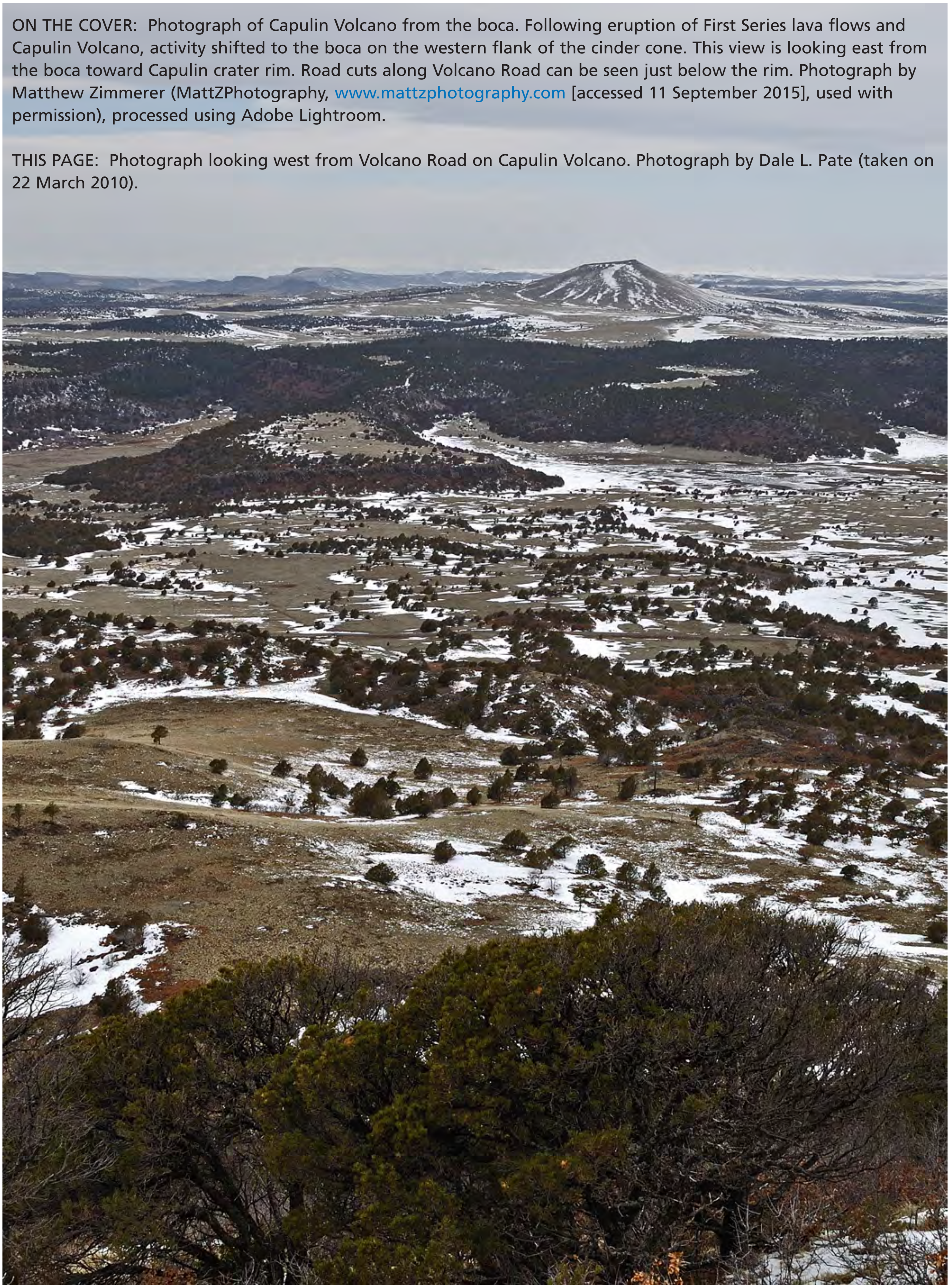
Natural Resource Stewardship and Science

Capulin Volcano National Monument

Geologic Resources Inventory Report

Natural Resource Report NPS/NRSS/GRD/NRR—2015/1031

ON THE COVER: Photograph of Capulin Volcano from the boca. Following eruption of First Series lava flows and Capulin Volcano, activity shifted to the boca on the western flank of the cinder cone. This view is looking east from the boca toward Capulin crater rim. Road cuts along Volcano Road can be seen just below the rim. Photograph by Matthew Zimmerer (MattZPhotography, www.mattzphotography.com [accessed 11 September 2015], used with permission), processed using Adobe Lightroom.



THIS PAGE: Photograph looking west from Volcano Road on Capulin Volcano. Photograph by Dale L. Pate (taken on 22 March 2010).

Capulin Volcano National Monument

Geologic Resources Inventory Report

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

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

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

This report is available from the Geologic Resources Inventory website (http://go.nps.gov/gripubs), and the Natural Resource Publications Management website (http://www.nature.nps.gov/publications/nrpm/). To receive this report in a format optimized for screen readers, please email irma@nps.gov.

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Executive Summary

The Geologic Resources Inventory (GRI) is one of 12 inventories funded by the National Park Service (NPS) Inventory and Monitoring Program. The Geologic Resources Division of the NPS Natural Resource Stewardship and Science Directorate administers the GRI. This report synthesizes discussions from a scoping meeting for Capulin Volcano National Monument (New Mexico) on 10 May 2011, which was held by the Geologic Resources Division to identify geologic resources of significance and geologic resource management issues, as well as determine the status of geologic mapping. It is a companion document to previously completed GRI GIS data.

About 55,000 years ago, Capulin Volcano erupted with molten rock launched thousands of feet into the air. The rain back to earth of cooling cinders and other pyroclastic materials, such as ash and bombs, formed the volcano. Although extinct today and unlikely to erupt again, Capulin Volcano is dramatic evidence of the spectacular volcanic events that formed the Raton-Clayton volcanic field of northeastern New Mexico.

Much of the attraction of Capulin Volcano is a road that leads to the volcano rim, providing outstanding views of the surrounding wide-open country of the High Plains and the Raton-Clayton volcanic field. The road is called "Volcano Road." In addition, five trails wind through the volcanic terrain at the monument.

This GRI report compiles geologic information for Capulin Volcano National Monument and discusses management issues related to the geologic features contained within its boundaries. The report was written for resource managers to support science-informed decision making. It may also be useful for interpretation. The report was prepared using available geologic information, and the NPS Geologic Resources Division conducted no new fieldwork in association with its preparation. Chapters of the report discuss distinctive geologic features and processes, highlight geologic issues facing resource managers, describe the geologic history leading to the present-day landscape, and provide information about the GRI GIS data set. Two posters (in pocket) illustrate these data: one is a volcanic features map of the monument; the other is a map showing the lava flow series in the Capulin Volcano area. The Map Unit Properties Table (in pocket) summarizes report content for each geologic map unit.

Geologic features and processes at Capulin Volcano National Monument include the following:

- **Volcanic Rocks and Volcanoes**. Capulin Volcano and all the other volcanic features in Capulin Volcano National Monument are composed of basalt—an extrusive igneous rock with less than 52% silica. Geologists use silica content as a means for classifying volcanic rocks. The percentage of silica influences many properties of magma, including viscosity (internal friction) and explosiveness, as well as the type of volcano that forms during an eruption. Capulin Volcano is a classic example of a cinder cone.
- **Capulin Basalt**. Capulin Volcano National Monument and the surrounding area are composed entirely of a single, formally named map unit—Capulin Basalt. Analysis of rock samples from Capulin Volcano and nearby Baby Capulin, a cinder cone outside the monument, found that the rock is technically a "trachybasalt," having more abundant alkali elements, such as sodium and potassium, than true basalt. The presence of Dakota Sandstone xenoliths (foreign rock fragments) and xenocrysts (foreign crystals) is a characteristic feature of Capulin Basalt. Silica from Dakota Sandstone quartz grains is a factor in the relatively high amount of silica (50%–55%) in Capulin Basalt.
- **Raton-Clayton Volcanic Field**. Capulin Volcano National Monument is part of the 20,000-km^2 (8,000-mi^2) Raton-Clayton volcanic field, which has been active episodically for the past 9 million years in three phases: (1) Raton phase, which had two distinct episodes (9.0 million–7.3 million years ago and 5.6–3.5 million years ago); (2) Clayton phase (3.0 million–2.2 million years ago); and (3) Capulin phase (1.69 million–32,000 years ago). Capulin Volcano erupted during the Capulin phase. The volcanic field consists of an estimated 125 vents and is characterized by a low volumetric eruption rate and inverted topography.

- **Capulin Volcano**. Not only is Capulin Volcano a type example of a cinder cone, it is archetypal—bigger and more perfectly formed than most cinder cones. The beauty of this volcano is the reason for its inclusion in the National Park System.
- **Volcanic Features**. Richman (2010)—the source for the GRI GIS data set—mapped Capulin Volcano and the complex boca, delineating two boca ramparts, 16 lava cascades, 19 lava lakes, 15 lava levees, 18 lava ridges, one pooled lava flow, one push-up, two rafted cinder cones, 24 spatter deposits, one spatter flow, 23 squeeze-ups, 18 tumuli, and seven vents.
- **Age of Capulin Volcano**. Once considered less than 10,000 years old, Capulin Volcano is now known to have formed 55,000 ± 2,000 years ago.
- **View from Capulin Volcano**. The view from the crater rim is probably what led Homer Farr, the custodian of Capulin Mountain National Monument (former name of the monument) from 1923 to 1955, to build a road to the summit. The "dramatic view" is one of four statements of significance identified in the monument's general management plan; the other three are the classic cinder cone, occurrence in the geologically diverse Raton-Clayton volcanic field, and the cinder cone's accessibility.
- **Playa Lakes**. Playa lakes—ephemeral lakes in arid or semiarid regions that appear in the wet season and subsequently dry up—are one of the only nonvolcanic features in the viewshed of Capulin Volcano National Monument. Playa lakes are visible to the south and east of Capulin Volcano.
- **Aeolian Features**. A notable aeolian (windblown) feature at Capulin Volcano National Monument is the asymmetrical crater rim, which is higher on the northeastern side. At the time of cone building, prevailing southwesterly winds caused more cinders to accumulate on the opposite (northeastern) side of the volcano. Loess (windblown dust) is another aeolian feature at the monument. This material fills vesicles and cracks on lava flows. Loess-infilling serves as an informal dating method of lava flows and associated landscapes. Loess also plays a role in soil formation.
- **K-T Boundary**. Although Capulin Volcano National Monument does not contain the Cretaceous-Tertiary ("K-T") boundary, the nearby exposure at Goat Hill may be of interest to visitors. This boundary marks a massive, worldwide extinction of an estimated 50% of all species, including dinosaurs, 66 million years ago.
- **Paleontological Resources**. To date, no paleontological resources have been documented in Capulin Volcano National Monument. The discovery of tree molds or pack rat middens is possible, however. Tree molds (trace fossils formed by the envelopment of a tree by a lava flow) occur in some volcanic settings in the National Park System. Pack rat middens are a potential source of paleontological and paleoenvironmental information.

Geologic resource management issues identified during the GRI scoping meeting included the following:

- **Volcano Road**. First constructed in 1925, Volcano Road is a distinctive feature and an important part of Capulin Volcano National Monument's cultural landscape. It is significant for the scientific, educational, and public enjoyment opportunities it provides. However, it also has the greatest impact on the monument's geologic resources, specifically the cinder cone. The road's impervious surface and many of its culverts concentrate runoff which erodes, sometimes severely, the sides of the volcano. According to the NPS natural resource condition assessment for the monument, Volcano Road and its effects on Capulin Volcano have resulted in a condition of "significant concern" and "a declining trend." In 2012, a Federal Highway Administration project incorporated erosion control measures and repaired road shoulders, drainage structures, and eroded hill slope areas.
- **Erosion**. Erosion is arguably the greatest threat to the geologic resources at Capulin Volcano National Monument. A primary gap in understanding is the degree and severity of unnatural as opposed to natural erosion. Existing information related to soil erosion at Capulin Volcano National Monument includes a NPS Soil Resources Inventory (SRI) and a rapid soil assessment and trip report. In addition to Volcano Road, erosion is affecting sections of the Lava Flow Trail, Crater Rim Trail, and a fire road in the southern part of the monument.
- **Slope Movements**. Slope movements are ongoing at Capulin Volcano National Monument and cause cinders to slide, debris flows to form, and entire sections of slopes to fail. These processes are a particular concern along Volcano Road. A data

need at the monument is a better understanding of the triggers and timing of these gravity-driven events.

- **Aeolian Processes**. Wind is a primary geologic agent at Capulin Volcano National Monument. Wind transports cinders onto Volcano Road, which is a concern for maintenance and safety. Dust storms are rare now that grazing has stopped within the monument but can take place, primarily in March and April. Construction sites are sources of windblown dust.
- **Wind Energy Development**. Wind energy development is a concern for the preservation of the monument's viewshed. The National Park Service uses a combined technical and policy approach to manage and protect park resources and values as renewable energy potential is identified and developed near NPS areas.
- **Cave Management**. An inventory of caves (as geologic resources) is needed at Capulin Volcano National Monument. No cave management plan has been completed to date. The NPS Geologic Resources Division has expertise to assist with the preparation of a cave management plan.
- **Cinder Mining**. Cinder mining has occurred in the vicinity of Capulin Volcano National Monument, for example, at Twin Mountain—a cinder cone northeast of Capulin Volcano. The monument contains three "test pits," which scoping participants identified but did not deem in need of restoration. Monument managers may wish to include these sites in the NPS Abandoned Mineral Lands (AML) database. The NPS Geologic Resources Division (GRD) manages the AML database and has expertise to assist with restoration projects, if needed in the future.
- **Volcano Hazards and Risk**. Volcanism in the Raton-Clayton volcanic field began about 9 million years ago and no evidence suggests that it has ended. An eruption in the future is likely, though an eruption at an existing volcano, such as Capulin Volcano, is unlikely. Rather, a new batch of magma will probably extrude through a new vent, possibly forming a new cinder cone. In addition to cone building, other potential hazards include localized ash fall, earthquakes (as magma rises to the surface), volcanic gases, lava eruptions (flows), volcanic projectiles, and wildfires.
- **Geothermal Systems and Hydrothermal Features**. Capulin Volcano National Monument is not known for its geothermal resources or hydrothermal features and is not included on the list of 16 parks that are designated under the Geothermal Steam Act of 1970, as amended in 1988. However, during the 2011 GRI scoping meeting, participants discussed a "hot vent" near the maintenance building, which may be an indicator of heat transfer. No known documentation exists. Investigating this "vent" may be a project for a Geoscientist-In-the-Parks (GIP) participant. This program is administered by the NPS Geologic Resources Division.

Products and Acknowledgments

The NPS Geologic Resources Division partners with institutions such as Colorado State University, the US Geological Survey, state geological surveys, local museums, and universities to develop GRI products. This chapter describes those products and acknowledges contributors to this report.

GRI Products

The objective of the Geologic Resources Inventory is to provide geologic map data and pertinent geologic information to support resource management and science-informed decision making in more than 270 natural resource parks throughout the National Park System. To realize this objective, the GRI team undertakes three tasks for each natural resource park: (1) conduct a scoping meeting and provide a summary document, (2) provide digital geologic map data in a geographic information system (GIS) format, and (3) provide a GRI report (this document). These products are designed and written for nongeoscientists.

Scoping meetings bring together park staff and geologic experts to review and assess available geologic maps, develop a geologic mapping plan, and discuss geologic features, processes, and resource management issues that should be addressed in the GRI report. Following the scoping meeting, the GRI map team converts the geologic maps identified in the mapping plan to digital geologic map data in accordance with the GRI data model. After the map is completed, the GRI report team uses these data, as well as the scoping summary and additional research, to prepare the GRI report.

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

Additional information regarding the GRI, including contact information, is available at http://go.nps.gov/gri. The current status and projected completion dates of products are available at http://go.nps.gov/gri_status.

Acknowledgments

Thanks very much to **Stephanie O'Meara** (Colorado State University), **Michael Ort** (Northern Arizona University), and **Mike Timmons** (New Mexico Bureau of Geology and Mineral Resources) for interpreting and verifying the locations of volcanic vents for use in the GRI GIS data set for Capulin Volcano National Monument. Additionally, thanks to **Matthew Smith** (Western Archeological and Conservation Center) for tracking down information about caves at the monument. Also, thanks very much to **Trista Thornberry-Ehrlich** (Colorado State University) for developing graphics and **Matthew Zimmerer** (New Mexico Bureau of Geology and Mineral Resources) for sharing photographs used as figures in this report. **Gina D'Ambrosio** (New Mexico Bureau of Geology and Mineral Resources) provided photographs from the bureau for use in this report.

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Geologic Setting and Significance

This chapter describes the regional geologic setting of Capulin Volcano National Monument and summarizes connections among geologic resources, other park resources, and park stories.

Capulin Volcano is one of the tallest and most perfectly formed cinder cones in North America. The volcano stands 2,494 m (8,182 ft) above sea level and nearly 400 m (1,300 ft) above the surrounding plain. It is the primary geologic feature at Capulin Volcano National Monument and a fundamental resource and value of the monument (National Park Service 2014c).

Capulin Volcano is also one of the most accessible volcanoes in North America. Only two other cones—Lava Butte and Pilot Butte, both near Bend, Oregon—have paved roads to their summits (Mathis 1999). Volcano Road at the monument spirals around the cinder cone to a parking lot at the crater rim.

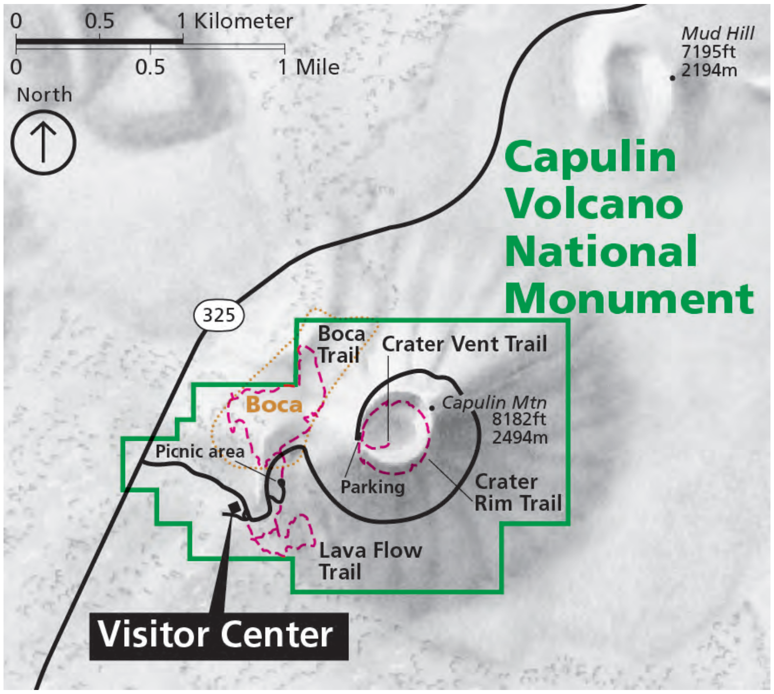


Figure 1. Map of Capulin Volcano National Monument. The monument encompasses 320.86 ha (792.84 ac) of all federal land. Volcano Road spirals to the top of the volcano with an area for parking at the rim. Five trails within the monument lead around and through the volcanic terrain: Crater Vent Trail, Crater Rim Trail, Lava Flow Trail, and Boca Trail (delineated here); Nature Trail is adjacent to the visitor center. National Park Service graphic available at http://www.nps.gov/hfc/cfm/carto-atoz.cfm (accessed 10 October 2014).

Five trails also lead around and through the volcanic terrain at the monument (fig. 1). First, Crater Rim Trail is a paved, 1.6 km (1 mi) loop around the top of the volcano. The trail supplies the equivalent of an aerial view of the morphologic features of nearby lava flows and volcanoes, as well as gives panoramic views of the entire Raton-Clayton volcanic field, of which Capulin Volcano is a part. Wayside exhibits along the trail provide information about the surrounding physiographic features. Second, Crater Vent Trail is a paved 0.3 km (0.2 mi) route descending to the vent at the bottom of the crater. This trail provides an opportunity to hike into a volcano. The trail is a good place to imagine events that took place 55,000 years ago when cinders erupted into the air and fell back down around the vent to form the volcano. Third, Lava Flow Trail at the base of the volcano is an unimproved, 1.6 km (1 mi) loop that goes out onto one of the lava flows, specifically the "Second Series" lava flows (see lava flow series map, in pocket). Fourth, Nature Trail is a figure-eight, wheelchair-accessible loop adjacent to the visitor center (fig. 2). The trail has stops that discuss wildlife, plant life, and geology. Fifth, Boca Trail is an unimproved, 3 km (2 mi) journey through the mouth of the volcano at the western base of the cinder cone; "boca" means "mouth" in Spanish. Richman (2010)—the source of the GRI GIS data set—mapped Capulin Volcano's complex boca in detail (see volcanic features map, in pocket; and "Geologic Map Data" chapter).

Four major lava flows are associated with Capulin Volcano. The flows cover about 40 km^2 (16 mi^2) and extend well beyond the monument boundary (see lava flow series map, in pocket). The monument contains the cinder cone, boca, and a portion of each of these flows (see Map Unit Properties Table and posters, in pocket). Sayre and Ort (1999) delineated the flows into four series. First Series lava flows were extruded before and during the cone-building eruption. Later, lava flows spread southeast (Second Series), southwest (Third Series), and north (Fourth Series) of the cinder cone.

Figure 2. Photograph of Nature Trail at Capulin Volcano National Monument. The wheelchair-accessible trail adjacent to the visitor center provides opportunities to see wildlife, plant life, and geologic features. Note the tumulus (mound of lava on the surface of a lava flow) on the right. Jose Butte is in the background. National Park Service photograph by Ally Buccanero available at http://www.nps.gov/cavo/planyourvisit/accessibility.htm (accessed 10 October 2014).

These later lava flows emerged from vents in the boca on the western side of the volcano.

Capulin Volcano lies near the center of the 20,000 km^2 (8,000 mi^2) Raton-Clayton volcanic field, which extends for more than 130 km (80 mi) between the cities of Raton and Clayton from which the field received its name. The volcanic field spans roughly the same distance north to south (see fig. 8 in “Geologic Features and Processes” chapter).

