National Park Service
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Natural Resource Stewardship and Science

Craters of the Moon National Monument and Preserve

Geologic Resources Inventory Report

Natural Resource Report NPS/NRSS/GRD/NRR—2018/1783





ON THE COVER

Photograph of spatter cone with Big Cinder Butte in the background. The Craters of the Moon lava field was active as recently as about 2,100 years ago. The lava field contains a remarkable and unusual diversity of exquisitely preserved basaltic volcanic features. NPS photograph by Dave Clark available at https://www.nps.gov/crmo/learn/photosmultimedia/photogallery.htm (accessed 28 August 2018; modified from original size).

THIS PAGE

Photograph of pahoehoe lava flow and flowers. Wildflowers bloom throughout the summer at Craters of the Moon National Monument and Preserve. Beautiful lava features can be viewed all year long. NPS photograph available at https://www.nps.gov/crmo/learn/photosmultimedia/photogallery.htm (accessed 17 July 2018).

Craters of the Moon National Monument and Preserve

Geologic Resources Inventory Report

Natural Resource Report NPS/NRSS/GRD/NRR—2018/1783

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

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Contents

Executive Summary ..... **xv**
Products and Acknowledgments ..... **xix**
GRI Products xix
Acknowledgments xix
Geologic Setting and Significance **1**
Park Establishment 1
Park Geologic Setting 1
Regional Geologic Setting 5
Geologic Features and Processes **9**
Volcanic Rocks and Lava 9
Volcanic Features 11
Lava Tubes 27
Cave Resources 32
Paleontological Resources 34
Loess, Soil, and Kipukas 36
Eolian Features and Processes 38
Faults 39
Geologic Resource Management Issues **41**
Paleontological Resource Inventory, Monitoring, and Protection 41
Visitor Use Impacts 42
Cave Resource Management 43
Waterhole Inventory and Ice Lenses 45
Slope and Rock Stability 46
Climate Change Impacts to Geologic Resources 46
Abandoned Mineral Lands 47
Earthquakes 48
Volcano Hazards 49
Wind Erosion 52
Mining 53
Geologic History **55**
Mississippian Marine Deposition and Mountain Building 55
Cretaceous Mountain Building 55
Eocene Volcanism 55
Basin and Range Faulting 56
Volcanism Associated with the Yellowstone Hot Spot 56
Quaternary Basaltic Volcanism on the Snake River Plain 56
Pleistocene Glaciation and Volcanism 57
Predominantly Holocene Great Rift Volcanism 58
Ongoing Sedimentation 59
Geologic Map Data **61**
Geologic Maps 61
Source Maps 61
Source GIS Data 62
GRI GIS Data 62
GRI Map Posters 62
Use Constraints 62
Literature Cited **67**
Additional References **77**
Bureau of Land Management 77
Climate Change Resources 77
Geological Surveys and Societies 77

Geology of National Park Service Areas 77
NPS Resource Management Guidance and Documents 77
US Geological Survey Reference Tools 77
Volcano Observatories 77
Appendix A: Scoping Participants 79
1999 Scoping Meeting Participants 79
2017 Conference Call Participants 79
Appendix B: Geologic Resource Laws, Regulations, and Policies 81

Figures

Figure 1. Map of Craters of the Moon National Monument and Preserve. 6
Figure 2. Photographs of the Great Rift volcanic rift zone. 7
Figure 3. Geologic time scale. 8
Figure 4. Map of the Yellowstone hot-spot track. 10
Figure 5. Map of the rifts and lava fields of the eastern Snake River Plain. 11
Figure 6. Graphic of Basin and Range extension. 12
Figure 7. Photograph of pahoehoe. 15
Figure 8. Photograph of a'a. 15
Figure 9. Photograph of shelly pahoehoe. 16
Figure 10. Photograph of slab pahoehoe. 16
Figure 11. Photograph of block lava. 16
Figure 12. Photographs of Blue Dragon Basalt. 17
Figure 13. Satellite image of Craters of the Moon lava field. 18
Figure 14. Photograph of Kings Bowl lava field. 20
Figure 15. Photograph of Big Cinder Butte. 22
Figure 16. Photograph of Crescent Butte. 23
Figure 17. Photographs of The Watchman. 23
Figure 18. Photograph of Laidlaw Butte. 24
Figure 19. Photographs of bombs. 25
Figure 20. Photograph of Kings Bowl. 26
Figure 21. Photographs of lava channels and levees. 27
Figure 22. Photograph of pressure plateau. 28
Figure 23. Map of some rafted blocks. 29
Figure 24. Photographs of rafted blocks and monoliths. 30
Figure 25. Photographs of rootless vents. 30
Figure 26. Photographs of spatter cones. 32
Figure 27. Photograph of squeeze-ups. 33
Figure 28. Photograph of tumulus. 34
Figure 29. Photographs of xenolith. Kuntz et al. 35
Figure 30. Graphic showing lava-tube formation. 36
Figure 31. Photograph of Buffalo Cave. 36
Figure 32. Photograph of Indian Tunnel entrance. 37
Figure 33. Photograph of collapsed lava tube. 39
Figure 34. Photograph of arch. 39
Figure 35. Photograph of high-lava marks. 40
Figure 36. Photograph of lavacicles and icicles. 40
Figure 37. Photograph of lining. 40
Figure 38. Photograph of remelt feature. 41
Figure 39. Photograph of speleothems. 43
Figure 40. Photograph of differential weathering cave. 43
Figure 41. Photograph of ice floor. 44
Figure 42. Photograph of tumulus cave. 44
Figure 43. Photographs of tree molds. 45
Figure 44. Photograph of packrat midden. 46
Figure 45. Photograph of kipukas. 48
Figure 46. Photographs of windblown features. 49
Figure 47. Graphic of fault types. 50
Figure 48. Photograph of bat survey. 55
Figure 49. Photographs of Borah Peak. 60
Figure 50. Map of Quaternary faults near the eastern Snake River Plain. 61
Figure 51. Photograph of wind storm. 66
Figure 52. Photograph of Challis Volcanic Group rock. 70

Figure 53. Cross section of the eastern Snake River Plain. 71
Figure 54. Graphic of eruptive periods of the Craters of the Moon, Wapi, and Kings Bowl lava fields. 74
Figure 55. Index map of GRI GIS data for Craters of the Moon National Monument and Preserve. 81

Tables

Table 1. Classification and characteristics of volcanic rocks. 9
Table 2. Prominent cinder cones at Craters of the Moon National Monument and Preserve. 21
Table 3. Hazards associated with basaltic volcanism on the eastern Snake River Plain. 56
Table 4. Map unit symbols in the GRI GIS data sets. 69
Table 5. GRI GIS data layers for crmo_geology.mxd (scale 1:100,000). 70
Table 6. GRI GIS data layers for cotm_geology.mxd (scale 1:24,000). 70

Executive Summary

The Geologic Resources Inventory (GRI) provides 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. The 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 held in 1999 and a follow-up conference call in 2017 (see Appendix A). Chapters in this report discuss the geologic setting of Craters of the Moon National Monument and Preserve (referred to as the "park" throughout this report), highlight distinctive geologic features and processes in the park, address geologic issues facing resource managers, describe the geologic history leading to the present-day landscape, and provide information about the previously completed GRI map data. Posters (in pocket) illustrate these data.

This report is accompanied by two GRI GIS data sets—a 1:100,000-scale data set (crmo_geology.mxd) and a 1:24,000-scale data set (cotm_geology.mxd). Because the 1:100,000-scale data set covers a much greater area—i.e., all of the NPS monument and most of the preserve, including all of the Craters of the Moon and Kings Bowl lava fields and most of the Wapi lava field—it was the primary data set used in preparing this report. By comparison, the 1:24,000-scale data set covers much of the Craters of the Moon lava field but none of the Wapi or Kings Bowl lava fields. Because the cotm_geology.mxd data set provides more detail, many features mapped in it are highlighted in this report. Furthermore, because of the greater detail provided in the cotm_geology.mxd data set, researchers and resource managers are encouraged to use it when they need geologic information about the original monument or wilderness area.

Notably, the map unit symbols of the crmo_geology.mxd and cotm_geology.mxd data sets differ in format (see table 4 and "Geologic Map Data"). Map unit symbols of the crmo_geology.mxd data set are used in this report.

"Craters of the Moon" has inspired geologic curiosity for more than a century, beginning with Israel C. Russel in 1901 then Harold T. Stearns in the 1920s, followed by Mel A. Kuntz in the 1980s to the present day. Stearns was the first to use the name "Craters of the Moon" when he suggested in 1923 that a national monument be established. After the name appeared in a *National Geographic* article by Robert W. Limbert in 1924, it became affixed. Later that year, the name would become official when the area was set aside by President Calvin Coolidge as a national monument under the Antiquities Act.

Since 1924, the original monument has expanded and boundary adjustments have been made through five presidential proclamations. The most recent expansion, referred to as the "expansion area" in this report, greatly increased the size of the monument and designated the preserve. The National Park Service (NPS) retains management of the original monument area and administers the preserve; the Bureau of Land Management (BLM) manages the new monument area. As a result of the most recent proclamation, many more volcanic features—including most of the 80-km- (50-mi-) long Great Rift volcanic rift zone and the Craters of the Moon, Wapi, and Kings Bowl volcanic fields—are managed and protected as part of Craters of the Moon National Monument and Preserve.

Distinctive geologic features and processes in the park include the following:

- **Volcanic Rocks and Lava**. The park's landscape is dominated by solidified lava, which geologists describe using rock names and physical appearance. Kuntz et al. (2007)—a source map for the GRI GIS data—described two primary types of lava in the park: pahoehoe and a'a. Block lava is a third type of lava used in descriptions by Kuntz et al. (2007). The lava in the park ranges in shades of black, dark brown, gray, oxidized reds and yellows, and even shades of blue, green, and purple. Perhaps the most distinctive is the Blue Dragon Basalt, which is iridescent blue.
- **Volcanic Features**. The park is noted for its diversity of large and small volcanic features. Of greatest significance are the three lava fields: Craters of the Moon, Wapi, and Kings Bowl. The Craters of the Moon lava field is the largest and best studied. Other large-scale features include vents (any opening at

Earth's surface through which magma erupts or volcanic gases are emitted) and their associated landforms (eruptive fissures, cinder cones, and shield volcanoes), as well as lava flows. At a scale of 1:100,000, 43 lava flows were mapped within the park. In addition, this report describes 22 small-scale volcanic features—from bombs to xenoliths—that are common in the park.

- **Lava Tubes**. Lava tubes are the principal means by which pahoehoe lava spreads widely and thinly. The majority of lava flows in the park had a tube-fed component. Lava tubes form by the crusting over of lava channels. The flowing, dripping, splashing, accreting, and pulling apart of molten or partially consolidated lava created many interesting lava formations within the lava tubes at the park. The park's lava tubes also contain collapse features, ice, and speleothems (mineral deposits).
- **Cave Resources**. Most of the documented caves in the park are lava tubes, but other types occur, including differential weathering, lava blister, rift/fissure, spatter cone, rootless vent, talus, and tumulus.
- **Paleontological Resources**. Tree molds (a cylindrical hollow or a horizontal impression formed by the envelopment of a tree by a lava flow or by the tree falling onto the surface of a lava flow) are the primary type of fossil in the park. Carbonized wood and lava trees are other types of fossils associated with lava flows. The Mississippian (359 million–323 million-year-old) rocks in the northern part of the park yield the oldest fossils (ammonoids, conodonts, and brachiopods), as well as the trace fossil *Helminthoida* (worm burrows) along bedding planes. Mississippian fossils are indicative of a former marine setting. Caves in the park preserve Late Pleistocene to Holocene (less than 15,000-year-old) animal remains and bones in packrat (*Neotoma* spp.) middens.
- **Loess, Soil, and Kipukas**. Loess (windblown dust) underpins the ecosystems at the park. It plays a primary role in soil formation and makes up the soil that now covers the kipukas (individual "islands" of older rock surrounded by one or more, younger lava flows). Kipukas preserve isolated, largely undisturbed vegetation communities, and in many instances, the expanse of rugged lava surrounding kipukas has protected them from people, animals, and even nonnative plants. Also, accumulations of loess serve as an informal, relative-dating method for lava flows, which is useful for field geologists.
- **Eolian Features and Processes**. At a scale of 1:100,000, Kuntz et al. (2015)—a source map of the GRI GIS data—mapped no eolian (windblown) features within the park but delineated a substantial deposit of eolian sand east of the Wapi lava field. The source material for this sand was probably sediments of the Bonneville Flood, which took place about 14,500 years ago. Another interesting eolian feature is the asymmetry of many of the cinder cones in the park. As a result of prevailing winds, cinders blew and landed to the east or northeast during eruptions, causing asymmetry. Many small-scale eolian features occur in the park, including saltating cinders, ripple marks, and lag deposits. Also, the deposition of loess (windblown dust) seems to be a primary control on plant growth and distribution.
- **Faults**. The Craters of the Moon area has had a long history of faulting. The oldest rocks in the park provide evidence that this part of Idaho was tectonically active since at least the Late Devonian Period (about 370 million years ago). The majority of the faults mapped in the Craters of the Moon area occur north of the park in the Pioneer Mountains. Within the park, two instances of faulting—on North Crater and Broken Top—are associated with Late Pleistocene and Holocene activity.

The NPS Geologic Resources Division provides technical and policy assistance for resource managers. Geologic resource management issues identified during the 1999 scoping meeting and 2017 conference call include the following, which are ordered and discussed based on management priority:

- **Paleontological Resource Inventory, Monitoring, and Protection**. A variety of servicewide inventories have been conducted on tree molds, packrat middens, and paleontological resources associated with caves, which provide information about the park's fossils. In addition, Kenworthy et al. (2005) completed a baseline paleontological inventory for the Upper Columbia Basin Network, including Craters of the Moon National Monument and Preserve. Tree molds are the park's primary paleontological resource. The first systematic study of tree molds in the park was conducted in 2001–2002 and documented 141 sites. The second inventory and survey in 2012 discovered 22 more tree molds. Santucci et al. (2009) described five methods and vital signs for monitoring in situ paleontological resources, which may be useful for park managers to address damage caused to tree molds.
- **Visitor Use Impacts**. Most direct human impacts such as theft, damage to volcanic resources, and vandalism have taken place along trails and close to roads. Park managers have implemented a stay-on-the-trail program that reminds visitors to tread lightly and educates them about the damage they cause to irreplaceable geologic resources by going off trails. A

development concept plan that incorporates visitor-use and GIS data on the key geologic features in the Kings Bowl lava field (part of the expansion area) is a management need. A Geoscientists-in-the-Parks (GIP) intern and collaboration with the Bureau of Land Management may be able to address this need.

- **Cave Resource Management**. Completing a new cave management plan is a high priority management need at the park. The existing cave management plan was completed in 1993 and does not cover the expansion area. The NPS Geologic Resources Division can facilitate the development of such a plan.
- **Slope and Rock Stability**. Slope movements at the park include the downslope acceleration of volcanic material on cinder cones and other slopes as a result of human foot traffic, as well as an avalanche in the Little Cottonwood Creek drainage. Rockfall from cave roofs, namely at the entrances to lava tubes, is the primary geohazard (geologic condition or phenomenon—natural or brought about by human activity—that represents a threat to human life, welfare, or property) in the park. This safety issue has gone largely unaddressed. The inspection and monitoring of cave geohazards would be a particular component of a cave management plan.
- **Climate Change Impacts to Geologic Resources**. Climate change is anticipated to impact groundwater recharge, streamflow, waterholes, ice lenses within the lava fields, and ice caves. Data collected during a waterhole inventory by two GIP participants (Ruffini and Edie 2010) provide a baseline to monitor future changes to the waterholes, including ice level. At present, no formal planning for climate change is taking place at the park. The state of the park report proposed collaborating with the National Oceanic and Atmospheric Administration (NOAA) on climate change monitoring as part of the nationwide Climate Reference Network. Other suggestions for climate change planning include characterizing park exposure to recent climate change in a vulnerability assessment, developing plausible and divergent futures for use in a scenario planning workshop, and synthesizing desired future conditions for use in a resource stewardship strategy or other management plan.
- **Abandoned Mineral Lands.** The Martin Mine, which is located in the Little Cottonwood Creek drainage within the Lava Creek Mining District, is the only mine on park land known to have produced commodities, including copper, gold, lead, silver, and zinc. It was active from 1922 to 1929. According to the servicewide abandoned mineral lands (AML) database and Burghardt et al. (2014), the park contains 53 AML features at five sites. None of these features or sites requires mitigation. The Idaho Geological Survey (IGS) also maintains a mine and minerals database. That database includes four sites within the park, including three mines and one unnamed prospect. Furthermore, the GRI GIS data set cotm_geology.mxd shows 30 mine point features (prospects, mines, and borrow pits), 14 of which are within the park. Resolving discrepancies among the servicewide AML database, IGS mine and minerals database, and GRI GIS data is needed to identify human safety hazards, contamination issues, habitat for bats and other animals, and opportunities for interpretation as cultural resources; collaboration among park, Geologic Resources Division, and IGS staff members will likely be required.
- **Earthquakes**. Compared to the surrounding Basin and Range province, which is characterized by active faulting, the eastern Snake River Plain is quiet. According to the USGS Quaternary faults database/viewer, no "active" faults (faults that have moved in the past 2.6 million years) occur in the park. The closest active fault is in the Lost River Range, north of the eastern Snake River Plain.
- **Volcano Hazards**. The lava fields in the park erupted 2,100 years ago and are likely to do so again. The next eruption will be similar to recent, past eruptions, which occurred as discrete eruptive episodes (each from a single batch of magma) lasting a relatively short period of time—a few days or months up to 1,000 years. The primary hazard will be basaltic lava flows. Kuntz et al. (1986a) suggested that the next eruption will begin in the central part of the Craters of the Moon segment of the Great Rift (i.e., between Big Cinder Butte and Sheep Trail Butte) then possibly move toward the northern part (i.e., between the Lava Creek vents to Big Cinder Butte). The US Geological Survey (USGS) Cascades Volcano Observatory monitors volcanic activity in Washington, Oregon, and Idaho, including the Craters of the Moon and Wapi lava fields.
- **Wind Erosion**. Eolian processes, including erosion, are ongoing at the park. Eolian erosion is notable on Inferno Cone. Also, wind erosion abrades the terminal buds of limber pines and exposes plant roots. Older lava flows, where thick deposits of loess have accumulated, are particularly sensitive to erosion after fire. The main impacts are loss of soil-forming loess and dust storms. In addition to fire, activities such as grazing, recreation, and construction can cause vegetation die-back, which increases the potential for removal of sediment by the wind.

- **Mining**. The northern part of the park is in the Lava Creek Mining District, which is primarily known for silver that was extensively mined around 1913. Currently, no active mining operations are taking place in the Lava Creek District. No mining claims exist in the park, although the Idaho Transportation Department holds three right-of-ways in the park for mineral materials sites (sand and gravel) along US Highway 93/26/20.
- **Waterhole Inventory and Ice Lenses**. Work by two Geoscientists-in-the-Parks (GIP) interns, Ruffini and Edie (2010), completed an inventory of 21 waterholes in the park. Most of these are associated with ice in lava tubes, craters, and fissures.

Products and Acknowledgments

The NPS Geologic Resources Division partners with Colorado State University, Department of Geosciences, to produce GRI products. The US Geological Survey, state geological surveys, local museums, and/or universities developed the source maps and reviewed GRI content. This chapter describes GRI products and acknowledges contributors to this report.

GRI Products

The GRI team undertakes three tasks for each park in the Inventory and Monitoring program: (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 GIS 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 GRI team conducts no new field work in association with their products.

The compilation and use of natural resource information by park managers is called for in the 1998 National Parks Omnibus Management Act (§ 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

The GRI team thanks the participants at the 1999 scoping meeting and 2017 conference call (see Appendix A) for their assistance with this inventory. Special thanks go to **Mel Kuntz** (US Geological Survey) for his years of investigation and production of geologic information about the Craters of the Moon volcanic field and the eastern Snake River Plain. He is the primary investigator of myriad papers and maps, which were used in preparation of this report. The GRI Program provided funding to the US Geological Survey to support geologic mapping at the park by Kuntz. Additionally, thanks very much to **Doug Owen** (Craters of the Moon National Monument and Preserve) who prepared many guides and presentations about the park's geologic features, which were used in preparation of this report. Prompt responses by **Bill Phillips** and **Virginia Gillerman** at the Idaho Geological Survey during the report-writing process are most appreciated. Thanks to **Dale Pate** (NPS Geologic Resources Division, Cave and Karst Program) for his input on cave management planning. Thanks to **Trista Thornberry-Ehrlich** (Colorado State University) for producing many of the graphics in this report. Thanks to **Linda Manning** (Craters of the Moon National Monument and Preserve) for reviewing this report and tracking down and answering "final" questions needed for its completion.

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Geologic Setting and Significance

This chapter describes the geologic setting (local and regional) of Craters of the Moon National Monument and Preserve (referred to as the "park" throughout this report) and summarizes connections among geologic resources, other park resources, and park stories.

Park Establishment

In 1924, 45 years before the first moon landing, President Calvin Coolidge preserved the original Craters of the Moon National Monument to protect a "weird and scenic landscape" in south-central Idaho that "contains many curious and unusual phenomena of great educational value." The name "Craters of the Moon" for the landscape became popularized in an article by R. W. Limbert in *The National Geographic Magazine* (Limbert 1924) and remained affixed even after the first lunar landing in 1969, which revealed that most of the lunar craters were formed by meteoroid impacts, not volcanic activity. Nevertheless, moon rocks are similar to three types of igneous rocks on Earth, though the lava on the moon was created when meteors crashed onto its surface, not as magma erupting beneath it. Even though the process of formation is different, rock type serves as a connection between lunar rocks, namely basalt, and Craters of the Moon rocks, also basalt. The other two types of lunar rocks are anorthosite (also formed by lava but quite rare on Earth) and breccia (older rocks broken apart by meteoroid impacts) (Casper Planetarium 2017).

Another connection between the park and the moon is that astronauts have walked on both of them. In 1969, Apollo 14 astronauts Alan Shepard, Edgar Mitchell, Joe Engle, and Eugene Cernan came to the monument to prepare for a rare opportunity to collect samples of rock from the moon's surface. Because only a limited amount of material—about 390 kg (850 lbs) total for six lunar missions—could be brought back to Earth, knowing some geology was very important for these men, who were pilots not geologists, to select the most scientifically valuable specimens. In 1999, Cernan, Engle, and Mitchell (Shepard died in 1998) returned after 30 years to help celebrate the monument's 75th anniversary. At that time, these men discussed how beneficial their training at the monument had been for preparing them for their missions to the moon (National Park Service 2017).

Since its establishment in 1924, the monument has been expanded through five presidential proclamations. The most recent and largest expansion occurred on 9 November 2000 when William J. Clinton signed Presidential Proclamation 7373. The proclamation enlarged the protected area 13 fold, from 21,701 ha (53,622 ac) to 289,310 ha (714,876 ac), and designated the preserve. The National Park Service (NPS) retains management of the original monument area and administers the preserve; the Bureau of Land Management (BLM) manages the new monument area (fig. 1). The NPS-managed areas (i.e., original monument and preserve) are surrounded by public lands managed primarily by the BLM through the Upper Snake, Shoshone, and Burley Field Offices.

Five predominantly rural counties (Blaine, Butte, Lincoln, Minidoka, and Power) contain portions of the park. The towns nearest the park's headquarters are Minidoka, 24 km (15 mi) to the south; Arco, 29 km (18 mi) to the northeast; and Carey, 39 km (24 mi) to the northwest. Large areas of private agricultural lands border the park near the towns of Arco and Carey and along the eastern side of the Wapi lava field at the southern end of the preserve. The park is within a one- to two-hour drive of Twin Falls, Idaho Falls, Pocatello, and other population centers along the Interstates 84, 86, and 15 corridors. US Highway 93/26/20 crosses the park and provides access from these interstate corridors.

Current NPS management is focused in the original monument where most facilities, and therefore most visitors, are located (National Park Service 2016b). Annual visitation increased from approximately 3,349 visitors in 1925 until reaching a high of nearly 294,387 in 1982. Visitation for the past 10 years (2008–2017) averaged 223,600 visitors annually (National Park Service 2018).

Park Geologic Setting

The 2000 expansion incorporated the Craters of the Moon, Wapi, and Kings Bowl lava fields and most of the Great Rift volcanic rift zone into the National Park System (fig. 1). The Great Rift system was designated as a national natural landmark in 1968. Great Rift System National Natural Landmark covers 69,608 ha (171,999 ac) in Blaine, Minidoka, and Power Counties. The Great Rift system represents a tensional fracture in Earth's crust that may extend to the crust-mantle interface. It is an aligned concentration of eruptive sites or linear clustering of surface vents. According to the National Natural Landmarks Program, the Great Rift system is unique in North America and has few counterparts in the world (National Park Service 2016a). It is the world's deepest known land-based open volcanic rift

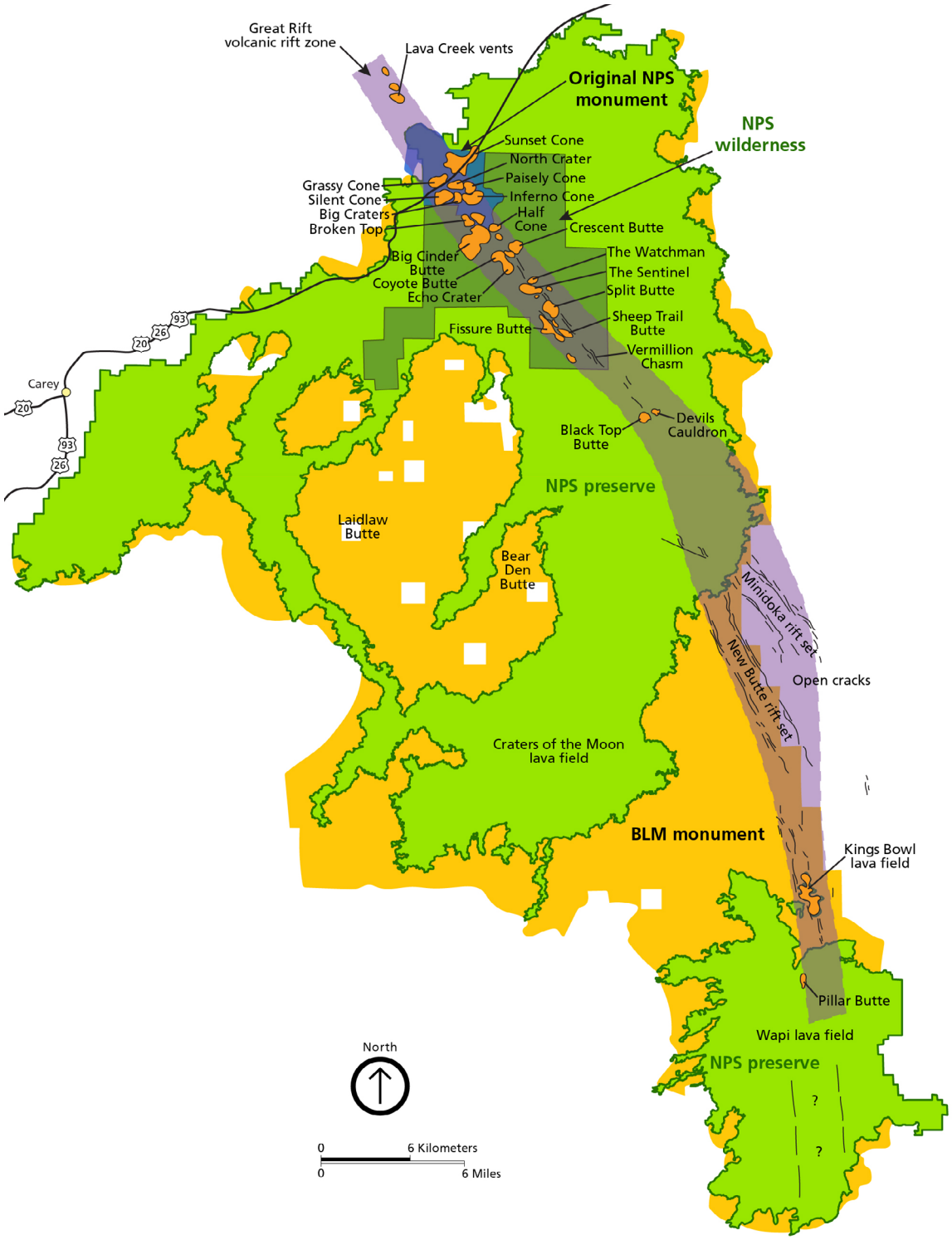


Figure 1. Map of Craters of the Moon National Monument and Preserve.
The National Park Service and Bureau of Land Management jointly administer Craters of the Moon National Monument and Preserve, which includes all of the Craters of the Moon, Wapi, and Kings Bowl lava fields and most of the Great Rift volcanic rift zone. The blue area on the graphic delineates the original NPS monument. The dark green area delineates the NPS wilderness area. The light green area delineates the NPS preserve. The yellow area delineates the BLM monument. White areas within the BLM monument delineate non-federal land. Graphic by Trista Thornberry-Ehrlich (Colorado State University) after Kuntz et al. (2004, figure III-5) and map in National Park Service (2014).

(National Park Service 2016b). Unlike the East Africa Rift, which runs for thousands of miles and is in the process of splitting the Africa plate into two smaller tectonic plates—the Somali and Nubian plates (e.g., see Fernandes et al. 2004)—the Great Rift is not a developing divergent tectonic plate boundary. The Great Rift may be compared to other volcanic rift zones in Hawaii, the Canary Islands, and Iceland, although these volcanic rift zones do not occur on land.

The Great Rift extends for more than 80 km (50 mi) and ranges in width between 2 km (1 mi) and 8 km (5 mi). At the surface, the Great Rift is marked by short cracks, less than 2 km (1 mi) long. Below the surface, these cracks extend an estimated 200 m (650 ft) deep (fig. 2). Magma under pressure can follow these cracks to the surface, making the volcanic rift zone the site of many volcanic features, including the park's three lava fields: (1) Craters of the Moon, the largest field and farthest north; (2) the mid-sized Wapi; and (3) the small Kings Bowl (see posters, in pocket). These lava fields contain a variety of small-scale volcanic features and some of the best examples of open rift cracks on Earth.

The topography of the park is rugged with an average elevation of about 1,990 m (6,305 ft), ranging from 1,625 m (4,880 ft) at the southeastern boundary to 2,355 m (7,730 ft) in the northern foothills of the Pioneer Mountains. Two spring-fed, perennial streams—Leach Creek and Little Cottonwood Creek—drain the Pioneer Mountains and flow into the park (see posters, in pocket). Springs in the foothills of the Pioneer Mountains give rise to small wetlands at the north end of the park, which provide important wildlife habitat.

The northern part of the park extends into the Pioneer Mountains, which is composed of the Eocene (56 million–34 million years old; fig. 3) Challis Volcanic Group (**Tcv**) and rocks that intruded the group such as the Eocene hornblende diorite of Little Cottonwood Creek (**Tchd**) and the Eocene biotite granite of Cottonwood Creek (**Tcbg**). The Challis Volcanic Group consists of a remarkable variety of volcanic rocks, including andesite, dacite, basalt, and rhyolite (table 1), as well as ignimbrites (deposits of pyroclastic flows [hot, fast-moving mixture of rock fragments, gas, and ash]), lava flows, domes, dikes (intrusive, sheet-like bodies of rock), plutons (massive bodies of igneous rock), and minor interbedded sedimentary rocks.

The park primarily encompasses a landscape of younger (than Eocene) basaltic volcanic features. The three lava fields in the park are the result of the most recent volcanic activity on the eastern Snake River Plain. Large-scale volcanic features of these fields include eruptive fissures, cinder cones, a shield volcano, and



Figure 2. Photographs of the Great Rift volcanic rift zone.
The Great Rift is an 80-km- (50-mi-) long volcanic rift zone on the eastern Snake River Plain. It is characterized by volcanic features such as spatter cones, cinder cones, and eruptive fissures of the Craters of the Moon, Wapi, and Kings Bowl volcanic fields. The Great Rift is the deepest land-based open volcanic rift in the world; it is also one of the longest volcanic rifts in the continental United States. The dirt road in the top photograph provides a sense of scale. The large "hole" is Kings Bowl. The vertical crack shown in the bottom photograph is at the southern end of the Kings Bowl lava field. Note the person for scale. Top: NPS photograph. Bottom: NPS photograph from Owen and Melander (2014, figure 9).

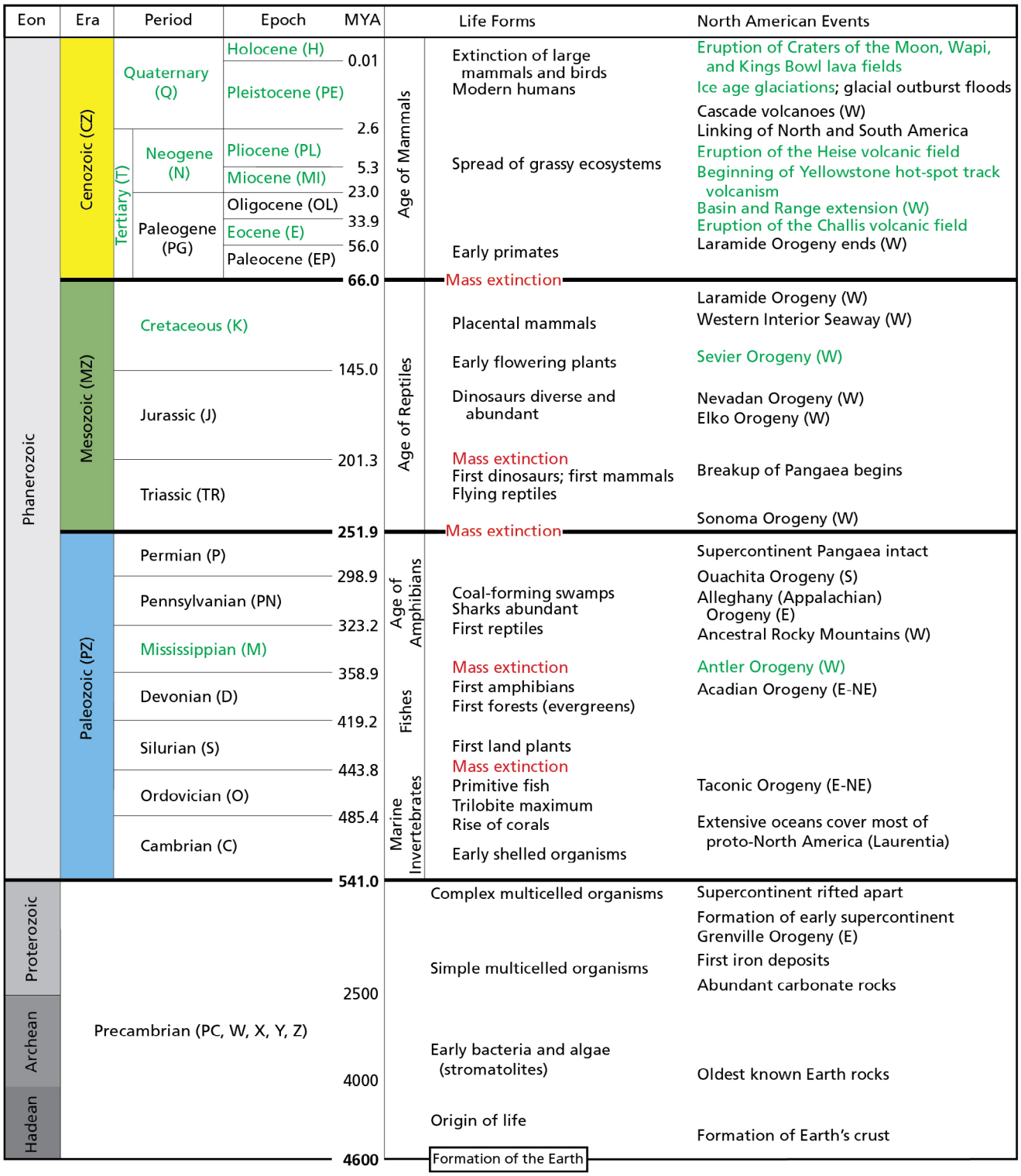


Figure 3. Geologic time scale.
The divisions of the geologic time scale are organized stratigraphically, with the oldest divisions at the bottom and the youngest at the top. GRI map abbreviations for each time division are in parentheses. Geologic events of greatest significance for the park's present-day landscape took place in the Quaternary (Q) Period, but rocks and faults also record events of the Mississippian (M) and Cretaceous (K) Periods and Tertiary (T) time; these are highlighted in green on the time scale. Compass directions in parentheses indicate 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).

Table 1. Classification and characteristics of volcanic rocks.

Silica content and eruption temperature also influence the color, viscosity, and eruption style of a volcano.
The relative color of these rocks ranges from lighter (rhyolite) to darker (basalt).
The relative viscosity of magma ranges from less mobile flows (rhyolite) to more mobile flows (basalt).
The typical style of eruption ranges from more explosive (rhyolite) to less explosive (basalt).
[1]Silica percentages from Clynne and Muffler (2010).
[2]Eruption temperatures from Price (2010).

Rock Name:	Rhyolite	Rhyodacite	Dacite	Andesite	Basaltic Andesite	Basalt
Silica (SiO_2) content[1]	>72%	68%–72%	63%–68%	57%–63%	52%–57%	<52%
Eruption Temperature[2]	800°C (1,500°F)	Intermediate	Intermediate	Approximately 1000°C (1,800°F)	Intermediate	1,160°C (2,120°F)

lava flows; the lava flows contain many interesting small-scale volcanic features. Some areas of older basaltic lava, now covered by loess (windblown dust) and soil, were surrounded but not covered by younger lava flows. These sites, known as kipukas (meaning "opening" in Hawaiian), occur throughout the park as both small pockets and large plains; kipukas appear as "islands" of older rock in younger lava flows. In addition, the lava fields contain hundreds of lava tubes and fossils such as tree molds (cavities or impressions left by lava-incinerated trees).

The Craters of the Moon lava field erupted during "predominantly Holocene" time—described as less than 15,000 years ago by Kuntz et al. (2007)—during a series of eight major eruptive periods, H (oldest) through A (youngest). Notably, some of the "predominantly Holocene" flows are from the Late Pleistocene Epoch (126,000 to 11,700 years ago). The most recent eruptions (eruptive period A) occurred about 2,100 years ago when the Craters of the Moon lava field erupted for the eighth time and the Wapi and Kings Bowl lava fields were created.