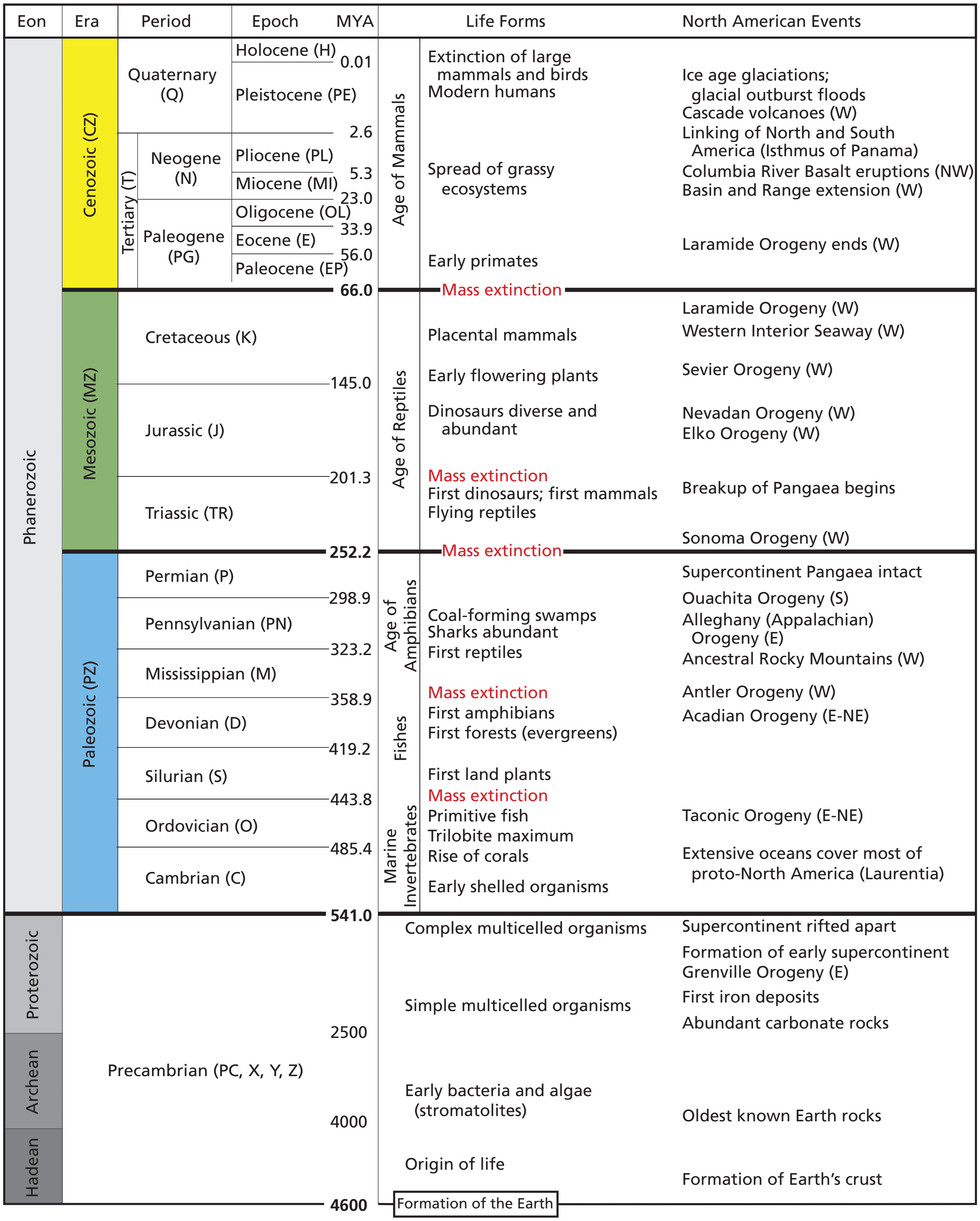
The Raton-Clayton volcanic field erupted in three phases: (1) Raton phase, which had two distinct episodes (9.0 million–7.3 million years ago and 5.6–3.5 million years ago); (2) Clayton phase (3.0 million–2.2 million years ago); and (3) Capulin phase (1.69 million–32,000 years ago) (Stroud 1997; Zimmerman 2015). Formally named rock units—Raton, Clayton, and Capulin basalts—correlate to these phases (Scott et al. 1990).

The eruption of Capulin Volcano occurred about 55,000 years ago (Pleistocene Epoch; fig. 3) toward the end of the most recent phase of volcanism in the Raton-Clayton volcanic field. Hills, peaks, and other features both younger and older than Capulin Volcano formed as a result of regional volcanic activity. These features can be seen from the Crater Rim Trail. The largest of these features is Sierra Grande, an extinct volcano rising 670 m (2,200 ft) above the surrounding plain to the southeast of Capulin Volcano. To the northwest, mesas such as Johnson Mesa are capped with some of the oldest lava in the field.

The Raton-Clayton volcanic field occurs on the Jemez lineament (fig. 4)—a southwest-to-northeast–oriented zone of weakness in Earth’s crust where recent (Pliocene–Pleistocene epochs; fig. 3) volcanic activity is concentrated. In New Mexico, this swath of volcanism incorporates the Raton-Clayton volcanic field, Ocaté volcanic field (see GRI report about Fort Union National Monument by KellerLynn 2012b), Mount Taylor, and the Zuni-Bandera volcanic field (see GRI report about El Malpais National Monument by KellerLynn 2012a). The most spectacular volcanic activity occurred where the Rio Grande rift intersects the lineament at Valles caldera (see GRI report about Bandelier National Monument by KellerLynn 2015). At this location, two huge, caldera-forming eruptions occurred 1.61 million and 1.25 million years ago, emplacing the famous Bandelier Tuff that dominates the landscape at Bandelier National Monument and is a “must see” for volcano enthusiasts.

The entrance to the Capulin Volcano National Monument is from New Mexico Highway 325, 5 km (3 mi) north of the town of Capulin (fig. 5). Highway 325 intersects US highway 64/87, which runs diagonally across the Raton-Clayton volcanic field. The High Plains environment, which is neither complicated by mountainous terrain nor obscured by forests, allows for broad views of volcanic features for travelers along the highway (Stormer 1994). In the past, the volcano served as a landmark along the Santa Fe Trail. The Cimarron Route of the trail runs to the south of the monument; the Mountain Route runs to the west (fig. 5).

On 9 August 1916, President Woodrow Wilson proclaimed Capulin Mountain as a national monument, applying the 1906 Act for the Preservation of American Antiquities (“Antiquities Act”). This milestone legislation gives the president the power to set aside and protect as a national monument any federal lands deemed historically or scientifically important. The proclamation states that Capulin Mountain is “a striking



Eon	Era	Period	Epoch	MYA		Life Forms	North American Events
Phanerozoic	Cenozoic (CZ)	Quaternary (Q)	Holocene (H)	0.01	Age of Mammals	Extinction of large mammals and birds Modern humans	Ice age glaciations; glacial outburst floods Cascade volcanoes (W)
			Pleistocene (PE)	2.6			Linking of North and South America (Isthmus of Panama)
		Tertiary (T) Neogene (N)	Pliocene (PL)	5.3		Spread of grassy ecosystems	Columbia River Basalt eruptions (NW)
			Miocene (MI)	23.0			Basin and Range extension (W)
		Paleogene (PG)	Oligocene (OL)	33.9			
			Eocene (E)	56.0			Laramide Orogeny ends (W)
			Paleocene (EP)	66.0		Early primates Mass extinction	
	Mesozoic (MZ)	Cretaceous (K)		145.0	Age of Reptiles	Placental mammals Early flowering plants	Laramide Orogeny (W) Western Interior Seaway (W) Sevier Orogeny (W)
		Jurassic (J)		201.3		Dinosaurs diverse and abundant	Nevadan Orogeny (W) Elko Orogeny (W)
		Triassic (TR)		252.2		Mass extinction First dinosaurs; first mammals Flying reptiles Mass extinction	Breakup of Pangaea begins Sonoma Orogeny (W)
	Paleozoic (PZ)	Permian (P)		298.9	Age of Amphibians		Supercontinent Pangaea intact Ouachita Orogeny (S)
		Pennsylvanian (PN)		323.2		Coal-forming swamps Sharks abundant First reptiles	Alleghany (Appalachian) Orogeny (E) Ancestral Rocky Mountains (W)
		Mississippian (M)		358.9			
		Devonian (D)		419.2	Fishes	Mass extinction First amphibians First forests (evergreens)	Antler Orogeny (W) Acadian Orogeny (E-NE)
		Silurian (S)		443.8		First land plants Mass extinction	
		Ordovician (O)		485.4	Marine Invertebrates	Primitive fish Trilobite maximum Rise of corals	Taconic Orogeny (E-NE)
		Cambrian (C)		541.0		Early shelled organisms	Extensive oceans cover most of proto-North America (Laurentia)
Proterozoic		Precambrian (PC, X, Y, Z)		2500		Complex multicelled organisms Simple multicelled organisms	Supercontinent rifted apart Formation of early supercontinent Grenville Orogeny (E) First iron deposits Abundant carbonate rocks
Archean				4000		Early bacteria and algae (stromatolites)	Oldest known Earth rocks
Hadean				4600		Origin of life Formation of the Earth	Formation of Earth's crust

Figure 3. Geologic time scale. The divisions of the geologic time scale are organized stratigraphically, with the oldest divisions at the bottom and the youngest at the top. Capulin Volcano National Monument is entirely covered by a single rock formation, Capulin Basalt. All volcanic activity at the monument took place during the Pleistocene Epoch, about 55,000 years ago. Volcanic activity in the Raton-Clayton volcanic field began during the Miocene Epoch, about 9 million years ago. GRI map abbreviations for each time division are in parentheses. Compass directions in parentheses indicate the regional locations of events. Boundary ages are millions of years ago (MYA). National Park Service graphic using dates from the International Commission on Stratigraphy (http://www.stratigraphy.org/index.php/ics-chart-timescale; accessed 6 August 2015).

example of recent extinct volcanoes and is of great scientific and especially geologic interest.”

On 31 December 1987, the monument was redesignated “Capulin Volcano National Monument” to highlight its volcanic origin. In this report, the use of “Capulin Volcano” rather than “Capulin Mountain” reflects this change and volcanic significance. As a matter of interest and clarification, the word “capulin” is not related to volcanic processes, rather it is Spanish for chokecherry (*Prunus virginiana*), which grows well in the region and is present in the monument, including the crater of Capulin Volcano.

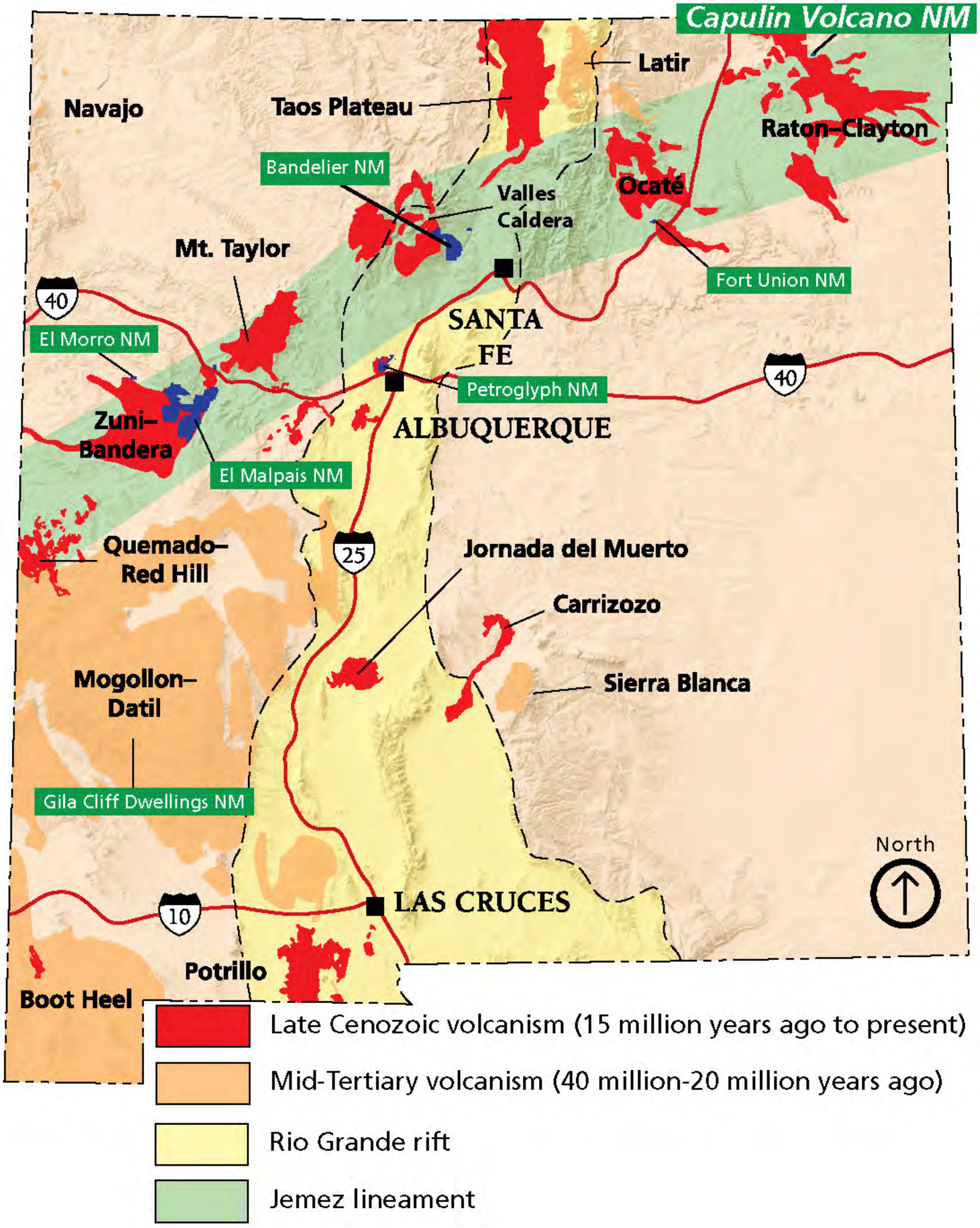


Figure 4 (facing page). Map of major volcanic fields in New Mexico. Capulin Volcano National Monument is in the Raton-Clayton volcanic field in northeastern New Mexico. This and many other volcanic fields lie on the Jemez lineament, a zone of crustal weakness and concentrated volcanism that runs across the state. 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 Jemez Mountains volcanic field; Valles caldera lies near the center of this field. Fort Union National Monument is surrounded by the Ocaté volcanic field. The north–south-oriented Rio Grande rift intersects the Jemez lineament near Valles caldera. Earth's crust is pulling apart along this rift. Petroglyph National Monument lies in the Rio Grande rift near Albuquerque. New Mexico Bureau of Geology and Mineral Resources graphic, modified by Philip Reiker (NPS Geologic Resources Division).

Figure 5. Regional map. Capulin Volcano National Monument is in the northeastern corner of New Mexico. US highway 64/87 provides a scenic drive through this part of the country. When the Santa Fe Trail was in use as a transportation route (1821–1880), Capulin Volcano served as a landmark. The Mountain Route of the Santa Fe Trail is north of the monument; the Cimarron Route is south of the monument. National Park Service graphic, available at http://www.nps.gov/hfc/cfm/carto-atoz.cfm (accessed 10 October 2014).

Geologic Features and Processes

This chapter describes noteworthy geologic features and processes in Capulin Volcano National Monument.

During the 2011 scoping meeting (see KellerLynn 2011) participants (see Appendix A) identified the following geologic features and processes:

- Volcanic Rocks and Volcanoes
- Capulin Basalt
- Raton-Clayton Volcanic Field
- Capulin Volcano
- Volcanic Features
- Age of Capulin Volcano
- View from Capulin Volcano
- Playa Lakes
- Aeolian Features
- K-T Boundary
- Paleontological Resources

Figure 6. Photograph of Capulin Basalt. Basalt covers the landscape of Capulin Volcano National Monument. The summit of Capulin Volcano at 2,494 m (8,182 ft) above sea level appears in the background of the photograph. National Park Service photograph available at http://www.nps.gov/storage/images/cavo/Webpages/originals/361.jpg (accessed 6 October 2014).

Volcanic Rocks and Volcanoes

A single, formally named, rock unit—Capulin Basalt (see "Capulin Basalt" section)—covers Capulin Volcano National Monument (fig. 6). All volcanic features within the monument are composed of Capulin Basalt. Capulin Basalt originated as magma (molten rock) beneath the surface, traveled through preexisting rocks of Earth's crust, then extruded out of vents (openings at Earth's surface through which magma erupts or volcanic gases are emitted). Once at the surface, magma, now referred to as lava, formed volcanoes, lava flows, and other volcanic features (see "Volcanic Features" section).

Basalt is an extrusive igneous rock, which by definition contains 52% or less of silica (silicon dioxide, SiO_2) (table 1). The amount of silica assigned to a category of volcanic rock may vary depending on whether rhyodacite and basaltic andesite, for example, are included in an investigation's classification scheme. The amount of silica influences many properties of magma, including viscosity (internal friction) and explosiveness. In general, lavas with more silica are more viscous and more explosive. Flows of andesite (57%–63% SiO_2) and dacite (63%–68% SiO_2), for example, tend to be thick and sluggish, traveling only short distances from a vent. Lavas of dacite and rhyodacite (68%–72% SiO_2) commonly squeeze out of a vent to form irregular mounds or lava domes. Red Mountain, which is composed of the formally named Red Mountain Dacite (Collins 1949; Scott et al. 1990), is a dome. This dome sits atop Johnson Mesa, northwest of Capulin Volcano. By contrast, basalt forms lava flows that spread out in broad, thin sheets up to several kilometers wide. Repeated eruptions of basaltic flows in a volcanic field may build a shield volcano (fig. 7). Individual basaltic eruptions commonly form cinder cones, such as beautiful Capulin Volcano (see "Capulin Volcano" section). Notably, eruptions of basalt, though lower in silica content than andesite or dacite, can be spectacular, with fire fountains jetting upwards to 900 m (3,000 ft) above the ground. These features are typical of Hawaiian–style basaltic volcanism (Dunbar 2010; see GRI report about Hawaii Volcanoes National Park by Thornberry-Ehrlich 2009).

The most explosive volcanoes on Earth are generally rhyolitic (>72% SiO_2). After an eruption of rhyolite,

Table 1. Classification and characteristics of volcanic rocks

Rock Name:	Rhyolite	Rhyodacite	Dacite	Andesite	Basaltic Andesite	Basalt
Silica (SiO_2) content[1]	>72%	68%–72%	63%–68%	57%–63%	52%–57%	<52%
Color	Lighter					Darker
Viscosity of magma	Thick (less mobile flows)					Fluid (more mobile flows)
Typical style of eruption	Explosive					Effusive
Eruption temperature[2]	Cooler, 800°C (1,500°F)					Hotter, 1,160°C (2,120°F)

[1] Silica percentages from Clynne and Muffler (2010). [2] Eruption temperatures from Price (2010).

volcano edifices often do not look like volcanoes because the eruptions are so explosive that the volcano ends up collapsing in on itself, forming a caldera. The eruption that formed Valles caldera was this type (see GRI report about Bandelier National Monument by KellerLynn 2015). It is the oldest of three young caldera-forming volcanoes in the United States; the others are Yellowstone in Wyoming and Long Valley in California (US Geological Survey 2014). In addition, the Bursum and Gila Cliff Dwellings calderas, which surround Gila Cliff Dwellings National Monument in New Mexico (see GRI report by KellerLynn 2014a), are the result of rhyolitic explosions about 28 million years ago.

The four major types of volcanoes are (1) cinder cones, (2) shield volcanoes, (3) stratovolcanoes (also called composite volcanoes), and (4) lava domes (fig. 7). Of interest for the National Park System, Lassen Volcanic National Monument in California contains all four primary types of volcanoes (see GRI report by KellerLynn 2014b). A combination of physical attributes—such as size, shape, slope angle, type and composition of volcanic materials, and eruption style—determine the type of a particular volcano. These types provide a system for classification and a means for understanding and communication. In reality, volcanoes occur in a continuum of sizes and shapes and have a variety of origins (Michael Clynne, US Geological Survey, research geologist, written communication, 21 November 2013).

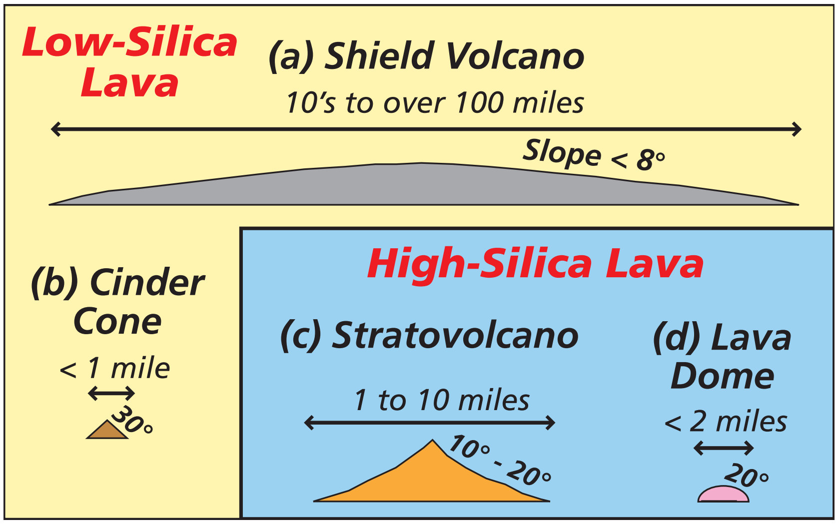


Figure 7. Schematic illustration of volcano types. The size and shape of volcanoes are influenced by the amount of silica and gas in the erupting lava. Low-silica lavas, such as basalt, produce broad shield volcanoes (a). If basaltic lava has a lot of gas, a central vent may erupt like a fire hose, forming a cinder cone (b). Higher silica lavas, andesite to rhyolite, form composite volcanoes, also called "stratovolcanoes" (c). Lava domes form around a vent that erupts high-silica lava such as dacite (d). Graphic by Jason Kenworthy (NPS Geologic Resources Division) after Lillie (2005, figure 2.18).

Capulin Basalt

Capulin Volcano National Monument is composed of a single rock unit—Capulin Basalt—which Collins (1949) originally mapped and identified, Baldwin and Muehlberger (1959) mapped in greater detail, and Scott et al. (1990) formally named. Technically, Capulin Basalt is a “trachybasalt” (Sayre and Ort 1999), meaning it has more abundant alkali elements, such as sodium and potassium, than true basalt. For simplicity, this report refers to the volcanic rock of Capulin Volcano as “basalt.”

Capulin Basalt contains a relatively high percentage of silica for a basalt (50%–55%; Sayre and Ort 1999). It owes this higher amount to the presence of quartz grains. The mineral quartz, which is composed entirely of silica, was derived from sedimentary rocks (e.g., Dakota Sandstone) that underlie Capulin Volcano. As the volcano erupted, magma traveled through these rocks before reaching the surface, picking up silica on the way.

The presence of Dakota Sandstone xenoliths (foreign rock fragments) and xenocrysts (foreign crystals, much smaller than xenoliths) is a characteristic feature of Capulin Basalt at the monument and surrounding area (Sayre and Ort 1999). Xenoliths may have come from the sides of a magma chamber, walls of an erupting lava conduit, or the base of a lava flow. Xenocrysts did not crystallize from the host magma and may be fragments of xenoliths. Xenoliths and xenocrysts can provide important information about the composition of Earth’s mantle, which is generally inaccessible. The ones in Capulin Basalt, however, are from the upper crust (KellerLynn 2011).

Raton-Clayton Volcanic Field

Capulin Volcano National Monument is part of the large, long-lived Raton-Clayton volcanic field, which is mostly in northeastern New Mexico but also southeastern Colorado and the panhandle of Oklahoma (fig. 8). Notably, Mesa de Maya (Black Mesa), which erupted during the Clayton phase (Luedke and Smith 1978), is in Colorado, New Mexico, and Oklahoma. The mesa is the highest point in Oklahoma, 1,516 m (4,973 ft) above sea level.

The 20,000-km^2 (8,000-mi^2) volcanic field has been active episodically for the past 9 million years. Using petrology, geochemistry, and both relative and isotopic dating methods, investigators have divided the field’s volcanic activity into three phases: (1) Raton phase, which had two distinct episodes (9.0 million–7.3 million years ago and 5.6–3.5 million years ago); (2) Clayton phase (3.0 million–2.2 million years ago); and (3) Capulin phase (1.69 million–32,000 years ago). The Capulin phase includes the eruption that created Capulin Volcano (see “Geologic History” chapter).

Most of the volcanoes that were active in the Raton phase are on the western side of the volcanic field near the town of Raton. The lava flows and volcanoes of the Clayton phase span north to south, from Mesa de Maya in Colorado to the Yates flows south of Gladstone. Capulin phase features are clustered in the central part of the field in the vicinity of the towns of Capulin and Folsom (fig. 8).

The Raton-Clayton volcanic field consists of an estimated 125 volcanic vents (Dunbar 2005). These vents extruded primarily basaltic lava and produced mainly lava flows and cinder cones. One of the distinctive characteristics of the Raton-Clayton volcanic field is the presence of lavas with silica contents as low as 35% (Stormer 1994). The field also contains volcanoes, such as Sierra Grande, that erupted andesite, dacite, and rhyodacite; that is, lavas with up to 70% silica (Aubele and Crumpler 2001). This range of silica compositions is noteworthy, and the Raton-Clayton volcanic field is arguably the most chemically and mineralogically diverse volcanic field in the United States (Stormer 1994).

Another interesting characteristic of the Raton-Clayton volcanic field is its low volumetric eruption rate, which is interpreted as evidence for relatively small amounts of melting in the underlying mantle over extended periods of time (hundreds of thousands to millions of years) (Crumpler et al. 1992; Aubele and Crumpler 2001). As a result, discrete batches of magma worked their way to the surface, ultimately resulting in a series of isolated eruptions that are petrologically unrelated to surrounding eruptions (Aubele and Crumpler 2001).

Inverted topography is another notable characteristic of the Raton-Clayton volcanic field (fig. 9). Lava flows, particularly those from the Raton phase, initially spread down river valleys (or other topographic lows) before solidifying. The valley walls (or other topographic highs) were composed of softer sedimentary rock—such as the Raton Formation (see “K-T Boundary” section) and the Ogallala Formation (composed of sediments shed from the uplifting Rocky Mountains)—and eroded more quickly than the harder lava in the valleys. Additionally, the resistant cap of lava protected the softer, underlying rock from wind and rain erosion. As a result, valleys into which the lava once flowed

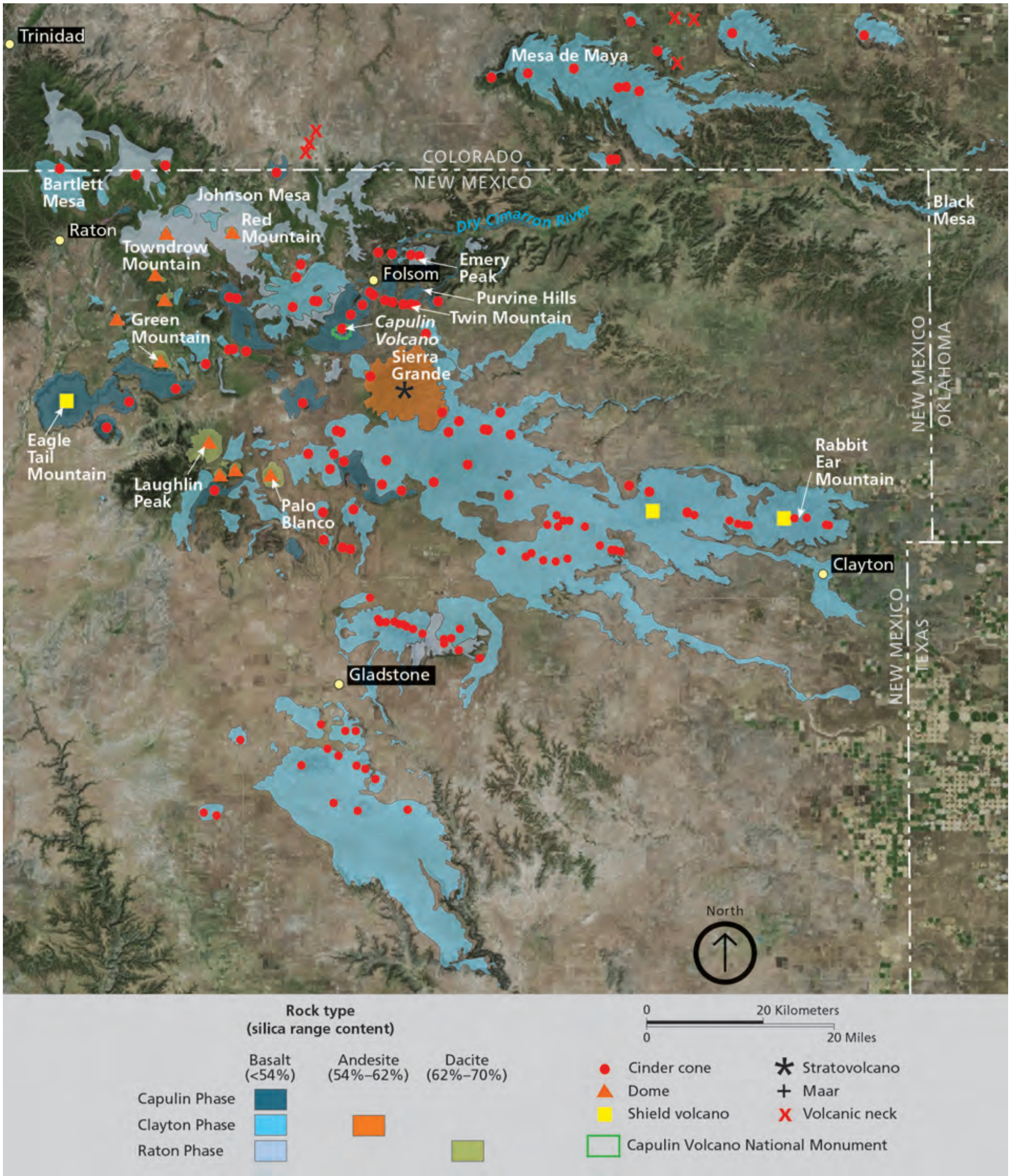


Figure 8. Map of Raton-Clayton volcanic field. The volcanic field, which is primarily in New Mexico but also has vents and/or lava flows in Colorado and Oklahoma, erupted episodically in three phases: Raton (9.0 million–3.5 million years ago), Clayton (3.0 million–2.2 million years ago), and Capulin (1.69 million–32,000 years ago). Basalt was deposited during each of these phases. Capulin Volcano erupted 55,000 ± 2,000 years ago during the Capulin phase. Sierra Grande—which is the largest volcano in the volcanic field—erupted 3.8 million–2.6 million years ago, overlapping in time with the Raton and Clayton phases. Andesite erupted at Sierra Grande. The formally named Red Mountain Dacite, which occurs in scattered lava domes such as Red Mountain, Green Mountain, and Palo Blanco, was deposited about 7 million years ago during the Raton phase. Graphic by Trista Thornberry-Ehrlich (Colorado State University) after Luedke and Smith (1978, plate 2), Crumpler and Audele (2008, online map), and Price (2010, p. 315). Silica range content is from Luedke and Smith (1978, plate 2).

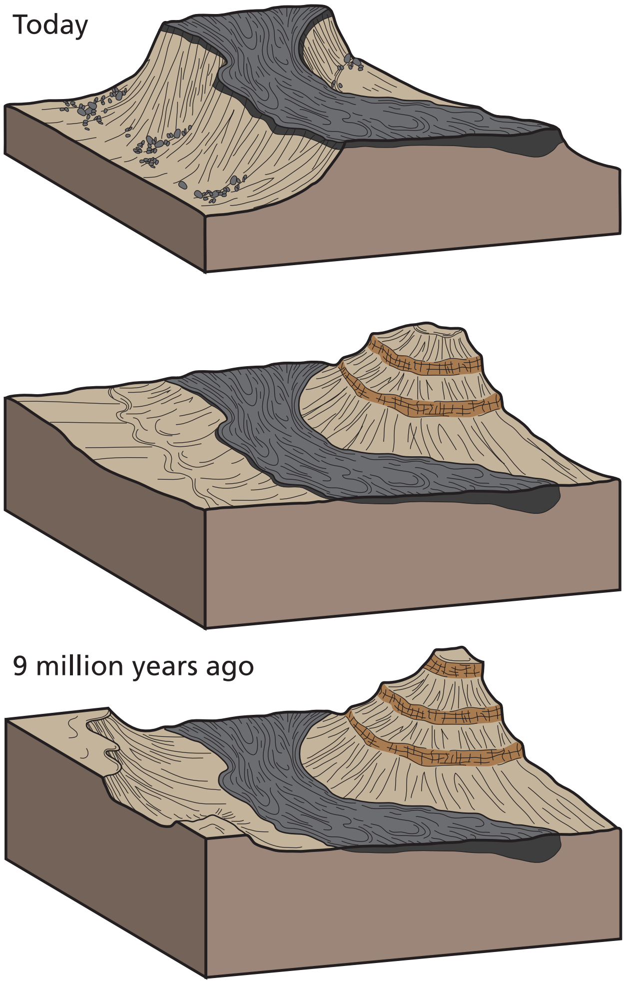


Figure 9. Schematic illustrations of the formation of inverted topography. Many of the lava flows in the Raton-Clayton volcanic field initially occupied stream valleys or other topographically low areas (9 million years ago, lower graphic). The hardened lava was more resistant to erosion than the valley walls, and it protected the underlying soft sandstone and shale from wind and rain erosion (middle graphic). Today, stream valleys in which the lava once flowed stand as high mesas above modern valleys (upper graphic). Graphic by Trista Thornberry-Ehrlich after Muehlberger et al. (2005, p. 4).

now stand as high mesas (fig. 9). These lava-capped mesas include Johnson, Bartlett, Barella, Horse, Kiowa, and Kelleher mesas, and Mesa Larga and Mesa de Maya or Black Mesa (Aubele and Crumpler 2001). Several of these are visible from the summit of Capulin Volcano (see “View from Capulin Volcano” section). To the northwest, Johnson Mesa is capped by an approximately 8-million-year-old lava flow. Mesa de Maya is covered by 5-million-year-old lava and marks the northeastern margin of the volcanic field (fig. 8).

Capulin Volcano

“Cinder cones,” as the name suggests, are conical hills built from fragments of ejected lava called cinders (fig. 10). In the scheme of classic volcano types (fig. 7), cinder cones are relatively small, usually less than 300 m (1,000 ft) high. Capulin Volcano exceeds this general range by about 90 m (300 ft). In terms of geologic time, the formation of cinder cones happens quickly. Capulin Volcano, for example, built up over a period of weeks to years (Sayre and Ort 1999). During the eruption, cinders fountained high into the air, perhaps as high as 500 m (1,600 ft), and fell back to the ground around the vent, creating a pile of cinders and other pyroclastic material (rock fragments formed by volcanic explosion or aerial expulsion from a vent). Because unconsolidated pyroclastic materials such as cinders maintain a high angle of repose (30°–40°), volcanoes of this type have very steep slopes. Where the buildup of cinders exceeds the angle of repose, they avalanche downslope, creating a layered deposit (fig. 11). The inclined layers that make up Capulin Volcano are beautifully exposed along Volcano Road (fig. 12). Each layer represents an episode in the cone-building eruption.

Although mostly composed of cinders, the deposits of Capulin Volcano contain other pyroclasts such as ash (fine-grained material), pumiceous material (with vesicles [“gas bubbles”]), bombs (viscous material,

Figure 10. Photograph of cinders. Capulin Volcano is composed primarily of cinders—glassy, vesicular, pyroclastic fragments that explode from a vent then fall to the ground in an essentially solid condition. The large, triangular, red cinder (arrow) is approximately 4 cm (1.5 in) long. Photograph by Katie KellerLynn (Colorado State University).

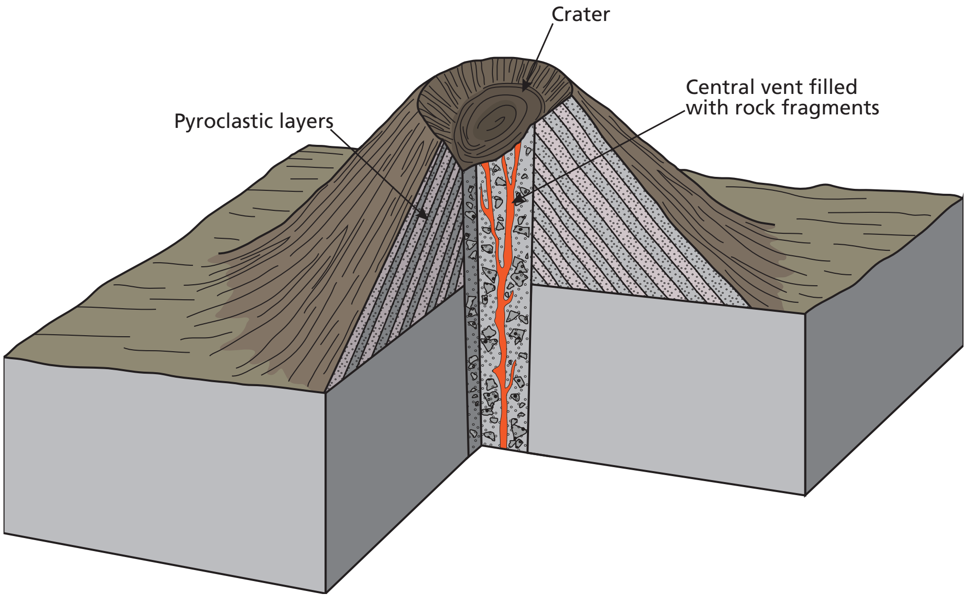


Figure 11. Schematic illustration of a cinder cone. Cinder cones are built from ejected lava fragments. Inclined pyroclastic layers show where the angle of repose was exceeded and cinder tumbled down the slope. Most cinder cones have a bowl-shaped crater at the summit. Graphic by Trista Thornberry-Ehrlich (Colorado State University) after Lutgens and Tarbuck (1992, figure 4.9).

Figure 12. Photographs of exposures along Volcano Road. During the cone-building eruption, layer upon layer of cinders and other pyroclastic material erupted into the air and fell to the surface around a central vent, constructing the cinder cone. Thin layers of ash separate the layers of cinders. Top: US Geological Survey photograph available at http://3dparks.wr.usgs.gov/cavo/html2/capu21.htm (accessed 2 October 2014). Bottom: National Park Service photograph by Ally Buccanero available at http://www.nps.gov/cavo/planyourvisit/auto-touring.htm (accessed 10 October 2014).

Figure 13. Photograph of a bomb. Bombs ejected out of a vent are 64 mm (2.5 in) or more in diameter and have a hollow or vesicular interior. They are viscous pyroclasts, shaped while in flight. This one is exposed in a layer of welded cinders along Volcano Road. Photograph by Katie KellerLynn (Colorado State University).

Figure 14. Photograph a block along Volcano Road. Blocks are ejected in a solid state. This block (arrow) is an estimated 2 m (6 ft) long. Photograph by Katie KellerLynn (Colorado State University).

greater than 64 mm [2.5 in] across, ejected then shaped while in flight; fig. 13), and blocks (material greater than 64 mm [2.5 in] across, ejected in a solid state; fig. 14). Bombs were deposited up to 1 km (0.6 mi) from the vent. Pullouts on Volcano Road are excellent places to see bombs that landed on cinder beds or became embedded within welded (consolidated or compacted) cinders. Closer to the rim and vent, pyroclastic materials are commonly welded (KellerLynn 2011).

In eruptions like Capulin Volcano, magmatic gases provide some force to help launch lava skyward, but breaking of the lava into cinders tends to happen passively in the air (Sayre and Ort 1999). By comparison, in eruptions of higher silica magmas, magmatic gases provide explosive force and break the magma into pieces, forming pumice.

The cinder-cone eruption ceased when magmatic gases tapered off, resulting in less pressure to send the lava flying into the air. As the eruptive column decreased in height, cinders changed to spatter (larger pieces of lava, heavier and with less gas pressure behind them leading to less airtime for cooling), forming the spatter rampart that protects the rim and coats the inside of the cinder cone.

Twenty-four spatter deposits and one spatter flow) are part of the GRI GIS data set (see Map Unit Properties Table and volcanic features map, in pocket). These spatter deposits, however, were mapped in the boca (mouth of the volcano), and not shown as part of the cinder cone itself.

Volcanic Features

In addition to Capulin Volcano, Richman (2010)—the source map for the GRI GIS data set—included the following volcanic features: two boca ramparts), 16 lava cascades, 19 lava lakes, 15 lava levees, 18 lava ridges, one pooled lava flow one push-up, two rafted cinder cones, 24 spatter deposits, one spatter flow, 23 squeeze-ups, and 18 tumuli (see Map Unit Properties Table and volcanic features map, in pocket). With the exception of the pooled lava flow east of the main cone, all of these features occur on the western side of the volcano in the boca, which Richman (2010) mapped in detail. In addition, the GRI GIS data set identifies seven vents: four within Capulin Volcano National Monument, two at Mud Hill, and one at Baby Capulin.

The following descriptions of these volcanic features/map units were compiled using Mathis (1999), Sayre and Ort (1999), Dektor (2007), and Richman (2010).

Boca Rampart

Eruptions that occur on the flanks or at the base of a cinder cone are referred to as coming from the boca, meaning “mouth” in Spanish. Capulin Volcano’s boca is the area on the western side of the cone where volcanic activity was concentrated following the cone-building eruption. Because activity shifted to the boca, the cinder cone was never breached, and its classic shape was preserved (KellerLynn 2011). Lava for the Second Series, Third Series, and Fourth Series flows emanated from vents in the boca (Sayre and Ort 1999).

Boca eruptions are commonly associated with cinder-cone eruptions. Capulin Volcano's boca, however, is more complex than most. The boca rampart is a massive feature created by the accumulation of other features such as lava levees, lava lakes, and lava tubes (Richman 2010). The surface level of the boca varied throughout the eruption: as some lava flows built up, others would drag portions of the boca away. The features in the boca today are the last things to have developed, or represent rocks that were not carried away by flowing lava. For example, the southern and western walls of the boca formed when lava flows spread out from a vent. These rubbly walls of rock were left behind when the lava flow either receded, stopped, or was redirected. The walls served as margins that contained lava lakes and through which lava cascaded. Variations in topography and landforms of today's boca make it an ideal place to visualize complex processes that occurred as lava erupted (Mathis 1999).

Lava

As delineated by Richman (2010), the lava map unit represents solidified lava flows; that is, a lateral, surficial outpouring of molten rock from a vent or fissure. A distinctive characteristic of the lava flows associated with Capulin Volcano are pressure ridges—elongate, usually arcuate ridges formed on the congealed crust of a lava flow. Pressure ridges form under lateral compression or where blocky lava is forced to pile up. The ridges are generally perpendicular to the direction of flow and are convex downstream. Pressure ridges are visible on a Second Series flow lobe, south of Capulin Volcano (fig. 15).

Lava Cascade

Lava cascades resemble fluvial features or "rivers of stone" (Mathis 1999, p. 53). They form as fluid, incandescent lava passes over a cliff or other precipitous segment along the course of a lava flow. These features occur where lava cascaded through the boca wall or between lava levees in the boca. They are shown as line features on the digital geologic map (Richman 2010; see volcanic features map, in pocket).

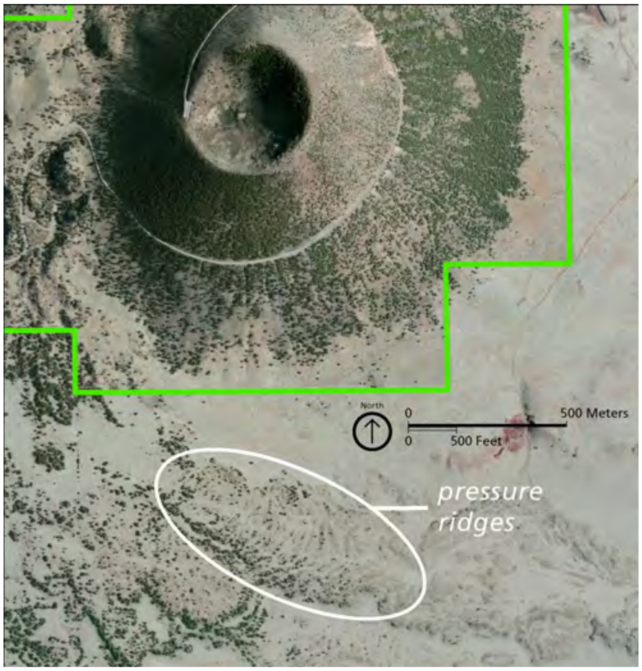


Figure 15. Satellite imagery of pressure ridges and cinder cone. Second Series lava flows south of Capulin Volcano have prominent pressure ridges, which formed at the time of the eruption. Graphic compiled and annotated by Jason Kenworthy (NPS Geologic Resources Division). Aerial imagery from ArcGIS "World Imagery" basemap using data from Esri, DigitalGlobe, GeoEye, i-cubed, USDA, USGS, AEX, Getmapping, Aerogrid, IGN, IGP, swisstopo, and the GIS User Community.

Lava Lake

During an eruption, a lava lake consists of molten lava pooled within a depression or low area, including a volcano's crater. As bubbles of gas burst through the surface of a lake, spatter is deposited on surrounding "banks" (see "Spatter Deposit" section). Additionally, lava lakes may show evidence of having swirled like a whirlpool.

The boca at Capulin Volcano contains 19 lava lakes, which are topographically recognizable as flat areas. Lava lakes also occur in the Second Series and Third Series lava flows (Dektor 2007). They were not all active at the same time.

The flatness and accessibility of one solidified lava lake in the boca prompted the National Park Service to use it as a campground (fig. 16). Although the campground was closed in 1969, a stone fireplace remains, standing as a remnant of past use (fig. 17).

Figure 16. Photograph of lava lake. A lake of pooled lava now appears as a flat, grassy area (oval) in the boca at Capulin Volcano National Monument. In the 1930s–1960s, the flat area hosted a campground. Photograph from Sayre and Ort (1999, figure 14) available at http://geoinfo.nmt.edu/publications/openfile/downloads/OFR500-599/526-550/541/ofr_541.pdf (accessed 29 October 2014).

Figure 17. Photograph of stone fireplace. Perhaps unbeknown to its builders in 1934, the stone fireplace was constructed in an ancient lava lake, which provided a flat area for a campground. The campground closed in 1969, but the fireplace still stands. National Park Service photograph from Cordero (2011, front cover).