The "rounded numbers" of 15,000 and 2,100 years ago—provided by Kuntz et al. (2007) and used in this report—are based on radiocarbon (also referred to as carbon-14 [^{14}C]) dating. The "rounded age" of 15,000 years old comes from the Kimama pahoehoe basalt flow (map unit symbol **Qcfh1**), which was dated at 15,100 ± 160 years before present (BP, where "present" is 1950) (Kuntz et al. 1986b). The "rounded age" of the last eruptive period comes from a radiocarbon date of 2,130 ± 130 years BP for the Kings Bowl rift as determined by Prinz (1970). For comparison, 15,100 ± 160 years BP is between 16,750 and 16,020 calendar years ago; 2,130 ± 130 years BP is between about 2,500 and 1,800 calendar years ago or between 492 BCE (before common era) and 135 CE (common era, preferred to AD). These calendar years were converted from radiocarbon years using the online tool OxCal 4.3 at https://c14.arch.ox.ac.uk/oxcal/OxCal.html. The crmo_geology.mxd data set includes "geologic sample localities" for ages based on the radiocarbon method, as well as paleomagnetism, potassium-argon (K-Ar), and argon-argon (Ar-Ar) methods.

Regional Geologic Setting

The regional geologic setting of the park incorporates two "big picture" geologic features—the Yellowstone hot-spot track and the Basin and Range, which is experiencing extension (pulling apart of Earth's crust) and tectonism (large-scale movement and deformation of Earth's crust).

Yellowstone Hot-Spot Track

The track of the Yellowstone hot spot is recorded in the eastern Snake River Plain (fig. 4). Eight basalt or basalt-dominated lava fields comprise the eastern Snake River Plain (fig. 5). These fields, from west to east, are the Shoshone, Craters of the Moon, Wapi, Kings Bowl, North Robbers, South Robbers, Cerro Grande, and Hells Half Acre. The park contains the youngest and most geologically diverse section of basaltic lava terrain of the eastern Snake River Plain (Kuntz et al. 1992).

Rhyolitic rocks (table 1) underlie the basalt flows of the eastern Snake River Plain. Stratigraphy—basalt over rhyolite—led geologists to conclude that the eastern Snake River Plain was the site of a northeasterly propagating system of huge, caldera-forming rhyolitic volcanic centers (Good and Pierce 1996). The cause involves plate tectonics—a unifying theory of geologic processes resulting from the interaction of large, mobile plates that compose Earth's outer crust.

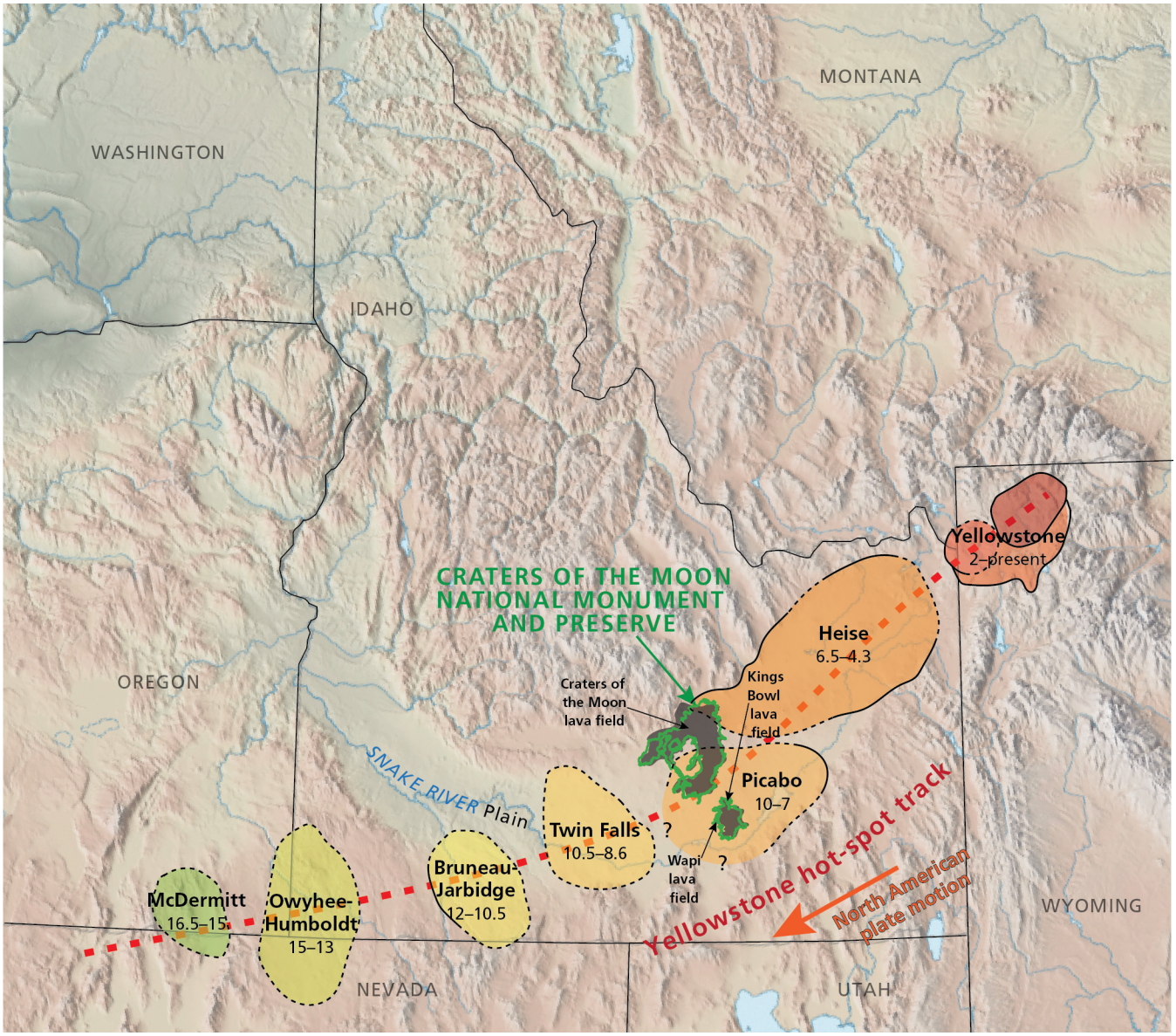


Figure 4. Map of the Yellowstone hot-spot track.
The park is about 240 km (150 mi) southwest of Yellowstone National Park. The map highlights the Yellowstone hot-spot track, which is composed of seven volcanic fields. The hot spot remained stationary as the North American plate moved to the southwest (arrow). The ages (in millions of years, on the figure) of the various volcanic fields indicate this progression, starting with the McDermitt volcanic field (approximately 16.5 million–15 million years ago) to the present location under Yellowstone. The park area was situated over the hot spot between about 6.5 million and 4.3 million years ago. Heise Group (Th) rhyolitic rocks in the northern part of the park represent that period of time. Ages are from Smith and Siegel (2000). Graphic by Trista Thornberry-Ehrlich (Colorado State University).

As a result of the southwesterly movement of the North American plate over a stationary hot spot (rising plume of molten rock), the eastern Snake River Plain records progressively younger rhyolitic eruptions to the northeast (fig. 4). For the past 16.5 million years, the rate of migration of the North American plate over the hot spot has been about 2.9 cm (1.1 in) per year (Pierce and Morgan 1992). Each field was active for less than 3 million years. Southern Idaho passed over the hot spot between about 6.5 million and 4.3 million years ago. On the northwest edge of the park, the Heise Group (**Th**) of rocks is composed of rhyolite that represents volcanism

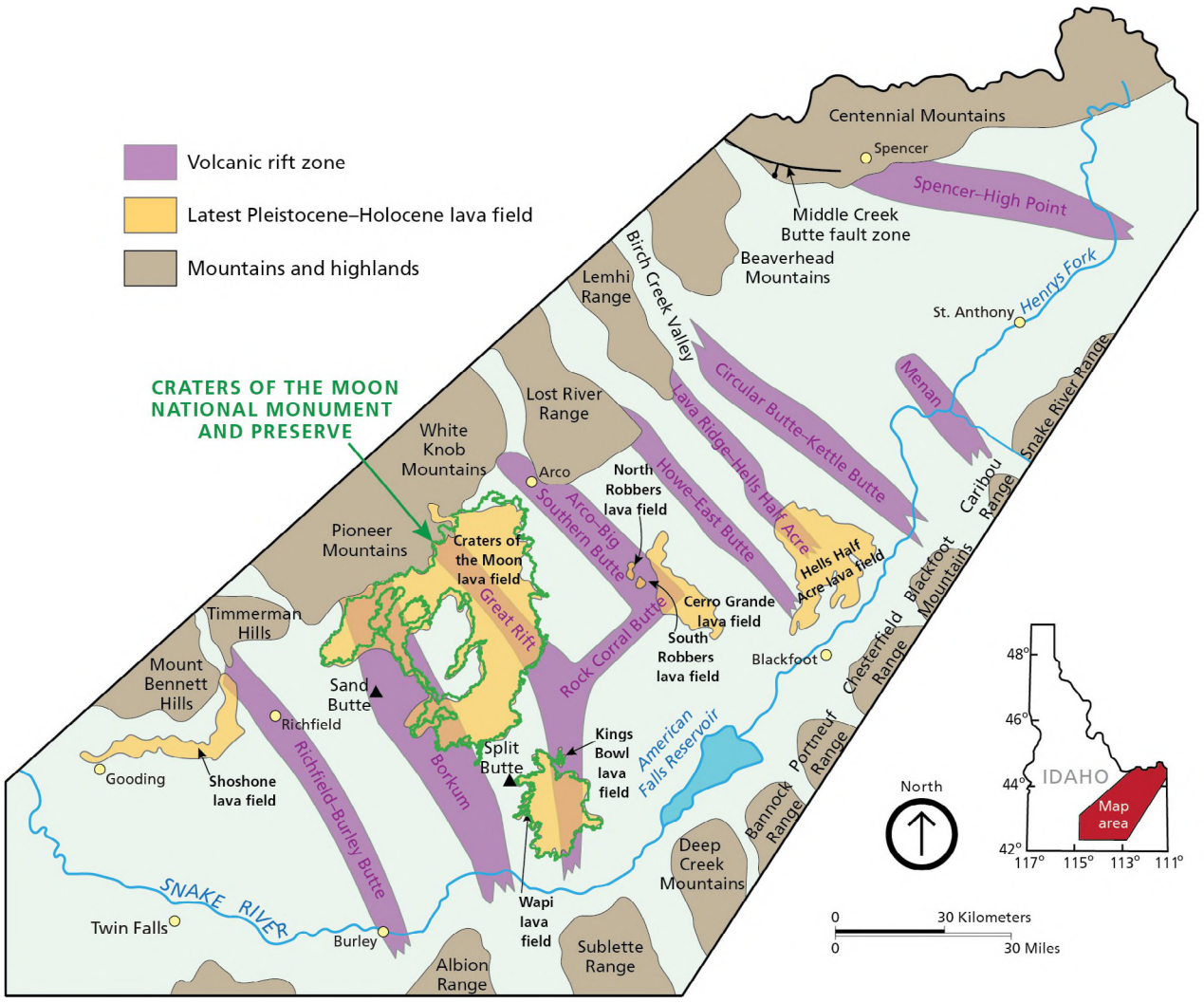


Figure 5. Map of the rifts and lava fields of the eastern Snake River Plain.
Volcanic rift zones (purple) and lava fields (yellow) compose today's basalt-covered plain. Volcanic activity on the eastern Snake River Plain is concentrated in volcanic rift zones, though it is not confined to them. The Craters of the Moon, Wapi, and Kings Bowl lava fields and most of the Great Rift volcanic rift zone are within the park. The figure shows the relationship between adjacent mountain ranges (brown) and volcanic rift zones. At one time, the Snake River, from whence the plain gets its name, flowed across the northern part of the plain but now flows along the southern margin, having been pushed there by successive lava flows. Graphic by Trista Thornberry-Ehrlich (Colorado State University) after Kuntz et al. (1992, figures 2 and 7).

that took place directly over the hot spot at that time. Currently, hot-spot activity is below Yellowstone, concentrating there for the past 2 million years.

As the North American plate moved toward the southwest, rhyolitic eruptions ceased, but the heat contained below the surface remained and continued to produce upwelling basaltic magma, which erupted onto the surface and covered the formerly active calderas. Furthermore, the eastern Snake River Plain subsided as the locus of the expanding plume of hot magmatic material changed. This material, which was embedded in Earth's crust, had caused the land surface to rise dramatically. In its absence, the land surface collapsed and a series of rifts or fissures opened up. The Great Rift is the northern segment of the most recently opened rift.

Basin and Range

The Basin and Range is a sprawling area that stretches from southeastern Oregon to northern Mexico. It encompasses parts of Idaho, California, Oregon, and Texas; more than half of Arizona; about half of New Mexico and Utah; and the entire state of Nevada (Kiver

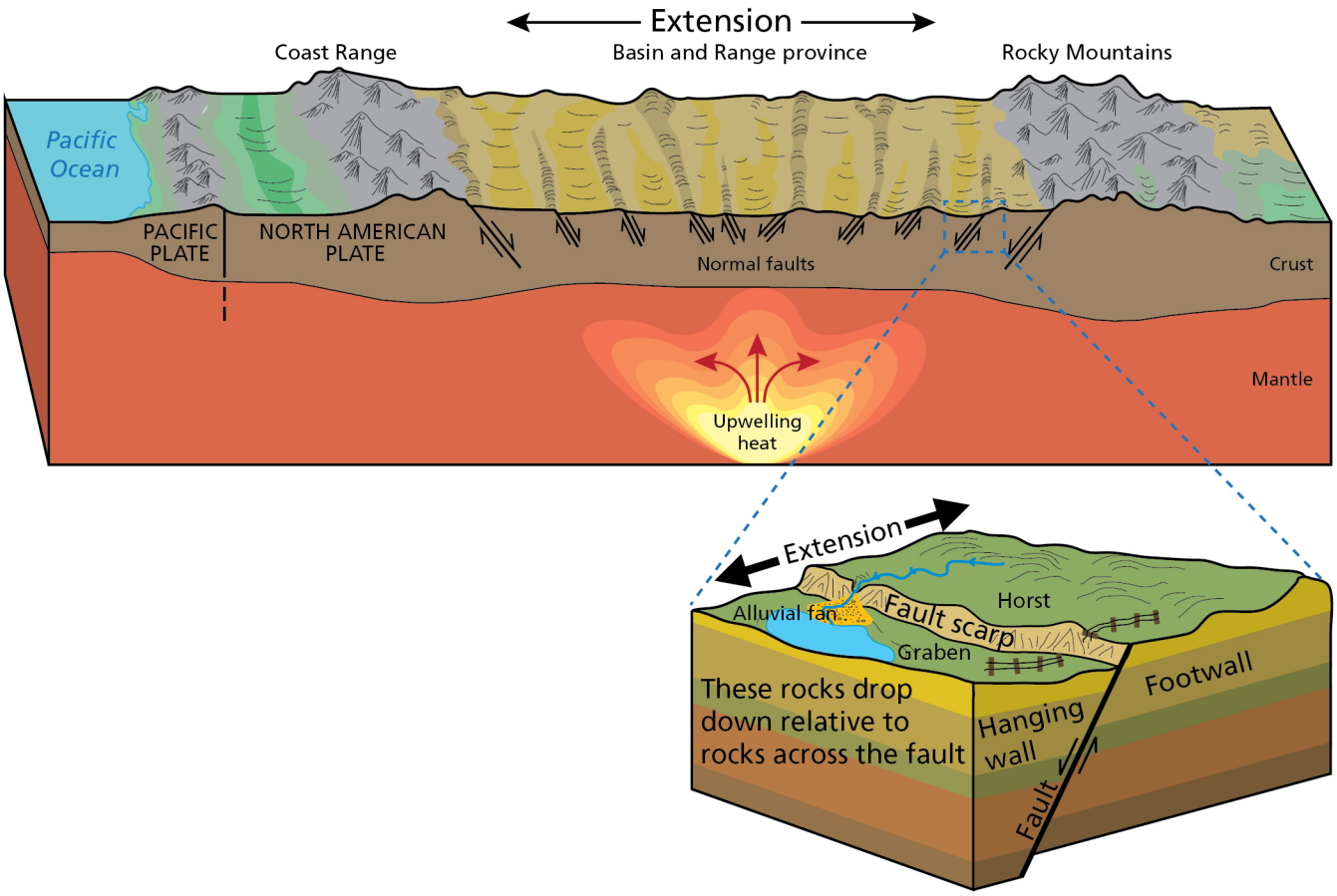


Figure 6. Graphic of Basin and Range extension.
The entire Basin and Range province has been subjected to extension. Earth's crust (and upper mantle) has been stretched up to 100% of its original width. The crust thinned and cracked as it pulled apart, creating normal faults. Along these roughly north–south-trending faults, mountains were uplifted and valleys dropped down, producing the distinctive alternating pattern of linear mountain ranges (referred to as "horsts") and valleys (referred to as "grabens") of the Basin and Range province. Graphic by Trista Thornberry-Ehrlich (Colorado State University) after Idaho Geologic Survey (2011, p. 2).

and Harris 1999). As the name implies, the province has mountain ranges—more than 400, if all the small ranges are included—with basins between them.

The Basin and Range landscape started forming about 15 million years ago when Earth's crust began pulling apart. In general, north–south-oriented structural basins, which dropped down along normal faults (fig. 6), separate adjacent mountain ranges, which were lifted upwards along these same faults.

Most of the volcanic rift zones of the eastern Snake River Plain, including the Great Rift, are aligned with the mountains and valleys of the Basin and Range province to the north and south (fig. 5). The crests of mountain ranges and axes of intermontane valleys are spaced about 35 km (22 mi) apart. The collinear continuations of Basin and Range–type (normal) faults and mountains that adjoin the plain suggest that the eastern Snake River Plain may be affected by the same extensional forces as the Basin and Range province (Truitt and Lillie 2007). Also, regional extensional strain is clearly manifested in the faults and mountains north and south of the eastern Snake River Plain (Kuntz et al. 1992); Basin and Range north–northwest-trending normal faults cut the Mississippian and Tertiary rocks in the northern part of the park (Kuntz et al. 2007). Yet whether Basin and Range faults extend into the bedrock beneath the basaltic lava flows of the eastern Snake River Plain is unknown. The abrupt termination of fault-block mountains at the margins of the eastern Snake River Plain may reflect their proximity to the now-buried walls of the calderas that lie within the plain (Kuntz et al. 1992).

Geologic Features and Processes

These geologic features and processes are significant to the park's landscape and history.

A tremendous diversity of volcanic features and active geologic processes are the defining resources of the park and led to designation of Craters of the Moon National Monument and Preserve as a National Park System unit (National Park Service 2014). Other geologic features also contribute to the essential character of the park's landscape. During the 1999 scoping meeting (see National Park Service 1999) and 2017 conference call, participants (see Appendix A) identified the following geologic features and processes as significant and worthy of documenting in the geologic resources inventory:

- Types of Volcanic Rocks and Lava
- Volcanic Features
- Lava Tubes
- Cave Resources
- Paleontological Resources
- Loess, Soil, and Kipukas
- Eolian Features and Processes
- Faults

Volcanic Rocks and Lava

The park's landscape consists of basalt, which overlies rhyolite (see "Yellowstone Hot-Spot Track"). Basalt and rhyolite are at opposite ends of the silica-content spectrum of volcanic materials (table 1) and form under radically different conditions. The most explosive volcanoes on Earth are generally rhyolitic. After an eruption of rhyolite, a volcano edifice may not look like a volcano because these types of eruptions are so explosive that the volcano ends up collapsing in on itself, creating a caldera. The eruptions that deposited the Heise Group (map unit symbol **Th**) of rocks in the park were this type. By contrast, basalts primarily form lava flows that spread out in broad, thin sheets up to several kilometers wide. The park contains many fine examples of basaltic lava flows (see "Lava Flows").

Geologists commonly describe lava by its rock name. In their map unit descriptions, Kuntz et al. (2007) used three—basalt, hawaiite, and latite—or combinations thereof (e.g., basalt-hawaiite and hawaiite-latite):

- Basalt is a characteristically dark-colored rock that contains 53% or less silica (table 1) and is rich in iron and magnesium. It is commonly extrusive but is locally intrusive (e.g., as dikes).
- Hawaiite is olivine-rich basalt. Olivine is a silicate (silicon + oxygen) mineral of magnesium and iron; it is commonly olive-green.
- Latite is porphyritic (consisting of abundant coarse-grained crystals in a fine-grained groundmass); the coarse-grained crystals, called "phenocrysts," are mostly plagioclase and potassium feldspar minerals in nearly equal amounts, with little or no quartz. The groundmass is finely crystalline to glassy (texture similar to glass and developed as a result of rapid cooling of lava).



Figure 7. Photograph of pahoehoe.
If a lava flow cools slowly and does not move too fast, it forms smooth ropy lava called pahoehoe. If a flow cools quickly and moves fast, it can tear into clinkery pieces called aʻa (see fig. 8). NPS photograph from Owen (2011b).



Figure 8. Photograph of aʻa.
Aʻa lava is much more viscous than pahoehoe, creating blocky, rubbly, or clinkery deposits. NPS photograph from Owen (2011b).

Geologists also describe lava by its physical appearance. Kuntz et al. (2007) described two primary types of lava in the park: pahoehoe and a‘a. These are Hawaiian words applied to lava to indicate smooth, ropy, or billowy surfaces of pahoehoe (fig. 7) or rough, jagged, or clinker-like surface of a‘a (fig. 8). Pahoehoe can be further classified as shelly or slab. Shelly pahoehoe forms from highly gas-charged material that creates “shells” of lava, consisting of large and small open tubes, blisters, and thin crusts (fig. 9). *Geologic Map of the Core Visitation Area of the Craters of the Moon National Monument and Preserve, South-Central Idaho, with Descriptions of 38 Points of Geologic Interest* (Niles et al. 2011) highlighted shelly pahoehoe as a “point of geologic interest.” Slab pahoehoe is composed of jumbled plates or slabs of broken pahoehoe crust (fig. 10). A third type of lava used in descriptions by Kuntz et al. (2007) is “block lava,” which is very dense and has a surface composed of angular chunks (fig. 11). Some flows in the park consist of all three types, for example, the Highway block, a‘a, and pahoehoe latite flow (**Qcfa10**).



Figure 9. Photograph of shelly pahoehoe. Thin crusts, blisters, and small open tubes form on shelly pahoehoe flows, commonly near a vent where the lava was still very hot, fluid, and gas charged. Thickness of shells ranges from 7 cm (3 in) to 30 cm (12 in) (Niles et al. 2011). NPS photograph from Owen (2011b).



Figure 10. Photograph of slab pahoehoe. Slab pahoehoe is composed of jumbled-up plates or slabs of broken pahoehoe crust. NPS photograph from Owen (2011b).



Figure 11. Photograph of block lava. In addition to pahoehoe and a‘a, Kuntz et al.(2007) mapped block lava in the flows of the Craters of the Moon lava field. NPS photograph from Owen (2011b).

Rock Colors and Blue Dragon Basalt

Much of the lava at the park appears monochromatic. Upon closer field inspection, however, the lava ranges in shades of black, dark brown, gray, oxidized reds and yellows, blue, green, and purple. Most basalt and hawaiite pahoehoe flows have glassy crusts that are blue or olive green. Black, glassy crusts are typical of latite flows (Kuntz et al. 2007). Colors used in the map unit descriptions by Kuntz et al. (2007) were taken from the 1975 Rock Color Chart of the Geological Society of America.

Long noted for its distinctive color, the Blue Dragon Basalt warrants further discussion (fig. 12). This lava's striking appearance was first noted by Russell (1902); Limbert (1924) and Sterns (1928) later coined the name "Blue Dragon." The Blue Dragon flows (**Qcfa2**), which Kuntz et al. (2007) described as basalt-hawaiite, contain the most notable of the colorful lavas in the park. Surfaces of thin pahoehoe lava, which extends southwest from the base of Big Cinder Butte (**Qccc1**), reflect various shades of blue light.

The iridescent color of the Blue Dragon flows is due to intense blue light being reflected from clusters of microscopic titanium magnetite crystals, which together with tiny crystals of the minerals plagioclase and olivine, are dispersed throughout an outer layer of clear brown volcanic glass. Faye and Miller (1973) proposed that the blue color was a result of an electron transfer between iron ions (Fe^{2+} to Fe^{3+}) or iron and titanium ions (Fe^{2+} to Ti^{4+}). Miller (1969, 1970) proposed that just before the eruption of the Blue Dragon Basalt, the source magma probably was confined at an elevated temperature in a reducing environment. Ferrous iron (Fe^{2+}) content was high due to the presence of 2%–3% phosphorus as a reducing agent. Owen (2008) suggested that further research was needed to clearly understand this phenomenon.

Since 2008, no further research on the origin of the striking blue color has been reported in the scientific literature, but the blue colors have provided evidence for multiple eruptive phases of the Blue Dragon flows. In high-resolution multispectral remote sensing imagery (fig. 13), the intensity of color and morphological characteristics vary across the surface of the Blue Dragon flows; also, field observations show that color boundaries correspond to flow boundaries and stratigraphic offsets, providing evidence for multiple eruptive phases (Johnson et al. 2014). Landsat and AVIRIS (airborne visible infrared imaging spectrometer) images reveal that these boundaries define distinct sub-areas of the flow that each have different visible and near-IR reflectance characteristics, due largely to differences in the amount of the blue color. Five eruptive phases of the Blue Dragon flows have been mapped; the first four are dominated by "slabby," "shelly," and "spiny" pahoehoe morphologies, and the final, least voluminous episode was an a'a phase. AIRSAR (airborne synthetic aperture radar) data show roughness variability among the different spectral regions, also suggesting that each resulted from a distinct eruption event, possibly with different effusion rates and flow viscosities (Nayel et al. 2012).

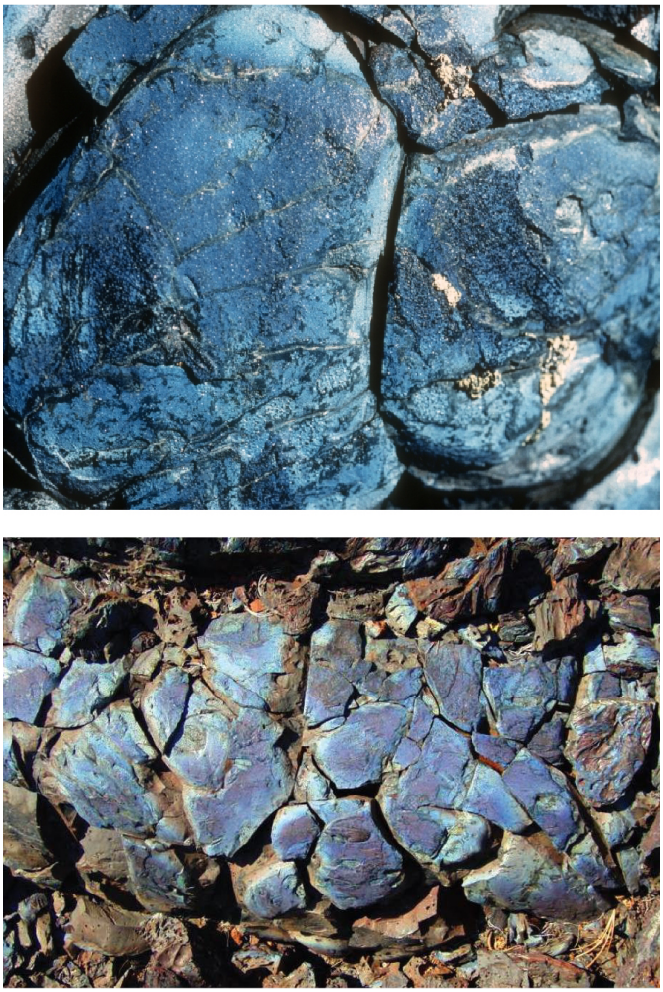


Figure 12. Photographs of Blue Dragon Basalt. Scientists have pondered the striking color of the Blue Dragon flows since the 1920s. Kuntz et al. (2007) mapped these flows (Qcfa2) as pahoehoe and a'a basalt hawaiite. Top: NPS photograph. Bottom: NPS photograph from Niles et al. (2011).

Volcanic Features

The following discussion divides the volcanic features at the park into large- and small- scale features. Large scale features include lava fields, vents and associated features, and lava flows. Twenty-one small-scale features are discussed. Lava tubes, which are a significant component of the lava flows at the park, are discussed in a separate section, "Lava Tubes."



Figure 13. Satellite image of Craters of the Moon lava field.
Many notable features are revealed in this satellite image such as lava flows, including multiple phases of the Blue Dragon lava flow; kipukas, which appear as lighter colored "openings" in the lava flows; drainages in the Pioneer Mountains and the lack of drainages on the basalt surfaces of the eastern Snake River Plain. The Kings Bowl and part of the Wapi lava fields are in the lower right corner of the image. Landsat 8 image courtesy of (and processed by) John Chadwick (College of Charleston).

Lava Fields

The eight lava fields on the eastern Snake River Plain represent the entire range of basaltic lava–field types, eruption processes, and eruption durations. The fields include short-duration (a few days), low-volume (<0.1 km^3 [0.02 mi^3]) eruptions from a long eruptive fissure (e.g., Kings Bowl lava field [**Qwfa1**]); intermediate-volume and intermediate-duration eruptions that formed lava cones or small shields (e.g., Devils Cauldron flow [**Qcfb3**] of the Craters of the Moon field); and large-volume (1–6 km^3 [0.2–1.4 mi^3]), relatively long duration (several months) eruptions from a central vent (e.g., Wapi field [**Qwfa2**]). Three of these lava fields occur in the park.

Craters of the Moon Lava Field

The Late Pleistocene and Holocene Craters of the Moon lava field is the largest and farthest north of the lava fields in the park. It covers an area of about 1,600 km^2 (620 mi^2) and has an estimated volume of more than 30 km^3 (7 mi^3). It is the largest and most complex of the predominantly Holocene lava fields on the eastern Snake River Plain and is the largest of its type in the contiguous 48 states (National Park Service 2014). It is considered a "composite field" with 43 mapped and named flows, 21 prominent cinder cones (table 2), and seven eruptive fissures (see 1:100,000-scale GRI GIS data).

In contrast to most of the other lava fields on the eastern Snake River Plain (including the Kings Bowl and Wapi), which are monogenetic (erupting a narrow range of lava types during a single eruptive period), the Craters of the Moon lava field is polygenetic, erupting a broad range of lava types during eight eruptive periods, starting about 15,000 years ago (see "Geologic History"). Each eruptive period lasted several hundred years or less and was separated from other eruptive periods by intervals without volcanic activity, which lasted several hundred years to about 3,000 years (Kuntz et al. 1992).

Wapi Lava Field

Researchers obtained a radiocarbon age of 2,270 ± 50 years before present (BP) for Wapi lava field (**Qwfa2**). The Wapi lava field probably began as a fissure eruption and, with more prolonged activity, progressed to a sustained eruption from a central vent complex, forming a low shield (Kuntz et al. 1992). Most flows in the medial and distal parts of the Wapi field are tube-fed pahoehoe composed of numerous flow units piled side by side and atop one another, forming a "compound" lava flow (Walker 1972).

Covering an area of approximately 0.5 km^2 (0.2 mi^2), the vent area for the Wapi field is 4 km (3 mi) south of the southernmost vents of the Kings Bowl lava field. A complex of five major vents and six smaller vents constitutes the vent area. The vents are steep-sided, roughly circular depressions typically 100 m (300 ft) in diameter and 10 m (30 ft) deep. The largest depression contains several pit craters that display the ledges of lava lakes that filled the crater (see "Small-Scale Volcanic Features"). Lava tubes are exposed in walls of some of the depressions (see "Lava Tubes"). Flows of the summit area of the shield are chiefly shelly pahoehoe and minor slab pahoehoe. Pillar Butte, a mass of agglutinate and layered flows, rises 18 m (59 ft) above the south side of the largest vent. The origin of Pillar Butte is unclear; its relief is due either to inflation by injection of dikes (see "Small-Scale Volcanic Features") or to deflation of the area around it (Champion 1973).

Kings Bowl Lava Field

A radiocarbon age of 2,130 ± 130 years BP has been determined for the Kings Bowl lava field (Prinz 1970), but within limits of analytical error, the ages of the Wapi and Kings Bowl lava fields are identical (Kuntz et al. 1986b). The eruption that formed these fields probably started simultaneously, but eruption terminated at Kings Bowl after only a few hours or days but continued at Wapi for several months (Kuntz et al. 1992).

The Holocene Kings Bowl lava field (**Qwfa1**) lies along the southern part of the Great Rift volcanic rift zone, 12 km (8 mi) southeast of the Craters of the Moon lava field and 1 km (0.6 mi) north of the Wapi lava field. The Kings Bowl lava field is characterized by thin, fissure-fed flows adjacent to the 6-km- (4-mi-) long set of eruptive fissures of the Great Rift volcanic rift zone. The small Kings Bowl lava field contains excellent examples of certain volcanic landforms that are either poorly developed or simply not present elsewhere in the eastern Snake River Plain (Kuntz et al. 1992). These include a tephra blanket, explosion pits, lava lakes, squeeze-ups, and basalt mounds (see "Small-Scale Volcanic Features").

The fissure system in the Kings Bowl area consists of a central eruptive fissure set that is about 6 km (4 mi) long and trends N10°W. The central fissure set is flanked by two subparallel sets of non-eruptive fissures that are from 600 m (2,000 ft) to as much as 1,100 m (3,600 ft) from the main eruptive fissure (fig. 14). The western non-eruptive fissures have a fairly uniform width of about 200 m (660 ft); the eastern non-eruptive fissures have variable widths that range from a few meters (about 10 ft) to as much as 400 m (1,300 ft) wide.

Non-eruptive fissures also occur in the Craters of the Moon lava field; Niles et al. (2011) highlighted these as a "point of geologic interest." The GRI GIS data show

non-eruptive fissures as volcanic line features; 667 are shown in the crmo_geology.mxd data set, and 75 are shown in the cotm_geology.mxd data set.

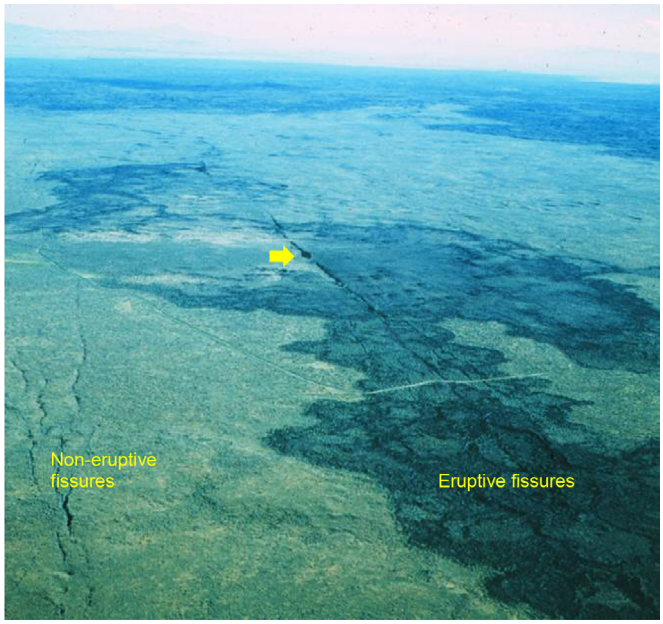


Figure 14. Photograph of Kings Bowl lava field. The Kings Bowl lava field consists of surface- and fountain-fed, proximal, medial, and distal basaltic pahoehoe lava flows (Qwfa1). Fissures on the right side of the photograph are eruptive. Fissures on the left are non-eruptive. The arrow points to Kings Bowl (explosion pit) (see also figs. 2 and 20). NPS photograph from Owen (2011b).

Vents

The volcanic material that makes up the three lava fields in the park was extruded through vents (any opening at Earth's surface through which magma erupts or volcanic gases are emitted). Vents are associated with eruptive fissures (see "Eruptive Fissures"), cinder cones (see "Cinder Cones"), and shield volcanoes (see "Shield Volcanoes") at the park.

Kuntz et al. (2015) identified a new type of eruptive center—a "vent complex"—in the north half of the Lake Walcott quadrangle. This vent complex consists of at least six vents that are aerially contiguous and distributed in a seemingly random spatial pattern, but paleomagnetic data for these vents are identical, suggesting that they erupted simultaneously or within a short span of time (less than 100 years).

The crmo_geology.mxd data set shows 14 vents that were mapped as volcanic point features (×). These mark a crater rim or volcanic vent, or a small vent that is a remnant of a larger vent but is now covered by a lava flow that ponded in a central vent depression (see poster [sheet 2], in pocket). That data set also shows 105 cones that were mapped as volcanic point features (*). These cones are small lava, cinder, or spatter cones. They have not been named like many of the larger cinder cones in the park (see table 2 and "Cinder Cones"). The GRI GIS data set cotm_geology.mxd has 37 cones mapped as volcanic point features.

Eruptive Fissures

Individual eruptive fissures on the eastern Snake River Plain range in length from 0.1 km (0.06 mi) to slightly more than 1 km (0.6 mi) and average 0.5 km (0.3 mi). Eruptive-fissures zones vary in length from less than 0.3 km (1.2 mi) to about 10 km (6 mi); the average is about 3 km (2 mi) (Kuntz et al. 1992). On the eastern Snake River Plain, shorter zones produced small-volume eruptions. Longer zones generated large-volume, cone- or shield-building eruptions. Sustained eruptions, which extruded lava from central vents overlying pipe-like conduits along eruptive fissures, built cinder cones and shield volcanoes (see "Cinder Cones" and "Shield Volcanoes"). The elongation of most vents in cones and shield volcanoes suggests that eruptive fissures influenced the location and shape of those central vents (Kuntz et al. 1992).

The crmo_geology.mxd data set shows eruptive fissures as both volcanic line features (37 of these, spanning about 15 km [9 mi]) and linear extrusive units (seven of these, spanning about 17 km [11 mi]) delineated by map unit symbols: (1) Fissure Butte (**Qcec2**; note: "**e**" in the third position of the map unit symbol indicates an eruptive fissure), (2) South Echo (**Qcec1**), (3) Deadhorse (**Qceb2**), (4) Vermillion Chasm (**Qceb1**), (5) Big Craters (**Qcea3**), (6) Trench Mortar Flat (**Qcea3**), and (7) Blue Dragon (**Qcea1**). Pyroclastic materials such as agglutinate, cinders, or spatter are associated with eruptive fissures. Like crmo_geology.mxd, the cotm_geology.mxd data set shows eruptive fissures as volcanic line features, but not as linear extrusive units.

An eruptive fissure and/or a cinder cone can be the source vent for a lava flow. For example, South Echo eruptive fissure (**Qcec1**) was the source vent for the South Echo flows (**Qcfc5**), which are between Echo Crater (**Qcec1**) on the north and The Sentinel (**Qccc4**) on the south; whereas both the Fissure Butte eruptive fissure (**Qcec2**) and the Fissure Butte cinder cone (**Qccc3**) were source vents for the Fissure Butte flows (**Qcfc7**).