Other than this fireplace, human-constructed features using local basalt are rare at Capulin Volcano National Monument. Cordero (2011) documented one other potentially historical (or possibly modern) feature at the monument—a rock wall composed of dry-laid, local, basalt cobbles. No artifacts are associated with the wall, so neither its age nor cultural affiliation could be established with any degree of certainty. The wall probably represents an episode of single use, but its function is unclear (Cordero 2011).

Lava Levee

Named for their similarity to fluvial levees, a lava levee is the chilled margin along an actively flowing "stream" of lava. Levees increase in height as a result of periodic overflow, and may be left higher than the surface of a lava flow when flow in the lava channel decreases. They are broad, low embankments on the side of a lava flow.

Lava Ridge

Richman (2010) mapped 18 lava ridges in Capulin Volcano's boca (see volcanic features map, in pocket). They are rocky features with a linear form similar to levee boundaries, but according to Richman (2010), ridges do not create a definable area of raised levees or spatter deposits.

Pooled Lava Flow

Sayre and Ort (1999) identified a feature that they referred to as a "pooled lava flow" on the eastern boundary of Capulin Volcano National Monument. Investigation by Richman (2010) revealed a lava feature in this general area, which was mapped as part of the First Series lava flows, and as such, would have been emplaced at the time of the cone-building eruption. It is not clear, however, if this feature was what Sayre and Ort (1999) were referring to as a "pooled lava flow" (Richman 2010).

Push-Up

A push-up is a hardened surface of a lava flow that has been pushed up from below and tilted by molten lava within a lava flow. Richman (2010) mapped one push-up on the eastern edge of the boca, above a levee feature.

Rafted Cinder Cone

Two rafted cinder cones occur in the boca. They now appear as hills composed of cinders resting at their angle of repose. They were parts of the main cinder cone that were carried away by flowing lava. They comprise the highest elevations in the boca.

Spatter Deposit

A spatter deposit is an accumulation of fluid pyroclasts that coats the surface around a vent or above a crack in the crust of a lava flow. A spatter deposit also may form as gas bubbles burst through a magma body, such as a lava lake. Spatter may build into small mounds or chimneylike spires, called spatter cones or hornitos (Spanish for "little oven"). At Capulin Volcano, spatter deposits coat the entire inside of the crater (Sayre and Ort 1999). Richman (2010) mapped 24 spatter deposits throughout the boca; they are irregular low rocky hills and mounds.

Spatter Flow

A spatter flow is a lava flow that originates as an accumulation of spatter but is hot and fluid enough to flow under its own weight. Richman (2010) mapped one spatter flow in the boca. Spatter flows also occur at the rim of Capulin Volcano (Sayre and Ort 1999).

Squeeze-Up and Tumulus

The GRI GIS data set includes 23 squeeze-ups (an accumulation of lava "squeezed up" through a crack in the surface of a lava flow; fig. 18) and 18 tumuli (doming up of a lava flow surface; fig. 19). Identification of a squeeze-up vs. a tumulus in the field is subjective, but based on the descriptions provided by Mathis (1999), Richman (2010) apparently mapped linear-shaped features as squeeze-ups whereas bulbous-shaped mounds were mapped as tumulus (see volcanic features map, in pocket). As such, these map units were categorized based on shape rather than genesis. Glossary of Geology (Neuendorf et al. 2005) defines squeeze-ups, not tumuli, as forming by extrusion of lava onto the surface of a flow. Tumuli result from buckling of the flow crust, aided by pressure of the underlying liquid lava.

Vent

A vent is an opening at Earth's surface through which volcanic materials explode, spatter, burst, or spill onto the surface. The GRI GIS data set shows seven vents: four are within the monument—one northeast of the main cone, one within the main cone, and two in the boca (see lava flow series map, in pocket). The two vents in the boca, one north and one south, are surrounded by spatter deposits built into ramparts. These are places where lava poured out and fed the lava flows on that side of the volcano (Michael Ort, Northern Arizona University, professor, email communication to Stephanie O'Meara, Colorado State University, geologist/GIS specialist/data manager, 6 November 2014). In the GRI GIS data set, the Capulin Volcano vent and the two vents in the boca consist of map units and point features. The other four vents are point features.

Figure 18. Photograph of a squeeze-up. This linear squeeze-up is displayed prominently in the picnic area of Capulin Volcano National Monument. Bulbous-shaped features were mapped as tumuli. Photograph from Sayre and Ort (1999, figure 10) available at http://geoinfo.nmt.edu/publications/openfile/downloads/OFR500-599/526-550/541/ofr_541.pdf (accessed 29 October 2014).

Figure 19. Photograph of a tumulus. Richman (2010) mapped this feature on the Nature Trail, next to the visitor center, as a tumulus (bulbous-shaped mound of lava). Linear-shaped features were mapped as squeeze-ups. Photograph by Shirley Lael from Huner and Lael (2003, figure 1.4).

Figure 20. Photograph of the Capulin Volcano vent. During the cone-building eruption, cinders and other pyroclasts were blasted upward from the vent of Capulin Volcano. Today, the vent is covered by volcanic rocks eroded from the crater walls. Photograph by Katie KellerLynn (Colorado State University).

Volcanic activity at Capulin Volcano started along a fissure or series of small vents (Sayre and Ort 1999). The vent northeast of the cinder cone is representative of this early eruptive phase (First Series). Eventually, extrusion of lava along this fissure or series of small vents coalesced into a single vent around which the Capulin Volcano cinder cone formed. This is the vent marked near the center of the main cone (Richman 2010). The vent for the cone-building eruption, located at the bottom of the crater, is now plugged and covered by blocks eroded from the crater (fig. 20; Mathis 1999).

After the cone-building eruption ceased, activity shifted to the boca, where lava oozed out of the side of the cinder cone and traveled south down a narrow valley through what is now the picnic area. Next, the southern vent in the boca began erupting, sending lava south with a westward component (Third Series). Finally, Fourth Series lava erupted from the northern vent in the boca, flowing north then between the main cone and Mud Hill (see lava flow series map, in pocket).

Age of Capulin Volcano

Capulin Volcano erupted 55,000 ± 2,000 years ago (Zimmerer et al. 2014; Zimmerer 2015). This age is a major revision from the originally published interpretation by Muehlberger (1955), which stated that Capulin Volcano erupted between 8000 BC and 2400 BC.

The idea that Capulin Volcano erupted less than 10,000 years ago was a part of scientific literature for many years. Notably, the original age estimate was not the result of analysis performed on Capulin Volcano rocks. As discussed below, Sayre et al. (1995) were the first to analyze rocks from Capulin Volcano to determine the volcano's age. The "less than 10,000-year-old age" was obtained through correlation with deposits at the well-known Folsom Site, which is 16 km (10 mi) from Capulin Volcano. Discovered in 1908 and excavated in 1926, the Folsom Site became a national historic landmark in 1961 (National Park Service 2014a). The site contains bones of an extinct bison (*Bison antiquus taylori*) and spear points in an alluvial deposit. The site is significant because of the direct association of projectile points with bison fossils, which pushed back the accepted timing that humans first arrived in the region (Cook 1927; Figgins 1927).

Bryan (1937) was the first to study the geology of the Folsom Site, and he identified two alluvial sequences, the lower of which is the Folsom occupation horizon. The lower alluvium has an age of 8000 BC; the upper alluvium has an age of 2400 BC (Muehlberger 1955). In the Dry Cimarron River valley, 14 km (9 mi) downstream from the Folsom Site, Muehlberger (1955) identified Capulin Basalt sandwiched between what he interpreted as Bryan's two alluvial deposits, thus deriving his original age estimate. Subsequent work by Anderson and Haynes (1979), however, identified several distinct alluvial deposits at the Folsom site (in addition to Byran's two), and concluded that the basalt flow in the Dry Cimarron valley overlies an alluvial sequence older than the Folsom occupation horizon (of 8000 BC). A baked organic soil from this horizon yielded an age of 22,360 ± 1,160 radiocarbon years before present (BP), or 25,091–27,442 calendar years

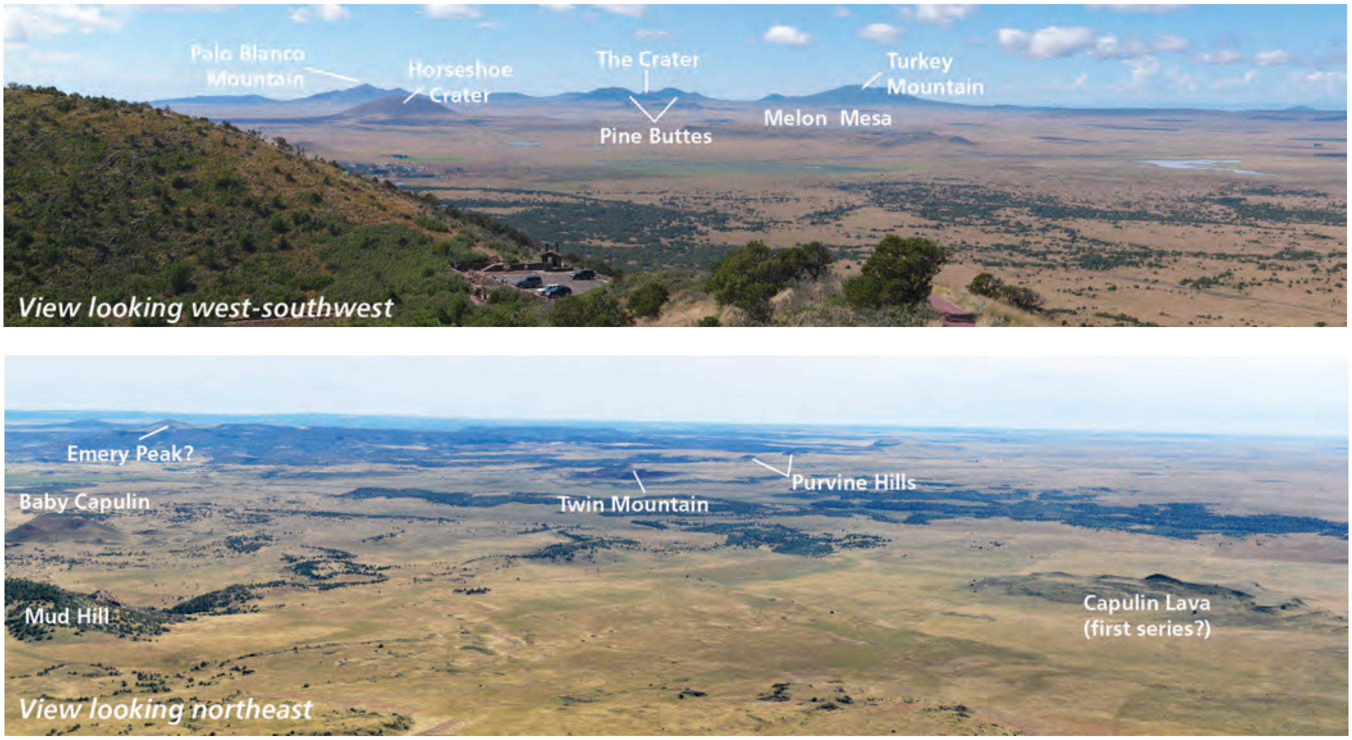


Figure 21. Panoramic views from Capulin Volcano. The summit of Capulin Volcano offers a 360° panoramic view. Both views shown here are from the Crater Rim Trail. Looking west-southwest (upper photograph), visitors can see some of the older volcanoes that are part of the Raton-Clayton volcanic field. The prominent rounded hill just beyond the town of Capulin is the 240,000 ± 7,000-year-old Horseshoe Crater. Note the playas in the middle ground of the photograph. Looking northeast (lower photograph), visitors can see Baby Capulin, which erupted 46,000 ± 4,000 years ago. The prominent quarry near the center of the photograph is the Twin Mountain volcano, which erupted 40,000 ± 4,000 year ago. The foreground contains the Capulin and Mud Hill lava flows. Photographs by Matthew Zimmerer (MattZPhotography, www.mattzphotography.com [accessed 11 September 2015], used with permission), processed using Adobe Lightroom and stitched together using Hugin.

ago or 25,776–23,540 BC (as calibrated using Stuiver et al. 2015). Thus the age of Capulin Volcano "became older" than originally interpreted. Furthermore, the age by Anderson and Haynes (1979) was a minimum age; the actual age could have been older due to contamination of the sample by modern plant material.

In 1995, W. O. Sayre and others analyzed rocks from Capulin Volcano to determine the volcano's age. They applied the cosmogenic helium technique, which is a useful method for dating young volcanic lava flows and provides information on how long a rock sample has been within 1 m (3 ft) of Earth's surface. These investigators selected a sample from the boca that yielded an age of 59,000 ± 6,000 (calendar) years old. In another study, Stroud (1997) used the argon-argon (Ar-Ar) technique to date four samples from various locations on the volcano that yielded a weighted average of 56,000 ± 8,000 years ago. These two studies—Sayre et al. (1995; cosmogenic helium) and Stroud (1997; Ar-Ar)—produced comparable dates, which also are consistent with the apparent state of erosion of cones of similar age throughout the Southwest (Aubele and Crumpler 2001).

Analytical improvements to the argon-40/argon-39 (^{40}Ar/^{39}Ar) dating technique provided another opportunity to date young volcanic rocks, to an unprecedented level of precision (Zimmerer et al. 2014). This recent study dated flows and cones in and surrounding Capulin Volcano National Monument, yielding a highly precise age of 55,000 ± 2,000 years ago for the eruption of Capulin Volcano (Zimmerer 2015).

View from Capulin Volcano

In the late 1930s and early 1940s, Homer Farr, the custodian of Capulin Mountain National Monument from 1923 to 1955, wrote many letters to the superintendent of the Southwestern National

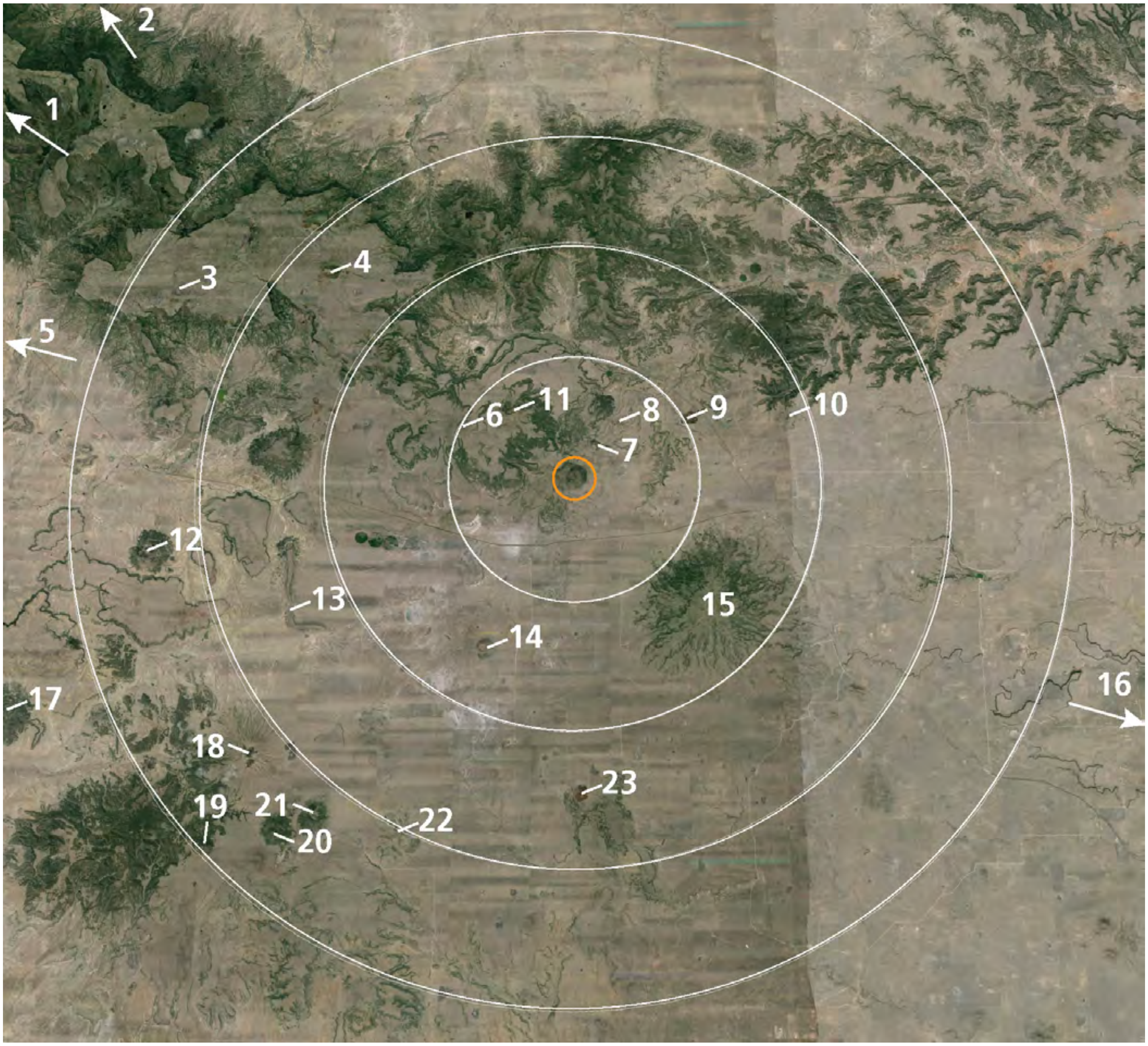


Figure 22. Satellite imagery with landmarks around Capulin Volcano. From the summit of Capulin Volcano (orange circle), visitors can see for miles on a clear day. White circles represent 5-mile increments from Capulin Volcano. Geographic points of interest include the following: 1. West Spanish Peak, 4,148 m (13,610 ft). 2. Greenhorn Mountain, 3,764 m (12,349 ft). 3. Towndrow Peak, 2,624 m (8,609 ft). 4. Red Mountain, 2,574 m (8,445 ft). 5. Culebra Range of the Sangre de Cristos, distance of 119 km (72 mi). 6. Jose Butte, 2,234 m (7,330 ft). 7. Mud Hill, 2,195 m (7,200 ft). 8. Baby Capulin, 2,102 m (6,900 ft). 9. Twin Mountain, 2,073 m (6,800 ft). 10. Gaylord (Carr) Mountain, 2,103 m (6,900 ft). 11. Robinson Peak, 2,495 m (8,185 ft). 12. Green Mountain, 2,410 m (7,900 ft). 13. Larga Mesa, 2,316 m (7,600 ft). 14. Horseshoe Mountain, 2,380 m (7,810 ft). 15. Sierra Grande, 2,655 m (8,711 ft).16. Rabbit Ear Mountain, 1,811 m (5,940 ft) and a distance of 27 km (44 mi). 17. Tinaja Peak, 2,380 m (7,810 ft). 18. Laughlin Peak, 2,688 m (8,820 ft). 19. Raspberry Mountain, 2,484 m (8,150 ft). 20 and 21. Pine Buttes, 2,560 m (8,400 ft) and 2,560 m (8,400 ft). 22. Palo Blanco, 2,556 m (8,385 ft). 23. Malpie Mountain, 2,268 m (7,440 ft). Graphic by Jason Kenworthy (NPS Geologic Resources Division), with annotations from Huner and Lael (2003, figure 5.1). Landsat imagery extracted from Google Earth.

Monuments that repeatedly pointed out what Farr considered the monument's two most important resources: (1) the volcano, and (2) the view from the top of the volcano (Huner and Lael 2003). The spectacular view is most likely what led Farr to build a road to the summit (Huner and Lael 2003).

Today, the Crater Rim Trail circumnavigates the volcano and provides a 360° view (fig. 21). In the past, monument staff claimed you could see five states from the crater rim, but without notable landmarks, identifying Kansas is impossible. Thus, touting a viewshed (area visible to the human eye from a fixed vantage point) of four states (New Mexico, Colorado, Oklahoma, and Texas) is the present custom and what is listed on current interpretive panels (Lynn Cartmell, Capulin Volcano National Monument, lead park ranger, written communication, 17 February 2015).

The "dramatic view" is one of four statements of significance identified in the monument's 2010 general management plan. The other three statement of significance are the classic cinder cone, occurrence in the geologically diverse Raton-Clayton volcanic field, and the cinder cone's accessibility (National Park Service 2010). The view is also one of the monument's fundamental resources and values identified in the foundation document (National Park Service 2014c). Taking into consideration factors such as artificial vs. natural features in the viewshed, the natural resource condition assessment (Bennetts et al. 2012) determined the current condition (quality) of the viewshed to be in good condition.

During the GRI scoping meeting in 2011, monument staff indicated that visitors are as interested, or perhaps more interested, in the surrounding viewshed and outlying volcanic landscape as they are in the volcano itself. The view seems to be the reason for return visits (KellerLynn 2011).

Because Capulin Volcano is centrally located in the Raton-Clayton volcanic field, its rim is an ideal place to get an overview of the important features of the volcanic field (figs. 8 and 22). The most recent volcanism (Capulin phase) took place in the immediate vicinity of Capulin Volcano, so the crater rim is a good place to see "fresh" volcanic features (Stormer 1987). Nearby topographic humps mark the locations of vents. Prominent pressures ridges and squeeze-ups rise above the otherwise level surfaces of lava flows. Volcanic landmarks in the vicinity include Baby Capulin, Mud Hill, and Sierra Grande (fig. 22).

Baby Capulin

Baby Capulin is one of the youngest volcanoes in the region (Muehlberger et al. 2010). Based on new dating by Zimmerer et al. (2014), it is now known to be the third youngest: Purvine Hills and Twin Mountain erupted 32,000 ± 5,000 and 40,000 ± 4,000 years ago, respectively; Baby Capulin erupted 46,000 ± 6,000 years ago.

Figure 23. Panoramic view of Baby Capulin. This panoramic view is looking east from Highway 325 toward Baby Capulin (on the left). Emery Peak is behind Baby Capulin. Photograph by Matthew Zimmerer (MattZPhotography, www.mattzphotography.com [accessed 11 September 2015], used with permission), processed using Adobe Lightroom and stitched together using Hugin.

The Baby Capulin cinder cone formed early in the volcanic eruption, along with a number of spatter cones that surround the cone to the south and east. These spatter cones fed the lava flows that traveled northward to Folsom and into the Dry Cimarron River valley (Sayre and Ort 1999). Thus like Capulin Volcano, Baby Capulin is a cinder cone that formed during a cone-building eruption. In contrast, however, the eruption of Baby Capulin produced more lava flows than pyroclasts (cinders).

Baby Capulin is outside Capulin Volcano National Monument but within its viewshed, approximately 3 km (2 mi) to the northeast (fig. 23). Baby Capulin's bare cone and crater are readily visible from Crater Rim Trail. Baby Capulin lavas are similar in petrographic appearance to Capulin Volcano lavas, except that they contain fewer xenocrysts.

Mud Hill

The big volcano about 0.6 km (1 mi) north of Capulin Volcano is Mud Hill. Its rim is covered with trees. Like Capulin Volcano, Mud Hill erupted during the Capulin phase but is significantly older (1.69 million ± 30,000 years ago; Zimmerer 2015).

Mud Hill formed by a very different process than Capulin Volcano. It was the result of a phreatomagmatic ("phreato" meaning reservoir or well in Greek; also called hydrovolcanic) eruption, where the interaction of magma and water (shallow groundwater or surface water) drives the explosion. As such, the Mud Hill eruption was considerably more violent than Capulin Volcano because heating of water flashed to steam, blasting magma and breaking it into fragments (pyroclasts).

Various descriptions of Mud Hill refer to it as a "maar volcano," "tuff ring," or both. Some geologists distinguish the two: a maar is a pyroclastic cone in which the crater lies below the surrounding ground level, whereas a tuff cone is a pyroclastic cone with the crater above the surrounding ground surface (Mathis 1999).

When most of the water had been used up in the explosion of Mud Hill, lava began to pour out of the vent. Eventually, a lave flow breached the southern side of Mud Hill, leaving a horseshoe-shaped edifice. Lava from Capulin Volcano subsequently altered the area to the south of Mud Hill (Sayre and Ort 1999).

Figure 24. Photograph of Sierra Grande. The largest volcano in the Raton-Clayton volcanic field is Sierra Grande, which rises about 600 m (2,000 ft) above the surrounding plain and is about 15 km (9 mi) in diameter. The volcano is an important component of Capulin Volcano National Monument's viewshed, and is visible in the distance to the southeast of Capulin Volcano (see fig. 22). Photograph by Matthew Zimmerer (MattZPhotography, www.mattzphotography.com [accessed 11 September 2015], used with permission), processed using Adobe Lightroom.

Sierra Grande

Standing 2,655 m (8,711 ft) above sea level, Sierra Grande is the largest volcano in the Raton-Clayton volcanic field (fig. 24). It is composed of 23 km^3 (6 mi^3) of thick, viscous lava flows and very little pyroclastic material (Wood and Kienle 1990; Sayre and Ort 1999; Aubele and Crumpler 2001). Sierra Grande is a notable exception to the basaltic cinder cones that characterize the Raton-Clayton volcanic field (fig. 8). Although the Sierra Grande eruption initially produced voluminous basalt flows, it ultimately constructed an edifice composed of andesite.

Aubele and Crumpler (2001, p. 72) described Sierra Grande as an "andesite *shield volcano* [italics added]" whereas Sayre and Ort (1999, p. 59) described it as a "*stratovolcano* [italics added] predominantly composed of andesite lavas." In short, Sierra Grande poses a challenge to classic classification schemes (fig. 7).

Based on its low profile and a slope of approximately 8°, Sierra Grande fits into the "shield volcano" category. However, shield volcanoes are characteristically composed almost entirely of fluid, basaltic lava flows that spread away from vents for tens of kilometers, but Sierra Grande consists almost entirely of andesitic lava flows (60%–62% silica) that spread less than 8 km (5 mi) from the vent, making the volcano only 15 km (9 mi) across. Therefore, based on rock type and volcano size, Sierra Grande fits into the "stratovolcano" category. Additionally, an essential feature of a stratovolcano is a conduit system through which magma from a reservoir deep in Earth's crust rises to the surface (Watson 2011). Sayre and Ort (1999) interpreted such a system for Sierra Grande.

Playa Lakes

Playa lakes—ephemeral lakes in arid or semiarid regions that appear in the wet season and subsequently dry up—are one of the only nonvolcanic features in the monument's viewshed (fig. 22). Baldwin and Muehlberger (1959) highlighted these lakes and concluded that most of them probably formed as a result of wind erosion that scoured depressions into bedrock (e.g., Dakota Sandstone) which became filled with water. Some playa lakes represent areas where the crust of a lava flow collapsed. The town of Clayton, southeast of Capulin Volcano National Monument, has examples of this type (Baldwin and Muehlberger 1959).

Aeolian Features

Sand dunes, sand sheets, and deposits of loess (windblown silt) are aeolian features created by wind erosion, transportation, and deposition of sediments (Lancaster 2009). In volcanic landscapes, ash (fine-grained material ejected from a volcano and transported by the wind) may be a significant aeolian feature. Compared to caldera-forming eruptions such as Mount Mazama (see GRI report about Crater Lake National Park by KellerLynn 2013) and Valles caldera (see GRI report about Bandelier National Monument by KellerLynn 2015), however, cinder cones produce very little ash. Unlike ash layers from the Yellowstone caldera, which completely covered New Mexico and surrounding states (see Izett and Wilcox 1982), ash from Capulin Volcano spread only an estimated 1 km (0.6 mi) away from the vent (Bill McIntosh and Nelia Dunbar, New Mexico Bureau of Geology and Mineral Resources, volcanologist and geologist, personal communication during GRI scoping meeting, 10 May 2011).

A notable aeolian feature at Capulin Volcano National Monument is the asymmetry of the crater rim; the rim is higher on the northeastern side (fig. 25). At the time of the cone-building eruption, prevailing southwesterly winds caused more cinders to accumulate on the opposite (northeastern) side of the volcano; this asymmetry remains today.

Loess is another aeolian feature at Capulin Volcano National Monument. Loess-infilling of vesicles and cracks on lava flow surfaces serves as an informal dating method. Based on the amount of loess infilling and cover, geologists can estimate the relative age of lava flows and associated landscapes. This field method is a form of relative dating used in the absence of isotopic ages. A clean, loess-free surface indicates a "young" flow. A surface where vesicles and cracks are filled with loess indicates a moderate age. Removal of topographic highs by loess indicates old age (KellerLynn 2011).

In addition, loess plays a role in soil formation. Weindorf et al. (2008) and Weindorf and Zhu (2010) investigated spatial variability of soil properties at Capulin Volcano National Monument. Bauman (1999) studied loess on the Carrizozo lava flow in south-central New Mexico (fig. 4) and analyzed the influences of climate, provenance (source of sediment), and surface cover types on soil formation. Bauman (1999) found that soils on the Carrizozo flow are aeolian in origin and not the outcome of basaltic weathering. These findings and methods may be applicable to the lava flows associated with Capulin Volcano.

K-T Boundary

A massive worldwide extinction marks the Cretaceous-Tertiary ("K-T") boundary 66.0 million years ago (fig. 3). An estimated 50% of all species, including terrestrial dinosaurs, did not survive this extinction event. An accepted scientific view is that these extinctions coincided with a cataclysmic collision of an asteroid or comet with Earth. The presence of extraterrestrial

Figure 25. Photograph of Capulin Volcano. Capulin Volcano is a classic example of a cinder cone. The crater is approximately 130 m (420 ft) deep and 440 m (1,450 ft) across. The base of the mountain is 6 km (4 mi) in circumference. Volcano Road spirals up the volcano, providing access to panoramic views of the surrounding Raton-Clayton volcanic field. Note the asymmetry of the cone, which is higher on the northeastern side as a result of aeolian processes during the cone-building eruption. National Park Service photograph available at http://www.nps.gov/storage/images/cavo/Webpages/gallery-01.html (accessed 20 January 2015).

material (iridium) associated with this collision has been identified in Cretaceous-Tertiary deposits around the globe. A few such deposits occur in New Mexico, notably in rocks along Interstate 25 through Raton Pass (fig. 26), and in an outcrop of the Raton Formation atop Goat Hill (fig. 27), just outside Raton. The actual, physical boundary is a thin layer of iridium-rich clay. At the exposure near Goat Hill, a sign “iridium layer” indicates the boundary’s location (fig. 27).

The K-T boundary often captures the public’s imagination because it resulted in a world without dinosaurs. Although Capulin Volcano National Monument does not contain the K-T boundary, the exposure at Goat Hill is publicly accessible, and its proximity to the monument may be of interest to visitors.

Paleontological Resources

No fossils have been discovered at Capulin Volcano National Monument, to date. While this report was in review, an updated summary of paleontological resources from the NPS Southern Plains Network, of which the monument is a part, was completed (Tweet et al. 2015). That report replaces the earlier report by Koch and Santucci (2003). In general, fossils are rare in igneous deposits, except for tree molds, which form when fluid lava engulfs a tree, which is later incinerated or decays away, leaving a cylindrical hollow. In some instances, tree molds preserve an impression of a tree’s original bark. Tree molds also may be horizontal impression on the surface of a lava flow where a tree fell over and was later incinerated or decayed away. Within the National Park System (see Santucci et al. 2012), this particular kind of fossil has been documented at

Figure 26. Photograph of the K-T boundary at Raton Pass. The famous Cretaceous-Tertiary (K-T) boundary is exposed in a few places in northeastern New Mexico, for example, along Interstate 25 at Raton Pass. The author (Katie "K-T" KellerLynn) points out the iridium-rich layer in the Raton Formation. Photograph by Lisa Norby (NPS Geologic Resources Division).

Craters of the Moon National Monument in Idaho, El Malpais National Monument in New Mexico (see GRI report by KellerLynn 2012a), Lava Beds National Monument in California (see GRI report by KellerLynn 2014c), and Hawaii Volcanoes National Park and Puuhonua o Honaunau National Historical Park in Hawaii (see GRI reports by Thornberry-Ehrlich 2009, 2011). No tree molds have been documented at Capulin Volcano National Monument to date (Justin Tweet, NPS Geologic Resources Division, guest scientist, email communication, 21 May 2015).

Pack rat (*Neotoma* spp.) middens are another potential source of paleontological information, though none have presently been documented in the monument to date. Pack rat middens are an important tool for reconstructing the paleoecology and climate of late Pleistocene and Holocene environments in western North America. Thirty-three National Park System units are known to contain pack rat middens (Tweet et al. 2012). Pack rat middens are primarily examined for plant macrofossils, but also pollen (Anderson and Van Devender 1995), insects (Elias et al. 1992), vertebrates (Mead and Phillips 1981), stomatal density/carbon isotopes in leaves (Van de Water et al. 1994), and fecal pellets (Smith et al. 1995; Smith and Betancourt 1998). Also, the dung of extinct mammals contained in pack rat middens may yield paleobotanical information (Davis et al. 1984; Mead et al. 1986; Mead and Agenbroad 1992; Hunt et al. 2012).

Figure 27. Photographs of the K-T boundary at Goat Hill. The iridium-rich clay layer that marks the worldwide extinction of dinosaurs is exposed near Capulin Volcano National Monument, on Goat Hill, just outside the city of Raton. Photographs by Katie KellerLynn (Colorado State University).

Larger cavities in basalt lava flows are potential locales for pack rat middens at Capulin Volcano National Monument. Climate is the main consideration; the monument is right on the eastern fringe of where ancient middens typically are found (Justin Tweet, NPS Geologic Resources Division, guest scientist, email communication, 21 May 2015). Preliminary paleontological resource management recommendations are presented by Tweet et al. (2015).

Geologic Resource Management Issues

This chapter describes geologic features, processes, or human activities that may require management for visitor safety, protection of infrastructure, and preservation of natural and cultural resources in Capulin Volcano National Monument. The NPS Geologic Resources Division provides technical and policy assistance for these issues.

During the 2011 scoping meeting (see scoping summary by KellerLynn 2011), participants (see Appendix A) identified the following geologic resource management issues:

- Volcano Road
- Erosion
- Slope Movements
- Aeolian Processes
- Wind Energy Development
- Cave Management
- Cinder Mining
- Volcano Hazards and Risk
- Geothermal Systems and Hydrothermal Features

Resource managers may find *Geological Monitoring* (Young and Norby 2009) useful for addressing these resource management issues. Geological Monitoring provides guidance for monitoring vital signs—measurable parameters of the overall condition of natural resources. Each chapter covers a different geologic resource and includes detailed recommendations for resource managers and suggested monitoring methods. An online version of the manual is available at http://go.nps.gov/geomonitoring (accessed 29 May 2015).

A foundation document (National Park Service 2014c) and natural resource condition assessment (Bennetts et al. 2012) also provide information about the geologic resources of the monument. The foundation document lists the following as fundamental resources or values: volcanic features and geologic processes, scenic/historic viewshed, and opportunities for scientific study. Other important resources in the monument as identified in the foundation document are cultural resources and rare species. Volcano Road and the Crater Rim Trail are part of a historic designated cultural landscape. The framework of the natural resource condition assessment includes the following components under "Geology": presence/absence of accelerated erosion and severity of erosion. Geologic features and processes and some of the resource management issues described in this chapter affect those values and resources.

In the following sections of this report, three investigations are proposed that could be conducted by a Geoscientists-In-the-Parks (GIP) participant: (1) triggers of slope movements (see "Slope Movements" section, (2) a cave inventory (see "Cave Management" section), and (3) hydrothermal features (see "Geothermal Systems and Hydrothermal Features" section). The GIP website (http://go.nps.gov/gip; accessed 27 January 2015) contains additional information about the GIP program. The NPS Geologic Resources Division administers this program.

Volcano Road

"Volcano Road" (as per Federal Highway Administration 2010) has been referred to as "Crater Ascent Road" (National Park Service 1977), "Mountain Road," and "Capulin Volcano Road." The road spirals up Capulin Volcano (fig. 25) and is an important part of Capulin Volcano National Monument's cultural landscape (National Park Service 2014). The road is eligible for inclusion in the National Register of Historic Places, thus establishing its significance in accordance with 36 Code of Federal Regulations (CFR) Part 800—Protection of Historic Properties (Bennetts et al. 2012). The road also has scientific and educational significance. Several pullouts provide access to sites of geologic interest, for example, exposures of inclined layers of cinders (fig. 12). The road's primary significance, however, is furnishing an incredible 360° panoramic view at the crater rim (see "View from Capulin Volcano" section).

Although Volcano Road is significant for the public enjoyment opportunities it provides, it also has the greatest impact on the monument's geologic resources, specifically the cinder cone (Bennetts et al. 2012). The road was built into the side of the volcano, undercutting slopes and impacting natural drainages. Along some road segments, the stability and integrity of the road

Figure 28. Photograph of storm-related damage along Volcano Road. Erosion on Capulin Volcano is primarily associated with Volcano Road. Culverts provide narrow paths for storm-water runoff, creating erosion channels and gullies down the sides of the mountain. National Park Service photograph (date unknown).

bench itself is at risk of failure (National Park Service 2012). Furthermore, the road's impervious surface concentrates runoff, causing accelerated, and in some places, severe erosion. Many of the culverts associated with the road are inadequate for conveying intense storm-related runoff (fig. 28; Greco 2001).

Based on the high proportion of culverts exhibiting accelerated erosion (66%) and the severity of that erosion (fig. 29), the natural resource condition assessment by Bennetts et al. (2012) considered the condition of "geology" (specifically the cinder cone) in the monument to be a "significant concern" with a "declining trend." Although the monument contains many geologic features (see "Geologic Features and Processes" chapter), Bennetts et al. (2012) focused on the cinder cone because it is the most prominent feature in the monument and comprises more than half (56%) of the monument's acreage. Erosion is expected to continue until solutions are determined and implemented. A $2 million effort to remediate hill slope erosion caused by Volcano Road was completed by the Federal Highway Administration in 2012. The project incorporated erosion control measures and repaired road shoulders, drainage structures, and eroded hill slope areas (National Park Service 2014c).

The geologic resources foundation summary (National Park Service 2012) identified five major aspects that contribute to the road's drainage/erosion problem:

- the ability of drainage inlets and culverts to handle storm events,
- the number of culverts needed to mimic natural hydrology,
- the alignment of drainage inlets and outlets to topography,
- the attenuation of discharge velocities (energy dissipation), and
- the reduction of accelerated erosional processes and the correction of altered sediment transport processes upslope and downslope of the road.

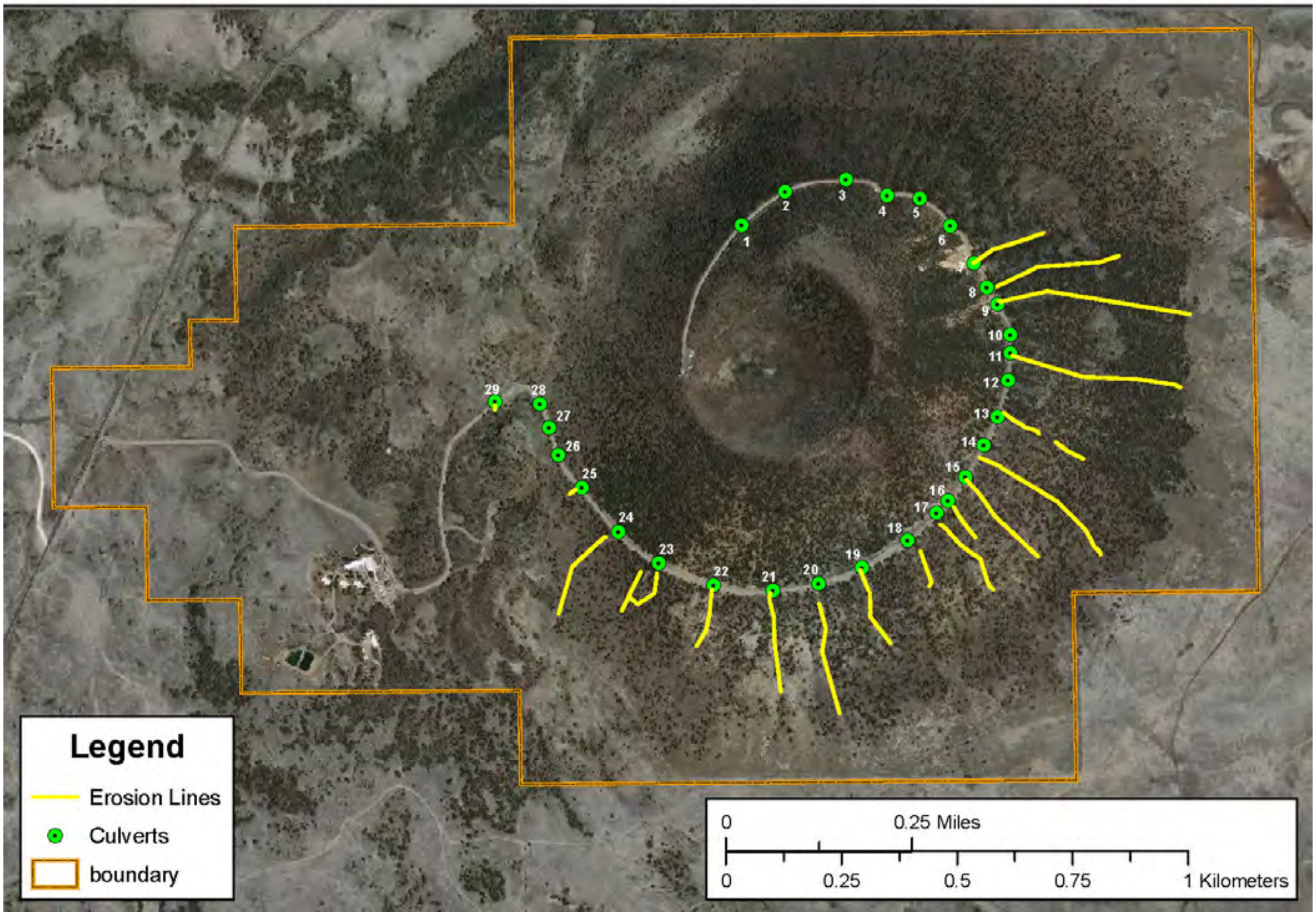


Figure 29. Satellite imagery with locations of culverts along Volcano Road. Accelerated erosion that creates gullies is associated with culverts along Volcano Road. Yellow lines delineate the length of an eroded area. Culvert numbers are shown for reference. Nineteen culverts (7–9, 11–15, and 29) are experiencing accelerated erosion. Lengths of eroded gullies range from 10 m (34 ft) to 419 m (1,373 ft), averaging 197 m (647 ft). Culverts with the longest erosion gullies are 9 (419 m [1,373 ft]), 11 (372 m [1,219 ft]), and 14 (345 m [1,130 ft]). Several of the gullies extend half way or more down the slope of the cinder cone. Graphic from Bennetts et al. (2012, figure 4.5.4-1).

Mitigation is essential for the long-term sustainability of Volcano Road and the reduction of visual impacts (National Park Service 2012). The geologic resources foundation summary (National Park Service 2012) recommended the completion of a long-term surface drainage/erosion mitigation plan. The NPS Geologic Resources Division could assist monument managers with preparing a monitoring and mitigation plan for Volcano Road. Photogrammetry could provide a means for quantitative measurement of erosion rates. The NPS Geologic Resources Division photogrammetry website (http://go.nps.gov/grd_photogrammetry; accessed 27 January 2015) supplies additional information.

Erosion

Erosion is arguably the most significant threat to the geologic resources at Capulin Volcano National Monument (Bennetts et al. 2012). Human developments, primarily Volcano Road, cause the most obvious and severe erosion (fig. 30), but steep slopes—generally between 40% and 60% approaching the crater—and highly erodible soils exacerbate the issue (Weindorf et al. 2008). Addressing this threat requires an understanding of erosional processes operating at the monument and the degree and severity of natural vs. unnatural erosion, which presently constitutes an information gap (Bennetts et al. 2012).

During the GRI scoping meeting/site visit on 10 May 2011, Nelia Dunbar and Bill McIntosh (New Mexico

Figure 30. Photograph of erosion along Volcano Road. In spring 1967 Volcano Road was closed while monument personnel assessed damages and made repairs. In 2012, a Federal Highways Administration project remediated some areas of severe erosion along the road. National Park Service photograph from Bennetts et al. (2012, figure 4.5.1-7).

Bureau of Geology and Mineral Resources, geologist and volcanologist) pointed out the natural tendency for cinders to erode into gullies. This type of erosion has been operating since the cinder cone formed 55,000 years ago. Various investigators have studied the progression of erosion on cinder cones. For example, a study by Renault (1989) of the Cima volcanic field in the eastern Mojave Desert would be applicable to Capulin Volcano. This study investigated four basaltic cinder cones of the Cima field in an attempt to understand the geomorphic and volcanic processes involved in the constructional and degradational evolution of late Quaternary cinder cones in arid climates. Additionally, several other papers—Fornaciai et al. (2010), Bemis et al. (2011), Doniz et al. (2011), and Inbar et al. (2011)—provide information about the morphological evolution of cinder cones through time (Nelia Dunbar, New Mexico Bureau of Geology and Mineral Resources, geologist, written communication, 4 August 2011).

Existing information related to soil erosion at Capulin Volcano National Monument includes a NPS Soil Resources Inventory (SRI), which can be found on the NPS Integrated Resource Management Applications (IRMA) at https://irma.nps.gov/App/Reference/Profile/1048838 (accessed 27 January 2015). Also, Biggam (2010) performed a rapid soil assessment and trip report.

Erosion-related issues occur in other areas of the monument, though they are less severe than those along Volcano Road. Erosion is affecting sections of both the Lava Flow Trail and the fire road in the southern part of the monument (Bennetts et al. 2012). Cinder-mining activities adjacent to the monument's northeastern boundary have eroded a Fourth Series lava flow (see "Abandoned Mineral Lands" section). Because the Crater Rim Trail has an impervious surface, it may pose some risk to the integrity of the cinder cone as a result of concentration of storm-water runoff. Work along the Crater Rim Trail during summer 2010 restored some eroded areas, attempting to mitigate future erosion (Bennetts et al. 2012).