Cinder Cones

A cinder cone is a conical hill, commonly steep, that formed by accumulation of solidified fragments of lava ("cinders") that fell around the vent during an eruption. Cinders are commonly glassy (a texture similar to glass [i.e., without distinctive crystallization] that developed as a result of rapid cooling of lava) and vesicular (containing cavities of variable shapes formed by the entrapment of gas bubbles during solidification of lava). Within the park, prevailing winds from the west and southwest caused the downwind accumulation of cinders, resulting in asymmetrical elongation of many cinder cones to the east or northeast (see "Eolian Features and Processes").

Table 2. Prominent cinder cones at Craters of the Moon National Monument and Preserve.

*Map unit symbols are from the GRI GIS data set, crmo_geology.mxd. The last letter in the map unit symbol indicates the eruptive period, H (oldest) to A (youngest). Numbers indicate stratigraphic position within an eruptive period. Cones mapped as Qcc are not assigned to a specific eruptive period and are said to have erupted during the lifespan of the Craters of the Moon lava field.

Cinder Cone	Map Unit Symbol*
Broken Top	**Qcca1**
Big Craters	**Qcca2**
The Watchman (fig. 17)	**Qcca3**
North Crater	**Qcca4**
Black Top Butte	**Qccb1**
Big Cinder Butte (fig. 15)	**Qccc1**
Sheep Trail Butte	**Qccc2**
Fissure Butte	**Qccc3**
The Sentinel	**Qccc4**
Silent Cone	**Qccd1**
Grassy Cone	**Qcce1**
Sunset Cone	**Qccg1**
Crescent Butte (fig. 16)	**Qcch1**
Inferno Cone	**Qcc**
Paisley Cone	**Qcc**
Unnamed cone west of Broken Top	**Qcc**
Half Cone	**Qcc**
Unnamed cone south of Half Cone	**Qcc**
Coyote Butte	**Qcc**
Echo Crater	**Qcc**
Split Butte	**Qcc**



Figure 15. Photograph of Big Cinder Butte. From its base, Big Cinder Butte (Qccc1), which is the largest volcano in the Craters of the Moon lava field, rises more than 200 m (700 ft) above the surface of the surrounding lava flows. The elevation at the summit is 1,984 m (6,509 ft) above sea level. NPS photograph from Owen (2011b).

Cinders cones grow in height as an eruption continues, but the angle of repose (commonly about 30°) remains the same (Lillie 2005). Big Cinder Butte (fig. 15), which rises more than 200 m (700 ft) above the surrounding plain (Blakesley and Wright 1988), is the tallest cinder cone in the park. It "ranks among the largest, purely basaltic cinder cones in the world" (Stearns 1928, p. 5). The prominent cinder cones in the park are generally located along the outer margins of the Great Rift volcanic rift zone (fig. 1).

Cones are a "point of geologic interest" highlighted by Niles et al. (2011). The crmo_geology.mxd data set shows 13 named cones associated with lava flows (figs. 15 and 16), six named cones not associated with lava flows (fig. 17), and two unnamed cones not associated with lava flows (table 2). That data set also has 94 small cones without names, as well as 11 small lava, cinder, or spatter cones (see "Spatter Cones and Spatter Ramparts").

Shield Volcanoes

A shield volcano is a broad, shield-shaped volcano that builds up by successive, mostly effusive, eruptions of low-silica lava (US Geological Survey 2016). The crmo_geology.mxd data set includes at least 20 shield volcanoes in the vicinity of the park. The largest of these is Laidlaw Butte (**Qsbd3**) (fig. 18), which is within the BLM monument. The only "predominantly Holocene" shield volcano within the park is associated with the Wapi lava field (**Qwfa2**) (see "Wapi Lava Field").



Figure 16. Photograph of Crescent Butte.
Crescent Butte (Qcch1) erupted about 15,000 years ago, during eruptive period H, and is the oldest volcano in the Craters of the Moon lava field. NPS photograph from Owen (2011b).

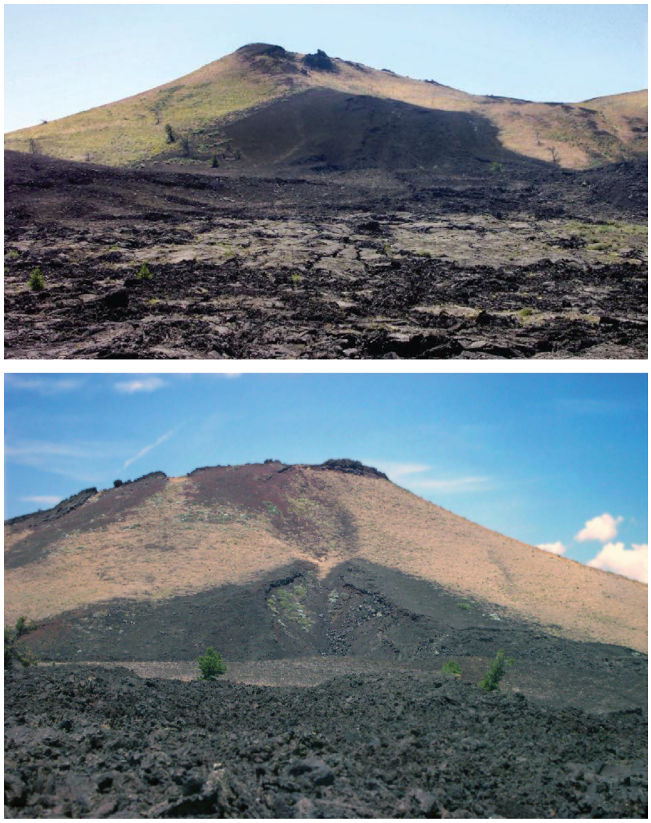


Figure 17. Photographs of The Watchman.
The Watchman cinder cone (Qcca3) formed during eruptive period A at the same time as the Trench Mortar Flat (Qcfa3) flows (i.e., about 2,100 years ago). The Watchman exhibits some of the best examples of flank eruptions in the park. The cone is 95 m (312 ft) high and about 0.8 km (0.5 mi) across. The top photo shows the north vent. The north slope of The Watchman consists of a pahoehoe flow. The bottom photo shows the south vent. The south slope consists of slab pahoehoe flow. The uppermost point of both the flow on the north and the flow on the south has a shallow valley or rift with small spatter ramparts on either side. NPS photographs from Niles et al. (2011).

Laidlaw Butte is one of the largest, highest, and most imposing shield volcanoes of the eastern Snake River Plain; it rises 160 m (520 ft) above surrounding younger lava flows on its north flank and 275 m (900 ft) above surrounding younger flows on its south flank. The vent is 1,000 m (3,300 ft) long and 30 m (100 ft) deep. Laidlaw Butte has an $^{40}Ar/^{39}Ar$ age of 425,000 ± 20,000 years. Laidlaw Butte is part of the largest kipuka surrounded by the Craters of the Moon lava field.

Lava Flows

The term "lava flow" denotes sheets of lava erupted from a fissure or a pipe-like vent. Volcanic line features in the GRI GIS data (crmo_geology.mxd and cotm_geology.mxd) indicate the direction of flow of all the lava flows that comprise the Craters of the Moon, Wapi, and Kings Bowl lava fields (see posters, in pocket).

Kuntz et al. (2007) identified surface-fed, channel-fed, and tube-fed flows; many flows were distributed via a combination of these. Surface-fed flows advance by supply of lava in broad sheets. Also at the surface but confined to a channel, lava in channel-fed flows is distributed via a developed channel, commonly lined by levees (see "Lava Channels and Lava Levees"). Tube-fed flows are large-volume pahoehoe flows that advance chiefly via a supply of lava through channels that have crusted over, creating lava tubes (see "Lava Tubes"). Lava can travel great distances through lava tubes with very little loss of heat. Some flows in the Craters of the Moon area extend as much as 50 km (30 mi) (Hughes et al. 1999). Typical basaltic lava flows of the eastern Snake River Plain consist of both shelly and slab pahoehoe and a'a lava (see "Types of Volcanic Rocks and Lava").

As depicted in the 1:100,000-scale GRI GIS data set (crmo_geology.mxd), the Craters of the Moon lava field contains 43 mapped and named lava flows (see crmo_geology.pdf). By contrast, the Kings Bowl lava field was mapped as one map unit: the Holocene surface- and fountain-fed, proximal, medial, and distal



Figure 18. Photograph of Laidlaw Butte.
Part of the Laidlaw Butte lava field (Qsbd3), Laidlaw Butte is a shield volcano, and now part of a kipuka, surrounded by the Craters of the Moon lava field. Towering more than 270 m (900 ft) above the surrounding flows, Laidlaw Butte is the largest volcano in the BLM monument. At 425,000 years old, it is much older than the volcanoes in Craters of the Moon lava field. NPS photograph from Owen (2011b).

basaltic pahoehoe lava flows of the Kings Bowl lava field (**Qwfa1**). The Wapi lava field also was mapped as a single unit: the Holocene proximal, medial, and distal, chiefly tube-fed, basaltic pahoehoe lava flows and near-vent deposits of the Wapi lava field (**Qwfa2**).

Small-Scale Volcanic Features

Many small-scale volcanic features of the Craters of the Moon, Wapi, and Kings Bowl volcanic fields have been described in general interest publications and the scientific literature. The features highlighted below were mentioned in map unit descriptions by Kuntz et al. (2007). They are also shown in the GRI GIS data—crmo_geology.mxd (scale 1:100,000) and/or cotm_geology.mxd (scale 1:24,000)—as either volcanic point features or volcanic line features. At a scale of 1:24,000, more detailed mapping took place in the Craters of the Moon lava field; therefore, many more of these features are highlighted as "volcanic point features" or "volcanic line features" in the cotm_geology.mxd data set than the crmo_geology data set. Examples of many of these features, along with their GPS coordinates, are showcased by Niles et al. (2011).

Descriptions for these features were compiled from a variety of sources including three versions of *Geology of Craters of the Moon* (Owen 2004, 2008, and Owen and Melander 2014), as well as *Craters of the Moon: Around the Loop* (Henderson 1986), *Teachers' Guide to Broken Top Loop* (Owen publication date unknown), and the USGS Volcano Hazards Program's online glossary at http://volcanoes.usgs.gov/vsc/glossary/. Small-scale features associated with lava tubes are discussed in "Lava Tubes."

Bombs

Volcanic bombs form when globs of molten rock are ejected into the air and shaped while in flight. Four kinds of volcanic bombs are found in the park: (1) a spindle bomb, which ranges from a few inches to several feet in length, gets twisted while in flight; (2) a ribbon bomb is very tiny and twisted; (3) a bread-crust bomb, named because of its similarity to rising bread in an oven, forms a crust as it flies through the air and the gases inside continue to expand and crack that crust; and (4) a cow-pie or pancake bomb, which did not completely solidify during flight, is flattened upon landing (fig. 19). Some cow-pie bombs in the park are more than 3 m (10 ft) long (Owen 2004). Kuntz et al. (2007) noted bombs associated with the Vermillion Chasm lava flows (**Qcfb1**) and Lava Creek cinder cone (**Qccg2**). Bombs are a "point of geologic interest" highlighted by Niles et al. (2011).

Blocks

Like bombs, blocks were ejected into the air but in a solid state. Blocks consist of material greater than 64 mm (2.5 in) in diameter. Blocks as large as 10 cm (4 in) in diameter were hurled westward from Kings Bowl for distances of 245 m (800 ft); many of the largest blocks poke through the crust of the lava. The Highway lava flow (**Qcfa10**), which has an extremely rough surface, contains blocks, as well as furrows and spires (see "Spires"), which produce a local relief of as much as 10 m (30 ft) (Kuntz et al. 2007).



Figure 19. Photographs of bombs.
Four kinds of volcanic bombs are found in the park, from top to bottom: bread-crust (because of their resemblance to bread rising in an oven), spindle (formed while twisted in flight), cow-pie (flattened upon landing), and ribbon (tiny and twisted). All bombs start as globs of molten rock ejected into the air during a volcanic eruption. The hand in the bottom photograph is for scale only; collecting rocks within the park is prohibited. NPS photographs from Owen (2011b).

Collapse Depressions/Pit Craters

Collapse depressions—also referred to as "collapse pits," "pit craters," and "sinks"—occur on the surface of lava flows within the park. The crmo_geology.mxd data set shows pit craters as volcanic line features. These features are elliptical to elongate depressions in the surface of a lava flow that formed by the collapse of a long lava tube or several short ones after the withdrawal of lava (see "Lava Tubes"). Pit craters range in diameter from about 10 m (a few tens of feet) to about 1.6 km (1 mi) and in depth from about 10 m (a few tens of feet) to more than 300 m (1,000 ft). In plan view, they appear as roughly circular or broad ovals. Where two adjacent pit craters overlap, they resemble a figure eight. In the early stages of development, the walls of pit craters are nearly vertical, but their rims quickly erode, and the fallen rock fragments accumulate as talus slopes against the foot of the walls (MacDonald 1972).

Collapse depressions along with other features such as pressure ridges, pressure plateaus, and tumuli (see "Flow Ridges, Furrows, and Cracks"; "Pressure Plateaus/Lava Rises"; and "Tumuli") indicate a high-volume, short-duration eruption (Kuntz et al. 2007). Collapse depressions are common on the surface of the Blue Dragon flows (**Qcfa2**), Minidoka flows (**Qcfb4**), Grassy flow (**Qcfe1**), and Carey flow (**Qcfg2**). On the Black Top Butte cinder cone (**Qccb1**), craters are filled by lava lakes and indented by collapse pits. In the Wapi lava field (**Qwaf2**), medial and distal pahoehoe flows are typified by collapse depressions and flow ridges. In addition, the Laidlaw Lake pahoehoe and a'a basalt flows (**Qcfe2**) and Sunset pahoehoe and slab-pahoehoe basalt-hawaiite flows (**Qcfg1**) have collapse depressions.

Craters

The cotm_geology.mxd and crmo_geology.mxd data sets show 98 and 201 craters, respectively, as volcanic line features. Craters are basin-like, rimmed structures at the top or on the flanks of a volcanic cone. They form by explosion or collapse.

Grassy Cone (**Qcce1**) consists of five nested craters; Silent Cone (**Qccd1**) consists of three nested craters; Sheep Trail Butte (**Qccc2**) consists of five nested cinder cones and associated craters; Black Top Butte (**Qccb1**) consists of at least three nested cones with craters that are filled by lava lakes and indented by collapse pits; and Big Craters (**Qcca2**) consists of at least nine nested cones and associated craters where the inner walls of southernmost crater are mantled by thin flows and agglutinated spatter. More than one crater associated with a cinder cone indicates a complicated eruptive history.

Dikes

Magma can remain within fissures (see "Eruptive Fissures") after an eruption ceases. The material then cools and solidifies into sheet-like bodies known as dikes. Dikes cut across horizontal strata, and may be exposed in the sides of a volcano. Because igneous rocks that cool below Earth's surface are generally harder and more resistant to erosion than the horizontal strata they intruded, dikes commonly stand out in relief.

In the crmo_geology.mxd data set, dikes are depicted as both linear features (**Td**) and rock units (**Tcd**). They occur in the Pioneer Mountains, north of the park. Some dikes (**Tcd**) form resistant ridges oriented north to northeast; the width is typically 1–2 m (3–7 ft). Both the dikes and the rocks they intruded are Eocene in age, though the dikes are obviously younger than the preexisting rocks they intruded. In the Pioneer Mountains, the dikes primarily intruded the Challis Volcanic Group (**Tcv**) (see "Geologic History"). The rhyolite, leucogranite, and granite pegmatite and aplite dikes (**Tcd**) also intruded Mississippian sedimentary rocks (**Mca**) and biotite granite of Cottonwood Creek (**Tcbg**).

Although the dikes shown in the GRI GIS data are Eocene in age, Kuntz et al. (2007) identified "feeder dikes" (conduits through which magma passes from the magma chamber to some localized intrusion) in one Late Pleistocene and two Holocene lava fields. The Late Pleistocene basaltic pahoehoe flows and near-vent pyroclastic deposits of west Wildhorse Butte lava field (**Qsbb8**) contain a feeder-dike system. Based on the configuration of the satellite and main vents, the orientation of the feeder-dike system is north–south. Additionally, both the Holocene Wapi and Kings Bowl lava fields have dikes. At the Wapi field (**Qwaf2**), dikes may have injected Pillar Butte, which is a mass of agglutinated, shelly pahoehoe flows that mark the summit region of the Wapi shield volcano. At the Kings Bowl lava field (**Qwaf1**), feeder dikes and breccia commonly fill eruptive fissures.

Explosion Pits

Explosion pits are the result of phreatic eruptions (steam-driven explosions that occur when water interacts with lava or hot rocks). The intense heat of such material, which is as high as 1,170°C (2,138°F) for basaltic lava, may cause water to boil and flash to steam, generating an explosion of steam, water, ash, blocks, and bombs. The Kings Bowl lava field (**Qwfa1**) takes its name from a phreatic explosion pit known as "Kings Bowl," which is 85 m (280 ft) long, 30 m (100 ft) wide, and 30 m (100 ft) deep (fig. 20). The field has other explosion pits, but that is the largest one.



Figure 20. Photograph of Kings Bowl.
The Kings Bowls lava field received its name from the Kings Bowl explosion pit (see also figs. 2 and 14), which resulted from a steam-driven explosion referred to as a "phreatic eruption." For a sense of scale, note the two people in the cleft at the top of the explosion pit. The pit is 30 m (100 ft) deep. NPS photograph from Owen (2011b).

Flow Ridges, Furrows, and Cracks

The cotm_geology.mxd data set delineates 7,620 flow ridges, furrows, or cracks on the surface of the lava flows in the park; they are delineated as volcanic line features. Flow ridges, also referred to as "pressure ridges," are elongate uplifts of the congealing crust of a lava flow, which probably result from the pressure of still-flowing lava beneath. As the lava current progresses, upward surges may generate pressure ridges that rise 10 m (30 ft) above the general level of the flow and may be as much as 1 km (0.6mi) long. Pressure ridges usually occur in two or three chains trending parallel to the margins of the flow (Scarth 1994).

Commonly, pressure ridges and collapse depressions form in conjunction (see "Collapse Depressions and Pits"). The Wapi lava field is typified by these features. In addition, pressure ridges formed on lava flows throughout the development of the Craters of the Moon lava field, from eruptive period H (i.e., Carey flows [**Qcfg2**]) through eruptive period A (e.g., Serrate flow [**Qcfa8**]).

Furrows and cracks are surface expressions of vertical or near vertical shear planes that separate an a'a flow into longitudinal lobes, as individual lobes move at different rates with respect to one another. The flow ridges and furrows/cracks may not be visible from ground level, but they are obvious on air photos (Kuntz et al. 2004). Kuntz et al. (2007) identified 10 of the flows in the Craters of the Moon lava field as having longitudinal furrows and cracks that are roughly parallel to the direction of flow movement: Serrate (**Qcfa8**), Indian Wells North (**Qcfc1**), Indian Wells South (**Qcfc2**), Sawtooth (**Qcfa3**), Silent Cone (**Qcfd1**), Carey Kipuka (**Qcfd2**), Little Park (**Qcfd3**), Little Laidlaw (**Qcfd4**), Grassy (**Qcfc1**), and Lava Point (**Qcfe3**). All of these flows are composed of a'a.

Lava Channels and Lava Levees

Kuntz et al. (2007) described lava flows as being surface-, channel-, and/or tube-fed. Both surface-fed and channel-fed lava flows occur at the surface of a flow, compared to tube-fed flows where lava was distributed in lava tubes below the surface (see "Lava Tubes"). In the case of channel-fed flows, lava was distributed from a vent via lava channels. Channels also extend from lava lakes.

A channel is commonly lined by conspicuous lava levees, which serve as a retaining wall of hardened lava along the side of a lava channel (fig. 21) or lake. Lava levees were built up incrementally by successive overflow, overthrusting of lava crusts or blocks, or spatter (Owen and Melander 2014).

Both the crmo_geology.mxd and cotm_geology.mxd data sets show lava channels as volcanic line features. The near-vent flows in the Wapi lava field (**Qwfa2**) are characterized by channels. The flows are typically a few hundred meters long and contain leveed channels that distributed lava. In the Late Pleistocene Broken Top lava field (**Qsbb5**), narrow channels, 10 m (30 ft) or less across, are present near the vent area and on the east side of Sand Butte (Kuntz et al. 2007).



Figure 21. Photographs of lava channels and levees. Top: The near-vent flows in the Wapi lava field (Qwfa2) are characterized by channels and levees. The Wapi flows contain leveed channels that distributed lava for hundreds of meters. The red arrows mark the levees. Bottom: Levees line the sides of a "river" of lava on the Blue Dragon flows (Qcfa2). Lava levees build up incrementally by successive overflow, overthrusting, or spatter. NPS photographs from Owen (2011b).

Lava Domes

Lava domes are steep-sided masses of viscous and commonly blocky lava extruded from a vent. They typically have a rounded top and cover a roughly circular area. Late and middle Pleistocene lava domes occur in the vicinity of the park, for example at Wagon Butte (**Qsbb13**), Serviceberry Butte (**Qsbb22**), and Pratt Butte (**Qsbc35**). In addition, the vent depression at Huddles Hole (**Qsbc39**) is atop a broad lava dome that is the summit of a large shield volcano, which is also a kipuka (see "Loess, Soil, and Kipukas"). Devils Caldron (**Qcfb3**) is the only lava dome in the park that is part of the recent eruptive history of the Craters of the Moon lava field; it formed during eruptive period B (see "Geologic History"). It has a radiocarbon age of 3,660 ± 60 years BP. During that eruption, pahoehoe basalt-hawaiite lava flowed out of a low, broad lava dome (Devils Caldron), which contains two lava-filled craters.

Lava Mounds

Lava mounds, also referred to as "basalt mounds" or "cinder mounds," are irregular-shaped, low mounds composed of rock fragments that exploded into the air and cooled on their way to the ground. The basalt mound (**Qcca5**) near the North Crater cinder cone (**Qcca4**) is less than 8 m (26 ft) high and less than 100 m (330 ft) in diameter. The origin of that lava mound is unknown but may be related to eruptions during collapse of the cinder cone. The Kings Bowl lava field (**Qwfa1**) has prominent basalt mounds about 3 m (10 ft) wide and less than 1 m (3 ft) high that are thought to be the remnants of levees (see "Lava Channels and Levees"); these mounds surround and define the limits of a distinctive lava lake (see "Lava Ponds/Lakes"). In addition, The Watchman cinder cone (**Qcca3**) has cinder mounds. Cinder mounds also are associated with the Vermillion Chasm lava flows (**Qcfb1**) and eruptive fissure (**Qceb1**), Broken Top Butte (**Qsbb5**), and many older buttes and vents associated with Snake River Plain volcanism (see "Geologic History"). Some of the mounds of these older deposits (e.g., **Qsbc11**) consist of notable red-oxidized cinders.

Lava Ponds/Lakes

Lava ponds or lakes are basalt filled depressions surrounded by levees. They have little surface relief. Both the crmo_geology.mxd and cotm_geology.mxd data sets show them as volcanic line features. Usually, lava ponds form where basaltic magma wells up in a pit or crater. They may also form on pahoehoe surfaces where flows are ponded by an obstacle (Scarth 1994).

Kuntz et al. (2007) described a roughly circular lava lake about 1 km (0.6 mi) in diameter that surrounded Kings Bowl prior to the eruption that created the Kings Bowl explosion pit. The lava lake is flat and broken into large plates as a result of subsidence of underlying lava. In addition, Black Top Butte (**Qccb1**) consists of at least three nested cones; craters in Black Top Butte are filled by lava lakes and indented by collapse pits. An example of a somewhat older feature (Late Pleistocene) is Bear Den Butte, which has a lava-lake complex. The Bear Den Butte cinder cone is breached on its southeast flank, where a channel leads to a 900-m- (3,000-ft-) long lava lake with confining levees as high as 10 m (30 ft). The Bear Den Butte lava flows (**Qsbb2**) make up the southeastern "thumb" of the largest kipuka surrounded by the Craters of the Moon lava field. As a final example, the Late Pleistocene basaltic pahoehoe flows and near-vent pyroclastic deposits of Horse Butte lava field (**Qsbb25**) between the Craters of the Moon field on the north and the Wapi field on the south contains a 500-m- (1,640-ft-) wide, leveed lava lake at the south end of its crater.

Pahoehoe Toes

The Blue Dragon flows (**Qcfa2**) have the most spectacular examples of pahoehoe toes in the park (Kuntz et al. 2007). Also referred to as "lava toes," these features appear as appendages, breaking out beyond the perimeter of a partially solidified flow. The Wapi lava field (**Qwfa2**) also has notable pahoehoe toes; the proximal flows include pahoehoe flows that consist largely of surface-fed pahoehoe toes (Kuntz et al. 2007).



Figure 22. Photograph of pressure plateau. Pressure plateaus, also called "lava rises," are flat-topped areas of pahoehoe lava flows. They are produced by sill-like injection of new lava beneath the solidified crust of a flow. NPS photograph from Owen (2011b).

Pressure Plateaus/Lava Rises

In a field of pahoehoe lava, pressure plateaus, also referred to as "lava rises," make up the flat-topped portion (fig. 22). A pressure plateau is produced by sill-like (parallel) injection of new lava beneath the crust of a flow that had not completely solidified. Along with pressure ridges and collapse depressions, pressure plateaus are indicative of a high-volume, short-duration eruption.

Pressure plateaus are common on the surface of the Blue Dragon flows (**Qcfa2**), Minidoka flows (**Qcfb4**), Grassy flow (**Qcfe1**), and Carey flow (**Qcfg2**). The medial and distal flows of Horse Butte (**Qsbb25**), between the Craters of the Moon field on the north and the Wapi field on the south, are characterized by pressure plateaus, as well as many tumuli (see "Tumuli") and pressure ridges (see "Flow Ridges, Furrows, and Cracks"). Local relief on the Horse Butte flows and near-vent deposits (**Qsbb25**) is 4 m (13 ft) or less. Also in the vicinity of the park, the medial and distal basaltic pahoehoe flows of Wagon Butte (**Qsbb13**) are characterized by many tumuli and pressure plateaus; local relief on these flows is 8 m (26 ft) or less (Kuntz et al. 2007).

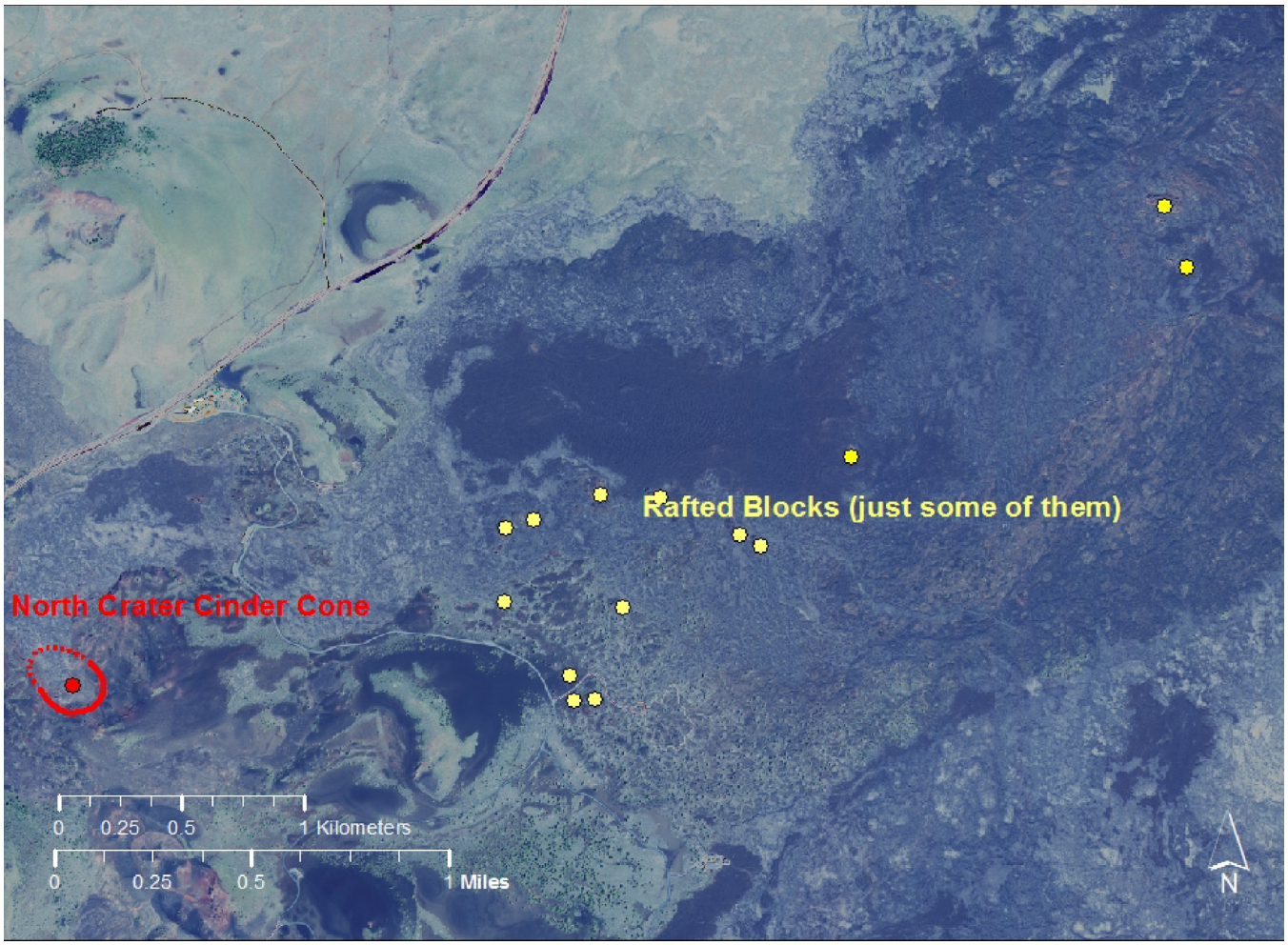


Figure 23. Map of some rafted blocks.
The North Crater cinder cone (Qcca4 and Qcca5) was erupting about 2,300 years ago during eruptive period A. Five lava flows—Highway, Devils Orchard, Serrate, Big Craters Northeast, and North Crater—erupted from vents in the area. Three of these—Highway, Devils Orchard, and Serrate—were viscous enough to break apart cinder cones and carry pieces of the crater wall as much as 13 km (8 mi) away. This map marks some of the rafted blocks that were carried away from the North Crater cinder cone. Graphic by Todd Stefanic (Craters of the Moon National Monument and Preserve).

Rafted Blocks and Monoliths

During some eruptions, pieces of crater walls were carried off like icebergs by the lava flows. Some pieces were carried as far as 13 km (8 mi) (Brossy 2003) (fig. 23). These wall chunks, known as rafted blocks (fig. 24), can be the size of houses (Scarth 1994). Only a‘a flows are thick enough to float such massive blocks to new locations (Henderson 1986).

Devils Orchard in the northern part of the park is an entire field of rafted blocks, which have lengths and widths of as much as 100 m (300 ft) and heights of 20 m (70 ft). The Devils Orchard block and a‘a latite flow (**Qcfa9**) contains rafted blocks of bedded cinders and ash derived from a cinder cone, probably North Crater. The crater of the North Crater cinder cone (**Qcca4**) is open to the north, as a result of cone collapse and rafting of remnants of crater walls by viscous lava flows. The Serrate block and a‘a latite flow (**Qcfa8**) also contains rafted blocks of bedded cinders and ash, which were derived from a shattered cinder cone (probably North Crater). These rafted blocks have lengths and widths of as much as 150 m (490 ft) and exposed heights of up to 30 m (100 ft).

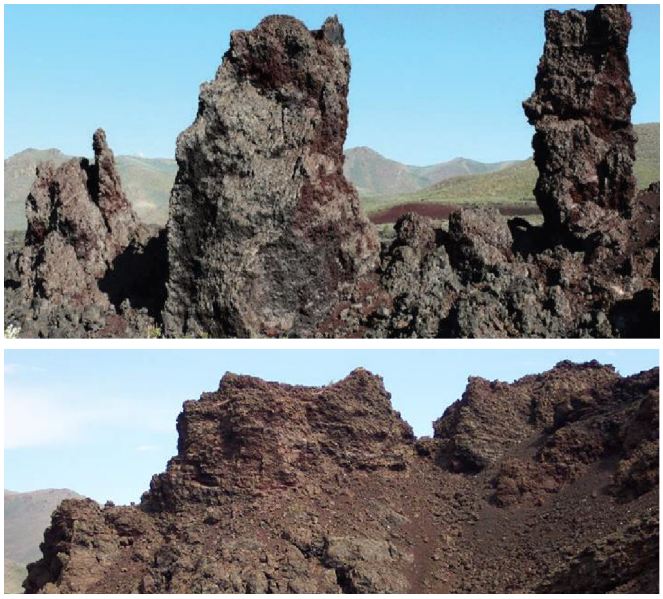


Figure 24. Photographs of rafted blocks and monoliths.
Devils Orchard is known for its monolithic lava forms, which may have rafted to their present positions or formed in place. Top: These monoliths along the North Crater Flow trail are volcanic necks of now-missing volcanoes. They formed in place. Bottom: Known as “Warehouse Rock,” this piece of a crater wall is from the North Crater cinder cone (Qcca4); it rafted about 0.6 km (1 mi) away from the cinder cone during eruptive period A. NPS photographs [top] from Niles et al. (2011) and [bottom] Owen (2011b).

Other a‘a flows in the park with notable rafted blocks include Indian Wells North (**Qcfc1**), Indian Wells South (**Qcfc2**), Silent Cone (**Qcfd1**), Little Park (**Qcfd3**), and Little Laidlaw Park (**Qcfd4**). Also, the southwestern (main) lobe of the Lava Point a‘a basalt flows (**Qcfe3**) contains rafted blocks of bedded cinders; these are as much as 100 m (300 ft) long and 20 m (70 ft) high.

Monoliths are a “point of geologic interest” highlighted by Niles et al. (2011). Some monoliths are rafted blocks but others formed in situ as volcanic necks (cooled conduits of lava from a now missing cone) (fig. 24).

Rootless Vents

Rootless vents are secondary sources of lava, not directly connected to a deep-magma-reservoir conduit. Most are openings in lava tubes. The Craters of the Moon lava field contains a plethora of rootless vents. Rootless vents are commonly referred to as “hornitos,” meaning “little ovens” in Spanish (fig. 25); Kuntz et al. (2007) did not use this term, however. Niles et al. (2011) highlighted hornitos as a “point of geologic interest.”



Figure 25. Photographs of rootless vents.
Also known as hornitos (“little ovens” in Spanish), rootless vents are fed through a hole in a lava tube. NPS photographs from Owen (2011b).



Figure 26. Photographs of spatter cones.
Spatter cones have "rooted vents" fed directly from an eruptive fissure. The cone in the top photograph does not have a formal name but is referred to as "Spatter Cone." The trail in that photograph provides a sense of scale. For scale in the bottom photograph, note the people along the ridge, which is located at South Grotto. NPS photographs from Owen (2011b).

The crmo_geology.mxd data set shows 121 rootless vents as volcanic point features (**+**); the cotm_geology.mxd data set shows 56 (see posters, in pocket). The Blue Dragon pahoehoe and a'a basalt-hawaiite flows (**Qcfa2**) and Minidoka pahoehoe basalt flows (**Qcfb4**) of the Craters of the Moon field have notable rootless vents. Rootless vents in these flows are associated with lava-tube systems (see "Lava Tubes") that experienced overflow or outflow of lava within an otherwise solidified lava flow.

In contrast to the Craters of the Moon lava field, neither the Kings Bowl lava field, which is characterized by thin, fissure-fed flows, nor the Wapi lava field, which is a shield-type field, have rootless vents.

Spatter Cones and Spatter Ramparts

Short, steep-sided spatter cones (fig. 26) form when spatter (fluid globs of lava) is ejected short distances, generally less than 60 m (200 ft), from a vent. The cotm_geology.mxd data set notes a spatter cone (volcanic point feature) on the Blue Dragon flow. The crmo_geology.mxd data set has 11 small lava, cinder, or spatter cones as volcanic point features.

In addition to the Blue Dragon fissure system (**Qcea1**) and associated flows (**Qcfa2**), which are marked by spatter cones, the Kings Bowl lava field (**Qwfa1**) has spatter cones, as well as spatter ramparts, as prominent features. Spatter ramparts form where a contiguous segment of an eruptive fissure erupts simultaneously, depositing spatter in ridges alongside the fissure. Many eruptive fissures in the park have spatter ramparts aligning them, for example, Trench Mortar Flat (**Qcea2**), Big Craters (**Qcea3**), Vermillion Chasm (**Qceb1**), and Deadhorse (**Qceb2**). Also, fissure vents at The Watchman cinder cone (**Qcca3**) are flanked by spatter ramparts.

Some ramparts can be large features; for example, the spatter ramparts at Vermillion Chasm are 20 m (70 ft) high and 200 m (700 ft) wide. By contrast, the Fissure Butte eruptive fissure (**Qcec2**), which extends about 2 km (1.2 mi) northwest of Fissure Butte cinder cone (**Qccc3**), is flanked by spatter ramparts that are less than 5 m (16 ft) high.

Spires

Spires are similar in appearance to spatter cones but formed from spatter ejected from holes in the crust of a lava flow instead of directly from a vent. The bizarre spires found in the Wapi lava field (**Qwfa2**) average 4 m (12 ft) high and 2 m (5 ft) across. They consist of rounded, imbricated (tilted and partly overlapping, so that their flat surfaces dip "upstream") slabs of lava that range from about 13 cm (5 in) ×13 cm (5 in) ×3 cm (1 in) to 30 cm (12 in) ×23 cm (9 in) ×10 cm (4 in) (Greeley 1977). In the Craters of the Moon lava field, the Highway block, a'a, and pahoehoe latite flow (**Qcfa10**), which has an extremely rough surface, contains spires, blocks, and furrows that produce a local relief of as much as 10 m (30 ft).

Squeeze-Ups and Squeeze-Outs

The crust of a pahoehoe flow quickly becomes fractured as a result of shrinkage by cooling or distortion by the movement of flowing lava beneath it. The below-surface lava may be squeezed up either into an elongate bulb-like structure with a round top that tends to spread over the adjacent lava surface, or into a sharp-pointed wedge that projects a few centimeters (inches) to a meter (a few feet) into the air (fig. 27). In the original description by Nichols (1946)—from the McCartys flow at El Malpais National Monument in New Mexico (see GRI report about El Malpais National Monument by KellerLynn 2012)—these formations were called "squeeze-ups." Owen and Melander (2014) noted that the interior of the lava lake at Kings Bowl has squeeze-ups. When the lake was still molten, lava oozed up through the holes punched in its crust, resulting in squeeze-up mounds of gas-charged lava (Hughes et al. 1999). Many of the squeeze-ups look like mushrooms or Hershey's Kisses®. Squeeze-ups are a "point of geologic interest" highlighted by Niles et al. (2011).



Figure 27. Photograph of squeeze-ups. If pressure is sufficient, lava can rise up through a tension fracture in the top of a lava flow, flow ridge, pressure ridge, or elongate tumulus and squeeze out onto the surface. The red arrows mark some of the push-ups in the photograph. NPS photograph from Owen (2011b).

Although Kuntz et al. (2007) did not mention squeeze-ups, they did mention "squeeze-outs." The Serrate block and a'a latite flow (**Qcfa8**) has bulbous lobes of lava, squeezed out at the edges of the flow. Additionally, they noted squeeze-outs as common in the Devils Orchard block and a'a latite flow (**Qcfa9**) and the Lava Point a'a basalt flows (**Qcfe3**), as well as in the a'a latite flows of Indian Wells North (**Qcfc1**), Indian Wells South (**Qcfc2**), and Sawtooth (**Qcfc3**).

Tephra Blankets

Because they are formed by pyroclastic fragments such as ash (fine-grained material, less than 2 mm [0.08 in] across, ejected from a volcano) and lapilli (pyroclastic material ranging between 2 and 64 mm [0.08 and 2.5 in] across with no characteristic shape) settling more or less vertically from the air, tephra blankets tend to form continuous mantles over whatever topography they fall upon. Commonly, beds of tephra are well sorted according to the size of the pyroclastic fragments; individual beds show a size gradation both vertically and laterally. The fragments are usually larger near the base of the bed because the larger fragments thrown out during any one explosion fall through the air faster than the smaller ones and strike the ground first. Likewise, larger fragments fall closer to a vent, while smaller ones are carried farther away by the wind (MacDonald 1972).

The most notable tephra blanket at the park covers part of the Kings Bowl lava field (**Qwfa1**). The blanket, which consists of primarily lapilli but also ash, spread across an area of 0.15 km^2 (0.06 mi^2) and lies east (downwind) of the Kings Bowl explosion pit. Investigators have shown that the volume of the tephra blanket falls short of that needed to occupy the cavity of Kings Bowl, indicating that the vent area probably collapsed following the explosion (King 1977).

Other examples of tephra blankets in the park include the one covering the Vermillion Chasm basaltic eruptive-fissure deposits (**Qceb1**); these deposits are marked by tephra-mantled furrows as wide as 10 m (30 ft) and as deep as 10 m (30 ft). The Sawtooth a'a latite flows (**Qcfc3**) have tephra as thick as 2 m (7 ft) mantling proximal parts. The flanks of the Sunset Cone (**Qccg1**) complex are mantled by fine tephra. The western margin of the Little Prairie pahoehoe and a'a basalt flows (**Qcfh4**) are mantled by a thin blanket of tephra. The western flank of the Crescent Butte cinder cone (**Qcch1**) is mantled by tephra from the Trench Mortar Flat eruptive fissures (**Qcea2**).

Tumuli

Tumuli (plural of tumulus) are a "point of geologic interest" highlighted by Niles et al. (2011). They were named by the famous Canadian geologist, R. A. Daly, who thought they resembled ancient burial mounds called "tumuli." Tumuli are created when the upward pressure of slow-moving, still-molten lava within a flow swells or pushes the overlying solidified crust upward (fig. 28). Pahoehoe flows on flat or gentle slopes commonly exhibit these elliptical, domed structures.

The following pahoehoe flows within the park contain tumuli: Minidoka (**Qcfb4**), Grassy (**Qcfe1**), Broken Top Butte (**Qsbb5**), west Wildhorse Butte lava field (**Qsbb8**), Horse Butte (**Qsbb25**), and Wagon Butte (**Qsbb13**). Additionally, east of the Kings Bowl and Wapi lava fields, the pahoehoe basaltic lava flows of the Grandview Crater lava field (**Qwfb3**) have tumuli.



Figure 28. Photograph of tumulus.
A tumulus is a doming upward of lava. This tumulus was inflated about 5 m (18 ft). The edge has a 40° slope. NPS photograph from Niles et al. (2011).

Xenoliths

From the Greek xeno- meaning "stranger" or "guest," and lith meaning "rock" or "stone," xenoliths are fragments of rock, formed elsewhere, that become entrained in magma. Xenoliths may have come from the sides of a magma chamber, the walls of an erupting lava conduit, or the bedrock underlying a lava flow. These "foreign" inclusions differ distinctly from their host lava (fig. 29; see also fig. 53).

Kuntz et al. (2007) described three flows as having notable xenoliths: Serrate (**Qcfa8**), Devils Orchard (**Qcfa9**), and Highway (**Qcfa10**). Xenoliths are a "point of geologic interest" highlighted by Niles et al. (2011).





Figure 29. Photographs of xenolith. Kuntz et al. (2007) noted xenoliths in the Highway flow (Qcfa10). This xenolith is estimated to have come from 42 km (26 mi) below the surface, ultimately falling onto the surface of the North Crater flow from a volcanic neck (Doug Owen, Craters of the Moon National Monument and Preserve, park geologist, retired, telephone communication, 22 June 2018). The North Crater eruption brought up lower crustal materials, such as this boulder, as well as Challis Volcanic Group rocks (see fig. 52). NPS photographs from Owen (2011b).

Lava Tubes

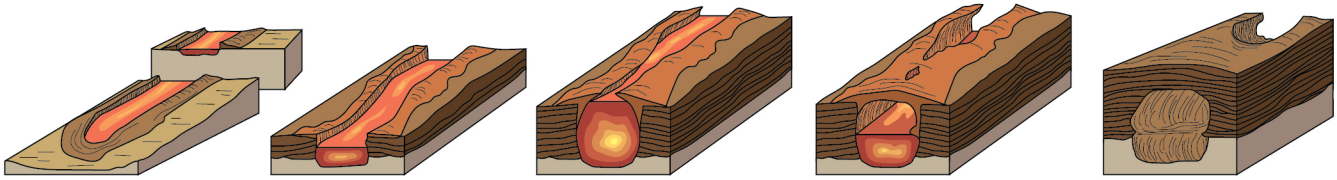
Lava tubes are the principal means by which pahoehoe flows spread widely and thinly during an eruption (Larson 1990). The majority of lava flows in the park had a tube-fed component (Kuntz et al. 2007). The following flows were distributed by notable lava-tube systems:

- Minidoka pahoehoe basalt flows (**Qcfb4**) spread as far as 35 km (22 mi) southwest from an obscure, lava-filled vent complex about 3 km (2 mi) east of New Butte;
- basaltic pahoehoe flows and near-vent pyroclastic deposits of Monument Butte lava field (**Qsbb9**) spread for 3 km (2 mi) from a vent atop a broad summit dome;
- basaltic pahoehoe flows and pyroclastic deposits of Bear Den Butte lava field (**Qsbb2**) traveled for 5 km (3 mi) in a channel–lava-tube system, which led southwest from the distal part of a lava pond (see "Lava Ponds/Lakes");
- basaltic pahoehoe flows and near-vent pyroclastic deposits of Horse Butte lava field (**Qsbb25**), between the Craters of the Moon and Wapi lava fields, were deposited via several lava-tube systems with the most prominent being the Bear Trap system that extends for a distance of about 35 km (22 mi); and
- basaltic, near-vent and proximal, medial, and distal pahoehoe lava flows of the Wapi Park lava field (**Qwfb15**), which spread about 13 km (8 mi) from where the flows of the Wapi Park lava field emerge from beneath the Wapi lava field.

Lava tubes form by the crusting over of lava channels (fig. 30). When the supply of lava stops at the end of an eruption or where lava is diverted elsewhere, lava in the lava tube drains downslope and leaves empty conduits beneath the surface, forming caves (fig. 31). The flows in the "Cave Area" of the park formed during the eruption of Blue Dragon Basalt (see "Types of Volcanic Rocks and Lava" and "Geologic History").

Five of the caves within the park—(1) Indian Tunnel (fig. 32), (2) Dewdrop, (3) Boy Scout, (4) Beauty, and (5) Buffalo—have been minimally developed for visitor access, though the cave interiors are wild and unimpaired. These caves have improved trails constructed to the entrances (four of them paved) and attract approximately 40,000 visitors annually (Owen 2011a). The park's website (https://www.nps.gov/crmo/planyourvisit/caves-trail.htm) provides information to visitors about these caves.

Lava tubes may be referred to as "tunnels of volcanic origin" (see cotm_geology.mxd); these include Indian



1. Lava flows from volcanic eruptions tend to become "channeled" into a few main streams.

2. The overflows of lava from these streams cool and solidify, creating stacked layers of lava around the flow.

3. After many hours or days, the lava melts downward into the ground giving the tube a taller, more narrow cross section.

4. A solid crust can form overhead and enclose the tube. The tube then insulates the flowing lava within, allowing it to flow great distances.

5. After the eruption subsides and the flows harden, these lava tubes become a cave, commonly with remnants of the ebbing lava flows preserved.

Figure 30. Graphic showing lava-tube formation.
The numbers and text describe a typical progression of events. In step 4, a crust may develop along the edges of a channel and merge like a zipper in the center. Alternatively, separate crustal plates may form, tear loose, and drift along until they fuse to one another and the channel sides. In a turbulent lava flow, splashing and overflow along the channel create levees that may arch over the channel and join. A crust may thicken via repeated overflows onto its surface and accretion of cooled lava on its underside. Lava can also erode downward, deepening the tube and leaving empty space above the flowing lava. Graphic by Trista Thornberry-Ehrlich (Colorado State University) after USGS graphic by Bruce Rogers.



Figure 31. Photograph of Buffalo Cave.
Housed in the Broken Top flow (Qcfa1), Buffalo Cave has multiple levels and six entrances. The multiple levels suggest that when the initial tube became clogged during an eruption, flowing lava created a new tube stacked above the clogged one (Niles et al. 2011). The height of the opening in the upper level shown in the photograph is about 1 m (4 ft). NPS photograph from Niles et al. (2011).



Figure 32. Photograph of Indian Tunnel entrance.
The 240-m- (800-ft-) long Indian Tunnel lava tube is accessible by a metal staircase and rock steps. In the foreground of the photograph, note the breakdown (pile of rubble), which collapsed from the cave ceiling as a result of the formation of the skylight. NPS photograph available at https://www.nps.gov/crmo/learn/photosmultimedia/photogallery.htm (accessed 19 July 2018).

Tunnel and Tom Thumb Tunnel in the Blue Dragon flow. The cotm_geology.mxd data set shows 21 caves of volcanic origin as volcanic point features. Because the National Park Service considers caves as sensitive features, these particular volcanic point features in the GRI GIS data may only be viewed on an NPS computer connected to the NPS network.

Lava Tube Features

The following features occur in the lava tubes at the park. These features were identified by Taylor-Edmonston (1994), Quick (2004), Ruffini and McHenry (2010), and Owen and Melander (2014). In contrast to true speleothems in caves which grow rather slowly, lava formations grow rapidly by the flowing, dripping, splashing, accreting, and pulling apart of molten or partially consolidated lava, and by the interaction of associated volcanic gases (Hill and Forti 1997).

Collapse Features

Although many of the lava tubes in the park have remained intact for 2,100 years, the ultimate fate of all lava tubes is to collapse (Owen publication date unknown) (fig. 33). Long after an eruption, frost wedging (prying apart of materials via the expansion of water upon freezing in cracks, pores, or along bedding planes), mechanical weathering by plant roots, or a major earthquake are the most likely agents that lead to the collapse of the lava tubes at the park (Owen publication date unknown). At the park, frost wedging breaks down the surfaces of lava flows as well cave roofs. Geohazards associated with cave collapse are discussed in "Slope and Rock Stability."

While still hot and plastic, a cave roof may sag, creating a bowl-like depression at the surface. Once a roof has had time to cool and harden, however, cracks may form as a result of contraction, causing the roof to weaken and collapse into a pile of rubble, referred to as "breakdown." If lava is still flowing within the lava tube, the breakdown may then be transported some



Figure 33. Photograph of collapsed lava tube. As shown in the figure, a lava tube in the Broken Top flow (Qcfa1) has collapsed, creating an accumulation of breakdown. NPS photograph from Owen (2011b).



Figure 34. Photograph of arch. This arch in the Craters of the Moon lava field formed as a result of lava tube collapse; the arch is a remnant of a lava tube's ceiling. NPS photograph available at https://www.nps.gov/crmo/learn/photosmultimedia/photogallery.htm (accessed 18 July 2018).

distance along the cave floor. As a result of roof collapse and the accumulation of breakdown, lava tubes do not extend the length of the original lava-tube conduit. For example, one of the longest caves in the area, Bear Trap Cave, which lies between the Craters of the Moon and Kings Bowl lava fields, is 16 km (10 mi) long, but is not continuously passable.

Collapse as a tube cools and contracts, or in response to some later event, creates skylights, which provide entry into a lava tube. Skylights appear as volcanic point features in the cotm_geology.mxd data set. Because skylights are considered entrances into caves, they are classified as a "sensitive locality" in the GRI GIS data and, therefore, only viewable on an NPS computer connected to the NPS network.

Natural bridges and natural arches (fig. 34) are found throughout the Craters of the Moon lava field. Forming as a result of lava tube collapse, a bridge or arch is a remnant of a lava tube's ceiling. The cotm_geology.mxd data set shows two natural arches in the Blue Dragon flows. Like skylights, these features are classified as a "sensitive locality" in the GRI GIS data. Niles et al. (2011) highlighted a small natural bridge as "points of geologic interest" along the Tree Molds trail in the park.

In sedimentary rocks, "bridges" and "arches" are distinguished from each other on the basis of their origin; specifically, bridges are remnants of stream-cut tunnels (see GRI reports about Arches National Park by Graham 2004 and Natural Bridges National Monument by Thornberry-Ehrlich 2004). No distinction based on origin is made for bridges and arches in the volcanic rocks of the Craters of the Moon lava field, however. For example, the "Bridge of Tears" at the edge of the Little Prairie flow was mapped as a "natural arch of volcanic origin" in the cotm_geology.mxd data set.

Floor Squeeze-Ups

Like pahoehoe at the surface, flowing lava within a lava tube can form a crust that becomes fractured as a result of shrinkage by cooling or distortion by movement of lava beneath it. The still-molten lava below the crust may get squeezed up onto the floor of the tube, creating floor squeeze-ups.

Flowstone

Flowstone—masses of solidified lava that mimic calcite flowstone found in limestone caves—forms where lava moves down-gradient in a tube.

High-Lava Marks

Like the high-water mark of a river at flood stage, high-lava marks on the walls of a lava tube record the high-stage position of lava flowing within a tube (fig. 35). Similarly, relatively wide "terraces" mark former "floodplains." Additionally, a series of "bathtub rings" on the walls of a lava tube mark where draining lava temporarily maintained a constant level.

Ice Formations

As snow melts in spring, runoff seeps through porous cave roofs. At night, the temperature drops and



Figure 35. Photograph of high-lava marks. Resembling "bathtub rings" and commonly referred to as such, horizontal lines on the walls of a lava tube were left by flowing lava during a period of relatively constant lava discharge. Note ball cap for scale. NPS photograph from Owen (2011b).

dripping water freezes into icicles that hang down from the cave ceiling (fig. 36). Because they occur in a cave setting, these icicles are sometimes referred to as "ice stalactites." "Ice stalagmites," which grow upwards from the cave floor, also occur. In most of the park's caves, the summer heat destroys ice formations, but in a few, ice remains all year (Taylor-Edmonston 1994).



Figure 36. Photograph of lavacicles and icicles. Lava stalactites, hanging down from the ceiling of a lava tube, are commonly called lavacicles because of their resemblance to icicles, whereas icicles, in cave environments, may be called ice stalactites because of their resemblance to that well-known cave form. This lava tube—Moonshine Cave—at the park has both lavacicles and icicles. Note the shorter lavacicles hanging from the cave roof and the longer icicles at the center of the photograph. The icicles are about 0.5 m (1.5 ft) long. NPS photograph from Owen (2011a, p. 10).

In Crystal Ice Cave, icicles are several feet across and tens of feet high (Doug Owen, Craters of the Moon National Monument and Preserve, park geologist, retired, telephone communication, 22 June 2018). Notably, Crystal Ice Cave is in the Great Rift, not a lava tube (see "Rift/Fissure Caves").

Lava Stalactites

Deposits hanging down from the ceiling of a lava tube—either called "lava stalactites" because of their resemblance to that well-known cave feature or "lavacicles" because of their resemblance to icicles (fig. 36)—can be conical, bulbous, cylindrical, or tear-drop shaped. Some lava stalactites resemble shark teeth, and others resemble soda straws. These features form as viscous lava drips or sags away from a ceiling or is forced through small cracks or holes during cooling (Hill and Forti 1997).

Linings

Linings are relatively thin shells of lava plastered against the inside surface of a lava tube (fig. 37). Where linings do not reach the ceiling of a tube, their upper surfaces may mark the upper limits of secondary flows. In cross section, multiple linings may look like the layers of a cut onion. Where the entire wall has melted to a depth of about 1 cm (0.4 in), the lining may slump or partially sag down the wall (Rogers and Mosch 1997a).



Figure 37. Photograph of lining. Shells of lava plastered against the inside of a lava tube are referred to as "linings." Some linings display features that were apparently remelted in the intense heat of a lava tube. The width of the area shown in the photograph is about 0.6 m (2 ft). NPS photograph from Owen and Melander (2014, figure 14).

Remelt Features

As lava tubes form, the gases within them can be hotter than the lava coursing over the floor or forming the walls (Rogers and Mosch 1997b). For example, gas temperatures of 1,150°C–1,555°C (2,102°F–2,831°F) have been measured in the tubes of Hawaii (Swanson 1973). Interior surfaces melt under these conditions, creating interesting features as a result of flowing (fig. 38), dripping, collapsing, sagging, or pulling apart of molten or partially consolidated lava, and by the interaction of associated gases in the lava tube (Hill and Forti 1997).



Figure 38. Photograph of remelt feature. High temperatures in a lava tube can cause lava to melt and flow down a wall. This remelt feature is about 5 cm (2 in) wide and18 cm (7 in) long. Its submetallic appearance is characteristic of remelt features. NPS photograph from Owen (2011b).

Speleothems

Speleothems are mineral deposits formed in caves (fig. 39). Floor mounds and mineral coatings on ceilings and walls are examples of speleothems in the lava tubes at the park.

The floor mounds are composed of sulfate, carbonate, and bicarbonate minerals such as thenardite, burkeite, mirabilite, and trona. Floor mounds are probably biological in origin, created by microbial processes (Ruffini and McHenry 2010).

The mineral coatings consist of white and orange encrustations and altered surfaces with metallic luster. The white and orange coatings are mostly calcite, whereas the main constituents of the metallic coatings are hematite and silica. The calcite coatings are precipitates (products of the interaction between groundwater and basalt). Olivine, which is abundant in the unaltered basalt in lava tubes, is absent in the alteration surfaces with metallic luster; olivine was replaced by hematite and silica. This process likely occurred under hydrothermal conditions as the lava tube cooled (Ruffini and McHenry 2010).

Cave Resources

Most of caves in the park are lava tubes (see "Lava Tubes"), but at least six other types of cave occur in the park. Owen (2011a), WNS Working Group (2012), and Owen and Melander (2014) noted the following types:

Differential Weathering Caves

Differential weathering of agglutinated cinders created caves on some cinder cones (fig. 40); the deepest of these are about 3 m (10 ft).

Lava Blister Caves

Lava blisters that form from pockets of gas trapped beneath a congealing crust are commonly small, but produce caves that are den sites for animals.

Rift/Fissure Caves

The Great Rift has fissure caves. Many of these, such as Bear's Den waterhole (fig. 41) and Crystal Ice Cave, contain ice. Fissure caves may be roofed over by lava or spatter that was ejected from the eruptive fissure before the lava withdrew to greater depths. The cave also may be roofed over with material that has collapsed from the sides. The floors of fissure caves are mostly rubble, commonly poorly held together by ice. Though these caves can be sources of water, they are inherently dangerous because of their rubble-and-ice floors, which may be unsupported beneath.

Spatter Cones or Rootless Vent Caves

Spatter cones form when spatter is ejected short distances and accumulates immediately around a vent, forming short steep-sided cones (see "Spatter Cones and Spatter Ramparts"). The conduit(s) that fed the spatter cones can remain open after an eruption has ceased, and thus produce caves. Crystal Pit and Snow



Figure 39. Photograph of speleothems.
The white, yellow, and orange encrustations in Indian Tunnel are secondary mineralization that formed after the lava tube became a cave. NPS photograph available at https://www.nps.gov/crmo/learn/photosmultimedia/photogallery.htm (accessed 19 July 2018).



Figure 40. Photograph of differential weathering cave.
Differential weathering takes place at varying rates due to differences in the resistance and hardness of surface material: softer and weaker rocks are rapidly worn away; harder and more resistant rocks remain. This cave formed where poorly welded ash and cinders eroded from underneath layers of more resistant basalt. Note the park radio (sitting on the top) and trekking pole (leaning against the side) for scale. NPS photograph from Owen (2011b).



**Figure 41. Photograph of ice floor.
Bear's Den waterhole is a fissure cave associated with the Great Rift. Such caves commonly have ice floors as shown in this photograph. NPS photograph from Owen (2011b).**

Cone are good examples of this phenomenon. Rootless vents are similar to spatter cones except that they are tube-fed rather than fed directly by the eruptive fissure; rootless vents also can produce caves.

Talus Caves

Accumulations of talus (rock fragments, usually coarse and angular, lying at the base of a cliff or steep slope from which they have fallen) contain caves, for example, at the bottom of Big Craters.

Tumulus Caves

Tumuli (plural of tumulus) are created when the upward pressure of slow-moving, still-molten lava within a flow swells or pushes the overlying solidified crust upward. Commonly, tumuli have tension fractures that run down the axis. Once cooled, these fractures can become caves (fig. 42). Many contain breakdown (see "Collapse Features") or squeeze-ups (see "Squeeze-Ups and Squeeze-Outs"). The edges of highly inflated flow lobes and pressure plateaus also may have deep inflation clefts along their edges, which can form caves.



**Figure 42. Photograph of tumulus cave.
Tumuli commonly have tension fractures running down their axis. When a tumulus has drained and cooled, these fractures can become caves. This skylight, which is about 1 m (3 ft) across, provides an entrance to a cave that is roughly 2 m (7 ft) deep and has a length of 3 m (10 ft). NPS photograph from Owen (2011b).**

Paleontological Resources

The paleontological resources at the park include (1) Mississippian (approximately 330 million-year-old) fossils of the Copper Basin Group/Formation, (2) Late Pleistocene and Holocene (15,000–2,100-year-old) tree molds in lava flows, and (3) Late Pleistocene and Holocene packrat middens and animal remains in caves.

Depending on the investigation, the Mississippian rocks named for the exposures on the southern edge of the Copper Basin in Custer County, Idaho, have been mapped as a formation (e.g., Ross 1962) or a group (e.g., Paull et al. 1972). A formation is a fundamental rock-stratigraphic unit that is mappable, lithologically distinct from adjoining strata, and has definable upper and lower contacts. A group consists of two or more associated formations with significant features in common. The cotm_geology.mxd data set shows these

rocks as the Copper Basin Formation; crmo_geology.mxd data set shows them as the Copper Basin Group.

The Copper Basin Group has been divided into the Little Copper (**Mclc**) and Argosy Creek (**Mca**) Formations, which crop out in the park. The Little Copper Formation contains ammonoids and conodonts (Skipp and Kuntz 2009). The Argosy Creek Formation contains brachiopods and conodonts (Kuntz et al. 2007). In addition, some bedding planes of the argillite (weakly metamorphosed claystone) and siltite (more commonly referred to as "siltstone") of the Argosy Creek Formation, as described by Kuntz et al. (2007), have yielded the trace fossil *Helminthoida* (Kuntz et al. 1989c). A trace fossil preserves evidence of an organism's life, rather than the organism itself; those in the park are likely the burrows of a marine worm. The park's museum collection is thought to contain specimens of *Helminthoida* (Kenworthy et al. 2005).

The park's tree molds (impressions of trees, usually trunks but also branches, in solidified lava) are a trace fossil preserved in volcanic rock (fig. 43). They are rare because volcanic activity tends to destroy organic remains, which is a reason why most fossils worldwide are preserved in sedimentary, not igneous, rock. Tree molds form where flowing lava envelops trees, but the trees are not consumed by the heat or incinerated. Nevertheless, heated by the lava, the moisture content of these trees is released as steam, which accelerates cooling and allows time for the tree to form an impression in the molten material. Tree molds can be vertical (where the tree remained standing) or horizontal (where the tree fell). Surface details such as bark patterns are sometimes preserved, though these impressions generally do not enable identification of a species. If the lava flows are Pleistocene or Holocene in age, a taxonomic inference can possibly be made in an area with a low diversity of trees. In modern lava flows, where some of the original tree may not be fully incinerated, the species can be determined (Vince Santucci, NPS Geologic Resources Division, paleontologist, email communication, 17 July 2018).

At a scale of 1:24,000, the cotm_geology.mxd data set includes seven tree molds and one lava tree (discussed below) as volcanic point features. The crmo_geology.mxd, which consists of 1:100,000-scale mapping, does not include these smaller scale features. The tree mold and lava tree localities are identified as "sensitive" in the GRI GIS data and, thereby, only available on NPS computers connected to the NPS network.

Tree molds are a "point of geologic interest" highlighted by Niles et al. (2011). The Tree Molds Trail in the park leads visitors to the edge of the Blue Dragon flow where flowing lava once knocked down trees, charring the trunks and leaving impressions in the once-molten rock. In other places along the trail, the trees remained standing as the lava encased them, leaving vertical molds in the lava.

The deepest measured tree mold in the park is some 208 cm (82 in) deep; the widest tree molds are as much as 90 cm (35 in) across (Owen and Melander 2014). Investigators calculated the average diameter of 81 tree molds at Trench Mortar Flat to be 36.6 cm (14.4 in) (Bullard 1971). Of the lava flows mapped in the park, the Blue Dragon (**Qcfa2**) and Trench Mortar Flat (**Qcfa3**) flows have the most tree molds (Stearns 1928; Owen and Melander 2014).

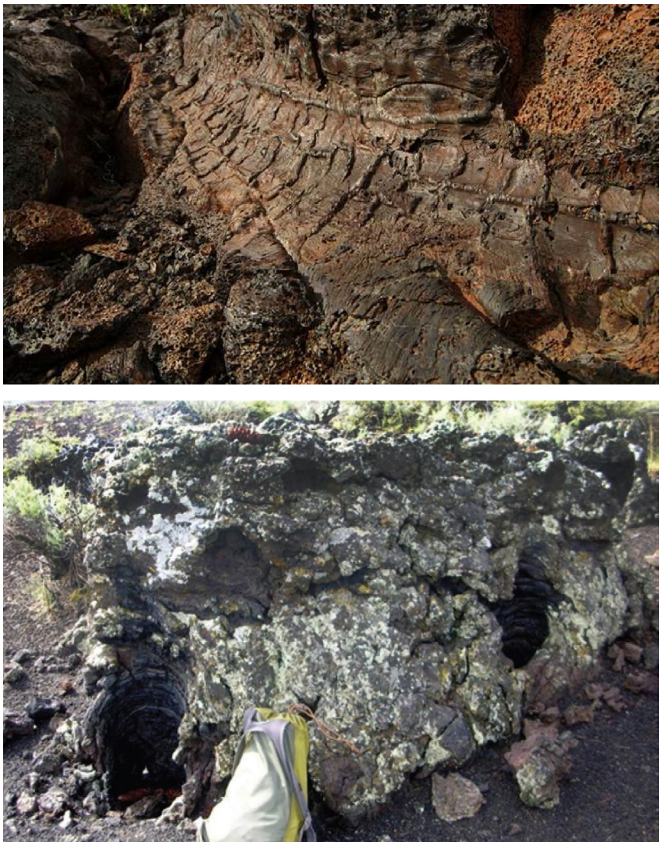


Figure 43. Photographs of tree molds. Horizontal (top photograph) and vertical (bottom photograph) tree molds are notable fossils at the park. Horizontal molds form where a tree falls onto the surface of a lava flow. Vertical molds form where a tree remains standing. In both cases, the tree began to burn, but released water and other vapors that sufficiently cooled the surrounding lava, leaving an imprint of the tree in the hardening basalt. Molds can preserve the outline and position of trunks, as well as limbs and root structures. Note the backpack for scale in the bottom photograph. NPS photographs [top] from Santucci et al. (2012) and [bottom] from Niles et al. (2011).

Carbonized wood has been found in some of the tree molds. This material was used for radiocarbon dating of the lava flows and was instrumental for determining the timing of eruptions in the Craters of the Moon, Kings Bowl, and Wapi lava fields (Kuntz et al 1982).

Another type of fossil at the park is a lava tree. These features, which rise above the surface of a lava flow by 0.3 to 1.5 m (1 to 5 ft), are typically formed from airborne lava spatter, which partially covers a tree, leaving behind a thin conical shell of lava with the impression of a tree trunk on the interior (John Apel, Craters of the Moon National Monument and Preserve, personal communication *in* Kenworthy et al. 2005, p. 16). Stearns (1928) was the first to document lava trees at Craters of the Moon. The cotm_geology.mxd data set includes a lava tree locality in the Trench Mortar Flat flow. Like other fossil resources, this lava tree is classified as a "sensitive locality" in the GRI GIS data and, therefore, only viewable on an NPS computer connected to the NPS network.

Packrats (*Neotoma* spp.), also known as woodrats or trade rats, are noted for their collecting and gathering behavior, primarily for food, as well as den construction. Caves at the park contain packrat dens called "middens" (fig. 44), which are collections of plant material, food waste, coprolites (fossilized dung), bones, and other biological materials that document the environment within the builder's foraging range. Middens can be well-preserved in arid, protected settings such as caves and rock shelters. The middens at the park have yielded fossils, including the bones of rodents belonging to the subfamily Microtinae (e.g., voles, lemmings, and muskrats). Middens are important tools for reconstructing the paleoecology and climate of the Late Pleistocene and Holocene Epochs of western North America (Santucci et al. 2001).

Reports of bone material in the park's caves date back to the 1880s. Modern and ancient animals used the caves as shelters (Kenworthy et al. 2005). Remains include a grizzly bear (*Ursus arctos*) skull and femur, a bison (*Bison bison*) skull and horn, bighorn sheep (*Ovis canadensis*) horns and a skull, cattle bones (historic), and other unidentified mammal bones.

In addition to lava tubes, lava blister caves have accumulated a faunal record. The openings to lava blisters are generally small and drop to a floor that can be 2 m (8 ft) to 3 m (10 ft) or more below the surface. This creates an excellent trap for larger animals that fall in and cannot escape. Generally, the "trapped" animals are carnivores that most likely followed smaller prey, such as a rabbit or squirrel, into the cave. Carnivore remains found in these blister traps on the eastern Snake River Plain include the now-extinct noble marten (*Martes americana nobilis*), as well as other animals no longer found in the area such as bison, wolverine (*Gulo* sp.), and Canada lynx (*Lynx canadensis*) (Miller 1989; Owen and Melander 2014).



Figure 44. Photograph of packrat midden. Middens (dens) of packrats (Neotoma spp.) are collections of plant material, food waste, coprolite (fossilized dung), bone, and other biological materials. The middens in the caves of the park have yielded fossils, including the bones of rodents belonging to the subfamily Microtinae (e.g., voles, lemmings, and muskrats). Middens are important tools for reconstructing the paleoecology and climate of the Late Pleistocene and Holocene Epochs. This midden is about 4–5 m (12–15 ft) long. For scale, note the blue, D-cell flashlight at the lower right corner of the photograph. NPS photograph from Owen and Melander (2014, figure 26).

Loess, Soil, and Kipukas

Loess (windblown dust)—or the lack thereof—is a distinctive feature at the park. The dark, loess-free surfaces of the Craters of the Moon, Kings Bowl, and Wapi lava fields are easy to differentiate in satellite imagery (see fig. 13). They surround lighter colored, loess and soil covered kipukas, which appear as "holes" or "openings" in the lava flows.

The distribution of loess on the eastern Snake River Plain suggests that during glaciations, extensive, active alluvial surfaces, namely outwash plains (valley floors) were the main sources of loess (Scott 1982; Vaughan 2008). Outwash plains were covered by glacially ground-up, silt-sized sediment "washed out" beyond the terminus of a glacier and transported downvalley by meltwater streams. Loess was deflated (removed by wind), transported, and redeposited during glacial episodes, which were characterized by high wind speeds (Summerfield 1994). Probably owing to the abrupt

retreat of continental and alpine glaciers, widespread loess deposition essentially terminated at the end of the Pleistocene Epoch (about 11,700 years ago) (Kuntz et al. 2004). In the absence of a major source of loess, relatively little mineral material accumulated on the "predominantly Holocene" lava flows (Vaughan et al. 2011).

At a scale of 1:250,000, a map by Scott (1982) shows three units of loess within the park; all were deposited during the Pleistocene Epoch. Each is defined by thickness and continuity (i.e., the amount of bedrock exposed). None of these units cover the lava fields, which Scott (1982) mapped as primarily basalt, with some cinder deposits and areas of colluvium. Although work by Scott (1982) is not part of the GRI GIS data, Kuntz et al. (2007) referred to it repeatedly in reference to unconsolidated surficial deposits.

Loess is significant at the park for at least three reasons. First, it can serve as an informal, relative dating method used by field geologists in the absence of isotopic dating. Based on the amount of loess infilling and cover, geologists can estimate the relative ages of lava flows and associated landscapes. A clean, loess-free surface indicates a relatively 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 (for more details, see the GRI report about Capulin Volcano National Monument by KellerLynn 2015). Although isotopic dating was necessary to finally decipher the park's geologic history, based on map-unit descriptions, both Scott (1982) and Kuntz et al. (2007) applied this field method during mapping.

Second, loess plays a role in soil formation. Soils at the park have been classified, described, and mapped (see Kukachka 2010). In 2013, the National Park Service in collaboration with the Natural Resources Conservation Service updated the digital data associated with the soil survey at the park (see National Park Service 2013). Notably, soil formation on older (more than 13,900-year-old) lava flows is the result of substantial accumulation of windblown silt rather than weathered basalt (Vaughan 2008).

Soil formation, and by association loess, is important for agriculture. Idaho's famous potatoes grow in the fertile soils of the eastern Snake River Plain, which primarily developed in windblown loess. The connection between farmland and geology was recognized by Kuntz et al. (2007). For example, basaltic pahoehoe flows and pyroclastic deposits of the Vent 5074 lava field (**Qsbc2**) are smooth and covered by thin deposits of loess, some of which are farmed. Also, some areas are dry farmed for hay on basaltic pahoehoe flows and pyroclastic deposits of Bowl Crater lava field (**Qsbc12**), which are mantled by a thin (2 m [7 ft] or less) veneer of loess and eolian sand. Within the park, both of these map units are part of kipukas (discussed below) and not farmed.

A third significance of loess is that it comprises the parent material of the soil that now covers the kipukas in the park (fig. 45). From the Hawaiian term meaning "opening," a kipuka is an area surrounded by a lava flow. On the eastern Snake River Plain, kipukas formed where younger lava flowed around, but not over, higher areas. The higher-and-older areas may consist of lava or another type of rock, but at the park, all kipukas are underlain by basalt. The kipuka in the Wapi lava field, for example, consists of basaltic, near-vent pyroclastic deposits and proximal and medial pahoehoe lava flows of the Higgins lava field (**Qwfc3**) that is 289,000 ± 5,000 years old (dated by the K/Ar method; Kuntz et al. 2015). It is surrounded by younger lava of the Wapi lava field (**Qwfa1**), which has a radiocarbon age of 2,270 ± 50 years BP.

In Landsat imagery (fig. 13), kipukas appear as lighter colored islands surrounded by black and/or dark-gray lava flows. They are readily apparent in figure 1 and on the poster (sheet 2) in the pocket of this report. Five medium to large kipukas predominate on the landscape, though the park contains an estimated 500 more (National Park Service 2014). Kipukas are a "point of geologic interest" highlighted by Niles et al. (2011).

Presidential Proclamation 7373 (9 November 2000), "Boundary Enlargement of the Craters of the Moon National Monument," makes special reference to the scientific importance of kipukas. In addition, the park's foundation document (National Park Service 2014) identifies kipukas as a fundamental resource and value. Kipukas, which typically have better developed soils and vegetative cover than the surrounding lava (thanks to the deposition of loess), preserve isolated, largely undisturbed vegetation communities, which are key benchmarks for scientific study of long-term ecological change in sagebrush steppe ecosystems (National Park Service 2014). In many instances, the expanse of rugged lava surrounding kipukas has protected them from people, animals, and nonnative plants.

On a parkwide scale, plant growth and distribution seem to be controlled by the deposition of loess, though the physical and chemical properties of different lava flows may locally influence vegetation distribution (National Park Service and US Geological Survey 2000).



Figure 45. Photograph of kipukas.
Kipukas consist of older lava than the surrounding lava flow. Also, kipukas are generally higher than the surrounding lava. In this photograph, the surrounding lava flow is the Blue Dragon pahoehoe and a'a basalt-hawaiite flows (Qcfa2). The left kipuka (referred to as #58) covers 11 ha (28 ac), the center kipuka (#57) is 0.6 ha (1.5 ac), and the one at the lower right (#11) is 8.5 ha (28 ac). These kipukas are just north of Huddles Hole (Qsbc39). NPS photograph from Owen (2011b).

Eolian Features and Processes

At a scale of 1:100,000, no eolian (windblown) features were mapped within the park. East of the Wapi lava field (outside the park), however, Kuntz et al. (2015) mapped a substantial deposit of eolian sand (**Qes**; see GRI GIS data set crmo_geology.mxd). Interestingly, most of this sand was deposited during the Bonneville Flood about 14,500 years ago (Malde 1968; O'Connor 1993). The Bonneville Flood was a catastrophic flooding event during the last ice age; it involved massive amounts of water inundating parts of southern Idaho and eastern Washington along the course of the Snake River.

Mapping at a scale of 1:24,000 could accommodate eolian features such as sand sheets and dunes. Yet, because the cotm_geology.mxd data set covers the Craters of the Moon lava field—an area consisting of "predominantly Holocene" lava flows, which are loess free (see "Loess, Soil, and Kipukas")—this data set includes no eolian features.