In parts of the monument, specifically on the cinder cone, removal of the pinyon-juniper overstory via mechanical thinning left the soil surface exposed, and the highly erodible soils show the dramatic impacts of sheet, rill, and channelized erosion. The resulting sediment discharge has plugged drainage culverts, causing excessive sediment accumulation on Volcano Road that requires removal (National Park Service 2012). The NPS Geologic Resources Division could assist with preparing erosion control procedures.

Slope Movements

Slope movements are ongoing on Capulin Volcano and cause cinders to slide (fig. 31), debris flows to form (fig. 32), and entire sections of slopes to fail (fig. 33). These gravity-driven processes are a particular concern at the monument where they impact infrastructure. The primary concern is Volcano Road, where sliding cinders

Figure 31. Photograph of a cinder slide on Volcano Road. Slope movements are ongoing at Capulin Volcano National Monument; the slide shown here took place in 2004. Cinder slides are a particular concern along Volcano Road. Keeping the road clear of cinders is a continuous maintenance activity. National Park Service photograph available at http://www.nps.gov/cavo/naturescience/environmentalfactors.htm (accessed 19 November 2014).

Figure 32. Photograph of a debris flow on Volcano Road. Slope movements are a common type of geologic hazard—a natural or human-caused condition that may impact park resources, infrastructure, or visitor safety. Debris flows have impacted Volcano Road, causing road closures and trapping vehicles above an affected road section. National Park Service photograph (date unknown).

Figure 33. Photograph of slope movements along Volcano Road. Slope movements include fall, topple, slide, spread, and flow of material under the influence of gravity. Rockfall, slope failure, and small debris flows are common along Volcano Road. Slope-movement events occur on time scales ranging from seconds to years, and may be triggered by storms and higher-than-average precipitation. National Park Service photograph (date unknown).

have covered sections of the road with deposits up to 1.5 m (5 ft) thick and as much as 60 m (200 ft) long (KellerLynn 2011).

Small-scale slope movements, such as cinders sliding onto the road, are continuous, but large-scale events seem to be associated with storms and higher than average annual precipitation (KellerLynn 2011). In 2010—a “wet year,” a debris flow moved across Volcano Road, inhibiting access and trapping vehicles at the summit. Precipitation in 2010 was 76 cm (30 in). By comparison, the annual average is 38 cm (15 in).

A data need at the monument is a better understanding of the timing and triggers of large-scale slope movements. Such events have not been well documented (KellerLynn 2011). Using long-term weather data and historical photographs retained in the monument’s archives, a GIP participant would likely be able to make correlations and provide documentation of links between storms and large-scale slope movements.

Bennetts et al. (2012) used the presence/absence of accelerated erosion and the severity of erosion as indicators/measures of the condition of geology at Capulin Volcano National Monument. In the *Geological Monitoring* chapter about slope movements, Wieczorek and Snyder (2009) described five vital signs for understanding and monitoring slope movements: (1) types of landslide, (2) landslide causes and triggers, (3) geologic materials in landslides, (4) measurement of landslide movement, and (5) assessment of landslide hazards and risks. Other sources of guidance for monitoring include The Landslide Handbook—A Guide to Understanding Landslides (Highland and Bobrowsky 2008), the USGS landslides website (http://landslides.usgs.gov/; accessed 27 January 2015), and the NPS Geologic Resources Division geohazards and slope-movement monitoring websites (http://go.nps.gov/geohazards and http://go.nps.gov/monitor_slopes; accessed 27 January 2015).

Aeolian Processes

Wind is a primary geologic agent at Capulin Volcano National Monument (Pete Biggam, NPS Geologic Resources Division, Soils Program lead, personal communication to Rob Bennetts, Southern Plains Network, network coordinator, November 2010). Capulin Volcano itself was shaped by the wind (see “Aeolian Features” section). Windblown transport of cinders onto Volcano Road is a concern for maintenance and safety, and dust storms can take place, primarily during March and April.

Grazing is commonly a factor in the amount of dust available for aeolian transport, but grazing within the boundaries of the monument ended in the late 1970s. Present-day construction activities, however, denude vegetation, making sediment available for aeolian transport and dust storms (KellerLynn 2011).

In the *Geological Monitoring* chapter about aeolian features and processes, Lancaster (2009) described the following methods and vital signs for monitoring aeolian resources: (1) frequency and magnitude of dust storms, (2) rate of dust deposition, (3) rate of sand transport, (4) wind erosion rate, (5) changes in total area occupied by sand dunes, (6) areas of stabilized and active dunes, (7) dune morphology and morphometry, (8) dune field sediment state (supply, availability, and mobility), (9) rates of dune migration, and (10) erosion and deposition patterns on dunes. Some but not all of these vital signs would be applicable to Capulin Volcano National Monument.

Wind Energy Development

Although aeolian processes are notable at Capulin Volcano National Monument, scoping participants did not consider large-scale development of wind energy an issue. Because the view from Capulin Volcano is such an important resource, however, the NPS Intermountain Region has a plan to study visitor attitudes towards potential wind farms within the monument's viewshed. The National Park Service uses a combined technical and policy approach to manage and protect park resources and values as renewable energy resources are identified and developed near NPS areas. The concerns associated with the development of onshore wind energy include potential habitat loss, land conversion, transmission infrastructure, and artificial light. The key impacts of onshore wind turbines include noise, turbine strikes, and visual impacts (National Park Service 2014b).

Cave Management

In volcanic landscapes composed of basalt, the most significant cave features are lava tubes (see GRI reports about El Malpais and Lava Beds national monuments by KellerLynn 2012a, 2014c). Lava tubes are the primary means for distributing lava away from an erupting vent in these terrains. When eruption ceases and lava stops flowing, a cave may remain as a cavernous segment of an evacuated lava tube. In many cases, however, the roofs of lava tubes will collapse, filling the opening with collapse debris.

Capulin Volcano National Monument has a few known cave features, as well as several collapsed lava tubes. The NPS geologic resources foundation summary for Capulin Volcano National Monument (National Park Service 2012) listed a survey and inventory of the caves as a planning and data need. No geologic study or cave inventory is known to have been conducted, though some information is available in archeological reports.

The Federal Cave Resources Protection Act of 1988 and its subsequent regulations issued in 1993 impose penalties for harming a cave or cave resources and exempts park managers from releasing specific location information for significant caves in response to a Freedom of Information Act (FOIA) request (see Appendix B of this report). These regulations also state that "no employee shall disclose information that could be used to determine the location of any significant cave unless the authorized officer determines that disclosure will further the purposes of the act and will not create a substantial risk to cave resources of harm, theft, or destruction. For the National Park Service, the "authorized officer" is the superintendent of a park unit.

The policy of the National Park Service, pursuant to the Organic Act of 1916 (16 U.S.C. 1, et seq.) and 2006 Management Policies (section 4.8.2.2; see also Appendix B), is that all caves are afforded protection and will be managed in compliance with approved resource management plans. Accordingly, all caves on NPS lands are deemed to fall within the definition of "significant cave."

The management of caves—including guidance and protocols for all cave activities—at Capulin Volcano National Monument should be discussed in some type of management plan (Dale L. Pate, NPS Geologic Resources Division, Cave & Karst Program coordinator, written communication, 30 January 2015). An in-depth cave management plan may not be necessary, however. The NPS Geologic Resources Division can facilitate the development of an appropriate plan for Capulin Volcano National Monument.

A good first step in identifying needs of the monument regarding cave resources would be submittal of a technical assistance request to the NPS Geologic Resources Division. Technical assistance would be provided by the cave and karst specialist and include a review of any reports or other documentation, a visit to Capulin Volcano National Monument to investigate known cave features and collapsed lava tubes, and recommendations for data and information needs to adequately manage these resources. This would include an evaluation of potential bat use and guidance concerning white-nose syndrome, a devastating disease to bats. Additional information about white-nose syndrome is available from the NPS Biologic Resources Division website at http://go.nps.gov/wns (accessed 11 September 2015).

Based on guidance and recommendations by a technical assistance request, potential sources for help in conducting a field survey and inventory at the monument may include a GIP participant. The GIP candidate (or anyone else) selected for this position should have thorough knowledge and adequate experience in the survey and inventories of caves, including how to move through and work in caves with minimal impacts to sensitive cave resources (Dale L. Pate, NPS Geologic Resources Division, Cave & Karst Program coordinator, written communication, 30 January 2015).

Following an inventory, a monitoring plan could be established for physical properties, as well as impacts to sensitive cultural artifacts (National Park Service 2012). In the *Geological Monitoring* chapter about caves and associated landscapes, Toomey (2009) described methods for inventorying and monitoring cave-related vital signs: (1) cave meteorology, such as microclimate and air composition; (2) airborne sedimentation, including dust and lint; (3) direct visitor impacts, such as breakage of cave formations, trail use in caves, graffiti, and artificial cave lighting; (4) permanent or seasonal ice; (5) cave drip and pool water, including drip locations, rate, volume, and water chemistry, pool microbiology, and temperature; (6) cave microbiology; (7) stability issues associated with breakdown, rockfall, and partings; (8) mineral growth of speleothems, such as stalagmites and stalactites; (9) surface expressions and processes that link the surface and the cave environment, including springs, sinkholes, and cracks; (10) regional groundwater levels and quantity; and (11) fluvial processes, including underground streams and rivers. Some of these vital signs may be pertinent to the caves at Capulin Volcano National Monument.

Cinder Mining

Cinder mining has occurred in the vicinity of Capulin Volcano National Monument. The most apparent operation is at Twin Mountain, which is 8 km (5 mi) to the northeast and visible from the crater rim (figs. 21 and 22). The original shape of Twin Mountain was two parallel ridges of cinders with a fissure, from which cinders erupted, between them (fig. 34). The northern ridge has been completely excavated, with cinders hauled away for railroad ballast by the Colorado and Southern Railway, and for manufacturing concrete cinder blocks and acoustical insulation (Muehlberger et al. 2005).

The NPS Geologic Resources Division can provide monument staff with policy and technical assistance regarding minerals and mining. Recommendations include remaining aware of public and private mineral ownership and speculation, exploration, or drilling activity on lands in the vicinity of the monument. Regulations and permit procedures vary among states.

Figure 34. Photographs of Twin Mountain. Cinder mining takes place at Twin Mountain, about 8 km (5 mi) northeast of Capulin Volcano National Monument. Originally, Twin Mountain consisted of two ridges. Between 1956 (left photograph) and 2005 (right photograph), much of the northern ridge had been excavated. New Mexico Bureau of Geology and Mineral Resources photographs from Muehlberger et al. (2005, p. 5 and 55).

Baldwin and Muehlberger (1959) noted that cinder cones in the Folsom area, including Capulin Volcano, have been prospected for sources of cinders. In 2011, scoping participants identified three "test pits" that had been prospected within the monument, but none were deemed in need of restoration (KellerLynn 2011). These sites could be included in the NPS Abandoned Mineral Lands (AML) database. As of January 2015, no AML sites or features for Capulin Volcano National Monument were included in this database. Burghardt et al. (2014) and the NPS AML Program website (http://go.nps.gov/grd_aml; accessed 27 January 2015) provides further information. The NPS Geologic Resources Division manages the AML database and has expertise to assist with restoration of past prospecting or mining operations, if needed in the future.

Volcano Hazards and Risk

Volcanism in the Raton-Clayton volcanic field began about 9 million years ago. The Capulin phase began 1.69 million years ago. Today, the volcanic field lies dormant, but no evidence suggests that volcanic activity has ended (Sayre and Ort 1999), and future eruptions will likely occur (Aubele and Crumpler 2001; Walkup 2012). A high-precision $^{40}Ar/^{39}Ar$ chronology of late-Quaternary volcanism in the Raton-Clayton volcanic field suggests a recurrence rate of 0 to as much as 17,000 years for volcanism in the vicinity of Capulin Volcano (Zimmerer et al. 2014; Zimmerer 2015). The recurrence rate (i.e., eruption frequency) between the eruption of Malpie Mountain and Purvine Hills is one eruption per 5,800 ± 1,000 years (i.e., five eruptions between 61,000 ± 500 and 32,000 ± 5,000 years ago). During this same interval, repose periods between individual eruptions have all been less than 17,000 years (Zimmerer et al. 2014; Zimmerer 2015).

Most of the volcanoes within the Raton-Clayton volcanic field, including Capulin Volcano, are monogenetic, that is, they are "born," erupt once only, and then "die." Other volcanoes, known as polygenetic, are longer lived and erupt more than once. This is an important distinction for understanding future eruptions in the Raton-Clayton volcanic field. Future eruptions will likely involve the eruption of a new monogenetic cone, rather than an eruption taking place from an existing volcano (Walkup 2012). This reflects a basic relationship between monogenetic and polygenetic volcanoes. Because polygenetic volcanoes have a sufficiently large and persistent magma-supply rate, a batch of ascending magma will preferentially follow the still-hot pathway of the preceding batch. Conversely, the magma supply of a monogenetic volcano is so small or episodic that any pathway has cooled down and is no longer favored for ascension by the next magma batch (Walker 2000). As a result, a new vent will form in another location.

Analysis of new $^{40}Ar/^{39}Ar$ ages by Zimmerer et al. (2014) in conjunction with some previously determined $^{40}Ar/^{39}Ar$ ages by Stroud (1997) identified vent migration patterns during the last 1.25 million years in the Raton-Clayton volcanic field (fig. 35). During this time, vent locations migrated to the northeast (i.e., approximately N74°E) at a rate of about 4.3 to 7.1 cm (1.7 to 2.8 in) per year. Although knowing when and where the next eruption in the Raton-Clayton field will take place is impossible, preliminary results suggest that future eruptions will likely occur to the east or northeast of Capulin Volcano National Monument. Future eruptions will likely be very similar to Capulin, in which the eruption builds a small cone with volumetrically minor lava flows (Zimmerer 2015). Additional work to understand the volcano hazards in the region is currently underway (Matthew Zimmerer, New Mexico Bureau of Geology and Mineral Resources, field geologist, written communication, 8 May 2015).

Walkup (2012) identified localized ash fall, earthquakes (as magma rises to the surface), volcanic gases, lava eruptions (flows), and volcanic projectiles as possible hazards of a future eruption in the Raton-Clayton volcanic field (fig. 36). Forest fires are another hazard that warrants mention. Pyroclastic material ejected from a volcano and lava flows can ignite a fire, which is particularly important for the desert southwest (Matthew Zimmerer, New Mexico Bureau of Geology and Mineral Resources, field geologist, written communication, 8 May 2015).

In the *Geological Monitoring* chapter about volcanoes, Smith et al. (2009) described seven vital signs and methodologies for understanding and monitoring volcanoes: (1) earthquake activity, (2) ground deformation, (3) emission at ground level, (4) emission of gas plumes and ash clouds, (5) hydrologic activity, and (6) slope instability. The NPS Geologic Resources Division Volcano Monitoring website (http://go.nps.gov/monitor_volcanic; accessed 3 February 2015) and US Geological Survey Volcano Hazards website

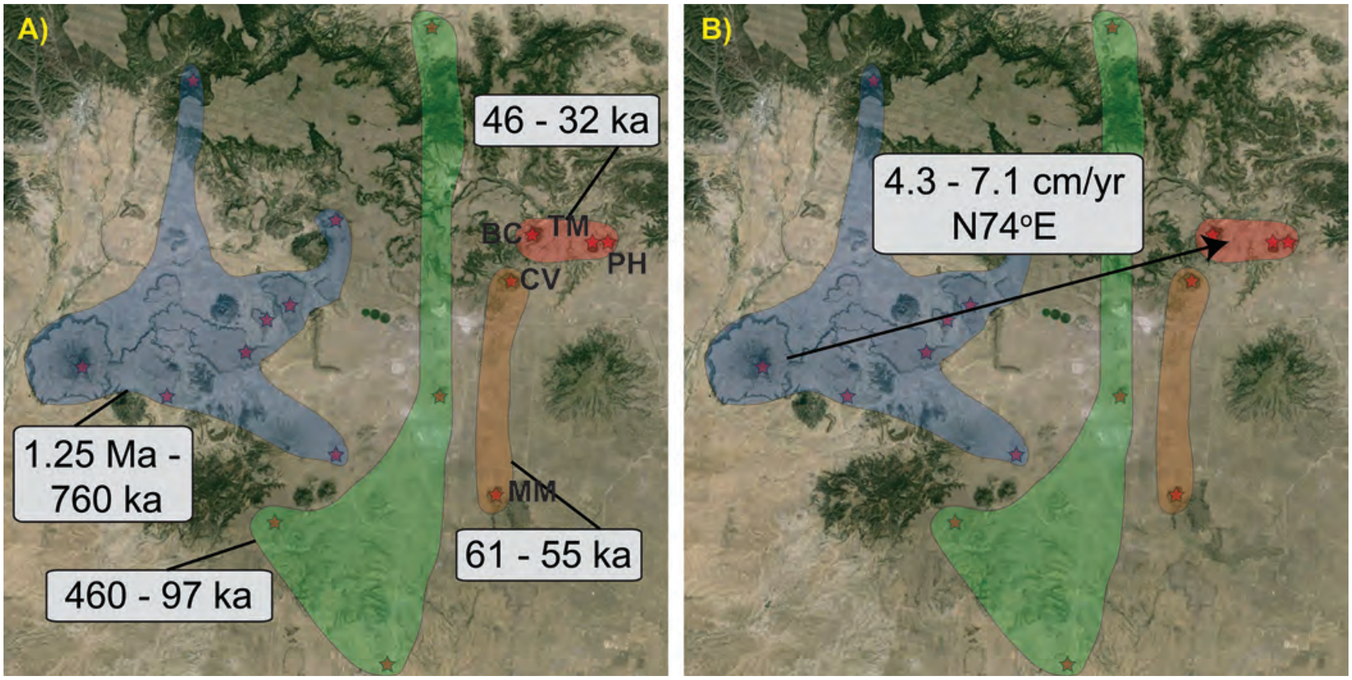


Figure 35. Maps of vent migration patterns. During the last 1.25 million years in the Raton-Clayton volcanic field, vent locations have migrated to the northeast. A) shows the age distribution of vents near Capulin Volcano National Monument. B) shows rate and direction of vent migration. MM = Malpie Mountain, CV = Capulin Volcano, BC = Baby Capulin, TM = Twin Mountain, and PH = Purvine Hills. Ma = millions of years; ka = thousands of years. Ages within blue-shaded area are from Stroud et al. (1997). All other ages are from work by Zimmerer et al. (2014) and Zimmerer (2015). Graphic from Zimmerer (2015, figure 1).

(http://volcanoes.usgs.gov/; accessed 3 February 2015) provide further information. Although the prediction of volcanic eruptions is not precise, monitoring allows for detection of changes in a volcanic field that precede an impending eruption.

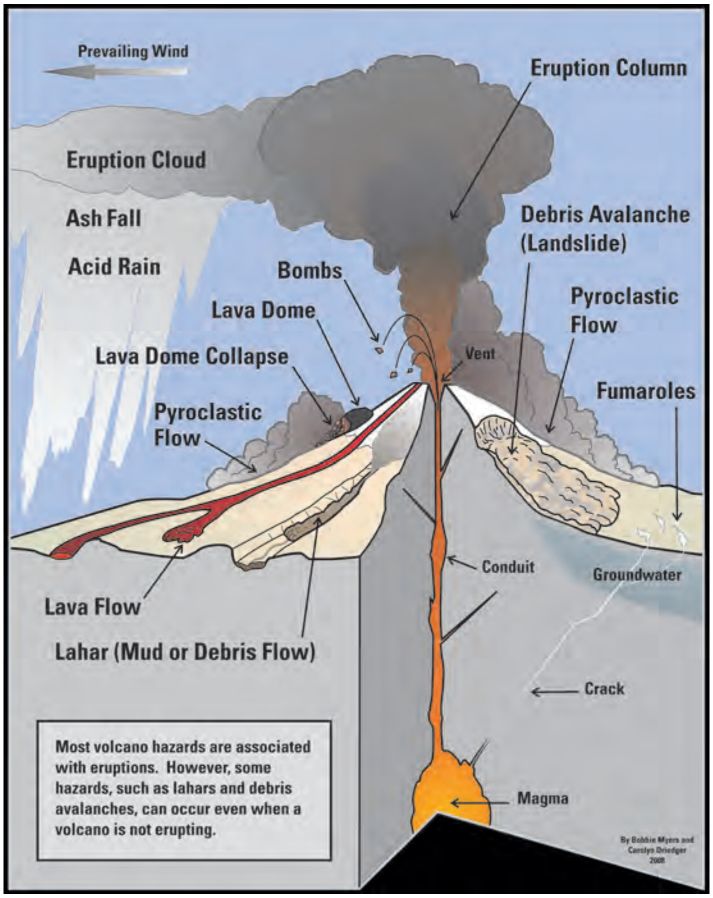
Geothermal Systems and Hydrothermal Features

The term "geothermal" refers to a system that transfers heat from within Earth to the surface. Where heat transfer involves water, hydrothermal features—such as hot springs, geysers, mud pots, and fumaroles—form at the surface and serve as indicators of an underlying geothermal system (Heasler et al. 2009).

Capulin Volcano National Monument is not known for its geothermal resources or hydrothermal features and is not included on the list of 16 parks that are designated under the Geothermal Steam Act of 1970, as amended in 1988 (see Appendix B of this report). This act prohibits geothermal leasing in these parks, and authorizes the secretary of the Interior to mitigate or not issue geothermal leases outside parks that would have a significant adverse impact on significant thermal features within these parks.

During the 2011 GRI scoping meeting, monument staff mentioned a "hot vent" near the maintenance building, which may be an indicator of heat transfer. However, nothing is documented about this "vent" and only anecdotal evidence exists. Locating this "vent" and researching information about it is a potential GIP project.

In the *Geological Monitoring* chapter about geothermal systems and hydrothermal features, Heasler et al. (2009) described the following methods and vital signs for understanding geothermal systems and monitoring hydrothermal features: (1) thermal feature location, (2) thermal feature extent, (3) temperature and heat flow, (4) thermal water discharge, and (5) fluid chemistry. The NPS Geologic Resources Division Geothermal Systems Monitoring website, http://go.nps.gov/monitor_geothermal (accessed 3 February 2015), provides additional information.



Most volcano hazards are associated with eruptions. However, some hazards, such as lahars and debris avalanches, can occur even when a volcano is not erupting.

By Bobbie Myers and Carolyn Driedger 2008

Figure 36. Schematic illustration of volcano hazards. A future eruption in the Raton-Clayton volcanic field will likely create a new cinder cone rather than erupting from an existing one. In addition to cone formation, other hazards include lava flows, localized ash fall, earthquakes (as magma rises and causes shaking), volcanic gases, and volcanic projectiles such as bombs. US Geological Survey graphic, available at http://pubs.usgs.gov/gip/64/gip64.pdf (accessed 2 January 2014).

Geologic History

This chapter describes the chronology of geologic events that formed the present landscape of Capulin Volcano National Monument.