Nevertheless, the park has notable "unmapped" eolian features (fig. 46). The influence of the wind on the park's landscape is shown in the shape of many of its cinder cones. Prevailing winds from the west and southwest caused a preponderance of downwind accumulation of cinders from many of the erupting vents. This resulted in an elongation of many cinder cones to the east or northeast, making them asymmetrical (Owen 2004). Moreover, on windy days, cinders saltate (bounce along the surface) and ripples of sediment migrate across the surfaces of cinder cones. Where fine material is removed from the surface, a residue of coarse particles, called "lag deposits," remain on many of the cinder cones. Also, many of the limber pines in the park are flagged (branches only growing on the downwind side of a trunk) via abrasion of terminal

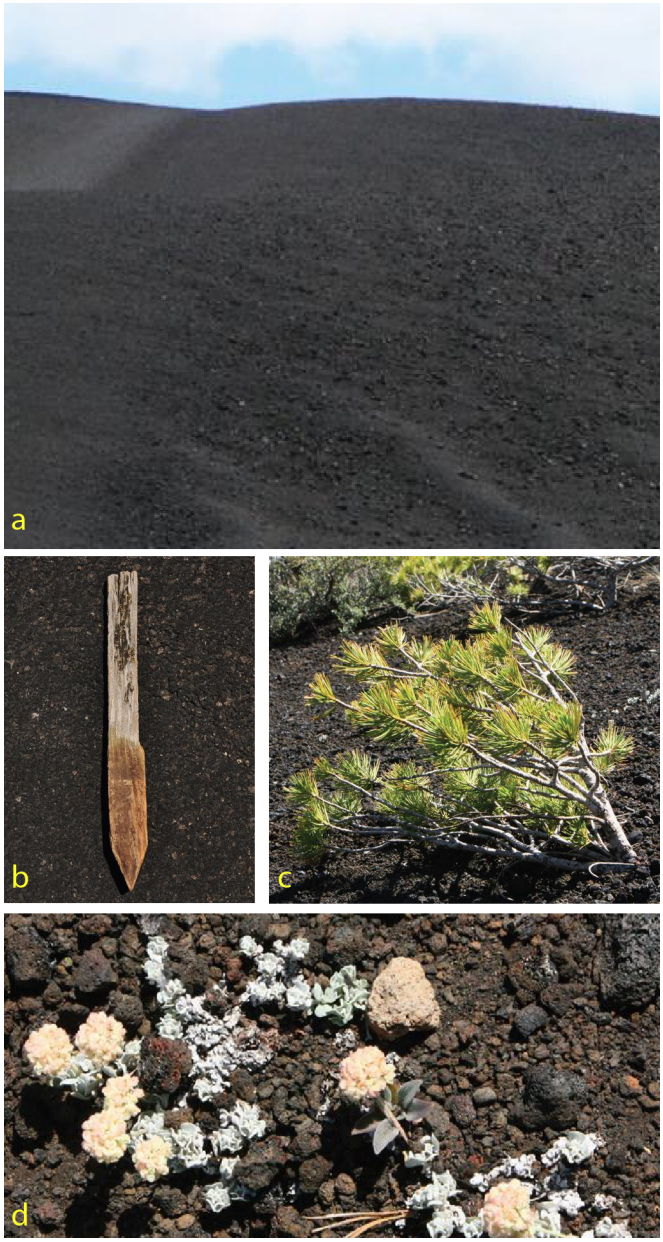


Figure 46. Photographs of windblown features. (a) As a result of a wind storm in June 2013, ripple marks formed in the cinders on Inferno Cone. This is a common occurrence at the park. (b) A "sandblasted" stake from Trench Mortar Flats attests to ongoing eolian processes such as abrasion from windblown sand and small volcanic fragments; the aboveground portion of the stake was exposed to the wind and slowly eroded over time, while the underground portion was protected from the wind. (c) This limber pine is "flagged" (branches only on the downwind side) as a result of wind abrasion. Also, the June 2013 wind storm partially buried it. (d) The June 2013 storm also partially buried a dwarf buckwheat plant. NPS photographs from Owen and Melander (2014, figure 22).

buds by windblown sediment in the summer and snow in the winter. Wind erosion also has exposed roots.

Loess also played a role in the preservation of fossils in lava tubes and other caves (see "Paleontological Resources"). Animal bones accumulated as cave inhabitants died naturally or when other animals were hunted and killed then drug into a cave. Windblown sediments buried the bones, helping in the preservation process (Owen and Melander 2014).

Faults

A fault is a fracture in rock along which movement has taken place. Movement along faults causes earthquakes (see "Earthquakes"). Faults are classified based on the motion of rocks on either side of the fault plane. The three primary types of faults are normal, reverse, and strike-slip (fig. 47).

The majority of the faults mapped in the Craters of the Moon area occur north of the park boundary in the Pioneer Mountains (see poster [sheet 2], in pocket). These include mostly thrust faults and normal faults, but also a left-lateral strike-slip fault. Only two instances of faulting are associated with the Late Pleistocene and Holocene lava flows in the park: (1) northwest-dipping normal faults that bound slump blocks on the north side of the North Crater cinder cone (**Qcca4**), and (2) northwest-trending fissures and normal faults with small displacement of 1 m (3 ft) or less on the Broken Top cinder cone (**Qcca1**).

The oldest rocks (**Mclc** and **Mca**) in the park provide evidence that this part of Idaho was tectonically active since at least the Late Devonian Period (about 370 million years ago). These rocks are exposed in the Pioneer and Copper Basin thrust faults, which represent Paleozoic and Mesozoic compression and thrusting associated with the Antler and Sevier Orogenies (mountain-building events; see "Geologic History"). Compression was followed by major extension and faulting in Tertiary time (Eocene through Miocene Epochs, 56 million–5 million years ago), which was accompanied by voluminous volcanism represented by the Challis Volcanic Group (**Tcv**; see "Geologic History"). Basin and Range faulting followed in Neogene time (Miocene and Pliocene Epochs, 23 million–3 million years ago) and continues today. The magnitude (M) 6.9 Borah Peak earthquake in 1983 (see "Earthquakes") attests to ongoing Basin and Range extension and faulting (Link and Janecke 1999).

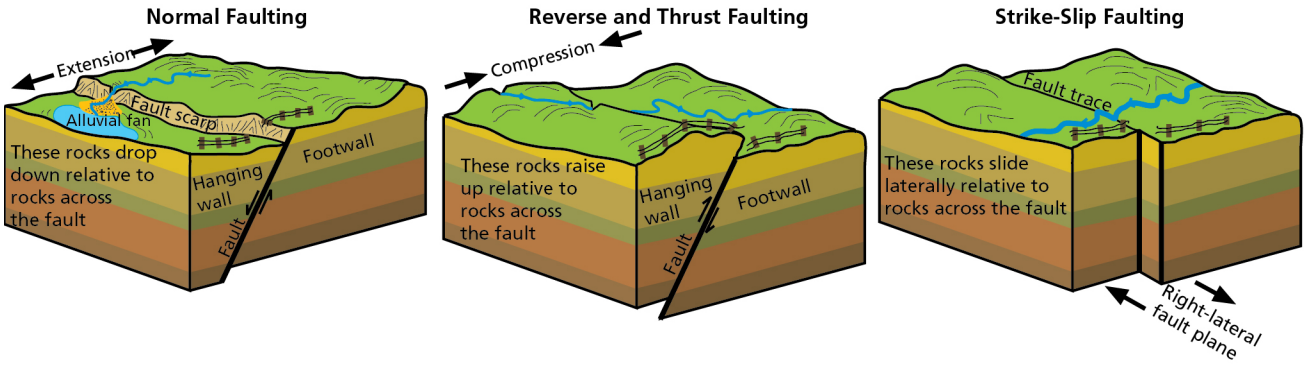


Figure 47. Graphic of fault types.
Movement occurs along a fault plane. Footwalls are below the fault plane, and hanging walls are above. In a normal fault, crustal extension (pulling apart) moves the hanging wall down relative to the footwall. In a reverse fault, crustal compression moves the hanging wall up relative to the footwall. A thrust fault is a type of reverse fault that has a dip angle of less than 45°. In a strike-slip fault, movement is horizontal. When movement across a strike-slip fault is to the right, it is a right-lateral strike-slip fault, as illustrated above. When movement is to the left, it is a left-lateral strike-slip fault. Basin and Range faulting is characteristically normal. The majority of the faults mapped in the Craters of the Moon area occur north of the park boundary in the Pioneer Mountains. These include mostly thrust faults and normal faults, but also a left-lateral strike-slip fault. Graphic by Trista Thornberry-Ehrlich (Colorado State University).

Geologic Resource Management Issues

Some geologic features, processes, or human activities may require management for human safety, protection of infrastructure, and preservation of natural and cultural resources. The NPS Geologic Resources Division provides technical and policy assistance for these issues.

The NPS Geologic Resources Division held a GRI scoping meeting for Craters of the Moon National Monument on 12–13 May 1999. The NPS Geologic Resources Division coordinated a follow-up conference call on 2 February 2017 to review geologic resource management issues and noteworthy geologic features in the park to ensure that the GRI report is up-to-date. During that meeting and conference call, participants identified the following resource management issues:

- Paleontological resource inventory, monitoring, and protection
- Visitor use impacts
- Cave resource management
- Waterhole inventory and ice lenses
- Slope and rock stability
- Climate change impacts to geologic resources
- Abandoned mineral lands
- Earthquakes
- Volcanic hazards
- Wind erosion
- Mining

The park's natural resource condition assessment (Erixson and Corrao 2012), foundation document (National Park Service 2014), and state of the park report (National Park Service 2016b) are primary sources of information for resource management. These publications were used in preparing this GRI report. In addition, a resource stewardship strategy workshop was held in 2017. That forthcoming report also will provide information for resource management at the park but, because of timing, was not used in preparing this GRI report.

Resource managers may find *Geological Monitoring* (Young and Norby 2009) useful for addressing geologic resource management issues. That publication is available online (http://go.nps.gov/geomonitoring) and provides guidance for monitoring vital signs—measurable parameters of the overall condition of natural resources. Each chapter in *Geological Monitoring* covers a different geologic resource and includes detailed recommendations for resource managers, suggested methods of monitoring, and case studies. As appropriate, various chapters are highlighted in the following discussions.

Park managers are encouraged to contact the Geologic Resources Division (http://go.nps.gov/geology) for assistance with resource inventories, assessments, and monitoring; impact mitigation, restoration, and adaptation; hazards risk management; law, policy, and guidance; resource management planning; data and information management; and outreach and youth programs. The Geologic Resources Division provides technical and policy support for geologic resource management issues in three emphasis areas: (1) geologic heritage, (2) active processes and hazards, and (3) energy and minerals management. Park staff can formally request assistance via https://irma.nps.gov/Star/.

The Geoscientists-in-the-Parks (GIP) and Mosaics in Science programs, administered by the Geologic Resources Division, are internship programs that place scientists (typically undergraduate students) in parks to complete geoscience-related projects that may address resource management issues. The park has sponsored nearly 30 GIP interns since 1998. Many of the products created by the program participants are available at http://go.nps.gov/gip_products. The programs' websites at http://go.nps.gov/gip and http://go.nps.gov/mosaics provide more information.

Paleontological Resource Inventory, Monitoring, and Protection

All paleontological resources are nonrenewable and subject to science-informed inventory, monitoring, protection, and interpretation as outlined by the 2009 Paleontological Resources Preservation Act (see Appendix B). As of July 2018, Department of the Interior regulations associated with the act were awaiting finalization.

A field-based paleontological resource survey can provide detailed, site-specific descriptions and resource management recommendations. Although that type of survey has not yet been completed at the park, a variety of servicewide inventories have been conducted on tree molds (Santucci et al. 2012), packrat middens (Tweet et al. 2012), and paleontological resources associated with caves (Santucci et al. 2001). In addition, Kenworthy et al. (2005) completed a paleontological resource summary for the Upper Columbia Basin Network, including Craters of the Moon National Monument and Preserve.

The park's primary paleontological resource is tree molds (see "Paleontological Resources"): 163 tree molds have been documented—141 during a survey in 2001–2002 and an additional 22 in 2012. The first systematic study was conducted by the park geologist in 2001–2002. Another systematic study (or inventory) was conducted in 2012, during which all previous sites were resurveyed, photographed, and assessed for condition (National Park Service 2016b).

During the 2001–2002 study, 11 tree molds were documented as showing damage by unknown causes, though human interference was suspected (National Park Service 2016b). The 2012 survey found 17 tree molds showing damage. The connection between these numbers and the sites they represent is unknown, but future monitoring may be able to clarify. A monitoring protocol has been prepared, though no sites have been checked to date (Doug Owen, Craters of the Moon National Monument and Preserve, park geologist, retired, telephone communication, 22 June 2018). Monitoring every 10 years is recommended (National Park Service 2016b), making monitoring due in the next five years. Monitoring the park's tree molds, and possibly lava trees, could be a project for a GIP intern.

Information about monitoring paleontological resources is provided by Santucci et al. (2009), which is chapter 8 in *Geological Monitoring* (Young and Norby 2009). Santucci et al. (2009) described the following five methods and vital signs for monitoring in situ paleontological resources: (1) erosion (geologic factors), (2) erosion (climatic factors), (3) catastrophic geohazards, (4) hydrology/bathymetry, and (5) human access/public use.

The NPS Geologic Resources Division is available to provide monument staff with policy and technical assistance regarding paleontological issues. The NPS Geologic Resources Division's Fossils and Paleontology website, https://www.nps.gov/subjects/fossils/index.htm, provides additional information.

Visitor Use Impacts

Geological features and processes at the park are generally considered to be in good condition with minimal threats from theft, damage, and vandalism (National Park Service 2016b). As a consequence of the remoteness and limited access to the expansion area, which comprises 88% of the land managed by the National Park Service, direct human impacts—such as rock collecting, which is illegal, and trampling—mostly take place in areas along trails and in proximity to roads, namely, the 11-km (7-mi) loop drive (National Park Service 2016b). Sites with notable impacts include Big Craters, Inferno Cone, areas adjacent to the North Crater Flow Trail, and along the Caves Trail (National Park Service 2014). Also, some lava rock exposures along US 93/26/20 have been illegally excavated for personal use, presumably landscaping.

Foot traffic causes erosion and compaction—notably on cinder cones, spatter cones, hornitos, and spatter ramparts—where foot traffic accelerates the downslope movement of unconsolidated or poorly consolidated material (National Park Service 2005). On some of the cones, more than 0.6 m (2 ft) of rock has been eroded off the rim by people climbing to the top and taking a look inside (Craters of the Moon National Monument 1993). Moreover, where unconsolidated volcanic material is exposed to sunlight, the surface typically becomes darker, so pathways compacted by foot traffic are noticeable on the landscape as lighter-colored areas for many decades (Erixson and Corrao 2012).

Park managers have implemented a stay-on-the-trail program with literature and signs that remind visitors to tread lightly and informing them of the damage they can do to the surrounding rocks by going off trail (National Park Service and US Geological Survey 2000). During ranger-led walks and talks, visitors receive resource protection messages; all visitors passing through the entrance station receive a handout about staying on the trails.

Resource managers have experimented with various methods to keep people on trails such as buck-and-rail fencing to delineate the edges of trails and cairns with posts and reflective tape to mark trails across rocky areas. Furthermore, curbs line almost all of the loop drive and spur roads to discourage vehicles from leaving the pavement. Signs along the roadway inform visitors that driving off road is prohibited. Bicycles are not permitted on any of the trails. In the past, a trail for cross-country skiing was groomed on the side of Inferno Cone, which resulted in a visible compaction scar. Grooming for cross-country skiing is now limited to the roadways (National Park Service and US Geological Survey 2000).

With respect to rock collecting, which is prohibited in NPS areas, potential targets include lava stalactites, volcanic bombs, Blue Dragon Basalt, and multicolored cinders. Park managers at Craters of the Moon National Monument and Preserve may find the experience at other parks useful in addressing resource theft; for example, Petrified Forest National Park's history is replete with programs aimed at minimizing the pilfering of petrified wood by souvenir collectors (Monkevich et al. 1994; Roggenbuck et al. 1997; see GRI report about Petrified Forest National Park by KellerLynn 2010).

The park's foundation document (National Park Service 2014) highlighted the Kings Bowl area of the preserve because it contains significant geologic features, including Crystal Ice Cave, Kings Bowl, and South Grotto. In addition to potential safety hazards posed by entry into fissure caves, resources in the King Bowl area have been degraded by all-terrain vehicle (ATV) use, which is not permitted, but trespass occurs (GRI conference call, 2 February 2017), and vandalism to signs and interpretive exhibits (National Park Service 2014). These public safety and resource threats are compounded by distance from NPS administrative facilities; a minimum four-hour round trip is required to reach Kings Bowl from park headquarters.

To improve protection and management of Crystal Ice Cave and the Kings Bowl area, a development concept plan is needed (National Park Service 2014). Developing such as plan requires that park managers address two high-priority data needs: (1) GIS data on the key geologic features in the Kings Bowl lava field, and (2) visitor-use data for the Kings Bowl area. The GRI GIS data provides a geologic map (scale 1:100,000) of the Kings Bowl area. Also, Covington (1977) produced a 1:48,000-scale preliminary geologic map of the Wapi and Kings Bowl lava fields. Park managers need to determine whether existing maps and/or data are adequate for resource management, and if not, identify the scale and type of map needed. This could be done as part of a proposal submitted to the GIP or Mosaics in Science programs, which the Geologic Resources Division administers (see http://go.nps.gov/gip and http://go.nps.gov/mosaics). Notably, the GRI GIS data for Capulin Volcano National Monument could serve as a model of mapping by a GIP intern; Richman (2010; scale 1:24,000) included the following volcanic features at Capulin Volcano: 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 GRI report about Capulin Volcano National Monument by KellerLynn 2015). With respect to visitor-use data, determining the frequency of day-use visitors through the use of traffic counters and active patrols, in cooperation with the Bureau of Land Management, would help to assess noncompliance and illegal activities as well as protect resources.

Appendix B of the park's foundation document (National Park Service 2014) lists other "opportunities" for protecting geologic features and processes at the park.

Cave Resource Management

The park contains outstanding cave resources (see "Lava Tubes" and "Cave Resources"). Completing a new cave management plan is a critical management action (National Park Service 2016b). The existing plan was completed in 1993, and, thereby, does not cover the expansion area. In particular, the Kings Bowl area is known to contain significant cave resources, including Crystal Ice Cave and South Grotto, which need protection through cave management planning.

Prior to being transferred to the National Park Service as a result of the 2000 expansion, Crystal Ice Cave was operated briefly as a commercial cave under a BLM lease in the 1970s. Since 2011, the cave has been officially closed to visitor use; however, staff observations suggest illegal access.

A new cave management plan would guide protection of cave resources, bat hibernacula, and archeological sites associated with caves, as well as serve as a document for resource–management decision making. A cave management plan can address which caves will be managed for visitor access and which caves will be managed without visitor access. The NPS Geologic Resources Division can facilitate the development of such a plan. Park staff can contact the division (http://go.nps.gov/geology) or formally request assistance via https://irma.nps.gov/Star/.

Ongoing resource management of cave features requires an accurate inventory and reporting to identify human safety hazards (see "Slope and Rock Stability"), habitat for bats and other animals, and opportunities for interpretation. Statistics compiled by the NPS Cave and Karst Program lists 344 caves in the park (342 are "volcanic" and two are talus), whereas the park's database includes 495 caves documented within the park. Thus, resolving discrepancies in the number and location of caves in the park is needed. Collaboration among park staff and Geologic Resources Division staff will likely be required.

Of the 495 caves documented in the park's cave inventory database, 92% have basic information such as location in GIS, cave size, entrances, hazards, and notable resources such as cave features. The design of the database allows for efficient entry of new cave locations (Quick 2004).

In 1984, only 53 caves were known, but these caves received a thorough inventory by Jex (1984), which classified caves according to hazardous conditions, the skills required for exploration, and their archeological, biological, and geological contents. That survey also noted the type and number of entrances, lengths of

passages, cave patterns and directional trends, vertical relief, and the presence of water.

Because much of the expansion area has not been explored for caves, the potential for discovery is great. In 2008, 12 previously undocumented caves were discovered as a result of a cave inventory project conducted by a GIP intern (Kohler 2008). Moreover, another GIP intern surveyed hundreds of miles of cave passage—mostly within the BLM monument as well as in the lava tubes at El Malpais National Monument, New Mexico—during the summers of 2012 and 2013 (Peinado 2013). These findings indicate the value of systematic inventorying and documentation.

A monitoring program can follow a systematic inventory, which is necessary to identify the resources to be monitored and the potential impacts to them. In *Geological Monitoring* (Young and Norby 2009), the chapter about caves and associated landscapes (Toomey 2009) described methods for inventorying and monitoring cave-related vital signs, including (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. This list of vital signs can serve as a guide to what might be monitored at the park, depending on resources needing management, potential and actual threats, budget, and availability of experienced assistance.

Bat Population

Significantly, the park's existing inventory database does not contain information about the cave-dwelling bat population. Such an inventory, including distribution, seasonal use, and hibernacula, is a high priority management need (National Park Service 2014). The importance of having information about the cave-dwelling bat population in the existing inventory database is prompted by the imminent threat of white-nose syndrome (WNS)—a fatal disease caused by the fungus *Pseudogymnoascus destructans* (see https://www.nps.gov/subjects/bats/white-nose-syndrome.htm). Notably, a five-year baseline study of hibernating bats at the park (discussed below) concluded that the park's caves are suitable for the growth of *Pseudogymnoascus destructans*. The park's caves were ranked along with all Idaho caves and assigned priority for bat swabbing and/or sediment testing for the actual presence of WNS in 2018 (Todd Stefanic, Craters of the Moon National Monument and Preserve, wildlife biologist, written communication, 14 June 2018).

In 2012, park staff formed a WNS Working Group and completed a response plan to reduce the chances of the human-assisted spread of the disease (WNS Working Group 2012). The park's biologist also serves on the state WNS planning team (Todd Stefanic, Craters of the Moon National Monument and Preserve, wildlife biologist, written communication, 14 June 2018).

Park staff completed a five-year baseline study of hibernating bats in 2017 and found that 50% of caves deemed suitable for hibernation are used by bats in the winter in at least one out of five years. At least six species of bats hibernate in the park's caves. Of these, 75% are Townsend's big-eared bats (*Corynorhinus townsendii*), which before the study were thought to be rare in the park. The western small-footed bat (*Myotis ciliolabrum*) is the second most common. Although sample size is too small for producing reliable numbers across the entire park, results suggest that the park may be home to an estimated 6,000 hibernating bats. Hibernacula surveys also led to the discovery of additional maternity colony and day roosting sites; the park has 13 known or suspected maternity colonies. Moreover, the park may be regionally significant for Townsend's big-eared bat maternity colonies and may be more important for maternity sites than hibernacula (Todd Stefanic, Craters of the Moon National Monument and Preserve, wildlife biologist, written communication, 14 June 2018).

Stewardship activities and accomplishments by park staff and partners include the maintenance of the park's cave resource inventory and surveying caves for bat populations (fig. 48). Bats are one of the vital signs selected for long-term monitoring by the Upper Columbia Basin Network. A monitoring protocol documenting methods and data management strategies is completed, and the plan is currently underway. This protocol and plan will ensure that bat monitoring will persist into the future and provide resource management staff with the information necessary to better manage cave resources (National Park Service 2016b).



Figure 48. Photograph of bat survey.
Winter surveys of lava tubes in the park began in 2012 in an effort to establish baseline trends prior to the anticipated arrival of the exotic fungal disease white-nose syndrome, which has wiped out many bat populations in eastern North American since 2007. Note the long icicle hanging from the cave roof. NPS photograph from National Park Service (2016b, p. 12).

Waterhole Inventory and Ice Lenses

Ruffini and Edie (2010) completed an inventory of 21 waterholes in the park. Most waterholes are associated with ice and meltwater in caves (see "Lava Tube Features"). Waterholes exist in caves due to the optimal conditions provided by trapping cold air in winter and the accumulation of significant amounts of ice that very slowly melt over the course of the summer. Waterholes existing outside of caves are almost all shielded from direct sunlight throughout the day by either a large boulder or pile of rocks, thereby reducing direct solar heating and evaporation of the water and assisting the persistence of ice beneath the liquid water. With the exception of one waterhole that had a water temperature of 4°C (39.2°F), which was probably caused by prolonged sun exposure, every waterhole had a recorded water temperature at or below 1.6°C (34.9°F). The inventory also studied two thermal springs, but temperatures from these springs are not reflected in the aforementioned numbers.

During the 2010 waterhole inventory, six of the historically documented waterholes were dry. All of the dry waterholes occurred as surface waterholes and not as pools in caves. Many of these dry waterholes were shown on the 1957 topographic map, but their exclusion on later maps suggests that they may have dried up long ago.

Nearly every waterhole had evidence of modern and/or historic human use, wildlife use, or both. Rusted tin cans and broken glass were found at many of the sites, as well as diffuse trails and rock cairns marking their locations. Animal bones, middens, and scat were common evidence of wildlife use. Additionally, sightings of squirrels, chipmunks, and birds at waterholes were common (Ruffini and Edie 2010).

Groundwater is generally 300 m (1,000 ft) below the surface of the lava flows in the park, but waterholes perched over ice lenses are present in some places. Ice lenses are the only practical mechanism to allow a water table to be perched in the lava fields tens of meters (hundreds of feet) above the saturated zone of the aquifer (Ruffini and Edie 2010). Surface water is scarce in the park and thus the presence of ice lenses and associated waterholes is critical to plant and animal species. Despite their ecological importance, little information is known about the ice lenses in the park's lava flows (National Park Service and US Geological Survey 2000).

Slope and Rock Stability

Slope movements are the downslope transfer of soil, regolith, and/or rock under the influence of gravity. Soil creep, rockfall, debris flows, and avalanches are common types of slope movements. As mentioned in "Visitor Use Impacts," foot traffic on cinder cones and other volcanic features accelerates the downslope movement of cinders and other loose volcanic material, causing unnatural scarring. Additionally, snow avalanches have occurred in the north part of the park. During winter 2016–2017, an avalanche flowed down a slope in the Little Cottonwood Creek drainage, removing trees and transporting debris (Linda Manning, Craters of the Moon National Monument and Preserve, chief of Integrated Resource Management, written communication, 4 June 2018). The primary geohazard (geologic condition or phenomenon—natural or brought about by human activity—that represents a threat to human life, welfare, or property) in the park, however, is rockfall from cave roofs. This safety issue has gone largely unaddressed (Doug Owen, Craters of the Moon National Monument and Preserve, park geologist, retired, telephone communication, 22 June 2018).

As discussed in "Collapse Features," large accumulations of angular rock debris in lava tubes are characteristic of environments with active freeze-thaw cycles (National Park Service and US Geological Survey 2000). Freeze-thaw is concentrated at skylights or cave entrances and is a perennial safety concern because it produces loose rocks that fall under the influence of gravity. Frost wedging also can cause rockfall or ceiling collapse within lava tubes, though this is probably less frequent than near entrances (National Park Service and US Geological Survey 2000).

The inspection and monitoring of cave geohazards, namely rockfall, would be a particular component of a cave management plan (see "Cave Resource Management"). In 1988, cave specialists identified the fragility of the caves and cave features, the danger they might pose to visitors, and the type of protection needed from the National Park Service (Blakesley and Wright 1988). A 2000 trip report prepared by GRD staff member Phil Cloues provides a reminder of the ongoing instability of lava tubes, particularly at cave entrances and around skylights (Geologic Resources Division 2000). Cave monitoring and inspection for potential hazards is a necessary piece of a new cave management plan.

The following references provide background information, suggested vital signs, and resources for assessing and documenting slope movements:

- Wieczorek and Snyder (2009)—the chapter in *Geological Monitoring* about slope movements
- US Geological Survey (USGS) publication *The Landslide Handbook—A Guide to Understanding Landslides* (Highland and Bobrowsky 2008)
- USGS landslides website (http://landslides.usgs.gov/)
- NPS Geologic Resources Division Geohazards website (http://go.nps.gov/geohazards)
- NPS Geologic Resources Division Slope Movement Monitoring website (http://go.nps.gov/monitor_slopes)
- If funding permits, resource managers could consider obtaining quantitative information to assess the frequency and magnitude of rockfall (and other slope movements) in high visitation areas. A photomonitoring program is one possibility. The GIP program is an option to support such a project. The NPS Geologic Resources Division Photogrammetry website (http://go.nps.gov/grd_photogrammetry) provides examples of how photographic techniques support structural analysis of rockfall areas.

Climate Change Impacts to Geologic Resources

Ongoing and future climate change will likely affect all aspects of park management, including natural and cultural resource protection, park operations, and visitor experience (National Park Service 2016b). Water supply, including the existing water-supply well, is an ongoing problem at the park and will likely be exacerbated by climate change (GRI conference call, 2 February 2017). Predicted climate change impacts to affect the park include the following, reported in Wagner et al. (2003), Monahan and Fischelli (2014), Mote et al. (2014), and National Park Service (2014):

- higher temperatures, in particular, the minimum temperature of the coldest month;
- regional aridification with increased evapotranspiration negating the effects of potential increased summer precipitation;
- reduced snowpack;
- changes in the timing of streamflow related to changing snowmelt; and
- reduced availability of water for many competing demands.

With respect to geologic features and processes, climate change is anticipated to impact groundwater recharge, streamflow, waterholes, ice lenses within the lava fields, and ice caves. Data collected during the waterhole inventory (Ruffini and Edie 2010) provide a baseline to monitor future changes to the waterholes, including ice level (see "Waterhole Inventory and Ice Lenses"). Waterholes are a "point of geologic interest"

highlighted by Niles et al. (2011). The GRI GIS data set cotm_geology.mxd includes three ice caves as geologic point features.

Effective planning and management related to climate change must be grounded in an understanding of past dynamics, and the waterhole inventory provides an example of the type of pertinent data gathering needed. The realization, however, that future conditions may shift beyond the historical range of variability is important. In fact, recent climatic conditions are already shifting beyond the historical range of variability; for example, Monahan and Fischelli (2014) found an "extreme" (exceeding 95% of the historical range) in the minimum temperature of the coldest month, which is getting warmer. Additionally, climate change will manifest itself not only as shifts in mean conditions but also as changes in climate variability such as intense storms and flooding (Monahan and Fischelli 2014).

At present, no formal planning for climate change is taking place at the park (GRI conference call, 2 February 2017), but Craters of the Moon National Monument and Preserve is a "climate friendly park" with an action plan for reducing greenhouse gas emissions and creating interpretive materials for communicating with local communities and park visitors (National Park Service 2010).

The state of the park report (National park Service 2016b) proposed collaborating with the National Oceanic and Atmospheric Administration (NOAA) on climate change monitoring as part of the nationwide Climate Reference Network, a network of identically equipped climate monitoring sites intended to operate for 50 years and provide highly accurate and reliable climate data. Other suggestions for climate change planning include the following:

- Characterize park exposure to recent climate change in a vulnerability assessment.
- Develop plausible and divergent futures for use in a climate change scenario planning workshop.
- Synthesize desired future conditions (i.e., reference conditions) for use in a resource stewardship strategy or other NPS management plan.
- The NPS Climate Change Response Program (see https://www.nps.gov/orgs/ccrp/index.htm) and "Additional References" in this report provide more information about climate change planning in the National Park Service.

Abandoned Mineral Lands

Abandoned mineral lands (AML) are lands, waters, and surrounding watersheds that contain facilities, structures, improvements, and disturbances associated with past mineral exploration, extraction, processing, and transportation, including oil and gas features and operations, for which the National Park Service takes action under various authorities to mitigate, reclaim, or restore in order to reduce hazards and impacts to resources and provide for visitor and staff safety. The NPS AML website, http://go.nps.gov/aml, provides further information.

The Martin Mine, which is located in the Little Cottonwood drainage, is the only mine on park land known to have produced commodities, including copper, gold, lead, silver, and zinc. The Martin Mine property remained a private inholding within the monument boundary until 1967. At that time, the Craters of the Moon Natural History Association purchased the land and relinquished the mining claim to the National Park Service. Past mining-related disturbances associated with the Martin Mine included four mine shafts, two buildings, several access roads, the foundation of a mill, and four small waste-rock dumps composed primarily of hydrothermally altered granite and limestone. All four of the waste-rock dumps were located within 45 m (150 ft) of the active stream channel. The four shafts and two buildings were closed or removed in the early 1980s. The National Park Service and the Bureau of Land Management cooperated to complete reclamation of the mine site in 1994 (Steensen et al. 1995).

Research for this GRI report found three sources of information about past mining at the park. First, the cotm_geology.mxd data set shows 30 mine point features (prospects, mines, and borrow pits), 14 of which are within the park. Second, the NPS AML database and Burghardt et al. (2014) record that the park contains 53 AML features at five sites; none of these features or sites requires mitigation. Third, the Idaho Geological Survey (IGS) maintains a mine and minerals database with an associated online map viewer (http://www.idahogeology.org/webmap/?show=mines). That database includes four sites within the park, including three mines and one unnamed prospect. The mine at the Wapi flow is distinctive in that it is not associated with past mining in the Pioneer Mountains or along US 93/26/20 in the park (see "Mining").

Comparison of these three sources of information reveals discrepancies in the number and location of sites. Ongoing resource management of AML features requires an accurate inventory and reporting to identify human safety hazards, contamination issues, habitat for bats and other animals, and opportunities for interpretation as cultural resources. Thus, resolving discrepancies in the number and location of AML features in the park is needed. Collaboration among park, Geologic Resources Division, and IGS staff members will likely be required.

Earthquakes

The Great Rift and other volcanic rifts that cut across the eastern Snake River Plain are predominantly parallel to Basin and Range faults north and south of the plain (see fig. 5). The Basin and Range region surrounding the plain is being stretched by extensional forces characterized by normal faults along which basins drop down and mountain ranges rise (see fig. 6). These faults are capable of magnitude 7 or greater earthquakes. They have recurrence intervals of thousands to tens of thousands of years. The magnitude (M) 6.9 Borah Peak earthquake, which took place in the Lost River Range in 1983 (fig. 49), is indicative of ongoing extension.

In contrast to the surrounding Basin and Range province, the eastern Snake River Plain is aseismic (seismically quiet). Crustal extension is probably being accommodated by the intrusion of dikes on the plain, rather than normal faulting. In addition, the alternating sequence of basalt and sediment that makes up the eastern Snake River Plain dissipates seismic energy to a greater extent than uniform basalt rock. As seismic waves pass through alternating layers of hard basalt and loosely consolidated (soft) sediments, their seismic energy is scattered and dampened. This results in earthquake ground motions that are 15%–25% lower than they would be in uniform basalt rock (Payne 2003).

The USGS Quaternary faults database/viewer (https://earthquake.usgs.gov/hazards/qfaults/map/#qfaults) is a primary source of information about "active" faults (faults that have moved in the past 2.6 million years) in the United States. This database shows no Quaternary faults in the park. The closest Quaternary fault to the park is the one that produced the Borah Peak earthquake (fig. 50).

Of the 1,225 earthquakes that occurred in Idaho between 1973 and 2009, most (739) were M 3.0–4.0; many of these will have been felt, with vibrations similar to those of a passing truck. By contrast, earthquakes of M 5.0 or greater, which can cause significant property damage, are relatively rare events; seven of these occurred in Idaho between 1973 and 2009 (Idaho Geological Survey 2011).

In cooperation with the park, the Idaho National Laboratory operates a seismic station in Craters of the Moon National Monument (Carpenter et al. 2010). This station is one of 27 in the Department of Energy's seismic network.



Figure 49. Photographs of Borah Peak. At 3,856 m (12,647 ft) above sea level, Borah Peak (top photograph) is the highest mountain in Idaho. As a result of the Borah Peak earthquake, the mountain grew about 0.3 m (1 ft) in elevation. Most of the displacement was downward along the graben (fault-bounded basin), as shown by the fault offset in the bottom photograph. Vertical offset along new fault scarps averaged 0.8 m (2.6 ft), exceeded 1.0 m (3.0 ft) along 43% of their length, and attained a maximum of 2.7 m (8.9 ft) along the broad and complex zone of deformation in the southern section of the Lost River fault (Crone and Machette 1984). NPS photographs from Owen (2011b).

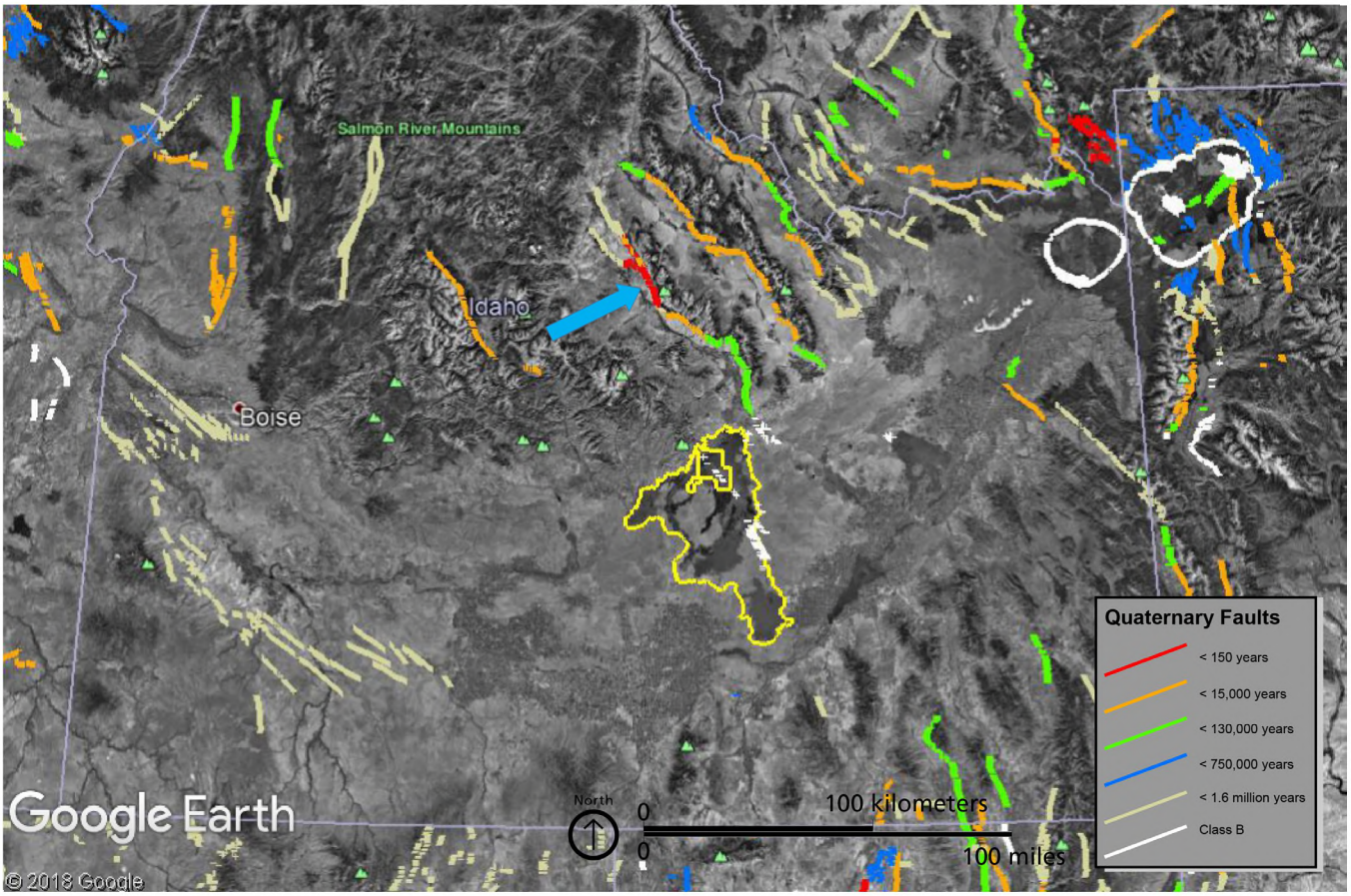


Figure 50. Map of Quaternary faults near the eastern Snake River Plain.
The eastern Snake River Plain is remarkably free of Quaternary faults. Quaternary faults, including the ones shown here, are considered "active," having moved during the past 2.6 million years; these faults have the potential to cause future earthquakes. A Quaternary fault (blue arrow pointing to red line) in the Lost River Range caused the 1983 Borah Peak earthquake. Yellow line indicates NPS boundary. Compiled from USGS data at https://earthquake.usgs.gov/hazards/qfaults/map/#qfaults (accessed 12 July 2018). Google Earth data SIO, NOAA, US Navy, NGA, GEBCO. Image Landsat/Copernicus US Dept of State Geographer.