Capulin Volcano National Monument lies near the center of the Raton-Clayton volcanic field, which became active 9 million years ago and erupted episodically in three phases (fig. 8). Earliest volcanism took place during the Raton phase, 9.0 million–3.5 million years ago, with most activity in the vicinity of Raton, New Mexico. The Clayton phase, 3.0 million–2.2 million years ago, followed the Raton phase and took place in the eastern part of the field, spanning north to south from Mesa de Maya in Colorado to the Yates flows south of Gladstone, New Mexico. Volcanic activity at Sierra Grande occurred 3.8 million–2.6 million years ago, overlapping in time with the Raton and Clayton phases. The most recent volcanism took place at the center of the field during the Capulin phase, 1.69 million–32,000 years ago. The Capulin phase covers all activity associated with Capulin Volcano National Monument, including eruption of First Series lava flows; eruption and development of Capulin Volcano; and eruption of vents in the boca that produced the Second Series, Third Series, and Fourth Series lava flows (see lava flow series map, in pocket).

Raton Phase
(9.0 million–3.5 million years ago)

The earliest lavas of the Raton-Clayton volcanic field flowed onto a surface of sediment that had shed eastward from the Sangre de Cristo Mountains. This sediment makes up the Ogallala Formation, which has particular significance for the region because it contains the Ogallala aquifer—the major source of water for agricultural and domestic use in the southern High Plains (Gustavson 1996). Lava flows of Raton Basalt, formally named by Scott et al. (1990), helped to date the end of Ogallala deposition (Gustavson and Finley 1985), which ties them to the geologic story of Alibates Flint Quarries National Monument and Lake Meredith National Recreation Area in the Texas Panhandle (see GRI report by KellerLynn in review).

Eruptions of the Raton phase consisted mostly of basaltic lava flows, which form the cap rock of high mesas in the northwestern part of the field. A peculiar feature of these mesa–capping lava flows is inverted topography where older flows are higher in elevation than younger flows (fig. 9). Stroud (1997) used this characteristic to reconstruct paleotopography and erosion rates of the region and concluded that climate change, namely a change to drier but stormier conditions, is the most likely cause of increased erosion.

Figure 37. Photograph of Towndrow Peak. During the Raton phase, dacite erupted and created lava domes such as Towndrow Peak. Rising 2,625 m (8,612 ft) above sea level, the peak sits atop Johnson Mesa. New Mexico Bureau of Geology and Mineral Resources photograph from Muehlberger et al. (2005, p. 27).

Red Mountain Dacite (Collins 1949; Scott et al. 1990) also erupted during the Raton phase, creating small volcanoes such as Red Mountain, Towndrow Peak (fig. 37), Green Mountain, Laughlin Peak, and Palo Blanco (fig. 8). Many Raton-age features have been significantly eroded so that the original morphology of these volcanoes is no longer evident (Mathis 1999).

In addition to basalt and dacite, an important rock type that erupted during the Raton and Clayton phases is the Sierra Grande andesite (Stroud 1997). Sierra Grande (figs. 8 and 24) is the most prominent feature consisting of andesite.

Clayton Phase
(3.0 million–2.2 million years ago)

The Clayton phase produced the greatest volume of magma of the three phases (Mathis 1999). Most of these rocks occur between Clayton on the east and Sierra Grande on the west, though Jose Butte and Robinson

Peak, west of Capulin Volcano, also are Clayton age (Sayre and Ort 1999). This phase of volcanism is characterized by outpourings of lava, mostly basalt, some with very low amounts of silica (42%–45%; Stroud 1997).

Volcanic activity of the Clayton phase began about 3 million years ago at Rabbit Ear Mountain, which is near Clayton, New Mexico, and visible from the Crater Rim Trail on clear days. The mountain served as an important landmark along the Cimarron Route of the Santa Fe Trail. As the first peak to rise above the plains, Rabbit Ear Mountain was undoubtedly a welcome site for travelers heading west (Parent 2006). It is 70 km (50 mi) east of Capulin Volcano. Over the last 3 million years, erosion has destroyed much of its volcanic form.

Capulin Phase (1.69 million–32,000 years ago)

The most recent phase of volcanic activity in the Raton-Clayton volcanic field started 1.69 million years (Pleistocene Epoch; fig. 3) with the eruption of Mud Hill and continued after the eruption of Capulin Volcano (fig. 38). The age range used here for the Capulin phase—1.69 million to 32,000 years ago—is from Zimmerer (2015). New ^{40}Ar/^{39}Ar ages indicate that at least three volcanoes erupted after the episode that built Capulin Volcano (table 2).

Figure 38. Satellite imagery of Capulin phase volcanoes. The Capulin phase of the Raton-Clayton volcanic field occurred 1.69 million–32,000 years ago. Capulin Volcano erupted about 55,000 years ago. Northeast of Capulin Volcano, Mud Hill erupted 1.69 million years ago and is, therefore, notably older than the surrounding volcanoes. Baby Capulin erupted 46,000 years ago and is thus younger than Capulin Volcano. The green outline delineates the boundary of Capulin Volcano National Monument. Landsat imagery (May 2014) extracted from Google Earth.

The eruption of Capulin Volcano took place 55,000 ± 2,000 years ago and may be divided into the following three episodes: (1) First Series lava flows, (2) cone-building eruption, and (3) boca eruption from which the Second Series, Third Series, and Fourth Series flows emerged.

First Series Lava Flows

Initially, lava associated with Capulin Volcano simply spread across the landscape. It erupted from a fissure

Table 2. ^{40}Ar/^{39}Ar ages for Capulin and surrounding volcanoes

Volcano	Age (years ago)	Comments from Zimmerer (2015)
Purvine Hills	32,000 ± 5,000	Youngest known eruption in the Raton-Clayton volcanic field. Age agrees with Sayre and Ort (1999) that suggested Purvine Hills are also younger than Capulin Volcano.
Twin Mountain	40,000 ± 4,000	New age agrees with previously determined 40Ar/39Ar ages of 48,000 ± 20,000 years ago from Stroud (1997). Ages agree with Sayre and Ort (1999) that suggested Twin Mountain is younger than Capulin Volcano.
Baby Capulin	46,000 ± 6,000	Age agrees with stratigraphy that suggests Baby Capulin is younger than Capulin Volcano. Flows from Baby Capulin traveled approximately 30 km (20 mi) down the Dry Cimarron River.
Capulin	55,000 ± 2,000	Agrees with previous age determinations, but new age is significantly more precise. New age is from sample of lava lake in the boca. An additional age from the crater (51,000 ± 5,000 years ago) agrees with the boca age, but is less precise.
Malpie Mountain	61,000 ± 500	Located south of Capulin Volcano National Monument. Very precise date.
Mud Hill	1,690,000 ± 30,000	Significantly older than surrounding volcanoes

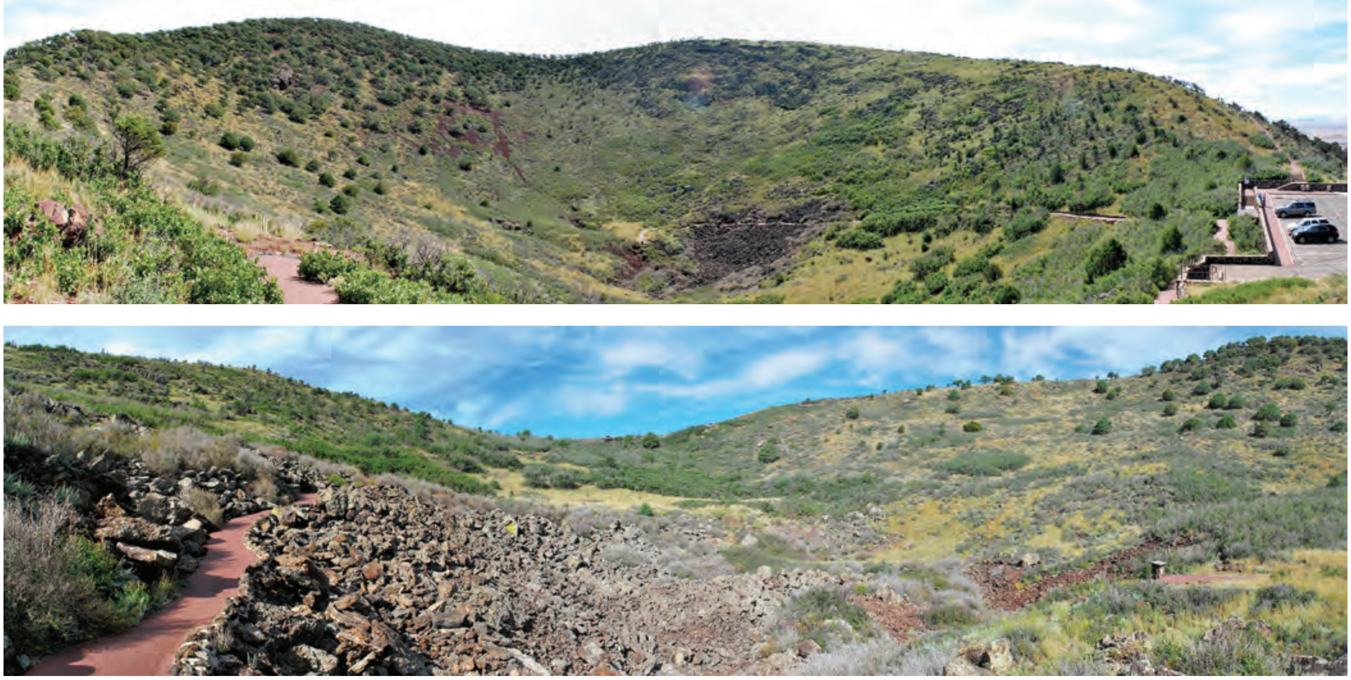


Figure 39. Panoramic views of Capulin crater and vent. From the Crater Rim Trail (upper photograph), visitors can look into Capulin crater. The view is from just north of the crater parking area. The lower photograph shows the rim from within the crater; it was taken near the vent. Note the irregular, jagged spatter that coats most of the inner walls of the crater and vent region. The paved pathway of Crater Vent Trail can be seen in the foreground. Photographs by Matthew Zimmerer (MattZPhotography, www.mattzphotography.com [accessed 11 September 2015], used with permission), processed using Adobe Lightroom and stitched together using Hugin.

or series of small vents, then flowed east to form the First Series lava flows (Sayre and Ort 1999). A mantle of cinders covers these flows, indicating that First Series lava had been emplaced before the construction of Capulin Volcano.

Cone-Building Eruption

Capulin Volcano built up quickly, in a matter of weeks to years (Sayre and Ort 1999). It was the second and most dramatic part of the volcano's eruption. The initial fissure or series of small vents coalesced into a single vent from which exploding gases propelled lava into the air. The eruption built up the cone from the ground surface as primarily cinders, but bombs and ash also accumulated around the vent. Repeated explosions kept the crater clear. When the slope of the growing pyroclastic pile became too steep, cinders and ash slid downward, forming distinctive layers (fig. 12). Prevailing southwesterly winds caused cinders to pile up higher on the northeastern side of the crater (fig. 25). As expulsion of volcanic gases waned, spatter was deposited on the rim and crater, marking the end of the cone-building episode (fig. 39).

Boca Eruption

After cone building, volcanism shifted to the boca on the western side of the cinder cone (see cover). The absence of cinders on top of volcanic features in the boca indicates that activity in the boca followed the cone-building eruption. During the boca eruption, lava extruded from multiple vents, two of which are included in the GRI GIS data set (see lava flow series map, in pocket). During the boca eruption, lava flowed to the southeast in Second Series lava flows, then to the southwest in Third Series lava flows, and finally north in Fourth Series lava flows. Many features were created while lava erupted from the boca, including boca ramparts lava, lava lakes, levees, push-ups, rafted cinder cones, spatter deposits, spatter flows, lava cascades, lava ridges, squeeze-ups, and tumuli (see volcanic features map and Map Unit Properties Table, in pocket).

Second Series Lava Flows

Second Series lava flows oozed out of the side of the cinder cone, traveling south down a narrow valley through what is now the picnic area at Capulin Volcano National Monument. A lava tube, squeeze-ups, and tumuli formed during this series, which ended when a chunk of the cinder cone rafted away from the main cone and blocked egress. This piece of cinder cone—the southern of the two rafted cinder cones mapped by Richman (2010)—is visible as the hill northwest of the hairpin turn near the picnic area. It is made of cinders and spatter.

Third Series Lava Flows

Following emplacement of Second Series lava flows, the presently visible lava lake system of the boca began to develop. Lava that fed this system came from the more southerly of the two vents in the boca (see volcanic features map, in pocket). Spatter extensively covers this vent area. Third Series lava formed a pair of lakes near the old campfire chimney in the boca (figs. 16 and 17), then traveled by lava tubes down to the area near the visitor center, where tumuli formed. From there, Third Series lava flows traveled via tubes and open flows down toward what is now the town of Capulin, and to the west. The lakes themselves were bounded by walls made of spatter and solidified lava from the edges of the flows. As time went by, these lakes were cut off from the vent, perhaps during a brief eruptive hiatus (Sayre and Ort 1999).

Fourth Series Lava Flows

Fourth Series lava erupted from the more northerly of the two vents in the boca (see volcanic features map, in pocket). The lava again filled a lava lake that eventually began to drain to the north, aided by lava tubes. This part of the eruption ceased when a large piece of the cinder cone rafted out about 100 m (300 ft). As a result, lavas subsequently extruded from the northeasternmost edge of the boca and then covered the area between Capulin Volcano and Mud Hill, and to the east on top of Mud Hill deposits. This rafted piece of cinder cone forms a ridge at the northern end of the boca that is clearly visible from the highway traveling southward.

The eruption of Capulin Volcano only lasted a short time, probably weeks to years, which is common for volcanoes of this type. In cinder-cone eruptions, the supply of magma is small or episodic, facilitating the cooling and clogging of a vent and subterranean pathway. As new magma forces its way up through the Earth’s crust, a different vent will form, creating a new volcano. Although Capulin Volcano is unlikely to erupt again, molten rock may once again flow across the plains of northeastern New Mexico from a newly formed vent in the Raton-Clayton volcanic field.

Geologic Map Data

This chapter summarizes the geologic map data available for Capulin Volcano National Monument. Two posters (in pocket) display the GRI GIS data draped over imagery of the monument and surrounding area. The Map Unit Properties Table (in pocket) summarizes this report's content for each geologic map unit. Complete GIS data are available at the GRI publications website: http://go.nps.gov/gripubs.

Geologic Maps

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

Geologic maps often depict geomorphic features, structural interpretations (such as faults or folds), and locations of past geologic hazards that may be susceptible to future activity. Anthropogenic features such as mines or quarries, as well as observation or collection locations, may be indicated on geologic maps. The American Geosciences Institute website, http://www.agiweb.org/environment/publications/mapping/index.html (accessed 3 February 2015), provides more information about geologic maps and their uses.

Source Maps

The GRI team digitizes paper maps and converts digital data to conform to the GRI GIS data model. GRI digital geologic map products include essential elements of the source maps such as map unit descriptions, a correlation chart of units, a map legend, map notes, references, and figures. The GRI team used the following source to produce the GRI GIS data for Capulin Volcano National Monument.

Richman, R. 2010. Digital volcanic geology of Capulin Volcano National Monument and vicinity (scale 1:24,000). Prepared by Student Conservation Association (SCA) geology and interpretation intern for Capulin Volcano National Monument, Capulin, New Mexico.

During mapping and report preparation, Richman (2010) used the following sources:

Mathis, A. 1999. Volcanology for interpreters. Unpublished geology guide. Capulin Volcano National Monument, Capulin, New Mexico.

Sayre, W. O., and M. H. Ort. 1999. A geologic study of Capulin Volcano National Monument and surrounding areas. Final report. Cooperative Agreement CA7029-1-0017 (4 December 1999). Submitted to Capulin Volcano National Monument, Capulin, New Mexico. College of Santa Fe, and Northern Arizona University, Santa Fe, New Mexico, and Flagstaff, Arizona. Published as Open-File Report 541 (August 2011). New Mexico Bureau of Geology and Mineral Resources, Socorro, New Mexico. http://geoinfo.nmt.edu/publications/openfile/downloads/OFR500-599/526-550/541/ofr_541.pdf (accessed 29 October 2014).

Sayre, W. O., M. H. Ort, and D. Graham. 1995. Capulin Volcano is approximately 59,100 years old: cosmogenic helium aging technique key to clearing up age old question. Park Science 15(2):10–11. http://www.nature.nps.gov/parkscience/archive/PDF/ParkScience15(2)Spring1995.pdf (accessed 4 November 2014).

GRI GIS Data

The GRI team implements a GIS data model that standardizes map deliverables. The data model is available at http://go.nps.gov/gridatamodel. 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 Capulin Volcano National Monument using data model version 2.1. The GRI Geologic Maps website, http://go.nps.gov/geomaps, provides more information about GRI map products.

GRI digital geologic data are available through the NPS Integrated Resource Management Applications (IRMA) portal (https://irma.nps.gov/App/Portal/Home). Enter "GRI" as the search text and select a park.

The GRI GIS data set for Capulin Volcano National Monument includes two parts: (1) cavo_geology.mxd, which contains volcanic features within the monument mapped by Richman (2010); and (2) cvlf_geology.mxd, which shows the full extent of the four series of lava flows and vents associated with Capulin Volcano, and also delineates Mud Hill and Baby Capulin and their vents. The following components are part of the data set:

- A GIS readme file (cavo_gis_readme.pdf) that describes the GRI data formats, naming conventions, extraction instructions, use constraints, and contact information.
- Data in ESRI geodatabase GIS format;
- Layer files with feature symbology (tables 3 and 4);
- Federal Geographic Data Committee–compliant metadata;
- An ancillary map information document (cavo_geology.pdf) that contains information captured from source maps;
- An ESRI map document (cavo_geology.mxd; cvlf_geology.mxd) that displays the digital geologic data; and
- A KML/KMZ version of the data viewable in Google Earth (tables 3 and 4).

GRI Map Posters

Two posters are included with the GRI report for Capulin Volcano National Monument. One displays the digital volcanic features map of the monument and vicinity, detailing the boca. These data are part of cavo_geology.mxd. The other displays the digital lava flows and vents of the Capulin Volcano area. In addition to the main cone and boca, this poster shows the extent of the four series of lava flows, Mud Hill, and Baby Capulin, as well as vents. These data are part of cvlf_geology.mxd. Both posters illustrate the GRI GIS data draped over a shaded relief image of the monument and surrounding area. Geographic information and selected features at the monument have been added to the posters. Digital elevation data and added geographic information are not included in the GRI GIS data set, but are available from a variety of online sources. Contact GRI for assistance locating these data.

Table 3. GRI GIS data layers of cavo_geology.mxd (volcanic features map of Capulin Volcano National Monument)

Data Layer	On Poster?	Google Earth Layer?
Volcanic Point Features	Yes	No
Volcanic Line Features	Yes	Yes
Volcanic Area Feature Boundaries	Yes	Yes
Volcanic Area Features	Yes	Yes

Map Unit Properties Tables

The Map Unit Properties Table is organized stratigraphically (younger on top of older units) following the lava flow series data and timing of eruptions established by Sayre and Ort (1999). The table correlates specific volcanic features mapped by Richman (2010) to their corresponding lava flow series. The table lists the geologic time division, map symbol, and a simplified description for each of the volcanic features in the GRI GIS data. Detailed descriptions of these volcanic features are included in the "Volcanic Features" section of this report. Following the structure of the report, the table summarizes the geologic features and processes, resource management issues, and history associated with each map unit.

Use Constraints

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

Table 4. GRI GIS data layers of cvlf_geology.mxd (lava flow series of Capulin Volcano area)

Data Layer	On Poster?	Google Earth Layer?
Vent Point Features	Yes	No
Volcanic Flow Unit Boundaries	Yes	Yes
Volcanic Flow Units	Yes	Yes

Glossary

These are brief definitions of selected geologic terms relevant to this report. Definitions are based on those in the American Geosciences Institute Glossary of Geology (5th edition; 2005). Additional terms are defined at http://geomaps.wr.usgs.gov/parks/misc/glossarya.html.

aeolian. Describes materials formed, eroded, or deposited by or related to the action of wind.

agglomerate. A consolidated pyroclastic rock made primarily of bombs. Roughly synonymous with spatter.

agglutinate. A welded pyroclastic deposit characterized by vitric material binding the individual clasts that commonly became fused while hot and viscous.

alkali. Describes silicate (silicon + oxygen) minerals that contain alkali metals such as sodium and potassium.

alkali metals. Any of the soft, white, low-density, low-melting, highly reactive metallic elements, including lithium, sodium, potassium, rubidium, cesium, and francium, belonging to Group 1A of the periodic table.

alluvium. Stream-deposited sediment.

andesite. A volcanic rock characteristically medium dark in color and containing approximately 57%–63% silica and moderate amounts of iron and magnesium.

ash. Fine-grained material, less than 2 mm (0.08 in) across, ejected from a volcano.

basalt. A volcanic rock that is characteristically dark in color (gray to black), contains approximately 53% silica or less, and is rich in iron and magnesium.

basaltic andesite. A volcanic rock that is commonly dark gray to black and contains approximately 53%–57% silica.

bedrock. Solid rock that underlies unconsolidated sedimentary deposits and soil.

block. A pyroclast ejected in a solid state; it has a diameter greater than 64 mm (2.5 in).

bomb. A viscous pyroclast more than 64 mm (2.5 in) in diameter ejected then shaped while in flight; it commonly has a hollow or vesicular interior.

breakdown. Collapse of a cave ceiling or walls of a cave. Also, the accumulation of debris thus formed.

caldera. A large, basin-shaped volcanic depression formed by collapse during an eruption.

channel. The bed where a natural body of surface water flows or may flow. Also, a natural passageway or depression of perceptible extent containing continuously or periodically flowing water, or forming a connecting link between two bodies of water.

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

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

cinder cone. A conical hill, commonly steep, ranging from tens to hundreds of meters tall, formed by the accumulation of solidified fragments of lava that fell around the vent during a basaltic or andesitic eruption.

clast. An individual constituent, grain, or fragment of a rock or unconsolidated deposit, produced by the mechanical or chemical disintegration of a larger rock mass.

composite volcano. Steep, conical volcanoes built by the eruption of viscous lava flows, tephra, and pyroclastic flows; usually constructed over tens to hundreds of thousands of years and may erupt a variety of magma types (basalt to rhyolite); typically consist of many separate vents. Synonymous with "stratovolcano."

crust. Earth's outermost layer or shell.

dacite. A volcanic rock that is characteristically light in color and contains approximately 63%–68% silica and moderate amounts of sodium and potassium.

debris flow. A moving mass of rock fragments, soil, and mud, with more than half of the particles larger than sand size. Slow debris flows may move less that 1 m (3 ft) per year; rapid ones reach 160 kph (100 mph).

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

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

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

ephemeral lake. A short-lived lake.

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

fissure. A fracture or crack in rock along which there is a distinct separation; commonly filled with mineral-bearing materials.

fissure (volcanic). An elongated fracture or crack at the surface from which lava erupts.

fissure vent. A volcanic conduit having the form of a crack or fissure at Earth's surface.

fissure volcano. One of a series of volcanic vents in a pattern of eruption along a fissure.

fluvial. Of or pertaining to a river or rivers.

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

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

fumarole. A vent, usually volcanic, from which gases and vapors are emitted.