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

Volcano Hazards

In the past 15,000 years, eruptions along the Craters of the Moon segment of the Great Rift have taken place about every 2,000 years, though intervals between eruptive periods have been as long as about 3,000 years and as short as about 500 years (Kuntz et al. 1986a).

Evidently an interval of about 2,000 years is necessary for a complex interplay of driving forces to take place that produce an eruption. The driving forces are probably related to the buildup of magmatic pressure and regional extension of Earth's crust (Kuntz et al. 1986a). Because the present interval between eruptions has lasted approximately 2,100 years (i.e., since eruptive period A; see "Geologic History"), another eruptive period seems likely to occur within the next 1,000 years (Kuntz et al. 1986a).

Volcanism related to the Yellowstone hot spot has migrated several hundred kilometers northeast of the Craters of the Moon area. Thus, the next eruption along the Great Rift volcanic rift zone will not be a rhyolitic, caldera-forming event. Rather, it will be characterized by basaltic volcanism, which has a mild, effusive style consisting of mainly lava flows from fissures, but also

low shield volcanoes and small cinder and spatter cones (see "Volcanic Features").

Similar to recent, past eruptions, the next eruption will occur as a discrete eruptive episode (from a single batch of magma) lasting a relatively short period of time—a few days or months up to 1,000 years. The steady-state nature of volcanism and the constancy of the most recent output rate at Craters of the Moon suggested to Kuntz et al. (1986a) that 5–6 km^3 (1.2–1.4 mi^3) of lava will be erupted during the next eruptive period. This estimate was based on magma output, which was constant at about 1.5 km^3 (0.25 mi^3) per 1,000 years from about 15,000 to 7,000 years ago, and was about 2.8 km^3 (0.67 mi^3) per 1,000 years from about 7,000 to 2,000 years ago (Kuntz et al. 1986a).

Table 3. Hazards associated with basaltic volcanism on the eastern Snake River Plain.

Source: Hackett et al. (2002).

Phenomenon (listed from highest to lowest relative hazard)	Frequency	Size or Area of Influence	Comments
Lava flows	Common	0.1–400 km^2 (0.02–150 mi^2) in area; up to 25 km (16 mi) in length based on sizes of lava flows of the past 400,000 years	Significant hazard; typical basaltic phenomenon; lava from fissures or shield volcanoes may inundate large areas downslope of vents
Ground deformation: fissuring, faulting, and uplift	Common; associated with virtually all shallow magma intrusion and eruption	Fissuring could affect areas to 2 × 10 km (1 × 6 mi); minor tilting and broad uplift in areas to 5 × 20 km (3 ×12 mi)	Significant hazard; due to shallow dike intrusion; "dry" intrusion may occur without lava flows; affects smaller areas than for lava inundation
Volcanic earthquakes	Common; associated with magma intrusion before and during eruption	Maximum magnitude (M) = 5.5 and most events M < 4; ground vibration may affect facilities within 25 km (16 mi)	Low to moderate hazard; swarms of shallow earthquakes (< 4 km [2.5 mi] focal depth) occur as dikes propagate underground
Gas release (toxic and corrosive vapors)	Common; associated with fissuring and lava eruption	Restricted to near-vent areas; may affect several square–kilometer area downwind	Low hazard; local plume of corrosive vapor, downwind from eruptive vent or fissure; cooled vapor may collect in local topographic depressions
Tephra fall (volcanic ash and bombs)	Common	Restricted to near-vent areas; may affect several square–kilometer area downwind; depending on the location of structures, roof collapse by tephra loading has the potential to take place	Low hazard; basaltic eruptions are inherently nonexplosive and may form small tephra cones but little fine ash to be carried downwind
Base surge (ground-hugging blast of steam and tephra)	Rare	Effects limited to radius of several kilometers from vent; < 10 km^2 (4 mi^2) area	Low hazard; steam explosions due to interaction between ascending magma and shallow groundwater
Tephra flow (ground-hugging flow of hot, pyroclastic material)	Extremely rare	Near vent; may affect area < 1 km^2 (0.4 mi^2)	Very low hazard; similar to tephra fall but affecting even smaller area

For the purpose of interpretation and discussion of where the next eruption might occur, Kuntz et al. (1986a) divided the Craters of the Moon segment of the Great Rift volcanic rift zone into three parts: (1) the northern part extends from the Lava Creek vents (**Qccg2**) to Big Cinder Butte (**Qccc1**), (2) the central part extends from Big Cinder Butte to Sheep Trail Butte (**Qccc2**), and (3) the southern part extends from Sheep Trail Butte to the buried vent complex for the Minidoka flows (**Qcfb4**). Because past eruptions at the Craters of the Moon lava field have generally occurred in areas of the Great Rift that have been quiet the longest, Kuntz et al. (1986a) predicted that the next eruption will begin in the central part then possibly move toward the northern part.

The probability is low of future eruptions from the Wapi lava field because it was a monogenetic (one-time) basaltic shield eruption (USGS Volcano Hazards Program 2015c). Moreover, no threatening hazard from the Black Butte Crater lava field (west of the park) is present because, like Wapi, that lava field was monogenetic; furthermore, the Black Butte Crater lava field is not part of a well-defined, volcanic-rift-zone system in the eastern Snake River Plain (USGS Volcano Hazards Program 2015a). Also, no threatening hazard is present from Hells Half Acre lava field (east of the park; see fig. 5), as it was a monogenetic basaltic shield eruption (USGS Volcano Hazards Program 2015b).

The most significant type of hazard in the next eruption of the Craters of the Moon lava field will be basaltic lava flows that spread across the landscape (table 3). Lava will flow east or west from the alignment of the Great Rift and take advantage of local topography. Furthermore, lava tubes will likely help distribute lava. The actual pathways affected, however, will depend on the exact location of future vents.

Because basalt is fluid and gas-poor, the lava flows will move slowly, that is, humans will be able to outrun them. These flows, however, will threaten property by inundation or burning, and threaten rangeland and farms. Also, they could ignite structural fires and wildfires. Moreover, US Highway 93/26/20 passes through the Craters of the Moon lava field and may become blocked by lava flows. The nearest populated communities (Arco and Carey, Idaho) are far from the area of future eruptions, and unlikely to experience eruptive phenomena. The Idaho National Laboratory, however, lies on the eastern margin of the Great Rift; its nuclear reactors and radioactive waste storage facility, which are in a topographic basin, may be impacted by a future eruption (US Geological Survey 2014).

Other hazards associated with basaltic volcanism on the eastern Snake River Plain are listed in table 3. None of these volcanic phenomena can be effectively controlled. With respect to ground deformation and gas release, engineering structures to withstand ground fracturing or faulting, or the long-term effects of corrosive gases, is generally not feasible. The most successful mitigation is avoidance through careful land-use planning and site selection (Hackett et al. 2002).

Park Planning and Monitoring

The 2016 state of the park report for Craters of the Moon National Monument and Preserve (National Park Service 2016b) listed three critical management actions with respect to volcano hazards:

- Complete a volcano hazard assessment to help understand the potential damage that could be caused by an eruption.
- Complete the emergency operations plan to address the responses to a volcanic eruption, including the direct impacts of the volcanic activity and the secondary impacts on local residents and visitors.
- Develop a continuity of operations plan for park staff should the main headquarters building or transportation corridors become unavailable.

The Bureau of Land Management has made progress on, though not completed, a joint hazards analysis and response plan, which was identified in the park's 2007 management plan (National Park Service and Bureau of Land Management 2007). Phase one, which was completed in 2011, was the collection of available geologic maps and relevant data for the last 30 years, including data on infrastructure (e.g., utility/transportation corridors), resident population, visitor use statistics, and critical facilities that could be impacted by a volcanic eruption. Older data sets were digitized, as needed, and all data were compiled into a GIS database. Data were collected by Portage, Inc. (Idaho Falls, Idaho) in accordance with contract L10PD04192 and delivered to the BLM Shoshone Field Office. These data would be useful for eruption scenarios, which are probably needed to plan for the safety and security of visitors and employees (National Park Service 2014). At present, the National Park Service is attempting to track down these data (Linda Manning, Craters of the Moon National Monument and Preserve, chief of Integrated Resources Management, email communication, 16 August 2018).

As part of a hazard assessment, hazard zone maps need to be generated (National Park Service 2014). Hazard zones are based on the locations of probable eruption sites, the likely paths of lava flows erupted from those sites, and the frequency of lava-flow inundation of an

area over the past several thousand years. The hazard zones also take into account structural and topographic features that would affect the direction of lava flows. Other hazard-zone maps could include ground deformation, volcanic gas, and tephra fall (Hackett et al. 2002). Work by the Idaho Geological Survey includes hazard mapping (mostly earthquakes and landslides), but volcano hazard mapping is also of interest as is assisting with future work by a GIP intern (Bill Phillips, Idaho Geological Survey, research geologist, email communication, 2 February 2017).

Once a hazard assessment has been completed and eruption scenarios are modelled and run, a response plan can be developed and finalized with appropriate partners, for example, the Yellowstone Volcano and Cascade Volcano Observatories, the Idaho Geological Survey, and the Idaho National Laboratory. Park managers may need to plan for increased visitation (from interested members of the public) while providing for visitor and staff safety in the midst of reactivated volcanic activity (National Park Service and US Geological Survey 2000). Because US Highway 93/26/20 passes through the Craters of the Moon volcanic field, development of a plan that addresses continuity of operations for park staff is needed should transportation corridors or the main headquarters building become unavailable (National Park Service 2016b).

Sources of information for a response plan include a preliminary volcanic resources and hazards inventory for the park (Walkup 2012). In addition, Bacon et al. (1997) provided recommendations for mitigation and emergency response of volcano and volcanic earthquake hazards at Crater Lake National Park (see GRI report by KellerLynn 2013), which may be applicable for emergency response planning at the park. Also, park managers at Lassen Volcanic National Park (see GRI report by KellerLynn 2014) developed an emergency operations plan and a site bulletin outlining basic evacuation procedures, which may be useful for park planning.

The "Volcano Monitoring" chapter (Smith et al. 2009) in *Geological Monitoring* provides monitoring methodologies and seven vital signs: (1) earthquake activity, (2) ground deformation, (3) gas emission at ground level, (4) emission of gas plumes and ash clouds, (5) hydrologic activity, and (6) slope instability. The USGS Cascades Volcano Observatory monitors volcanoes in Washington, Oregon, and Idaho (see https://volcanoes.usgs.gov/observatories/cvo/).

Regarding volcanic earthquakes, the Idaho National Laboratory monitors volcanic earthquakes in the vicinity of the park at several seismic stations located near or within identified volcanic rift zones. Seismic stations are designed to provide early warning in the event of potential volcanic eruptions by detecting low-magnitude microearthquake swarms that accompany the upward movement of magma through Earth's crust (Payne 2003).

Wind Erosion

Wind erosion is ongoing at the park (fig. 51). Erosion by the wind involves two linked processes: (1) abrasion (mechanical weathering of coherent materials) and (2) deflation (removal of loose materials) (Lancaster 2009). Conference call participants mentioned wind erosion on Inferno Cone (**Qcc**) and Big Craters (**Qcfa5**) where wayside exhibits seemed to have contributed to wind erosion there. Although these signs were removed primarily because the interpretive panels were dated, strong evidence suggests that the combination of these rigid structures set in concrete and eolian processes were causing unnatural erosion patterns around the base of the waysides (Ted Stout, Craters of the Moon National Monument and Preserve, chief of Interpretation, written communication, 4 June 2018).

Transport of fine sediment by wind may cause dust storms. During such events, visibility may be reduced to less than 1 km (0.6 mi) by blowing dust. Dust storms impact air quality in their immediate vicinity as well as in areas downwind.

Thick deposits of loess (windblown dust), which have accumulated on older lava flows in the park, are particularly sensitive to erosion after fire. Once fire destroys vegetation, the wind can transport huge volumes of material from burned areas, resulting in dust storms. In addition to fire, activities such as grazing, recreation, and construction can cause vegetation die-back, which increases the potential for deflation. Grazing allotments administered by the Bureau of Land Management (see Erixson and Corrao 2012) are not permitted on NPS lands; however, no fences exclude cattle or sheep from straying onto kipukas or lava flows in the park, so trespass occasionally takes place (Linda Manning, Craters of the Moon National Monument and Preserve, chief of Integrated Resource Management, written communication, 4 June 2018).

In the *Geological Monitoring* chapter about eolian (spelled "aeolian" in that publication) features and processes, Lancaster (2009) described the following methods and vital signs for monitoring: (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



Figure 51. Photograph of wind storm.
In June 2013, winds in excess of 100 kph (60 mph) transported tan-colored loess along the ground surface and through the air. Inferno Cone is in the background. The view is from the park's visitor center. In the foreground, the flagged tree (branches growing only on the downwind side) is an indication of ongoing eolian processes. NPS photograph courtesy of Ted Stout (Craters of the Moon National Monument and Preserve).

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. The NPS Geologic Resources Division Aeolian Resource Monitoring website, http://go.nps.gov/monitor_aeolian, provides additional information.

Mining

The north end of the park is part of the Lava Creek Mining District, which was mined extensively around 1913 (Craters of the Moon National Monument 1987). Operation of the Martin Mine in the district took place from 1922 to 1929. The Martin Mine is located on what is now monument property. Rights to the mine were transferred to the National Park Service in 1967, and most of the structures associated with the mine have been removed (see "Abandoned Mineral Lands").

Currently, no active mining operation is taking place in the Lava Creek District. The open pit silver and gold Champagne Mine in the district operated until the early 1990s, and a few small mines operated historically. The Idaho Geological Survey does not keep close tabs on "hobby miners" (Virginia Gillerman, Idaho Geological Survey, economic geologist, email communication, 24 May 2017).

Although a mining claim no longer exists in the park, the Idaho Transportation Department holds three right-of-ways for mineral material sites (sand and gravel) along US 93/26/20. These sites cover 126 ha (312 ac) at the park's northern boundary. The former General Land Office granted these rights-of-way in the 1940s during construction of the highway. These right-of-ways are held in perpetuity (National Park Service and Bureau of Land Management 2007); use has been infrequent since 2000 (National Park Service 2014).

The National Park Service works with adjacent land managers and other permitting entities to help ensure that park resources and values are not adversely impacted by external mineral exploration and development. Potential impacts include groundwater and surface water contamination, erosion and siltation, introduction of exotic plant species, reduction of wildlife habitat, impairment of viewsheds and night skies, excessive noise, and diminished air quality. Visitor safety and overall degradation of the visitor experience are particular concerns. The NPS Geologic Resources Division Energy and Minerals website, http://go.nps.gov/grd_energyminerals, provides additional information.

Geologic History

This chapter describes the chronology of geologic events that formed the present landscape.

The primary geologic resources at the park are those associated with the Craters of the Moon, Wapi, and Kings Bowl lava fields, which were described by Kuntz et al. (2007) as "predominantly Holocene," having erupted onto the landscape during the past 15,000 years. The rock record at the park, however, represents a far greater span of geologic time (see fig. 3). For example, sedimentary rocks in the northern part of the park date back more than 330 million years to the Mississippian Period. The next oldest rocks in the park are from the Eocene Period (56 million–34 million years ago); these rocks were deposited about 275 million years after the Mississippian rocks were deposited. The Eocene Period in the park is represented by the Challis Volcanic Group (**Tcv**) and associated rocks. The Heise Group (**Th**) of rocks at the park are from the Miocene Epoch and record an episode of caldera formation associated with the passing of the Yellowstone hot spot on the eastern Snake River Plain between 6.5 million and 4.3 million years ago. Pleistocene and Holocene alluvial and colluvial sedimentation has been ongoing since about 480,000 years ago.

Mississippian Marine Deposition and Mountain Building

The Mississippian rocks ("**M**" map units) in the park consist of the Little Copper Formation (**Mclc**) and Argosy Creek Formation (**Mca**), which are part of the Copper Basin Group (Link et al. 1996). They are turbidite deposits (Skipp et al. 2009), which formed as sediment-laden density currents moved down slopes and across the floor of an ocean basin. These formations consist of clastic material shed from a probable highland on the west into a basin on the east (Link et al. 1995; Link and Janecke 1999). Remnants of both the highland and the basin are exposed on the hanging walls of the Pioneer and Copper Basin thrust faults (see "Cretaceous Mountains Building") in the Fish Creek Reservoir area and Pioneer Mountains north of the park (Kuntz et al. 2007; Skipp and Kuntz 2009).

The Mississippian rocks in the park formed during the Antler Orogeny, which was a mountain-building event that affected the Paleozoic rocks of Nevada, western Utah, and Idaho. The Antler Orogeny took place between Late Devonian and Early Mississippian time (383 million to 347 million years ago). The cause of the orogeny has long been ascribed to plate convergence (i.e., collisions along the western margin of the North America continent). General acceptance of this concept is suggested in the scientific literature (Ketner 2012); however, the exact nature of the orogeny remains problematic, with a wide range of tectonic settings and a variety of models having been proposed over the years (Nilsen and Steward 1980).

Cretaceous Mountain Building

The Pioneer and Copper Basin thrust faults developed as a result of the Sevier Orogeny—a more recent mountain-building event than the Antler Orogeny—probably taking place at the end of the Cretaceous Period (between 165 million and 80 million years ago; Skipp and Kuntz 2009). This orogeny was the result of the Farallon plate subducting beneath the western edge of North America. Oceanic Farallon crust plunging beneath continental North American crust in the approximate position of modern central California was the driving force behind the Sevier thrust system. The collision produced deformation that started in the west and migrated eastward. It produced a linear zone of deformed rock strata in the western United States that extends from southeastern California northeastward through southern Nevada and western Utah to western Wyoming. It is a zone of eastward–directed thrust faults and folds that represent 40 to 65 km (25 to 40 mi) of crustal shortening in response to compressional forces. The Pioneer and Copper Basin thrust faults transported the park's Mississippian-age rocks eastward along with all other Paleozoic rocks in the area.

Eocene Volcanism

In contrast to the Sevier Orogeny, which is characterized by compression, the Craters of the Moon area has since been characterized by extension, as well as volcanism, for the last 55 million years. Sevier faults at the surface have been broken up and tilted steeply from their original gently dipping positions as a result of Earth's crust pulling apart in the Basin and Range province. Extension of Earth's crust accommodated the intrusion of magma below the surface and facilitated the extrusion of lava onto the surface. Extension in the Craters of the Moon area began before extrusion of the middle Eocene Challis Volcanic Group (**Tcv**; discussed below) (Link and Janecke 1999) (fig. 52).

Two models have been proposed to explain Eocene volcanism in the region. In one model, subduction of a very shallowly dipping Farallon plate beneath the North American continent created a wide volcanic arc (Lipman et al. 1971, 1972; Lipman 1980). In the other model, volcanic activity resulted from rifting as a result

of collision between the Pacific and North American plates (Ewing 1980; Fox 1983; Fox and Beck 1985). In either case, the result was a short-lived but intense magmatic episode from about 55 million to 40 million years ago (Moye et al. 1988). That episode created a belt of igneous rocks that extends from southern British Columbia across northeastern Washington and central Idaho into Montana and Wyoming. The area in central Idaho is known as the Challis volcanic field. It is the largest of several Eocene volcanic fields in the Pacific West (Sanford 2005).

The Challis Volcanic Group (**Tcv**) marks the peak of Eocene volcanic activity between 49 million and 48 million years ago (Skipp and Kuntz 2009). Early in the development of the Challis volcanic field, tuff of Antelope Creek (**Tcac**) was emplaced; this formation consists of ignimbrites. The eruptions that created the Antelope Creek ignimbrites would have been spectacular displays of swiftly flowing, incandescent clouds of ash and other pyroclastic material. Final stages of igneous activity in the Challis volcanic field involved the intrusion of granite (**Tcbg**), hornblende diorite (**Tchd**), and dikes (**Tcd**) into the Challis Volcanic Group (**Tcv**).

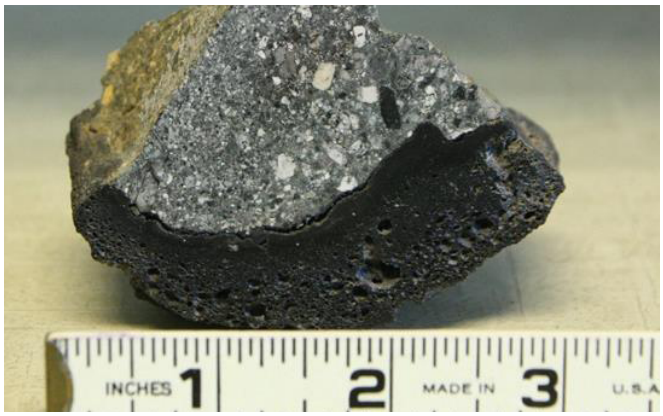


Figure 52. Photograph of Challis Volcanic Group rock.
The geologic history of the northwestern United States is characterized by a short-lived but intense magmatic episode from 55 million to 40 million years ago, which resulted in a belt of volcanic and plutonic rocks that extends from southern British Columbia across northeastern Washington and central Idaho and into Montana and Wyoming. The Challis volcanic field of central Idaho, represented by the Challis Volcanic Group in the park, is the largest and most diverse of the volcanic fields produced during this episode. The rock shown in the photograph consists of the Challis Volcanic Group and basalt from North Crater. The rock is a xenolith. NPS photograph from Owen and Melander (2014, figure 18).

Basin and Range Faulting

Basin and Range, normal faults cut the rocks of the Challis volcanic field, as well as the underlying Mississippian rocks. Basin and Range faulting initiated during the Neogene Period (23.0 million to 2.6 million years ago) and continues today (Kuntz et al. 2007). In the Craters of the Moon area, unnamed north– to northwest–trending normal faults east and subparallel to both the Pioneer and Copper Basin thrust traces may have first formed shortly after thrusting ceased at the end of the Sevier Orogeny, and then were offset and reactivated during one or more of the following three major extensional periods: (1) northwest–southeast extension during peak Challis volcanism, (2) east-northeast–west-southwest basin-forming extension during a younger middle Eocene to Oligocene time that also included the uplift of the Pioneer Mountains, and (3) northeast–southwest Basin and Range extension from the Miocene Epoch to the present (Janecke 1992; Rodgers et al. 1995; Link and Janecke 1999). In addition, a few small east-striking normal faults that may reflect late Cenozoic north–south extension in the wake of the Yellowstone hot spot are concentrated near the Snake River Plain (Skipp et al. 1990; Janecke et al. 2001; Janecke 2007). Faulting and earthquakes, as well as volcanism, associated with the Yellowstone hot spot in the adjacent Basin and Range mountains continue to affect the area (Skipp and Kuntz 2009).

Volcanism Associated with the Yellowstone Hot Spot

The eastern Snake River Plain records the "passing" of the Yellowstone hot spot (see fig. 4). Huge volumes of magma rose through the hot spot and erupted onto the surface (fig. 53). Because the hot spot is fixed and the North American continent is moving over it, the eruptions formed a chain of progressively younger calderas that stretch 800 km (500 mi) from the Idaho-Oregon-Nevada border northeastward along the eastern Snake River Plain to the Yellowstone Plateau in Wyoming. Many of these calderas overlap, but at least seven distinctive volcanic centers (and possibly as many as 13; Smith and Siegel 2000) formed during the past 16.5 million years. The Heise Group (**Th**) of rocks, which was mapped at the northwest edge of the park (see poster [sheet 2], in pocket, and crmo_geology.mxd), is associated with the Heise volcanic field, which at 6.5 million–4.3 million years old is the youngest field predating Yellowstone. These rocks consist of rhyolitic ignimbrites.

Quaternary Basaltic Volcanism on the Snake River Plain

As the hot spot passed under an area, the expanding plume of hot magmatic material embedded in the

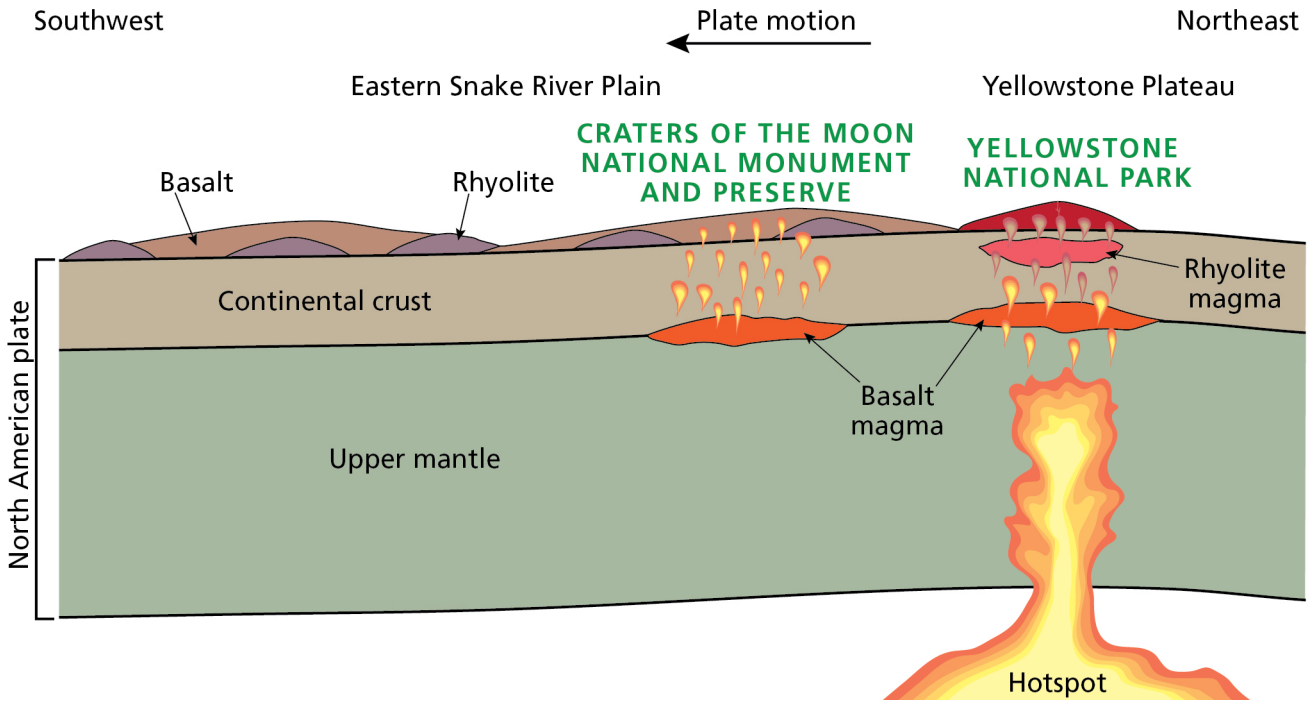


Figure 53. Cross section of the eastern Snake River Plain.
The figure shows basaltic volcanism overlying rhyolitic volcanism on the eastern Snake River Plain. Today, the potential for rhyolitic volcanism is under Yellowstone National Park, which lies directly above the Yellowstone hot spot. Graphic by Trista Thornberry-Ehrlich (Colorado State University) after Truitt and Lillie (2007, figure 3.4).

North American plate caused the land surface to rise dramatically, creating a bulge in Earth's crust; the Yellowstone Plateau represents today's "bulge." As the North American plate then migrated, shifting the locus of hot-spot activity, the eastern Snake River Plain subsided by as much as 610 m (2,000 ft) (Smith and Siegel 2000) and a series of rifts or fissures opened. The Great Rift volcanic rift zone is the northern segment of the most recently opened rift.

Quaternary volcanism of the eastern Snake River Plain is concentrated in these rifts, though it is not confined to them (Kuntz et al. 1992). The basaltic volcanism of this period is recorded in rocks at the park. The park contains portions of as many as 70 Quaternary basaltic lava flows ("**Qwfb**," "**Qwfc**," "**Qwfd**," "**Qsbb**," and "**Qsbc**" units), which range from the 690,000-year-old pahoehoe lava flow of vent 4640 (**Qwfd1**) to the 38,000-year-old basaltic lava flows of the Grandview Crater lava field (**Qwfb3**). Kuntz et al. (2007) referred to these flows as part of the Snake River Group (see poster [sheet 2], in pocket). They predate the "predominantly Holocene" flows of the Craters of the Moon, Wapi, and Kings Bowl lava fields.

Pleistocene Glaciation and Volcanism

While basalt was erupting onto the surface of the eastern Snake River Plain, ice-age glaciers were sculpting mountainous terrain and depositing meltwater sediments in the valleys. The Pinedale glaciation is the glacial interval of interest for the Craters of the Moon area (Scott 1982), though one map unit (older fan alluvium, **Qafo**) was correlated with the preceding Bull Lake glaciation (Kuntz et al. 2007; Skipp and Kuntz 2009). That deposit (**Qafo**) contains clasts of the Copper Basin Group.

The Wind River Range in Wyoming is the type area (reference location where these deposits were first studied) of the Pinedale and earlier (e.g., Bull Lake) glaciations. Investigators have correlated glacial deposits throughout the Rocky Mountains to the Wind Rivers. The timing of the Pinedale glaciation varied throughout the Rocky Mountains but is thought to have begun sometime between 50,000 and 25,000 years ago and lasted until about 14,000 years ago, or perhaps more recently in the Yellowstone region (Smith and Siegel 2000). Remnants of alpine glacial deposits, chiefly outwash, abound in the high valleys of the White Knob Mountains north of the park. In the park, the upper parts of main stream deposits (**Qmp**) were deposited during the Pinedale glaciation (Kuntz et al. 2007),

though deposition of the entire deposit ranges from before 120,000 years ago (i.e., about the same time that Quaternary basaltic lava flows such as units **Qsbb37**, **36**, **33**, and **32** were emplaced) to about 10,000 years ago (i.e., about the time of eruptive period F). In addition, the map unit "younger fan alluvium/fan alluvium" (**Qafy**) was deposited 120,000–10,000 years ago. Some single as well as coalescing fans formed at range fronts adjacent to the northern boundary of the park. Both main stream deposits (**Qmp**) and alluvial fans (**Qafy**) are indicative of a much wetter climate during the Pleistocene Epoch than today (Scott 1982).

Predominantly Holocene Great Rift Volcanism

The Great Rift is the northern segment of the most recently opened volcanic rift on the eastern Snake River Plain. The three lava fields in the park—Craters of the Moon, Wapi, and Kings Bowl—are aligned along the Great Rift. Volcanic activity in these fields has been divided into eight eruptive periods from H, oldest, to A, youngest (fig. 54). The first seven eruptive periods (H–B) supplied the Craters of the Moon lava field. The most recent eruptive period (A) supplied the Craters of the Moon, Wapi, and Kings Bowl lava fields. Various cinder cones without associated lava flows erupted throughout eruptive periods H–B; these cones are referred to basaltic cinder cones, undivided (**Qcc**) (table 2).

The sequential development of the eight eruptions that yielded the primary geologic features in the park is as follows. Each period lasted 1,000 years or less (some as short as 100 years, for example, eruptive periods D and C) and was separated by intervals of quiescence lasting from a few hundred to more than 2,000 years (Kuntz et al. 1982).

- Eruptive period H began about 15,000 years ago and consisted of eight pulses of volcanic activity that produced eight distinctive lava flows (oldest to youngest, map units **Qcfh8**, **7**, **6**, **5**, **4**, **3**, **2**, and **1**) and one cinder cone, Crescent Butte (**Qcch1**). Unit **Qcfh8** is the oldest and stratigraphically lowest lava flow. Crescent Butte erupted during the final pulse of activity in eruptive period H.
- Eruptive period G occurred about 12,500 years ago and consisted of three pulses of volcanic activity that produced three distinctive lava flows—the Lava Creek flows (**Qcfg3**), Carey flows (**Qcfg2**), and Sunset flows (**Qcfg1**)—and one cinder cone, Sunset Cone (**Qccg1**), which erupted during the final pulse of activity in eruptive period G.
- Eruptive period F took place between about 11,000 and 10,000 years ago and consisted of three episodes of volcanic activity that produced three distinctive flows with source vents on the Great Rift (Kuntz et al. 1982). No cinder cones are known to have been built during this eruptive period. The three flows are, from oldest to youngest, Bottleneck (**Qcff3**), Heifer Reservoir (**Qcff2**), and Pronghorn (**Qcff1**).
- Eruptive period E took place about 7,800 years ago and produced three flows and one cinder cone. The Lava Point (**Qcfe3**), Laidlaw Lake (**Qcfe2**), and Grassy (**Qcfe1**) lava flows were emplaced in three separate episodes; Grassy Cone (**Qcce1**) erupted during the last pulse of activity of eruptive period E.
- Eruptive period D occurred about 6,500 years ago. It consisted of four episodes of volcanic activity that produced four distinctive lava flows (**Qcfd4**, **3**, **2**, and **1**) and one cinder cone, Silent Cone (**Qccd1**).
- Eruptive period C began about 6,000 years ago. It consisted of eight episodes of volcanic activity that produced eight distinctive lava flows (**Qcfc8**, **7**, **6**, **5**, **4**, **3**, **2**, and **1**), as well as four cinder cones—The Sentinel (**Qccc4**), Fissure Butte (**Qccc3**), Sheep Trail Butte (**Qccc2**), and Big Cinder Butte (**Qccc1**)—during the final four episodes of activity. In addition, two eruptive fissures extruded lava during eruptive period C; the material was mapped as Fissure Butte (**Qcec2**) and South Echo (**Qcec1**) basaltic eruptive-fissure deposits.
- Eruptive period B began about 4,500 years ago. During the seven episodes of activity, seven lava flows (**Qcfb7**, **6**, **5**, **4**, **3**, **2**, and **1**) and one cinder cone, Black Top Butte (**Qccb1**), were emplaced. The Black Top Butte cinder cone was built during the period's final episode of volcanic activity. Also, two eruptive fissures extruded lava during eruptive period B; the material was mapped as Deadhorse (**Qceb2**) and Vermillion Chasm (**Qceb1**) basaltic eruptive-fissure deposits.
- Eruptive period A encompassed the most recent volcanic activity in the park. It consisted of eight eruptive episodes in the Craters of the Moon lava field and created the Wapi (**Qwfa2**) and Kings Bowl (**Qwfa1**) lava fields. Eight lava flows were emplaced in the Craters of the Moon field: Highway (**Qcfa10**), Devils Orchard (**Qcfa9**), Serrate (**Qcfa8**), Big Craters (**Qcfa5**), North Crater (**Qcfa4**), Trench Mortar Flat (**Qcfa3**), Blue Dragon (**Qcfa2**), and Broken Top (**Qcfa1**). During the final half of the eruptive period, four cinder cones built up: North Crater (**Qcca4**), The Watchman (**Qcca3**), Big Craters (**Qcca2),** and Broken Top (**Qcca1**). Additionally, two eruptive fissures extruded lava; the material was mapped as Trench Mortar Flat (**Qcea2**) and Blue Dragon (**Qcea1**) basaltic eruptive-fissure deposits. About 2,100 years ago, the Wapi lava field erupted over a period of months to decades, building into a shield volcano. Lava flows (**Qwfa2**) of the Wapi field were

erupted from vents at Pillar Butte. At about the same time as eruption of the Wapi field, the Kings Bowl lava field was created during a single eruptive episode that lasted only a few days (Putirka et al. 2009). Lava flows (**Qwfa1**) in the Kings Bowl field extruded from fissures.

Ongoing Sedimentation

Deposition of eolian sand and loess began in the Middle Pleistocene Epoch (about 780,000 years ago) and continues to the present day (see "Eolian Features and Processes"). Ongoing deposition of colluvium (**Qc**) and fan deposits of alluvium and colluvium (**Qfac**) began about 480,000 years ago. Colluvium consists of blocks and smaller clasts of locally derived material deposited at the base of slopes, such as along canyon walls in the Pioneer Mountains at the northwest corner of the park. Fan deposits and colluvium (**Qfac**) includes material deposited by streams and debris flows at mouths of small drainage basins. Along tributary streams at the northern edge of the park, deposition of alluvium (**Qta**) began about 120,000 years ago and continues to the present day. Low areas covered by alluvium (**Qta**) are subject to periodic flooding, high water tables, and poor drainage.

Although playas (dry, barren areas in the lowest part of a basin, sometimes containing an ephemeral lake) form elsewhere in the area, the only lake deposits in the park consist of thin (less than 1 m [3 ft] thick), parallel beds of well-sorted silt, clay, and minor sand and gravel. These lacustrine deposits (**Ql**) are present in former sites of two drained reservoirs in the Pioneer Mountains at the northwest corner of the park.

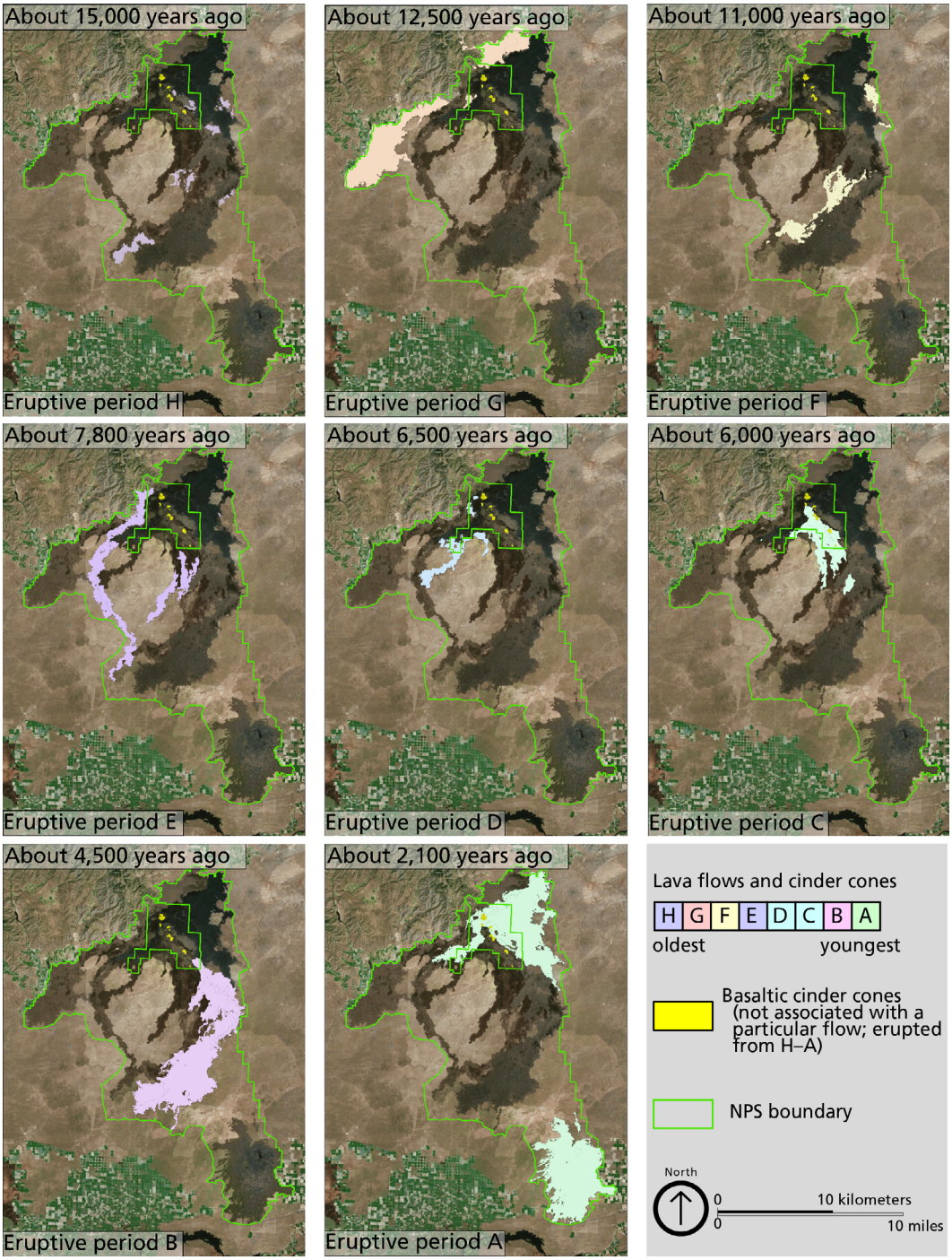


Figure 54. Graphic of eruptive periods of the Craters of the Moon, Wapi, and Kings Bowl lava fields. Between 15,000 and 2,100 years ago, the Craters of the Moon lava field erupted eight times, emplacing basaltic lava flows and cinder cones during eruptive periods H (oldest) through A (youngest). In addition, the Wapi and Kings Bowl lava fields were emplaced during eruptive period A. Satellite imagery of present-day lava is shown in each panel; the colored areas highlight the lava flows erupted during a particular period. Basaltic cinder cones, undivided, which were mapped as unit Qcc (see poster [sheet 2], in pocket), also are shown in each of the eight eruptive periods. These cones erupted during the lifespan of the Craters of the Moon lava field. Each of the eight eruptive periods lasted 1,000 years or less and was separated by intervals of quiescence lasting from a few hundred to more than 2,000 years. The southern portion of the Wapi volcanic field is not included in the GRI GIS data, but the entire field erupted at the same time and is "filled in" as part of eruptive period A on this graphic. Graphic by Michael Barthelmes (Colorado State University) using GRI GIS data (crmo_geology.mxd).

Geologic Map Data

A geologic map in GIS format is the principal deliverable of the GRI program. GRI GIS data produced for Craters of the Moon National Monument and Preserve compile the source maps listed here and include components described in this chapter. Two posters (in pocket) display the data draped over imagery of the park and surrounding area. Complete GIS data are available at the GRI publications website: http://go.nps.gov/gripubs.

Geologic Maps

A geologic map is the fundamental tool for depicting the geology of an area. Geologic maps are two-dimensional representations of the three-dimensional geometry of rock and sediment at or beneath the land surface (Evans 2016). Colors on geologic maps correspond to geologic map units (e.g., formations or deposits); lines and symbols correspond to other geologic features such as contacts between map units, faults, or folds. Map unit symbols consist of an uppercase letter indicating the age (e.g., "**Q**" for Quaternary; see fig. 3) and lowercase letters indicating the name of the rock formation or unconsolidated deposit. Anthropogenic features such as mines or quarries, as well as observation or collection locations, also may be indicated on geologic maps. The American Geosciences Institute website, http://www.americangeosciences.org/environment/publications/mapping, provides more information about geologic maps and their uses.

Geologic maps are typically one of two types: surficial or bedrock. Surficial geologic maps generally encompass deposits that are unconsolidated and formed during the past 2.6 million years (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. The GRI GIS data produced for Craters of the Moon National Monument and Preserve includes both surficial deposits and bedrock. Notably, much of the bedrock is from the Quaternary Period.

Source Maps

The GRI team does not conduct original geologic mapping. The team digitizes paper maps and converts digital data to conform to the GRI GIS data model. The team then compiles the newly digitized or converted data into a GRI GIS data set ("digital geologic map").

The GRI team produced two GRI GIS data sets for Craters of the Moon National Monument and Preserve: (1) *Digital Geologic Map of Craters of the Moon National Monument and Preserve, Idaho* (crmo_geology.mxd) at a scale of 1:100,000, and (2) *Digital Geologic Map of Portions of Craters of the Moon National Monument and Preserve, Idaho* (cotm_geology.mxd) at a scale of 1:24,000 (fig. 55). Both data sets include essential elements of the source maps such as map unit descriptions, a correlation chart of units, a map legend, map notes, cross sections, figures, and references. These items are included in the GRI ancillary map information documents: crmo_geology.pdf for the 1:100,000-scale data set and cotm_geology.pdf for the 1:24,000-scale data set. Users should be aware that the map unit symbols differ in the two data sets (table 4).

The GRI team used the following source maps to produce the crmo_geology.mxd (scale 1:100,000) data set:

- Kuntz et al. (2007) provided a geologic map of the Craters of the Moon 30' × 60' quadrangle.
- Skipp et al. (2009) provided a geologic map of the southern part of the Arco 30' × 60' quadrangle.
- Kuntz et al. (2015) provided a geologic map of the north half of the Lake Walcott 30' × 60' quadrangle.
- The crmo_geology.mxd data set covers most of the lands in the park (fig. 55). Only the southernmost part of the Wapi lava field, in the southern part of the preserve, is not covered; this portion of the Wapi lava field is beyond mapping covered by Kuntz et al. (2015). Because the crmo_geology.mxd data set covers most of the preserve and all of the monument and wilderness, it was the primary data set used in preparing this report, and its map unit symbols are used throughout.

The GRI team used the following four source maps to produce the cotm_geology.mxd (scale 1:24,000):

- Champion et al. (1989) provided a geologic map of the North Laidlaw Butte 7.5' quadrangle.
- Kuntz et al. (1990) provided a geologic map of the Fissure Butte 7.5' quadrangle.
- Kuntz et al. (1989a) provided a geologic map of the Inferno Cone 7.5' quadrangle.
- Kuntz et al. (1989b) provided a geologic map of The Watchman 7.5' quadrangle.

The cotm_geology.mxd data set covers most of the Craters of the Moon lava field (fig. 55). Investigators

and resource managers are encouraged to use this 1:24,000-scale data set if they are working in the NPS monument because it shows greater detail; for instance, a single map unit for a flow in the crmo_geology.mxd data set may be broken into more than one map unit in the cotm_geology.mxd data set. Also, the cotm_geology.mxd data set is spatially more accurate than the 1:100,000-scale data (see "Use Constraints").

Source GIS Data

GIS data for the *Digital Geologic Map of Portions of the Craters of the Moon Lava Field, Idaho* (cotm_geology.mxd) was produced by Geocode Computer Mapping Inc. and the GRI team. Geocode Computer Mapping Inc. contributed the bulk of the data for this data set. The work was contracted through the NPS Pacific West Regional Office. Geocode Computer Mapping Inc. digitized the source maps (see "Source Maps"), conducted edge-matching on the four 7.5-minute quadrangles, and provided its line work as shapefiles. The GRI team converted the data to the GRI GIS data model (see "GRI GIS Data"), validated topology, and digitized some features, namely symbology features and the O (older) and Y (younger) points associated with internal flow contacts.

GRI GIS Data

The GRI team standardizes map deliverables by using a data model. The GRI GIS data for the park was compiled using data model version 2.2, which 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 Geologic Maps website, http://go.nps.gov/geomaps, provides more information about the program's map products.

GRI GIS data are available on the GRI publications website http://go.nps.gov/gripubs and 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 from the unit list.

The following components are part of a data set:

- a GIS readme file 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 5 and 6);
- Federal Geographic Data Committee (FGDC)–compliant metadata;
- an ancillary map information document (crmo_geology.pdf or cotm_geology.pdf) that contains information captured from source maps such as map unit descriptions, geologic unit correlation tables, legends, cross sections, and figures;
- an ESRI map document (crmo_geology.mxd or cotm_geology.mxd) that displays the GRI GIS data; and
- a version of the data viewable in Google Earth (crmo_geology.kmz or cotm_geology.kmz) (tables 5 and 6).

GRI Map Posters

Posters of the GRI GIS data draped over a shaded relief image of the park and surrounding area are included with this report. The poster for *Digital Geologic Map of Craters of the Moon National Monument and Preserve, Idaho* (crmo_geology.mxd; scale 1:100,000) is referred to as sheet 2. *Digital Geologic Map of Portions of Craters of the Moon National Monument and Preserve, Idaho* (cotm_geology.mxd; scale 1:24,000) is referred to as sheet 1. Not all GIS feature classes are included on the posters (tables 5 and 6). Geographic information and selected park features have been added to the posters. Digital elevation data and added geographic information are not included in the GRI GIS data but are available online from a variety of sources. Contact the GRI team for assistance locating these data.

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 in a GRI GIS data set and on a poster. Based on the source maps' scales and US National Map Accuracy Standards, geologic features represented in the geologic map data are expected to be horizontally within 51 m (167 ft) of their true locations in the crmo_geology.mxd data set and on sheet 2 (scale 1:100,000) and 12 m (40 ft) in the cotm_geology.mxd data set and on sheet 1 (scale 1:24,000).

Table 4. Map unit symbols in the GRI GIS data sets.

Note: In map unit symbols for vents within the north half of the Lake Walcott quadrangle as shown in crmo_geology.mxd, the last letter (position 4) indicates age: Wapi and Kings Bowl are Qwfa (about 2,100 years old); Qwfb units have ages between 128,000 and 11,680 years old; Qwfc units have ages between 400,000 and 128,000 years old; Qwfd units have ages between 780,000 and 400,000 years old; and Qwfe units have ages greater than 780,000 years old.

Data set	Map unit
crmo_geology.mxd (scale 1:100,000)	e.g., Blue Dragon pahoehoe and a‘a basalt-hawaiite flows **Qcfa2** 12345 Position 1—age (Q = Quaternary) Position 2—lava field (c = Craters of the Moon; in other map units, w = vents within north half of the Lake Walcott quadrangle and s = Snake River Group) Position 3—type of deposit (f = flow; in other map units, c = cone/vent deposit and e = eruptive fissure deposit) Position 4—eruptive period (a = youngest/most recent; in other map units, a to h for eight eruptive periods) Position 5—stratigraphic order (1 = youngest, thus “2” is second to youngest)
cotm_geology.mxd (scale 1:24,000)	e.g., Blue Dragon flow, pahoehoe basalt-hawaiite flow **Qfa2p** 12345 Position 1—age (Q = Quaternary) Position 2—type of deposit (f = flow; in other map units, c = cone) Position 3—eruptive period (a = youngest/most recent; in other map units, a to h for eight eruptive periods) Position 4—stratigraphic order (1 = youngest, thus “2” is second to youngest) Position 5—type of lava (p = pahoehoe; in other map units, a = a‘a, r = rafted blocks, s = slab-lava flow, and z = squeeze-out flow)

Table 5. GRI GIS data layers for crmo_geology.mxd (scale 1:100,000).

Data Layer	On Poster (sheet 2)?	Google Earth Layer?
Geologic Cross Section Lines	No	No
Geologic Attitude and Observation Localities (strike and dip)	No	No
Geologic Measurement Localities (fault displacement amount, fold flexure offset)	No	No
Geologic Sample Localities	No	No
Geologic Point Features (breccia: fault or sedimentary)	No	No
Geologic Line Features (sackungs and veins)	No	Yes
Volcanic Point Features	Yes	No
Volcanic Line Features	Yes	Yes
Map Symbology (symbology for faults)	Yes	No
Folds	Yes	Yes
Faults	Yes	Yes
Linear Dikes	No	Yes
Linear Extrusive Units (eruptive-fissure deposits)	Yes	Yes
Geologic Contacts	Yes	Yes
Geologic Units	Yes	Yes

Table 6. GRI GIS data layers for cotm_geology.mxd (scale 1:24,000).

Data Layer	On Poster (sheet 1)?	Google Earth Layer?
Geologic Attitude and Observation Localities (strike and dip of inclined beds)	No	No
Geologic Point Features	No	No
Mine Point Features	No	No
Volcanic Point Features	Yes	No
Map Symbology (fault down-side indicators; age relationship indicators for contiguous geologic units)	Yes (for faults)	No
Volcanic Line Features	Yes	Yes
Faults	Yes	Yes
Ash Contacts	Yes	Yes
Ash Units	Yes	Yes
Geologic Contacts	Yes	Yes
Geologic Units	Yes	Yes

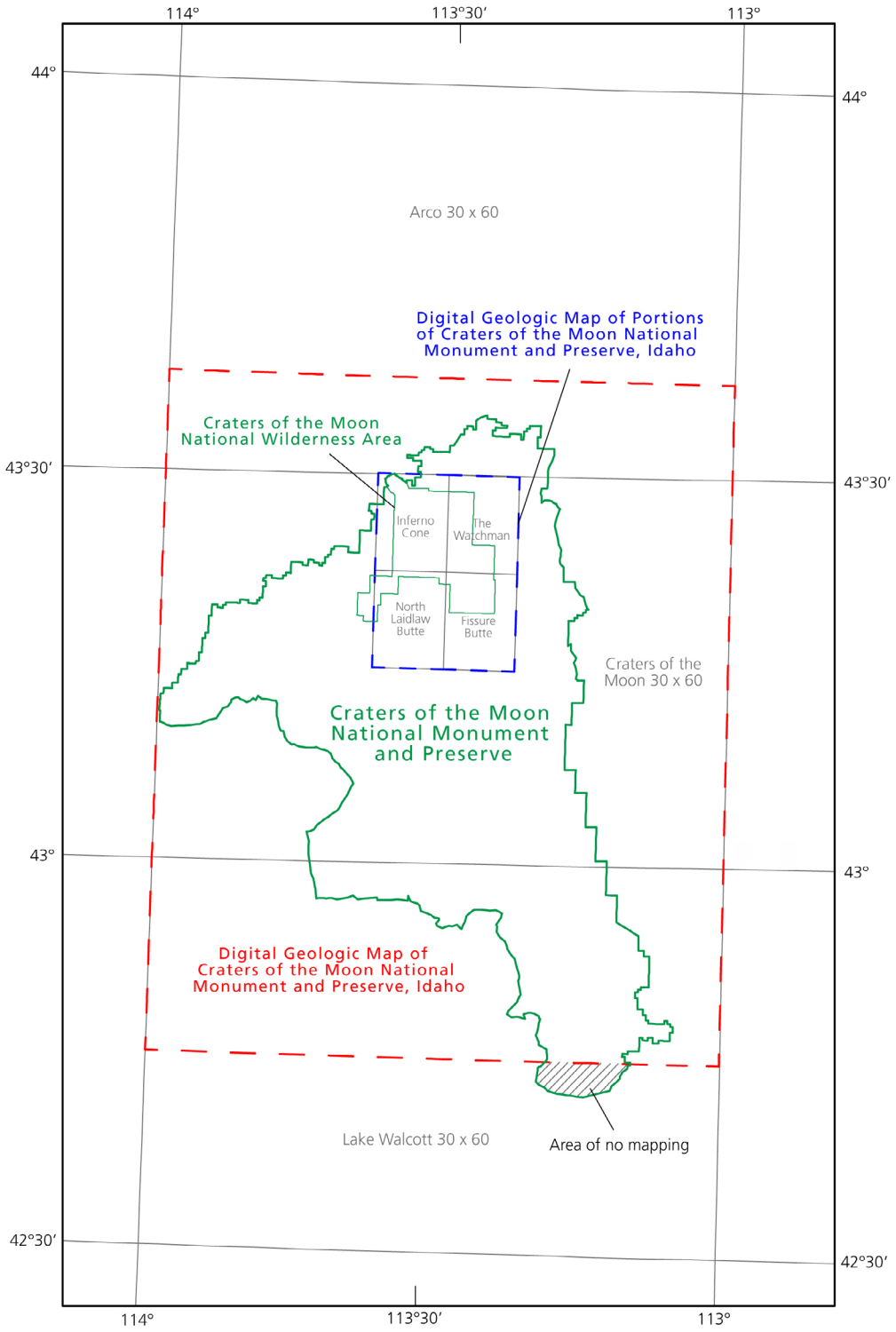


Figure 55. Index map of GRI GIS data for Craters of the Moon National Monument and Preserve. The extent of Digital Geologic Map of Craters of the Moon National Monument and Preserve, Idaho (crmo_geology.mxd; scale 1:100,000) is outlined with a dashed red line and includes the Craters of the Moon 30′ × 60′ quadrangle and portions of the Arco and Lake Walcott 30′ × 60′ quadrangles. The extent of Digital Geologic Map of Portions of Craters of the Moon National Monument and Preserve, Idaho (cotm_geology.mxd; scale 1:24,000) is outlined with a dashed blue line and includes the Fissure Butte, Inferno Cone, North Laidlaw Butte, and The Watchman 7.5′ quadrangles. The gray hatch pattern on the southern edge of the preserve represents an area with no GRI digital geologic map coverage. Graphic by James Winter and Stephanie O'Meara (Colorado State University).

Literature Cited

These references are cited in this report. Contact the Geologic Resources Division for assistance in obtaining them.

Bacon, C. R., L. G. Mastin, K. M. Scott, and M. Nathenson. 1997. Volcano and earthquake hazards in the Crater Lake region, Oregon (scale 1:100,000). Open-file report OF-97-487. US Geological Survey, Vancouver, Washington. http://vulcan.wr.usgs.gov/Volcanoes/CraterLake/Hazards/OFR97-487/framework.html.

Blakesley, J. A., and G. Wright. 1988. A review of scientific research at Craters of the Moon National Monument. Station Bulletin 50. University of Idaho; Forest, Wildlife and Range Experiment Station; Moscow, Idaho.

Braile, L.W. 2009. Seismic monitoring. Pages 229–244 *in* R. Young, R. and L. Norby, editors. Geological monitoring. Geological Society of America, Boulder, Colorado. http://go.nps.gov/seismic_monitoring.

Brossy, C. 2003. The North Crater neighborhood: more complex than Mr. Rogers', a discussion of cinder cones, lava flows, and rafted blocks. Report completed by Bureau of Land Management geology technician for Craters of the Moon National Monument and Preserve, Arco, Idaho. https://irma.nps.gov/DataStore/Reference/Profile/662638.

Bullard, F. M. 1971. Volcanic history of the Great Rift, Craters of the Moon National Monument and adjacent areas, south-central Idaho. Unpublished summary report C-28. Craters of the Moon National Monument, Arco, Idaho.

Burghardt, J. E., E. S. Norby, and H. S. Pranger II. 2014. Abandoned mineral lands in the National Park System: comprehensive inventory and assessment. Natural Resource Technical Report NPS/NRSS/GRD/NRTR—2014/906. National Park Service, Fort Collins, Colorado. http://go.nps.gov/aml_publications.

Carpenter, N. S., S. J. Payne, J. M. Hodges, and R. G. Berg. 2010. INL Seismic Monitoring Annual Report: January 1, 2009–December 31, 2009. INL/EXT-10-19925. Idaho National Laboratory, Idaho Falls, Idaho. https://inldigitallibrary.inl.gov/sites/sti/sti/4731794.pdf.

Casper Planetarium. 2017. What is the moon made of? Online information. Casper Planetarium, Casper, Wyoming. http://www.casperplanetarium.com/faqs/what-is-the-moon-made-of/ (accessed 17 May 2017).

Champion, D .E. 1973. The relationship of large-scale surface morphology to lava flow direction, Wapi lava field, southeast Idaho. Thesis. State University of New York, Buffalo, New York.

Champion, D. E., M. A. Kuntz, and R. H. Lefebvre. 1989. Geologic map of the North Laidlaw Butte quadrangle, Blaine and Butte Counties, Idaho (scale 1:24,000). Geologic Quadrangle Map GQ-1634. US Geological Survey, Reston, Virginia. https://pubs.er.usgs.gov/publication/gq1634.

Clynne, M. A., and L. J. P. Muffler. 2010. Geologic map of Lassen Volcanic National Park and vicinity, California (scale 1:50,000). Scientific Investigations Map 2899. US Geological Survey, Menlo Park, California. http://pubs.usgs.gov/sim/2899/.

Covington, H. R. 1977. Preliminary geologic map of the Pillar Butte, Pillar Butte NE, Pillar Butte SE, and Rattlesnake Butte quadrangles, Bingham, Blaine, and Power counties, Idaho (scale 1:48,000). Open-File Report OFR-77-779. US Geological Survey, Reston, Virginia. https://pubs.er.usgs.gov/publication/ofr77779.

Craters of the Moon National Monument. 1987. Resources management plan and environmental assessment. Craters of the Moon National Monument, Arco, Idaho.

Craters of the Moon National Monument. 1993. Erasing footprints. Site bulletin. Craters of the Moon Natural History Association, Inc., Arco, Idaho.

Crone, A. J., and M. N. Machette. 1984. Surface faulting accompanying the Borah Peak earthquake, central Idaho. Geology 12(11):664–667.

Erixson, J. A. and M. V. Corrao. 2012. Natural resource condition assessment: Craters of the Moon National Monument and Preserve. Natural Resource Report NPS/UCBN/NRR—2012/602. National Park Service, Fort Collins, Colorado. https://irma.nps.gov/DataStore/Reference/Profile/2191610.

Ewing, T. L. 1980. Paleogene tectonic evolution of the Pacific Northwest. Journal of Geology 88:619–638.

Faye, G. H., and R. M. Miller. 1973. "Blue Dragon" basalt from Craters of the Moon National Monument, Idaho: origin of color. American Mineralogist 58:1048–1051. http://www.minsocam.org/MSA/collectors_corner/arc/bluedragon.htm.

Fernandes, R. M. S., B. A. C. Ambrosius, R. Noomen, L. Bastos, L. Combrinck, J. M. Miranda, and W. Spakman. 2004. Angular velocities of Nubia and Somalia from continuous GPS data: implications on present-day relative kinematics. Earth and Planetary Science Letters 222(1):197–208. doi:10.1016/j.epsl.2004.02.008.

Fox, K. F. Jr. 1983. Melanges and their bearing on late Mesozoic and Tertiary subduction and interplate translation at the west edge of the North American plate. Professional Paper 1198. US Geological Survey, Reston, Virginia. http://pubs.usgs.gov/pp/1198/report.pdf.

Fox, K. F. Jr., and M. E. Beck. 1985. Paleomagnetic results for Eocene volcanic rocks from northeastern Washington and the Tertiary tectonics of the Pacific Northwest. Tectonics 4:323–341.

Geologic Resources Division. 2000. Trip report (20 September 2000)—inspection of potential geohazards, Craters of the Moon National Monument, 17–18 May 2000. From mining engineer, Minerals Operations Branch, to chief, Mineral Operations Branch, Geologic Resources Division (GRD), Lakewood, Colorado.

Good, J. M., and K. L. Pierce. 1996. Interpreting the landscapes of Grand Teton and Yellowstone National Parks—recent and ongoing geology. Grand Teton Natural History Association and Grand Teton National Park, Moose, Wyoming.

Graham, J. 2004. Arches National Park geologic resource evaluation report. Natural Resource Report NPS/NRPC/GRD/NRR—2004/005. National Park Service, Denver, Colorado. http://go.nps.gov/gripubs.

Greeley, R. 1977. Basaltic "plains" volcanism. Pages 23–44 *in* R. Greeley and J. S. King, editors. Volcanism of the eastern Snake River Plain, Idaho: a comparative planetary geology guidebook. National Aeronautics and Space Administration, Washington, DC.

Hackett, W. R., R. P. Smith, and S. Khericha. 2002. Volcanic hazards of the Idaho National Engineering and Environmental Laboratory, southeast Idaho. Pages 461–482 *in* B. Bonnichsen, C. M. White, and M. McCurry, editors. Tectonic and magmatic evolution of the Snake River Plain volcanic province. Bulletin 30. Idaho Geological Survey, Moscow, Idaho.

Henderson, P. 1986. Craters of the Moon: around the loop—a guide to the roads & trails of Craters of the Moon National Monument. Craters of the Moon Natural History Association, Arco, Idaho.

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

Hill, C., and P. Forti. 1997. Cave minerals of the world. 2nd edition. National Speleological Society, Huntsville, Alabama.

Hughes, S. S., R. P. Smith, W. R. Hackett, and S. R. Anderson. 1999. Mafic volcanism and environmental geology of the eastern Snake River Plain, Idaho. Pages 143–168 *in* S. S. Hughes and G. D. Thackray, editors. Guidebook to the geology of Eastern Idaho. Idaho Museum of Natural History, Pocatello, Idaho.

Idaho Geological Survey. 2011. Putting down roots in earthquake country: your handbook for earthquakes in Idaho, version 3/19/11. Idaho Geological Survey, Boise, Idaho. http://www.idahogeology.org/uploads/Hazards/Putting_Down_Roots_3_19_11.pdf.

Janecke, S. U. 1992. Kinematics and timing of three superposed extensional systems, east-central Idaho: evidence for an Eocene tectonic transition. Tectonics 11(6):1121–1138.

Janecke, S. U. 2007. Cenozoic extensional processes and tectonics in the northern Rocky Mountains: southwestern Montana and Eastern Idaho. Northwest Geology 36:111–132. https://www.researchgate.net/publication/228487848_Cenozoic_extensional_processes_and_tectonics_in_the_northern_Rocky_Mountains_Southwest_Montana_and_Eastern_Idaho.

Janecke, S. U., J. J. Blankenau, C. J. VanDenburg, and B. S. Gosen. 2001. Map of normal faults and extensional folds in the Tendoy Mountains and Beaverhead Range, southwest Montana and Eastern Idaho (scale 1:100,000). Miscellaneous Field Studies Map MF-2362. US Geological Survey, Reston, Virginia. https://pubs.usgs.gov/mf/2001/mf-2362/mf-2362.pdf.

Jex, S. C. 1984. 1984 cave mapping project. Unpublished report. Craters of the Moon National Monument, Arco, Idaho.

Johnson, A., D. Ruwadi, J. Chadwick, and N. Foster. 2014. Multiple eruptive phases of the Blue Dragon lava flow, Craters of the Moon National Monument, Idaho. Geological Society of America Abstracts with Programs 46(6):552. https://gsa.confex.com/gsa/2014AM/webprogram/Paper248878.html.

KellerLynn, K. 2010. Petrified Forest National Park: geologic resources inventory report. Natural Resource Report NPS/NRPC/GRD/NRR—2010/218. National Park Service, Fort Collins, Colorado. http://go.nps.gov/gripubs.

KellerLynn, K. 2012. El Malpais National Monument: geologic resources inventory report. Natural Resource Report NPS/NRSS/GRD/NRR—2012/578. National Park Service, Fort Collins, Colorado. http://go.nps.gov/gripubs.

KellerLynn, K. 2013. Crater Lake National Park: geologic resources inventory report. Natural resource report NPS/NRSS/GRD/NRR—2013/719. National Park Service, Fort Collins, Colorado. http://go.nps.gov/gripubs.

KellerLynn, K. 2014. Lassen Volcanic National Park: geologic resources inventory report. Natural resource report NPS/NRSS/GRD/NRR—2014/755. National Park Service, Fort Collins, Colorado. http://go.nps.gov/gripubs.

KellerLynn, K. 2015. Capulin Volcano National Monument: geologic resources inventory report. Natural Resource Report NPS/NRSS/GRD/NRR—2015/1031. National Park Service, Fort Collins, Colorado. http://go.nps.gov/gripubs.

Kenworthy, J. P., V. L. Santucci, M. McNerney, and K. Snell. 2005. Paleontological resource inventory and monitoring, Upper Columbia Basin Network. NPS Technical Information Center (TIC) number D-259. National Park Service, Washington, DC.

Ketner, K. B. 2012. An alternative hypothesis for the mid-Paleozoic Antler Orogeny in Nevada. Professional Paper 1790. US Geological Survey, Denver, Colorado. http://pubs.usgs.gov/pp/1790/PP1790_508.pdf.

King, J. S. 1977. Crystal Ice Cave and Kings Bowl crater, eastern Snake River Plain, Idaho. Pages 153–163 *in* R. Greeley and J. S. King, editors. Volcanism of the eastern Snake River Plain, Idaho—a comparative planetary geology guidebook. National Aeronautics and Space Administration, Washington, DC.

Kiver, E. P., and D. V. Harris. 1999. Geology of US parklands. Fifth edition. John Wiley & Sons, Inc., New York.

Kohler, R. 2008. Geoscientists in the Parks: Craters of the Moon National Monument and Preserve. Gaea (published by the Association for Women Geoscientists), November–December 2008:8–9.

Kukachka, F. R. 2010. Soil survey of Craters of the Moon National Monument and Preserve, Idaho. United States Department of Agriculture, Natural Resources Conservation Service, and United States Department of the Interior, National Park Service, in cooperation with United States Department of the Interior, Bureau of Land Management; University of Idaho, College of Agriculture; and Idaho Soil Conservation Commission. https://www.nrcs.usda.gov/Internet/FSE_MANUSCRIPTS/idaho/cratersNR_ID2010/CratersID.pdf.

Kuntz, M. A., D. E. Champion, and R. H. Lefebvre. 1990. Geologic map of the Fissure Butte quadrangle, Blaine and Butte Counties, Idaho (scale 1:24,000). Geologic Quadrangle Map GQ-1635. US Geological Survey, Reston, Virginia. https://pubs.er.usgs.gov/publication/gq1635.

Kuntz, M. A., D. E. Champion, E. C. Spiker, and R. H. Lefebvre. 1986a. Contrasting magma types and steady-state, volume-predictable, basaltic volcanism along the Great Rift, Idaho. Geological Society of America Bulletin 97:579–594.

Kuntz, M. A., D. E. Champion, E. C. Spiker, R. H. Lefebvre, and L. A. McBroome. 1982. The Great Rift and the evolution of the Craters of the Moon lava field, Idaho. Pages 423–437 *in* W. Bonnichsen, and R. M. Brecenridge, editors. Cenozoic geology of Idaho. Bulletin 26. Idaho Bureau of Mines and Geology, Boise, Idaho.

Kuntz, M. A., D. E. Champion, E. C. Spiker, R. H. Lefebvre, and L. A. McBroome. 1989c. The Great Rift and the evolution of the Craters of the Moon lava field, Idaho. Pages 423–437 *in* B. Bonnichsen and R. M. Breckenridge, editors. Cenozoic geology of Idaho. Bulletin 26. Idaho Geological Survey, Moscow, Idaho.

Kuntz, M. A., D. E. Champion, B. R. Turrin, P. B. Gans, and H. R. Covington. 2015. Geologic map of the north half of the Lake Walcott 30' x 60' quadrangle, Idaho (scale 1:100,000). Unpublished Scientific Investigations Map (SIM). US Geological Survey, Reston, Virginia.

Kuntz, M. A., H. R. Covington, and L. J. Schorr. 1992. An overview of basaltic volcanism of the eastern Snake River Plain, Idaho. Pages 227–268 *in* P. K. Link, M. A. Kuntz, and L. B. Platt, editors. Regional geology of eastern Idaho and western Wyoming. Memoir 179. Geological Society of America, Boulder, Colorado.

Kuntz, M. A., R. H. Lefebvre, and D. E. Champion. 1989a. Geologic map of the Inferno Cone quadrangle, Butte County, Idaho (scale 1:24,000). Geologic Quadrangle Map GQ-1632. US Geological Survey, Reston, Virginia. https://pubs.er.usgs.gov/publication/gq1632.

Kuntz, M. A., R. H. Lefebvre, and D. E. Champion. 1989b. Geologic map of The Watchman quadrangle, Butte County, Idaho (scale 1:24,000). Geologic Quadrangle Map GQ-1633. US Geological Survey, Reston, Virginia. https://pubs.er.usgs.gov/publication/gq1633.

Kuntz, M. A., D. E. Owen, D. E. Champion, P. B. Gans, S. C. Smith, and C. Brossy. 2004. Geology of the Craters of the Moon 30' × 60' map area and new perspectives on basaltic volcanism of the eastern Snake River Plain, Idaho. Pages 136–155 *in* K. M. Haller and S. H. Wood, editors. Geological field trips in southern Idaho, Eastern Oregon, and northern Nevada. Open-File Report OFR-2004-1222. US Geological Survey, Reston, Virginia. https://pubs.usgs.gov/of/2004/1222/chapters/Ch10.pdf.

Kuntz, M. A., B. Skipp, D. E. Champion, P. B. Gans, D. P. Van Sistine, and S.R. Snyders. 2007. Geologic map of the Craters of the Moon 30' × 60' quadrangle, Idaho (scale 1:100,000). Scientific Investigations Map SIM-2969. US Geological Survey, Reston, Virginia. http://pubs.usgs.gov/sim/2007/2969/.

Kuntz, M. A., E. C. Spiker, M. Rubin, D. E. Champion, and R. H. Lefebvre. 1986b. Radiocarbon studies of latest Pleistocene and Holocene lava flows of the Snake River Plain, Idaho—data, lessons, interpretations. Quaternary Research 25:163–176.

Lancaster, N. 2009. Aeolian features and processes. Pages 1–25 *in* R. Young and L. Norby, editors. Geological monitoring. Geological Society of America, Boulder, Colorado. http://go.nps.gov/monitor_aeolian.

Larson, C. 1990. A glossary of lava tube features. Pages 21–55 *in* V. Johnson, editor. National Speleological Society Convention guide book. National Speleological Society, Huntsman, Alabama, USA.

Lillie, R. J. 2005. Parks and plates: the geology of our national parks, monuments, and seashores. W. W. Norton and Company, New York.

Limbert, R. W. 1924. Among the craters of the moon: an account of the first expeditions through the remarkable volcanic lava beds of southern Idaho. The National Geographic Magazine 45:303–328. https://www.nps.gov/crmo/learn/historyculture/loader.cfm?csModule=security/getfile&amp%3bpageid=300995.

Link, P. K., and S. U. Janecke. 1999. Geology of east-central Idaho: geologic roadlogs for the Big and Little Lost River, Lemhi, and Salmon River valleys. Pages 295–334 *in* S. S. Hughes and G. D. Thackray, editors. Guidebook to the geology of eastern Idaho. Idaho Museum of Natural History, Pocatello, Idaho.

Link, P. K., J. B. Mahoney, D. J. Bruner, L. D. Batatian, E. Wilson, and F. J. C. Williams. 1995. Stratigraphic setting of sediment-hosted mineral deposits in the eastern part of the Hailey 1° × 2° quadrangle and part of the southern part of the Challis 1° × 2° quadrangle, south-central Idaho. Pages C1–C33 (Chapter C) *in* R. G. Worl, P. K. Link, G. R. Winkler, and K. M. Johnson, editors. Geology and mineral resources of the Hailey 1° × 2° quadrangle and the western part of the Idaho Falls 1° × 2° quadrangle, Idaho. Bulletin 2064. US Geological Survey, Denver, Colorado. https://pubs.usgs.gov/bul/2064a-r/report.pdf.

Link, P. K., I. Warren, J. M. Preacher, and B. Skipp. 1996. Stratigraphic analysis and interpretation of the Mississippian Copper Basin Group, McGowan Creek Formation, and White Knob Limestone, south-central Idaho. Pages 117–144 *in* M. W. Longman and M. D. Sonnenfeld, editors. Paleozoic systems of the Rocky Mountain region. SEPM (Society for Sedimentary Geology), Rocky Mountain Section, Denver, Colorado.

Lipman, P. W. 1980. Cenozoic volcanism in the western United States: implications for continental tectonics. Pages 161–174 *in* Studies in geophysics: continental tectonics. National Academy of Sciences, Washington, DC.

Lipman, P. W., H. J. Prostka, and R. L. Christiansen. 1971. Evolving subduction zones in the western United States, as interpreted from igneous rocks. Science 174:821–825.

Lipman, P. W., H. J. Prostka, and R. L. Christiansen. 1972. Cenozoic volcanism and plate-tectonic evolution of the western United States, early and middle Cenozoic. Philosophical Transactions of the Royal Society of London 271:217–248.

MacDonald, G. A. 1972. Volcanoes. Prentice-Hall, Inc., Englewood Cliffs, New Jersey.

Malde, H. E. 1968. The catastrophic Late Pleistocene Bonneville flood in the Snake River Plain, Idaho. Professional Paper 59. US Geological Survey, Reston, Virginia. https://pubs.usgs.gov/pp/0596/report.pdf.

Miller, R. M. 1969. Blue glass from Craters of the Moon National Monument, Idaho. Unpublished report. Henry Ford Community College, Science Division, Dearborn, Michigan. https://irma.nps.gov/DataStore/Reference/Profile/18037.

Miller, R. M. 1970. Blue glass from Craters of the Moon National Monument, Idaho. Geological Society of America Abstracts with Programs 2(6):397.

Miller, S. J. 1989. Paleontology of the eastern Snake River Plain. Unpublished manuscript. Organization and location unknown. [Cited in Owen and Melander (2014).]

Monahan, W. B., and N. A. Fisichelli. 2014. Recent climate change exposure of Craters of the Moon National Monument and Preserve. Climate change resource brief [based on] Climate exposure of US national parks in a new era of change. PLoS ONE 9(7):e101302. doi:10.1371/journal.pone.0101302. http://journals.plos.org/plosone/article?id=10.1371/journal.pone.0101302.

Monkevich, N. S., T. G. Gregoire, and J. W. Roggenbuck. 1994. Executive summary of assessing petrified wood change in Petrified Forest National Park. Pages 138–158 (Appendix I) *in* J. W. Roggenbuck, C. J. Widner, and D. W Stratton, editors. Reducing Theft of Petrified Wood at Petrified Forest National Park. NPS Technical Information Center (TIC) number D-173. Virginia Tech, Department of Forestry, Blacksburg, Virginia.

Mote, P., A. K. Snover, S. Capalbo, S. D. Eigenbrode, P. Glick, J. Littell, R. Raymondi, and S. Reeder. 2014. Chapter 21: Northwest. Pages 487–513 *in* J. M. Melillo, T. C. Richmond, and G. W. Yohe, editors. Climate change impacts in the United States: the third national climate assessment. US Global Change Research Program, Washington, DC. http://nca2014.globalchange.gov/report/regions/northwest.