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

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

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

horizon (archeology). A period during which the influence of a specific culture spread rapidly over a defined area.

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

hydrothermal. Of or pertaining to hot water, to the action of hot water, or to the products of this action.

hydrovolcanic. Term encompassing all volcanic activity that results from the interaction between lava, magmatic heat, or gases and water at or near the surface of the Earth. Synonymous with "phreatomagmatic."

igneous. Describes a rock or mineral that solidified from molten or partly molten material; also, describes processes leading to, related to, or resulting from the formation of such rocks. One of the three main classes or rocks—igneous, metamorphic, and sedimentary.

isotopic age. An age (in years) calculated from the quantitative determination of radioactive elements and their decay products.

isotopic dating. Calculating an age in years for geologic materials by measuring the presence of a short-lived radioactive element (e.g., carbon-14) or by measuring the presence of a long-lived radioactive element plus its decay product (e.g., potassium-40/argon-40). The term applies to all methods of age determination based on nuclear decay of naturally occurring radioactive isotopes.

landslide. A collective term covering a wide variety of slope-movement landforms and processes that involve the downslope transport of soil and rock material en masse under the influence of gravity.

lapilli. Pyroclastic materials ranging between 2 and 64 mm (0.08 and 2.5 in) across with no characteristic shape; may be either solidified or still viscous upon landing. An individual fragment is called a lapillus.

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

lava dome. A steep-sided mass of viscous, commonly blocky, lava extruded from a vent; typically has a rounded top and covers a roughly circular area; may be isolated or associated with lobes or flows of lava from the same vent; typically silicic (rhyolite or dacite) in composition.

lava lake. A lake of molten lava, usually basaltic, in a volcanic crater or depression. Also refers to solidified and partly solidified stages.

lava tube. Conduits through which lava travels beneath the surface of a lava flow; also, a cavernous segment of the conduit remaining after the flow of lava ceases.

levee (volcanic). A retaining wall of hardened lava alongside a lava channel; also, the freestanding cooled edge of a lava tongue or flow left after evacuation of the molten lava.

loess. Windblown silt-sized sediment.

maar. A low-relief, broad volcanic crater formed by multiple shallow explosive eruptions. It is surrounded by a low-relief rim of fragmental material, and may be filled by water.

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

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

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

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

mold. An impression made in the surrounding earth by the exterior or interior of a fossil shell or other organic structure and then preserved. Also, a cast of the inner surface of a fossil shell.

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

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

period. The fundamental unit of the worldwide geologic time scale. It is lower in rank than era and higher than epoch. The geochronologic unit during which the rocks of the corresponding system were formed.

phreatomagmatic. See "hydrovolcanic."

playa. A dry, vegetation-free, flat area at the lowest part of an undrained desert basin.

playa lake. A shallow, intermittent lake in an arid region, covering up or occupying a playa in the wet season but subsequently drying up.

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

pyroclast. An individual particle ejected during a volcanic eruption; usually classified according to size.

pyroclastic. Describes clastic rock material formed by volcanic explosion or aerial expulsion from a vent; also, describes a rock texture of explosive origin. It is not synonymous with "volcanic."

radiocarbon age. An isotopic age expressed in years and calculated from the quantitative determination of the amount of carbon-14 remaining in an organic material. Synonymous with "carbon-14 age."

relative dating. The chronological placement and ordering of rocks, events, or fossils with respect to the geologic time scale and without reference to numerical ages.

rhyodacite. A volcanic rock that contains approximately 68%–72% silica and is intermediate in composition between rhyolite and dacite.

rhyolite. A volcanic rock that is characteristically light in color, contains approximately 72% or more of silica, and is rich in potassium and sodium.

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

rill. A very small brook or trickling stream of water usually without any tributaries. Also, the channel formed by such a stream.

rock. An aggregate of one or more minerals (e.g., granite), a body of undifferentiated mineral matter (e.g., obsidian), or a body of solid organic material (e.g., coal).

rockfall. The most rapid type of slope movement in which a newly detached fragment of bedrock of any size falls from a cliff or other very steep slope, traveling straight down or in a series of leaps and bounds down a slope.

sand sheet. A sheetlike body of surficial sediment, commonly sand, that veneers the underlying stratigraphic units (unconsolidated deposits or bedrock) and can range in thickness from a few centimeters to tens of meters, with a lateral persistence of a few meters to tens of kilometers.

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

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

sedimentary. Pertaining to or containing sediment.

sedimentary rock. A rock resulting from the consolidation of loose sediment that has accumulated in layers; it may be "clastic," consisting of mechanically formed fragments of older rock; "chemical," formed by precipitation from solution; or "organic," consisting of the remains of plants and animals. One of the three main classes of rock—igneous, metamorphic, and sedimentary.

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

sheet erosion. The removal of thin layers of surface material more or less evenly from an extensive area of gently sloping land by broad continuous sheets of running water, rather than by streams flowing in well-defined channels.

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

sierra. A high range of hills or mountains, especially one having jagged or irregular peaks that resemble the teeth of a saw.

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

silt. Clastic sedimentary material intermediate in size between fine-grained sand and coarse clay, 0.0039 to 0.063 mm (0.00015 to 0.0025 in) across.

slope. The inclined surface of any part of Earth's surface, such as a hillslope. Also, a broad part of a continent descending into an ocean.

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

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

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

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

squeeze-up. A small accumulation of viscous lava extruded under pressure from a fracture or opening onto the solidified surface of a lava flow.

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

stratigraphic. Of or pertaining to strata.

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

stratotype. The original or subsequently designated standard of reference of a named layered stratigraphic unit or of a stratigraphic boundary; a specific interval or point in a specific sequence of rock strata that constitutes the standard of the definition and characterization of the stratigraphic unit or boundary being defined. Synonymous with "type section."

stratovolcano. A volcano that is constructed of alternating layers of lava and pyroclastic deposits, along with abundant dikes and sills. Viscous, high-silica lava may flow from fissures radiating from a central vent, from which pyroclastic material is ejected. Synonymous with "composite volcano."

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

tephra. A collective term used for all pyroclastic material, regardless of size, shape, or origin, ejected into the air during a volcanic eruption.

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

trace fossil. A fossilized feature such as a track, trail, burrow, or coprolite (dung), that preserves evidence of an organism's life activities, rather than the organism itself. Compare to "body fossil."

tree mold. A cylindrical hollow in a lava flow formed by the envelopment of a tree by the flow, solidification of the lava in contact with the tree, and disappearance of the tree by burning and subsequent removal of the charcoal and ash. The inside of the mold preserves the surficial features of the tree.

tuff. Consolidated or cemented volcanic ash and lapilli.

tumulus. A dome or small mound on the crust of a lava flow, caused by pressure due to the difference in the rate of flow between the cooler lava crust and the more fluid underlying lava.

type area. The geographic area or region that encompasses the stratotype or type locality of a stratigraphic unit or stratigraphic boundary.

type section. The originally described sequence of strata that constitute a stratigraphic unit. It serves as an objective standard with which spatially separated parts of the unit may be compared, and it is preferably in an area where the unit shows maximum thickness and is completely exposed (or at least shows top and bottom).

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

vent. Any opening at Earth's surface through which magma erupts or volcanic gases are emitted.

vesicle. A cavity of variable shape formed by the entrapment of a gas bubble during solidification of lava.

vesicular. Describes the texture of a rock, especially lava, characterized by abundant vesicles formed as a result of the expansion of gases during the fluid stage of a lava.

viscosity. The property of a substance to offer internal resistance to flow.

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

volcanism. The processes by which magma and its associated gases rise into Earth's crust and are extruded onto the surface and into the atmosphere.

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

welding. Consolidation of sediments under pressure. Also, the diagenetic process whereby discrete crystals and/or grains become attached to each other during compaction.

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

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

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Additional References

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

Geology of National Park Service Areas

- NPS Geologic Resources Division
  Energy and Minerals; Active Processes and Hazards; Geologic Heritage:
  http://nature.nps.gov/geology/
- NPS Geologic Resources Inventory: http://www.nature.nps.gov/geology/inventory/index.cfm
- NPS Geoscientist-In-the-Parks (GIP) internship and guest scientist program: http://www.nature.nps.gov/geology/gip/index.cfm
- NPS Views program (geology-themed modules are available for Geologic Time, Paleontology, Glaciers, Caves and Karst, Coastal Geology, Volcanoes, and a variety of geologic parks): http://www.nature.nps.gov/views/
- USGS Geology of National Parks (including 3D imagery): http://3dparks.wr.usgs.gov/

NPS Resource Management Guidance and Documents

- Management Policies 2006 (Chapter 4: Natural resource management): http://www.nps.gov/policy/mp/policies.html
- 1998 National parks omnibus management act: http://www.gpo.gov/fdsys/pkg/PLAW-105publ391/pdf/PLAW-105publ391.pdf
- NPS-75: Natural resource inventory and monitoring guideline: http://www.nature.nps.gov/nps75/nps75.pdf
- NPS Natural resource management reference manual #77: http://www.nature.nps.gov/Rm77/
- Geologic monitoring manual (Young, R., and L. Norby, editors. 2009. Geological monitoring. Geological Society of America, Boulder, Colorado): http://nature.nps.gov/geology/monitoring/index.cfm
- NPS Technical Information Center (TIC) (Denver, Colorado; repository for technical documents): http://www.nps.gov/dsc/technicalinfocenter.htm

Climate Change Resources

- NPS Climate Change Response Program Resources: http://www.nps.gov/subjects/climatechange/resources.htm
- US Global Change Research Program: http://globalchange.gov/home
- Intergovernmental Panel on Climate Change: http://www.ipcc.ch/

Geological Surveys and Societies

- New Mexico Bureau of Geology and Mineral Resources: http://geoinfo.nmt.edu/
- US Geological Survey: http://www.usgs.gov/
- Geological Society of America: http://www.geosociety.org/
- American Geophysical Union: http://sites.agu.org/
- American Geosciences Institute: http://www.americangeosciences.org/
- Association of American State Geologists: http://www.stategeologists.org/

US Geological Survey Reference Tools

- National geologic map database (NGMDB): http://ngmdb.usgs.gov/
- Geologic names lexicon (GEOLEX; geologic unit nomenclature and summary): http://ngmdb.usgs.gov/Geolex/geolex_home.html
- Geographic names information system (GNIS; official listing of place names and geographic features): http://gnis.usgs.gov/
- GeoPDFs (download searchable PDFs of any topographic map in the United States): http://store.usgs.gov (click on “Map Locator”)
- Publications warehouse (many publications available online): http://pubs.er.usgs.gov
- Tapestry of time and terrain (descriptions of physiographic provinces): http://tapestry.usgs.gov/Default.html

Appendix A: Scoping Participants

The following people attended the GRI scoping meeting for Capulin Volcano National Monument, held on 10 May 2011. Discussions during these meetings supplied a foundation for this GRI report. The scoping summary document is available on the GRI publications website: http://go.nps.gov/gripubs.

Name	Affiliation	Position
Peter Armato	Capulin Volcano National Monument	Superintendent
Rob Bennetts	NPS Southern Plains Network	Network Coordinator
Lynn Cartmell	Capulin Volcano National Monument	Lead Park Ranger
Tim Connors	NPS Geologic Resources Division	Geologist
Nelia Dunbar	New Mexico Bureau of Geology and Mineral Resources	Geologist
Bruce Heise	NPS Geologic Resources Division	Geologist/Program Coordinator
Adam Heberlie	Bent's Old Fort National Historic Site	Biological Sciences Technician
Katie KellerLynn	Colorado State University	Geologist/Research Associate
Bill McIntosh	New Mexico Bureau of Geology and Mineral Resources	Volcanologist
Fran Pannebaker	Bent's Old Fort National Historic Site	Chief of Resources
Phil Reiker	NPS Geologic Resources Division	Geologist/Writer-Editor
Karl Zimmerman	Sand Creek Massacre National Historic Site	Chief of Resources and Operations

Appendix B: Geologic Resource Laws, Regulations, and Policies

The NPS Geologic Resources Division developed this table to summarize laws, regulations, and policies that specifically apply to National Park Service minerals and geologic resources. The table does not include laws of general application (e.g., Endangered Species Act, Clean Water Act, Wilderness Act, National Environmental Policy Act, or National Historic Preservation Act). The table does include the NPS Organic Act when it serves as the main authority for protection of a particular resource or when other, more specific laws are not available. Information is current as of August 2015. Contact the NPS Geologic Resources Division for detailed guidance.

Resource	Resource-specific Laws	Resource-specific Regulations	2006 Management Policies
Paleontology	**National Parks Omnibus Management Act of 1998, 16 USC § 5937** protects the confidentiality of the nature and specific location of paleontological resources and objects. **Paleontological Resources Preservation Act of 2009, 16 USC § 470aaa et seq.** provides for the management and protection of paleontological resources on federal lands.	**36 CFR § 2.1(a)(1)(iii)** prohibits destroying, injuring, defacing, removing, digging or disturbing paleontological specimens or parts thereof. **Prohibition in 36 CFR § 13.35** applies even in Alaska parks, where the surface collection of other geologic resources is permitted. Regulations in association with 2009 PRPA are being finalized (August 2015).	**Section 4.8.2** requires NPS to protect geologic features from adverse effects of human activity. **Section 4.8.2.1** emphasizes Inventory and Monitoring, encourages scientific research, directs parks to maintain confidentiality of paleontological information, and allows parks to buy fossils only in accordance with certain criteria.
Rocks and Minerals	**NPS Organic Act, 16 USC § 1 et seq.** directs the NPS to conserve all resources in parks (including rock and mineral resources), unless otherwise authorized by law.	**36 CFR § 2.1** prohibits possessing, destroying, disturbing mineral resources… in park units. **Exception: 36 CFR § 13.35** allows some surface collection of rocks and minerals in some Alaska parks (not Klondike Gold Rush, Sitka, Denali, Glacier Bay, or Katmai) by non-disturbing methods (e.g., no pickaxes), which can be stopped by superintendent if collection causes significant adverse effects on park resources and visitor enjoyment.	**Section 4.8.2** requires NPS to protect geologic features from adverse effects of human activity.
Park Use of Sand and Gravel	**Materials Act of 1947, 30 USC § 601** does not authorize the NPS to dispose of mineral materials outside of park units.	None applicable.	**Section 9.1.3.3** clarifies that only the NPS or its agent can extract park-owned common variety minerals (e.g., sand and gravel), and: -only for park administrative uses; -after compliance with NEPA and other federal, state, and local laws, and a finding of non-impairment; -after finding the use is park's most reasonable alternative based on environment and economics; -parks should use existing pits and create new pits only in accordance with park-wide borrow management plan; -spoil areas must comply with Part 6 standards; and -NPS must evaluate use of external quarries. Any deviation from this policy requires a written waiver from the Secretary, Assistant Secretary, or Director.

Resource	Resource-specific Laws	Resource-specific Regulations	2006 Management Policies
Upland and Fluvial Processes	**Rivers and Harbors Appropriation Act of 1899, 33 USC § 403** prohibits the construction of any obstruction on the waters of the United States not authorized by congress or approved by the USACE. **Clean Water Act 33 USC § 1342** requires a permit from the USACE prior to any discharge of dredged or fill material into navigable waters (waters of the US [including streams]). **Executive Order 11988** requires federal agencies to avoid adverse impacts to floodplains. (see also **D.O. 77-2**) **Executive Order 11990** requires plans for potentially affected wetlands (including riparian wetlands). (see also D.O. 77-1)	None applicable.	**Section 4.1** requires NPS to manage natural resources to preserve fundamental physical and biological processes, as well as individual species, features, and plant and animal communities; maintain all components and processes of naturally evolving park ecosystems. **Section 4.1.5** directs the NPS to re-establish natural functions and processes in human-disturbed components of natural systems in parks, unless directed otherwise by Congress. **Section 4.4.2.4** directs the NPS to allow natural recovery of landscapes disturbed by natural phenomena, unless manipulation of the landscape is necessary to protect park development or human safety. **Section 4.6.4** directs the NPS to (1) manage for the preservation of floodplain values; [and] (2) minimize potentially hazardous conditions associated with flooding. **Section 4.6.6** directs the NPS to manage watersheds as complete hydrologic systems and minimize human-caused disturbance to the natural upland processes that deliver water, sediment, and woody debris to streams. **Section 4.8.1** directs the NPS to allow natural geologic processes to proceed unimpeded. Geologic processes…include… erosion and sedimentation…processes. **Section 4.8.2** directs the NPS to protect geologic features from the unacceptable impacts of human activity while allowing natural processes to continue.
Caves and Karst Systems	**Federal Cave Resources Protection Act of 1988, 16 USC §§ 4301 – 4309** requires Interior/Agriculture to identify "significant caves" on Federal lands, regulate/restrict use of those caves as appropriate, and include significant caves in land management planning efforts. Imposes civil and criminal penalties for harming a cave or cave resources. Authorizes Secretaries to withhold information about specific location of a significant cave from a Freedom of Information Act (FOIA) requester. **National Parks Omnibus Management Act of 1998, 16 USC § 5937** protects the confidentiality of the nature and specific location of cave and karst resources.	**36 CFR § 2.1** prohibits possessing/destroying/disturbing…cave resources…in park units. **43 CFR Part 37** states that all NPS caves are "significant" and sets forth procedures for determining/releasing confidential information about specific cave locations to a FOIA requester.	**Section 4.8.1.2** requires NPS to maintain karst integrity, minimize impacts. **Section 4.8.2** requires NPS to protect geologic features from adverse effects of human activity. **Section 4.8.2.2** requires NPS to protect caves, allow new development in or on caves if it will not impact cave environment, and to remove existing developments if they impair caves. **Section 6.3.11.2** explains how to manage caves in/adjacent to wilderness.

Resource	Resource-specific Laws	Resource-specific Regulations	2006 Management Policies
Mining Claims	**Mining in the Parks Act of 1976, 16 USC § 1901 et seq**. authorizes NPS to regulate all activities resulting from exercise of mineral rights, on patented and unpatented mining claims in all areas of the System, in order to preserve and manage those areas. **General Mining Law of 1872, 30 USC § 21 et seq.** allows US citizens to locate mining claims on Federal lands. Imposes administrative and economic validity requirements for "unpatented" claims (the right to extract Federally-owned locatable minerals). Imposes additional requirements for the processing of "patenting" claims (claimant owns surface and subsurface). Use of patented mining claims may be limited in Wild and Scenic Rivers and OLYM, GLBA, CORO, ORPI, and DEVA. **Surface Uses Resources Act of 1955, 30 USC § 612** restricts surface use of unpatented mining claims to mineral activities.	**36 CFR § 5.14** prohibits prospecting, mining, and the location of mining claims under the general mining laws in park areas except as authorized by law. **36 CFR Part 6** regulates solid waste disposal sites in park units. **36 CFR Part 9, Subpart A** requires the owners/operators of mining claims to demonstrate bona fide title to mining claim; submit a plan of operations to NPS describing where, when, and how; prepare/submit a reclamation plan; and submit a bond to cover reclamation and potential liability.	**Section 6.4.9** requires NPS to seek to remove or extinguish valid mining claims in wilderness through authorized processes, including purchasing valid rights. Where rights are left outstanding, NPS policy is to manage mineral-related activities in NPS wilderness in accordance with the regulations at 36 CFR Parts 6 and 9A. **Section 8.7.1** prohibits location of new mining claims in parks; requires validity examination prior to operations on unpatented claims; and confines operations to claim boundaries.
Nonfederal Oil and Gas	**NPS Organic Act, 16 USC § 1 et seq.** authorizes the NPS to promulgate regulations to protect park resources and values (from, for example, the exercise of mining and mineral rights).	**36 CFR Part 6** regulates solid waste disposal sites in park units. **36 CFR Part 9, Subpart B** requires the owners/operators of nonfederally owned oil and gas rights to -demonstrate bona fide title to mineral rights; -submit a plan of operations to NPS describing where, when, how they intend to conduct operations; -prepare/submit a reclamation plan; and -submit a bond to cover reclamation and potential liability.	**Section 8.7.3** requires operators to comply with 9B regulations.
Nonfederal minerals other than oil and gas	**NPS Organic Act, 16 USC §§ 1 and 3** **Surface Mining Control and Reclamation Act of 1977, 30 USC § 1201 et. seq.** prohibits surface coal mining operations on any lands within the boundaries of a NPS unit, subject to valid existing rights.	**NPS regulations at 36 CFR Parts 1, 5, and 6** require the owners/operators of other types of mineral rights to obtain a special use permit from the NPS as a § 5.3 business operation, and § 5.7 – Construction of buildings or other facilities, and to comply with the solid waste regulations at Part 6. **SMCRA Regulations at 30 CFR Chapter VII** govern surface mining operations on Federal lands and Indian lands by requiring permits, bonding, insurance, reclamation , and employee protection. Part 7 of the regulations states that National Park System lands are unsuitable for surface mining.	**Section 8.7.3** states that operators exercising rights in a park unit must comply with 36 CFR Parts 1 and 5.

Resource	Resource-specific Laws	Resource-specific Regulations	2006 Management Policies
Geothermal	**Geothermal Steam Act of 1970, 30 USC § 1001 et seq. as amended in 1988**, states that -no geothermal leasing is allowed in parks; -"significant" thermal features exist in 16 park units (features listed by the NPS at **52 Fed. Reg. 28793-28800** [August 3, 1987], and thermal features in Crater Lake, Big Bend, and Lake Mead); -NPS is required to monitor those features; and -based on scientific evidence, Secretary of Interior must protect significant NPS thermal features from leasing effects. **Geothermal Steam Act Amendments of 1988, Public Law 100--443** prohibits geothermal leasing in the Island Park known geothermal resource area near Yellowstone and outside 16 designated NPS units if subsequent geothermal development would significantly adversely affect identified thermal features.	None applicable	**Section 4.8.2.3** requires NPS to -preserve/maintain integrity of all thermal resources in parks. -work closely with outside agencies, and -monitor significant thermal features.
Soils	**Soil and Water Resources Conservation Act, 16 USC §§ 2011–2009** provides for the collection and analysis of soil and related resource data and the appraisal of the status, condition, and trends for these resources. **Farmland Protection Policy Act, 7 USC § 4201 et. seq**. requires NPS to identify and take into account the adverse effects of Federal programs on the preservation of farmland; consider alternative actions, and assure that such Federal programs are compatible with State, unit of local government, and private programs and policies to protect farmland. NPS actions are subject to the FPPA if they may irreversibly convert farmland (directly or indirectly) to nonagricultural use and are completed by a Federal agency or with assistance from a Federal agency. Applicable projects require coordination with the Department of Agriculture's Natural Resources Conservation Service (NRCS).	**7 CFR Parts 610 and 611** are the US Department of Agriculture regulations for the Natural Resources Conservation Service. Part 610 governs the NRCS technical assistance program, soil erosion predictions, and the conservation of private grazing land. Part 611 governs soil surveys and cartographic operations. The NRCS works with the NPS through cooperative arrangements.	**Section 4.8.2.4** requires NPS to -prevent unnatural erosion, removal, and contamination; -conduct soil surveys; -minimize unavoidable excavation; and -develop/follow written prescriptions (instructions).

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