Moye, F. J., W. R. Hackett, J. D. Blakley, and L. G. Snyder. 1988. Regional geologic setting and volcanic stratigraphy of the Challis volcanic field, central Idaho. Pages 87–97 *in* P. K. Link and W. R. Hackett, editors. Guidebook to the geology of central and southern Idaho. Bulletin 27. Idaho Geological Survey, Moscow, Idaho. http://geology.isu.edu/Digital_Geology_Idaho/papers/B-27ch01-4.pdf.

National Park Service. 1999. Geologic resources inventory workshop summary, Craters of the Moon National Monument, Idaho. Geologic Resources Division and Natural Resources Information Division, Denver and Fort Collins, Colorado. http://go.nps.gov/gripubs.

National Park Service. 2005. Craters of the Moon National Monument and Preserve proposed management plan/final environmental impact statement. National Park Service, Pacific West Regional Office, Oakland, California.

National Park Service. 2010. Climate friendly parks: Craters of the Moon National Monument and Preserve action plan. National Park Service, Climate Friendly Parks Program, Washington, DC. https://www.nps.gov/subjects/climatechange/cfpprogram.htm.

National Park Service. 2013. SRI - soil survey geographic (SSURGO) for Craters of the Moon National Monument and Preserve, Idaho. Developed in conjunction with the US Department of Agriculture, Natural Resources Conservation Service, Boise, Idaho. https://irma.nps.gov/DataStore/Reference/Profile/1049042.

National Park Service. 2014. Foundation document: Craters of the Moon National Monument and Preserve, Idaho (July 2014). Craters of the Moon National Monument and Preserve, Arco, Idaho, and Denver Service Center, Planning Division, Denver, Colorado. https://irma.nps.gov/DataStore/Reference/Profile/2219742.

National Park Service. 2016a. National Natural Landmarks: Great Rift system. Online directory. National Park Service, National Natural Landmarks Program, Pacific West Region, Sedro Woolley, Washington. https://www.nps.gov/subjects/nnlandmarks/nation.htm (accessed 21 August 2018).

National Park Service. 2016b. State of the park report for Craters of the Moon National Monument and Preserve. State of the Park Series No. 24. National Park Service, Washington, DC. https://www.nps.gov/stateoftheparks/crmo/CRMO_StateOfThePark.pdf.

National Park Service. 2017. Astronauts. Online information. Craters of the Moon National Monument and Preserve, Arco, Idaho. https://www.nps.gov/crmo/learn/historyculture/astronauts.htm (accessed 27 August 2018).

National Park Service. 2018. NPS stats, National Park Service visitor use statistics. Stats 2.6.0.14041_20171229:09:28:47. Online information. National Park Service, Washington, DC. https://irma.nps.gov/Stats/ (accessed 11 July 2018).

National Park Service and Bureau of Land Management. 2007. Craters of the Moon National Monument and Preserve management plan. NPS Technical Information Center (TIC) number D-92. Craters of the Moon National Monument and Preserve, Idaho. https://www.nps.gov/crmo/getinvolved/planning.htm.

National Park Service and US Geological Survey. 2000. Craters of the Moon National Monument: geologic processes & human influences that affect those processes. Data set report (GPRA goal Ib4). Scoping meeting held 31 August–1 September 2000. National Park Service, Geologic Resources Division, Denver, Colorado. http://www.nps.gov/crmo/naturescience/upload/crmo_geo_report.pdf.

Nayel, A., K. Murdaugh, J. Peers, and J. Chadwick. 2012. Hyperspectral mapping and geochemical analyses of multiple eruptive phases of the Blue Dragon lava flow, Craters of the Moon National Monument. Geological Society of America Abstracts with Programs 44(7):542. https://gsa.confex.com/gsa/2012AM/webprogram/Paper212219.html.

Nichols, R. L. 1946. McCartys basalt flow, Valencia [now Cibola] County, New Mexico. Geological Society of America Bulletin 57(11):1049–1086.

Niles, J. H., D. E. Owen, M. A. Kuntz, R, H. Lefebre, D. E. Champion, A. C. Barnes, B. R. Brulet, S. M. Chemtob, R. P. Clennon, N. Hansen, S. M. Keane, R. M. Kohler, B. L. Mocsny, T. A. Rivera, E. K. Shirley, K. E. Truitt, A. J. Tveter, and K. A. Wetherell. 2011. Geologic map of the core visitation area of the Craters of the Moon National Monument and Preserve, south-central Idaho (scale 1:24,000), with descriptions of 38 points of geologic interest [on accompanying poster]. National Park Service, Geological Society of America, Bureau of Land Management, and US Geological Survey. Prepared for Craters of the Moon National Monument and Preserve, Arco, Idaho.

Nilsen, T. H., and J. H. Stewart. 1980. The Antler Orogeny: mid-Paleozoic tectonism in western North America. Geology 8(6):298–302.

O'Connor, J. E. 1993. Hydrology, hydraulics, and geomorphology of the Bonneville Flood. Special Paper 274. Geological Society of America, Boulder, Colorado.

Owen, D. E. Publication date unknown. Teachers' guide to Broken Top loop. Craters of the Moon National Monument and Preserve, Arco, Idaho. https://www.nps.gov/crmo/learn/education/broken-top-loop-guide.htm.

Owen, D. E. 2004. Geology of Craters of the Moon. Craters of the Moon National Monument and Preserve, and Craters of the Moon Natural History Association, Arco, Idaho. https://web.archive.org/web/20080417221406/http://www.nps.gov/archive/crmo/geology/geology-1.htm.

Owen, D. E. 2008. Geology of Craters of the Moon (revised). Craters of the Moon National Monument and Preserve, and Craters of the Moon Natural History Association, Arco, Idaho.

Owen, D. E. 2011a. Caves at CRMO. Unpublished report. Craters of the Moon National Monument and Preserve, Arco, Idaho.

Owen, D. E. 2011b. Geologic story of Craters of the Moon and the eastern Snake River Plain. PowerPoint presentation. Crater of the Moon National Monument and Preserve, Arco, Idaho.

Owen, D. E., and S. Melander. 2014. Geology of Crater of the Moon. Craters of the Moon National Monument and Preserve, Arco, Idaho, and Geological Society of America, Boulder, Colorado. https://nature.nps.gov/geology/gip_embed/web_products/CRMO_2013_GIP_Melander_Sonja_GeologyGuide.pdf.

Paull, R. A., M. A. Wolbrink, R. G. Volkmann, and R. L. Grover. 1972. Stratigraphy of the Copper Basin Group, Pioneer Mountains, south-central Idaho. American Association of Petroleum Geologists Bulletin 56(8):1370–1401.

Payne, S. 2003. Earthquake activity in southeastern Idaho. Geoscience research, INEEL Seismic Monitoring Program. Idaho National Engineering and Environmental Laboratory, Idaho Falls, Idaho.

Peinado, J. G. 2013. El Malpais and Craters of the Moon National Monuments; management, protection, and discovery. Geological Society of America Abstracts with Programs 45(7):430. https://gsa.confex.com/gsa/2013AM/webprogram/Paper223455.html.

Pierce, K. L., and L. A. Morgan. 1992. The track of the Yellowstone hot spot: volcanism, faulting, and uplift. Pages 1–53 *in* P. K. Link, M. A. Kuntz, and L. B. Platt, editors. Regional geology of eastern Idaho and western Wyoming. Memoir 179. Geological Society of America, Boulder, Colorado. https://deepcarbon.net/sites/dco.rpi.edu/files/pierce_and_morgan_yellowstonehotspot11.pdf.

Price, L. G. 2010. The geology of northern New Mexico's parks, monuments, and public lands. New Mexico Bureau of Geology and Mineral Resources, Socorro, New Mexico.

Prinz, M. 1970. Idaho rift system, Snake River Plain, Idaho. Geological Society of America Bulletin 81:941–947.

Putirka, K. D., M. A. Kuntz, D. M. Unruh, and N. Vaid. 2009. Magma evolution and ascent at the Craters of the Moon and neighboring volcanic fields, southern Idaho, USA: implications for the evolution of polygenetic and monogenetic volcanic fields. Journal of Petrology 50(9):1639–1665.

Quick, A. M. 2004. Identification of lava tube resources at Craters of the Moon NM; aiding resource management and geologic study of basaltic volcanism. Geological Society of America Abstracts with Programs 36(5):190. https://gsa.confex.com/gsa/2004AM/finalprogram/abstract_81032.htm.

Richman, R. 2010. Digital volcanic geology of Capulin Volcano National Monument and vicinity (scale 1:24,000), including report on the creation of a geologic inventory map for Capulin Volcano National Monument. Prepared by Student Conservation Association (SCA) geology and interpretation intern for Capulin Volcano National Monument, Capulin, New Mexico.

Rodgers, D. W., P. K. Link, and A. D. Huerta. 1995. Structural framework of mineral deposits hosted by Paleozoic rocks in the northeastern part of the Hailey 1° x 2° quadrangle, south-central Idaho. Pages B1–B18 *in* R. G. Worl, P. K. Link, G. R. Winkler, and K. M. Johnson, editors. Geology and mineral resources of the Hailey 1° x 2° quadrangle and the western part of the Idaho Falls 1° x 2° quadrangle, Idaho. Bulletin 2064-B. US Geological Survey, Reston, Virginia. https://pubs.er.usgs.gov/publication/b2064AR.

Roggenbuck, J. W., C. J. Widner, and D. W Stratton. 1997. Reducing theft of petrified wood at Petrified Forest National Park. Final research report (August 1997). NPS Technical Information Center number D-173. Virginia Tech, Department of Forestry, Blacksburg, Virginia.

Rogers, B. W., and C. J. Mosch. 1997a. In the basement—lava-tube origins and morphology. Pages 61–68 *in* K. Mabery, editor. Natural history of El Malpais National Monument. Bulletin 156. New Mexico Bureau of Mines and Mineral Resources, Socorro, New Mexico. https://geoinfo.nmt.edu/publications/monographs/bulletins/downloads/156/B156.pdf.

Rogers, B. W., and C. J. Mosch. 1997b. Snowballs in the underground—lava-tube deposits and morphology. Pages 83–90 *in* K. Mabery, editor. Natural history of El Malpais National Monument. Bulletin 156. New Mexico Bureau of Mines and Mineral Resources, Socorro, New Mexico. https://geoinfo.nmt.edu/publications/monographs/bulletins/downloads/156/B156.pdf.

Ross, C. P. 1962. Upper Paleozoic rocks in central Idaho. American Association of Petroleum Geologists Bulletin 46(3):384–405.

Ruffini, J., and S. Edie. 2010. 2010 waterhole inventory. Geoscientists-in-the-Parks document, 2010-CRMO. National Park Service, Denver, Colorado. http://nature.nps.gov/geology/gip/web_products/CRMO_2010_GIP_Ruffini_WaterholeInventory.pdf.

Ruffini, J. J., and L. J. McHenry. 2010. Hematite & sulfate minerals in lava tubes; potential Mars analogues. Geological Society of America Abstracts with Programs 42(5):227–228.

Russell, I. C. 1902. Geology and water resources of the Snake River Plains of Idaho. Bulletin 199. US Geological Survey, Washington, DC. https://pubs.er.usgs.gov/publication/b199.

Sanford, R. F. 2005. Geology and stratigraphy of the Challis Volcanic Group and related rocks, Little Wood River area, south-central Idaho, with a section on geochronology by Lawrence W. Snee. Bulletin 2064-II. US Geological Survey, Reston, Virginia. https://pubs.usgs.gov/bul/2064/ii/pdf/B2064-II.pdf.

Santucci, V. L., J. P. Kenworthy, and R. Kerbo. 2001. An inventory of paleontological resources associated with National Park Service caves. NPS Technical Information Center (TIC) number D-2231. National Park Service, Geologic Resources Division, Lakewood, Colorado.

Santucci, V. L., J. P. Kenworthy, and A. L. Mims. 2009. Monitoring in situ paleontological resources. Pages 189–204 *in* R. Young and L. Norby, editors. Geological monitoring. Geological Society of America, Boulder, Colorado. http://go.nps.gov/paleo_monitoring (accessed Day Month Year).

Santucci, V. L., L. Walkup, T. Casadevall, J. Wood, and T. Connors. 2012. An inventory of National Park Service fossil tree molds preserved within lava flows. Poster. First International Congress on Management and Awareness in Protected Volcanic Landscapes, 21–25 May 2012, Olot, Spain.

Scarth, A. 1994. Volcanoes—an introduction. Texas A&M University Press, College Station, Texas.

Scott, W. E. 1982. Surficial geologic map of the eastern Snake River Plain and adjacent areas, 111° to 115° W., Idaho and Wyoming (scale 1:250,000). Miscellaneous Investigations Series Map I-1372. US Geological Survey, Reston, Virginia. https://pubs.er.usgs.gov/publication/i1372.

Skipp, B., and M. A. Kuntz. 2009. [Pamphlet to accompany] Geologic map of the Arco 30' × 60' quadrangle, south-central Idaho (scale 1:100,000). Mapped by B. Skipp, L. G. Snider, S. U. Janecke, and M. A. Kuntz. Geologic Map GM-47. Idaho Geological Survey, Moscow, Idaho. http://www.idahogeology.org/Products/MapCatalog/default.asp?switch=title&value=GM-47.

Skipp, B., M. A. Kuntz, and L. A. Morgan. 1990. Geologic map of Mackay 4 (Grouse) SE quadrangle, Butte County, Idaho (scale 1:24,000). Open-File Report OFR-89-431. US Geological Survey, Reston, Virginia. https://pubs.er.usgs.gov/publication/ofr89431.

Skipp, B., L. G. Snider, S. U. Janecke, and M. A. Kuntz. 2009. Geologic map of the Arco 30' × 60' quadrangle, south-central Idaho (scale 1:100,000). Geologic Map GM-47. Idaho Geological Survey, Moscow, Idaho. http://www.idahogeology.org/Products/MapCatalog/default.asp?switch=title&value=GM-47.

Smith, J. G., J. Dehn, R. P. Hoblitt, R. G. LaHusen, J. B. Lowenstern, S. C. Moran, L. McClelland, K. A. McGee, M. Nathenson, P. G. Okubo, J. S. Pallister, M. P. Poland, J. A. Power, D. J. Schneider, and T. W. Sisson. 2009. Volcano monitoring. Pages 273–305 *in* R. Young and L. Norby, editors. Geological monitoring. Geological Society of America, Boulder, Colorado. http://go.nps.gov/monitor_volcanic.

Smith, R. B., and L. J. Siegel. 2000. Windows into the Earth: the geologic story of Yellowstone and Grand Teton National Parks. Oxford University Press, New York, New York.

Stearns, H. T. 1928. The "craters of the moon" in Idaho. Geophysical Journal 71:43–49.

Steensen, D. L., V. A. Smith, and V. Snitzler-Neeck. 1995. Restoring for the future through cooperation: the Martin Mine reclamation project, Craters of the Moon National Monument. *In* R. M. Linn, editor. Sustainable society and protected areas: contributed papers of the 8th Conference on Research and Resource Management in Parks and on Public Lands. George Wright Society, Hancock, Michigan.

Summerfield, M. A. 1994. Aeolian process and landforms: fine-grained deposits. Pages 256–257 (section 10.3.7) *in* Global geomorphology: an introduction to the study of landforms. Longman Scientific & Technical, copublished in the United States with John Wiley & Sons, Inc., New York.

Swanson, D. A. 1973. Pahoehoe flows from the 1969–1971 Mauna Ulu eruption, Kilauea Volcano, Hawaii. Geological Society of America Bulletin 36(1):5–17.

Taylor-Edmonston, L. 1994. Caves of molten stone, Craters of the Moon National Monument. Site bulletin/field guide with maps by S. Earl and A. Earl, Idaho Cave Survey. Craters of the Moon Natural History Association, Arco, Idaho.

Thornberry-Ehrlich, T. 2004. Natural Bridges National Monument geologic resource evaluation report. Natural Resource Report NPS/NRPC/GRD/NRR—2004/003. National Park Service, Denver, Colorado. http://go.nps.gov/gripubs.

Toomey, R. S. III. 2009. Geological monitoring of caves and associated landscapes. Pages 27–46 *in* R. Young and L. Norby, editors. Geological monitoring. Geological Society of America, Boulder, Colorado. http://go.nps.gov/monitor_cavekarst.

Truitt, K. E., and R. J. Lillie. 2007. Interpreting a weird and scenic landscape to park visitors: tectonic and volcanic processes of Craters of the Moon National Monument and Preserve, Idaho. Oregon State University, Department of Geosciences, Corvallis, Oregon.

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

US Geological Survey. 2014. Volcanic hazards from the region around Craters of the Moon lava field. Online information. US Geological Survey, Volcano Hazards Program, Cascades Volcano Observatory, Vancouver, Washington. https://volcanoes.usgs.gov/volcanoes/craters_of_the_moon/craters_of_the_moon_hazard_115.html.

US Geological Survey. 2016. Glossary. Online information. US Geological Survey, Volcano Hazards Program, Reston, Virginia. http://volcanoes.usgs.gov/vsc/glossary/.

USGS Volcano Hazards Program. 2015a. Black Butte Crater lava field: summary. Online information. Cascades Volcano Observatory, Portland, Oregon. https://volcanoes.usgs.gov/volcanoes/black_butte_crater_lava_field/ (accessed 24 May 2017).

USGS Volcano Hazards Program. 2015b. Hell's Half Acre lava field: summary. Online information. Cascades Volcano Observatory, Portland, Oregon. https://volcanoes.usgs.gov/volcanoes/hells_half_acre/ (accessed 24 May 2017).

USGS Volcano Hazards Program. 2015c. Wapi lava field: summary. Online information. Cascades Volcano Observatory, Portland, Oregon. https://volcanoes.usgs.gov/volcanoes/wapi_lava_field/ (accessed 24 May 2017).

Vaughan, K. L. 2008. Pedogenesis at Craters of the Moon National Monument and Preserve, Idaho, USA. Dissertation. University of Idaho, Moscow, Idaho.

Vaughan, K. L., P. A. McDaniel, and W. M. Phillips. 2011. Episodic soil succession on basaltic lava fields in a cool, dry environment. Soil Science of America Journal 75:1462–1470.

Wagner, F. H., R. Angell, M. Hahn, T. Lawlor, R. Tausch, and D. Toweill. 2003. Natural ecosystems III. The Great Basin. Pages 207–240 *in* F. H. Wagner, editor. Rocky Mountain/Great Basin regional climate-change assessment. Report for the US Global Change Research Program. Utah State University, Logan, Utah.

Walker, G. P. L. 1972. Compound and simple lava flows and flood basalts. Bulletin of Volcanology 36:579–590.

Walkup, L. 2012. NPS volcanic resources/hazard inventory: Craters of the Moon National Monument and Preserve. Draft report by GSA GeoCorps America guest scientist. National Park Service, Geologic Resources Division, Lakewood, Colorado.

Wieczorek, G. F., and J. B. Snyder. 2009. Monitoring slope movements. Pages 245–271 *in* R. Young and L. Norby, editors. Geological monitoring. Geological Society of America, Boulder, Colorado. http://go.nps.gov/monitor_slopes.

WNS Working Group. 2012. White nose syndrome response plan, Craters of the Moon National Monument and Preserve (revised March 2012). Working group composed of Douglass Owen (geologist/education specialist/research permit coordinator), John Apel (chief of resource management), Todd Stefanic (wildlife biologist), and Ted Stout (chief of interpretation and education). Craters of the Moon National Park and Preserve, Arco, Idaho. https://www.nps.gov/crmo/getinvolved/planning.htm.

Young, R. and L. Norby, editors. 2009. Geological monitoring. Geological Society of America, Boulder, Colorado. http://go.nps.gov/geomonitoring.

Additional References

These references, resources, and websites may be of use to resource managers. Refer to Appendix B for laws, regulations, and policies that apply to NPS geologic resources.

Bureau of Land Management

- Craters of the Moon National Monument: https://www.blm.gov/programs/national-conservation-lands/national-monuments/idaho
- Upper Snake Field Office: https://www.blm.gov/office/upper-snake-field-office

Climate Change Resources

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

Geological Surveys and Societies

- Idaho Geological Survey: http://www.idahogeology.org/
- 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/

Geology of National Park Service Areas

- NPS Geologic Resources Division (Lakewood, Colorado) Energy and Minerals; Active Processes and Hazards; Geologic Heritage: http://go.nps.gov/geology
- NPS Geologic Resources Division Education Website: http://go.nps.gov/geoeducation
- NPS Geologic Resources Inventory: http://go.nps.gov/gri
- NPS Geoscientists-in-the-Parks (GIP) internship and guest scientist program: http://go.nps.gov/gip
- 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://go.nps.gov/views

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://go.nps.gov/geomonitoring
- NPS Technical Information Center (TIC) (Denver, Colorado; repository for technical documents): https://www.nps.gov/orgs/1804/dsctic.htm

US Geological Survey Reference Tools

- National geologic map database (NGMDB): http://ngmdb.usgs.gov/ngmdb/ngmdb_home.html
- Geologic names lexicon (GEOLEX; geologic unit nomenclature and summary): http://ngmdb.usgs.gov/Geolex/search
- Geographic names information system (GNIS; official listing of place names and geographic features): http://gnis.usgs.gov/
- GeoPDFs (download 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://pubs.usgs.gov/imap/i2720/

Volcano Observatories

- Yellowstone Volcano Observatory: https://volcanoes.usgs.gov/volcanoes/yellowstone/
- Cascade Volcano Observatory (CVO): https://volcanoes.usgs.gov/observatories/cvo/
- CVO information about the Craters of the Moon lava field: https://volcanoes.usgs.gov/volcanoes/craters_of_the_moon/
- CVO information about the Wapi lava field: https://volcanoes.usgs.gov/volcanoes/wapi_lava_field/

Appendix A: Scoping Participants

The following people attended the GRI scoping meeting, held on 12–13 May 1999, or the follow-up report writing conference call, held on 2 February 2017. 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.

1999 Scoping Meeting Participants

Name	Affiliation	Position
John Apel	Craters of the Moon National Monument	Chief of resource management
Dave Clark	Craters of the Moon National Monument	Chief of interpretation
Tim Connors	NPS Geologic Resources Division	Geologist
Marsha Davis	NPS Columbia Cascades Support Office	Geologist
Bob DeTar	Bureau of Land Management (Boise, Idaho)	Geologist
Joe Gregson	NPS Natural Resources Information Division	GRI coordinator
Ron Kerbo	NPS Geologic Resources Division	Cave specialist
Mel Kuntz	US Geological Survey	Geologist
Terry Maley	Bureau of Land Management (Boise, Idaho)	Geologist (minerals)
Jim Morris	Craters of the Moon National Monument	Superintendent
Doug Owen	Craters of the Moon National Monument	Geologist/education specialist/research permit coordinator

2017 Conference Call Participants

Name	Affiliation	Position
John Apel	Craters of the Moon National Monument and Preserve	Chief of resource management, retired
Michael Barthelmes	NPS Geologic Resources Division	Geologist, Writer/editor
Katie KellerLynn	Colorado State University	Geologist, GRI report writer
Jason Kenworthy	NPS Geologic Resources Division	Geologist, GRI reports coordinator
Mel Kuntz	US Geological Survey	Emeritus
Linda Manning	Craters of the Moon National Monument and Preserve	Chief of integrated resources
Doug Owen	Craters of the Moon National Monument and Preserve	Geologist and interpreter, retired
Dale Pate	NPS Geologic Resources Division	Cave and karst program lead
Bill Phillips	Idaho Geological Survey	Geologist
Ted Stout	Craters of the Moon National Monument and Preserve	Chief of interpretation and education
Wade Vagias	Craters of the Moon National Monument and Preserve	Superintendent

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 NPS 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 December 2017. Contact the NPS Geologic Resources Division for detailed guidance.

Resource	Resource-specific Laws	Resource-specific Regulations	2006 Management Policies
Caves and Karst Systems	**Federal Cave Resources Protection Act of 1988, 16 USC §§ 4301 – 4309** requires Interior/Agriculture to identify "significant caves" on Federal lands, regulate/restrict use of those caves as appropriate, and include significant caves in land management planning efforts. Imposes civil and criminal penalties for harming a cave or cave resources. Authorizes Secretaries to withhold information about specific location of a significant cave from a Freedom of Information Act (FOIA) requester. **National Parks Omnibus Management Act of 1998, 54 USC § 100701** protects the confidentiality of the nature and specific location of cave and karst resources. **Lechuguilla Cave Protection Act of 1993, Public Law 103-169** created a cave protection zone (CPZ) around Lechuguilla Cave in Carlsbad Caverns National Park. Within the CPZ, access and the removal of cave resources may be limited or prohibited; existing leases may be cancelled with appropriate compensation; and lands are withdrawn from mineral entry.	**36 CFR § 2.1** prohibits possessing/destroying/disturbing…cave resources…in park units. **43 CFR Part 37** states that all NPS caves are "significant" and sets forth procedures for determining/releasing confidential information about specific cave locations to a FOIA requester.	**Section 4.8.1.2** requires NPS to maintain karst integrity, minimize impacts. **Section 4.8.2** requires NPS to protect geologic features from adverse effects of human activity. **Section 4.8.2.2** requires NPS to protect caves, allow new development in or on caves if it will not impact cave environment, and to remove existing developments if they impair caves. **Section 6.3.11.2** explains how to manage caves in/adjacent to wilderness.
Paleontology	**National Parks Omnibus Management Act of 1998, 54 USC § 100701** 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. **43 CFR Part 49** (in development) will contain the DOI regulations implementing the Paleontological Resources Preservation Act.	**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.

Resource	Resource-specific Laws	Resource-specific Regulations	2006 Management Policies
Recreational Collection of Rocks Minerals	**NPS Organic Act, 54 USC. § 100101 et seq.** directs the NPS to conserve all resources in parks (which includes rock and mineral resources) unless otherwise authorized by law. **Exception: 16 USC. § 445c (c)** Pipestone National Monument enabling statute. Authorizes American Indian collection of catlinite (red pipestone).	**36 C.F.R. § 2.1** prohibits possessing, destroying, disturbing mineral resources…in park units. **Exception: 36 C.F.R. § 7.91** allows limited gold panning in Whiskeytown. **Exception: 36 C.F.R. § 13.35** allows some surface collection of rocks and minerals in some Alaska parks (not Klondike Gold Rush, Sitka, Denali, Glacier Bay, and Katmai) by non-disturbing methods (e.g., no pickaxes), which can be stopped by superintendent if collection causes significant adverse effects on park resources and visitor enjoyment.	**Section 4.8.2** requires NPS to protect geologic features from adverse effects of human activity.
Geothermal	**Geothermal Steam Act of 1970, 30 USC. § 1001 et seq. as amended in 1988**, states ● No geothermal leasing is allowed in parks. ● "Significant" thermal features exist in 16 park units (the features listed by the NPS at **52 Fed. Reg. 28793-28800** (August 3, 1987), plus the thermal features in Crater Lake, Big Bend, and Lake Mead). ● NPS is required to monitor those features. ● 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. ● Monitor significant thermal features.

Resource	Resource-specific Laws	Resource-specific Regulations	2006 Management Policies
Mining Claims (Locatable Minerals)	**Mining in the Parks Act of 1976, 54 USC § 100731 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. **43 CFR Part 36** governs access to mining claims located in, or adjacent to, National Park System units in Alaska.	**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, 54 USC § 100751 et seq.** authorizes the NPS to promulgate regulations to protect park resources and values (from, for example, the exercise of mining and mineral rights). Individual Park Enabling Statutes: • **16 USC § 230a** (Jean Lafitte NHP & Pres.) • **16 USC § 450kk** (Fort Union NM), • **16 USC § 459d-3** (Padre Island NS), • **16 USC § 459h-3** (Gulf Islands NS), • **16 USC § 460ee** (Big South Fork NRRA), • **16 USC § 460cc-2(i)** (Gateway NRA), • **16 USC § 460m** (Ozark NSR), • **16 USC § 698c** (Big Thicket N Pres.), • **16 USC § 698f** (Big Cypress N Pres.)	**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 outside of Alaska to • demonstrate bona fide title to mineral rights; • submit an Operations Permit Application 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. **43 CFR Part 36** governs access to nonfederal oil and gas rights located in, or adjacent to, National Park System units in Alaska.	**Section 8.7.3** requires operators to comply with 9B regulations.

Resource	Resource-specific Laws	Resource-specific Regulations	2006 Management Policies
Federal Mineral Leasing (Oil, Gas, and Solid Minerals)	**The Mineral Leasing Act, 30 USC § 181 et seq., and the Mineral Leasing Act for Acquired Lands, 30 USC § 351 et seq.** do not authorize the BLM to lease federally owned minerals in NPS units. **Combined Hydrocarbon Leasing Act, 30 USC §181**, allowed owners of oil and gas leases or placer oil claims in Special Tar Sand Areas (STSA) to convert those leases or claims to combined hydrocarbon leases, and allowed for competitive tar sands leasing. This act did not modify the general prohibition on leasing in park units but did allow for lease conversion in GLCA, which is the only park unit that contains a STSA. **Exceptions: Glen Canyon NRA (16 USC § 460dd et seq.), Lake Mead NRA (16 USC § 460n et seq.), and Whiskeytown-Shasta-Trinity NRA (16 USC § 460q et seq.)** authorizes the BLM to issue federal mineral leases in these units provided that the BLM obtains NPS consent. Such consent must be predicated on an NPS finding of no significant adverse effect on park resources and/or administration. American Indian Lands Within NPS Boundaries Under the **Indian Allottee Leasing Act of 1909, 25 USC §396, and the Indian Leasing Act of 1938, 25 USC §396a, §398 and §399, and Indian Mineral Development Act of 1982, 25 USCS §§2101-2108**, all minerals on American Indian trust lands within NPS units are subject to leasing. **Federal Coal Leasing Amendments Act of 1975, 30 USC § 201** prohibits coal leasing in National Park System units.	**36 CFR § 5.14** states prospecting, mining, and…leasing under the mineral leasing laws [is] prohibited in park areas except as authorized by law. **BLM regulations at 43 CFR Parts 3100, 3400, and 3500** govern Federal mineral leasing. **43 CFR Part 3160** governs onshore oil and gas operations, which are overseen by the BLM. Regulations re: Native American Lands within NPS Units: • **25 CFR Part 211** governs leasing of tribal lands for mineral development. • **25 CFR Part 212** governs leasing of allotted lands for mineral development. • **25 CFR Part 216** governs surface exploration, mining, and reclamation of lands during mineral development. • **25 CFR Part 224** governs tribal energy resource agreements. • **25 CFR Part 225** governs mineral agreements for the development of Indian-owned minerals entered into pursuant to the **Indian Mineral Development Act of 1982, Pub. L. No. 97-382, 96 Stat. 1938** (codified at **25 USC §§ 2101-2108**). • **30 CFR §§ 1202.100-1202.101** governs royalties on oil produced from Indian leases. • **30 CFR §§ 1202.550-1202.558** governs royalties on gas production from Indian leases. • **30 CFR §§ 1206.50-1206.62 and §§ 1206.170-1206.176** governs product valuation for mineral resources produced from Indian oil and gas leases. • **30 CFR § 1206.450** governs the valuation coal from Indian Tribal and Allotted leases.	**Section 8.7.2** states that all NPS units are closed to new federal mineral leasing except Glen Canyon, Lake Mead and Whiskeytown-Shasta-Trinity NRAs.

Resource	Resource-specific Laws	Resource-specific Regulations	2006 Management Policies
Nonfederal minerals other than oil and gas	**NPS Organic Act, 54 USC §§ 100101 and 100751**	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**.	**Section 8.7.3** states that operators exercising rights in a park unit must comply with **36 CFR Parts 1 and 5**.
Coal	**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.	**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.	None applicable.
Uranium	**Atomic Energy Act of 1954** Allows Secretary of Energy to issue leases or permits for uranium on BLM lands; may issue leases or permits in NPS areas only if president declares a national emergency.	None applicable.	None applicable.
Common Variety Mineral Materials (Sand, Gravel, Pumice, etc.)	**Materials Act of 1947, 30 USC § 601** does not authorize the NPS to dispose of mineral materials outside of park units. **Reclamation Act of 1939, 43 USC §387**, authorizes removal of common variety mineral materials from federal lands in federal reclamation projects. This act is cited in the enabling statutes for Glen Canyon and Whiskeytown National Recreation Areas, which provide that the Secretary of the Interior may permit the removal of federally owned nonleasable minerals such as sand, gravel, and building materials from the NRAs under appropriate regulations. Because regulations have not yet been promulgated, the National Park Service may not permit removal of these materials from these National Recreation Areas. **16 USC §90c-1(b)** authorizes sand, rock and gravel to be available for sale to the residents of Stehekin from the non-wilderness portion of Lake Chelan National Recreation Area, for local use as long as the sale and disposal does not have significant adverse effects on the administration of the national recreation area.	None applicable.	**Section 9.1.3.3** clarifies that only the NPS or its agent can extract park-owned common variety minerals (e.g., sand and gravel), and: • only for park administrative uses; • after compliance with NEPA and other federal, state, and local laws, and a finding of non-impairment; • after finding the use is park's most reasonable alternative based on environment and economics; • parks should use existing pits and create new pits only in accordance with park-wide borrow management plan; • spoil areas must comply with Part 6 standards; and • NPS must evaluate use of external quarries. Any deviation from this policy requires a written waiver from the Secretary, Assistant Secretary, or Director.

Resource	Resource-specific Laws	Resource-specific Regulations	2006 Management Policies
Coastal Features and Processes	**NPS Organic Act, 54 USC § 100751 et. seq.** authorizes the NPS to promulgate regulations to protect park resources and values (from, for example, the exercise of mining and mineral rights). **Coastal Zone Management Act, 16 USC § 1451 et. seq**. requires Federal agencies to prepare a consistency determination for every Federal agency activity in or outside of the coastal zone that affects land or water use of the coastal zone. **Clean Water Act, 33 USC § 1342/ Rivers and Harbors Act, 33 USC 403** require that dredge and fill actions comply with a Corps of Engineers Section 404 permit. **Executive Order 13089** (coral reefs) (1998) calls for reduction of impacts to coral reefs. **Executive Order 13158** (marine protected areas) (2000) requires every federal agency, to the extent permitted by law and the maximum extent practicable, to avoid harming marine protected areas. *See also "Climate Change"*	**36 CFR § 1.2(a)(3)** applies NPS regulations to activities occurring within waters subject to the jurisdiction of the US located within the boundaries of a unit, including navigable water and areas within their ordinary reach, below the mean high water mark (or OHW line) without regard to ownership of submerged lands, tidelands, or lowlands. **36 CFR § 5.7** requires NPS authorization prior to constructing a building or other structure (including boat docks) upon, across, over, through, or under any park area. *See also "Climate Change"*	**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 4.8.1** requires NPS to allow natural geologic processes to proceed unimpeded. NPS can intervene in these processes only when required by Congress, when necessary for saving human lives, or when there is no other feasible way to protect other natural resources/ park facilities/historic properties. **Section 4.8.1.1** requires NPS to: • Allow natural processes to continue without interference, • Investigate alternatives for mitigating the effects of human alterations of natural processes and restoring natural conditions, • Study impacts of cultural resource protection proposals on natural resources, • Use the most effective and natural-looking erosion control methods available, and avoid new developments in areas subject to natural shoreline processes unless certain factors are present. *See also "Climate Change"*

Resource	Resource-specific Laws	Resource-specific Regulations	2006 Management Policies
Climate Change	**Secretarial Order 3289** (Addressing the Impacts of Climate Change on America's Water, Land, and Other Natural and Cultural Resources) (2009) requires DOI bureaus and offices to incorporate climate change impacts into long-range planning; and establishes DOI regional climate change response centers and Landscape Conservation Cooperatives to better integrate science and management to address climate change and other landscape scale issues. **Executive Order 13693** (Planning for Federal Sustainability in the Next Decade) (2015) established to maintain Federal leadership in sustainability and greenhouse gas emission reductions.	*No applicable regulations, although the following NPS guidance should be considered:* **Coastal Adaptation Strategies Handbook (Beavers et al. 2016)** provides strategies and decision-making frameworks to support adaptation of natural and cultural resources to climate change. **Climate Change Facility Adaptation Planning and Implementation Framework**: The NPS Sustainable Operations and Climate Change Branch is developing a plan to incorporate vulnerability to climate change (Beavers et al. 2016b). **NPS Climate Change Response Strategy** (2010) describes goals and objectives to guide NPS actions under four integrated components: science, adaptation, mitigation, and communication. **Policy Memo 12-02** (Applying National Park Service Management Policies in the Context of Climate Change) (2012) applies considerations of climate change to the impairment prohibition and to maintaining "natural conditions". **Policy Memo 14-02** (Climate Change and Stewardship of Cultural Resources) (2014) provides guidance and direction regarding the stewardship of cultural resources in relation to climate change. **Policy Memo 15-01** (Climate Change and Natural Hazards for Facilities) (2015) provides guidance on the design of facilities to incorporate impacts of climate change adaptation and natural hazards when making decisions in national parks. *Continued in 2006 Management Policies column*	**Section 4.1** requires NPS to investigate the possibility to restore natural ecosystem functioning that has been disrupted by past or ongoing human activities. This would include climate change, as put forth by Beavers et al. (2016). *NPS guidance, continued:* **DOI Manual Part 523, Chapter 1** establishes policy and provides guidance for addressing climate change impacts upon the Department's mission, programs, operations, and personnel. **Revisiting Leopold: Resource Stewardship in the National Parks** (2012) will guide US National Park natural and cultural resource management into a second century of continuous change, including climate change. **Climate Change Action Plan** (2012) articulates a set of high-priority no-regrets actions the NPS will undertake over the next few years **Green Parks Plan** (2013) is a long-term strategic plan for sustainable management of NPS operations.

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. *2006 Management Policies, continued:* **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.	**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. *continued in Regulations column*

Resource	Resource-specific Laws	Resource-specific Regulations	2006 Management Policies
Soils	**Soil and Water Resources Conservation Act, 16 USC §§ 2011–2009** provides for the collection and analysis of soil and related resource data and the appraisal of the status, condition, and trends for these resources. **Farmland Protection Policy Act, 7 USC § 4201 et. seq.** requires NPS to identify and take into account the adverse effects of Federal programs on the preservation of farmland; consider alternative actions, and assure that such Federal programs are compatible with State, unit of local government, and private programs and policies to protect farmland. NPS actions are subject to the FPPA if they may irreversibly convert farmland (directly or indirectly) to nonagricultural use and are completed by a Federal agency or with assistance from a Federal agency. Applicable projects require coordination with the Department of Agriculture's Natural Resources Conservation Service (NRCS).	**7 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).

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

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National Park Service
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https://www.nps.gov/nature/index.htm