National Park Service
US Department of the Interior

Natural Resource Stewardship and Science

Lava Beds National Monument

Geologic Resources Inventory Report

Natural Resource Report NPS/NRSS/GRD/NRR—2014/804

ON THE COVER
Gillem Bluff rises from the plain in northwestern Lava Beds National Monument. A fault runs along the base of the bluff and bounds the western side of the Tule Lake basin. Displacement along the fault uplifted Gillem Bluff. The fault projects south, where it is buried by lavas of Medicine Lake Volcano. The basalts of Mammoth Crater (tan, covered in aeolian deposits of dust and sand) and Devils Homestead (black) flowed against the base of the bluff about 35,000 and 12,300 years ago, respectively. US Geological Survey photograph by Tanya Blacic.

THIS PAGE
Crystal Ice Cave contains some of the most spectacular ice formations in Lava Beds National Monument, which is known for these features. Over the past two decades, researchers and monument staff have observed the loss of year-round ice within the ice caves at the monument. Because of the sensitive nature of ice formations and cold environments within these caves, Crystal Ice Cave is open to visitors only on ranger-led tours during the winter months. Exploring Crystal Ice Cave is a remarkable way to experience the monument's volcanic geology while surrounded by stunning ice formations. Photograph by Kenneth Ingham (copyright 2011, used by permission).

Lava Beds National Monument

Geologic Resources Inventory Report

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Katie KellerLynn
Colorado State University Research Associate
National Park Service Geologic Resources Division
Geologic Resources Inventory
PO Box 25287
Denver, CO 80225

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Fort Collins, Colorado

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

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

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

Printed copies of this report are produced in a limited quantity and they are only available as long as the supply lasts. This report is available from the Geologic Resources Inventory website (http://www.nature.nps.gov/geology/inventory/gre_publications.cfm) and the Natural Resource Publications Management website (http://www.nature.nps.gov/publications/nrpm/). To receive this report in a format optimized for screen readers, please email irma@nps.gov.

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Executive Summary

The Geologic Resources Inventory (GRI) is one of 12 inventories funded by the National Park Service (NPS) Inventory and Monitoring Program. The Geologic Resources Division of the NPS Natural Resource Stewardship and Science Directorate administers the GRI. This report synthesizes discussions from a scoping meeting for Lava Beds National Monument (California) on 4 March 2004, which was held by the Geologic Resources Division to determine geologic resources, the status of geologic mapping, and geologic resource management issues and needs. It is a companion document to previously completed GRI digital geologic map data.

This Geologic Resources Inventory (GRI) report was written for resource managers at Lava Beds National Monument to assist in science-informed decision making. It may also be useful for interpretation. The report is publically available at http://www.nature.nps.gov/geology/inventory/gre_publications.cfm. The sections of the report discuss distinctive geologic features and processes within the monument, highlight geologic issues facing resource managers, describe the geologic history leading to the monument's present-day landscape, and provide information about the GRI geologic map data that accompany the report (attached CD). The Geologic Map Graphic (in pocket) illustrates these data. The Map Unit Properties Table (in pocket) summarizes content from the report for each map unit that occurs within the monument. A glossary of relevant geologic terms and a geologic time scale are also provided.

The source map of the GRI data set for Lava Beds National Monument, and a primary source of information for this report, is Donnelly-Nolan (2010; scale 1:50,000), which encompasses the entire Medicine Lake volcano edifice. Notably, this mapping effort incorporated previous mapping of Lava Beds National Monument by Donnelly-Nolan and Champion (1987; scale 1:24,000). In addition, Ramsey et al. (2010) created digital data from Donnelly-Nolan (2010), and the GRI team converted these data to a geographic information system (GIS) format that conforms to the GRI GIS data model (attached CD).

Geologic features and processes include the following:

- Medicine Lake Volcano. Lava Beds National Monument is on the northern flank of Medicine Lake volcano, which at an estimated 600 km^3 (150 mi^3) is the largest volcano by volume in the Cascade Range. This volcano is the primary source of "lava beds" at the monument, although a few lava flows exposed at Gillem Bluff were extruded earlier and predate Medicine Lake volcanism. The lava flows that make up the volcano consist of volcanic rocks with silica (SiO_2) compositions ranging from rhyolite with 77.1% SiO_2 to basalt with 42.7% SiO_2. More than 200 eruptions have occurred during the volcano's 500,000-year history.
- Volcanic Features at Lava Beds National Monument. Thirty-six eruptions of Medicine Lake volcano are represented in the monument. The oldest lava from the volcano is the basalt of Hovey Point (map unit PEbhp), which occurs along the northern boundary of the monument and has an argon-40/argon-39 age of 445,000 ± 25,000 years. The basaltic andesite of Callahan Flow (Hmcf) is the youngest lava at the monument; it has a calibrated radiocarbon age of 1,120 years before present (BP). Volcanic features include vents, commonly marked by cinder cones, and associated lava flows, as well as isolated cinder cones not associated with a flow. All distinctive landmarks within the monument are volcanic features.
- Lava Tubes. Basalt of Mammoth Crater (PEbmc) makes up the most extensive lava flow at Lava Beds National Monument; it is also one of the most extensive flows of Medicine Lake volcano. Lava tubes served as conduits that distributed this basalt from south to north, flowing across more than 70% of the monument area. The basalt covers an equivalent area outside the monument. Segments of the lava tubes became evacuated when lava stopped flowing, leaving caves. The basalt of Mammoth Crater hosts the majority of the more than 700 known caves at the monument. Many distinctive features occur within the caves, including lava cascades, lavacicles, lava pools, pillars, pull outs, rafted blocks and floor jams, high-lava marks, benches, balconies, stacked tubes, and tube-in-tubes.
- Tectonic Features. Tectonic features and seismic activity in the Medicine Lake volcano region are a consequence of interactions between the compressional setting of the Cascadia subduction zone and the extensional setting of the Basin and Range physiographic province. Medicine Lake volcano lies east of the axis of the Cascade volcanic arc, which formed at the surface above the Cascadia subduction zone. The volcano is west of the Basin and Range, an area of active rifting (pulling apart) in Earth's crust. Distinctive features associated with this tectonic regime at Lava Beds National Monument include Gillem fault and north–south-oriented faults and ground cracks.
- Paleontological Resources. Lava Beds National Monument is one of five NPS areas known to contain

tree molds—trace fossils that form when lava engulfs a forest or individual tree. Tree molds preserved within three lava flows provided material (charcoal and charred wood) used to date the basalts of Valentine Cave (PEbvc; 12,260 years BP) and Black Crater and Ross Chimneys (Hbbr; 3,080 years BP); and the basaltic andesite of Callahan Flow (Hmcf; 1,120 years BP). Caves at the monument have yielded the remains of Pleistocene (mastodon, camel, bear, jaguar, and bison) and extirpated Holocene (bighorn sheep) mammals. Caves also contain packrat middens, which are important for reconstructing late Pleistocene and Holocene paleoecology and climate. Lake deposits (HPEl) are repositories for microfossils. A Tule Lake sediment core contains diatoms, pollen, and ostracodes as old as 3 million years.

- Lake Deposits. Fine gravel, sand, and silt comprise lake deposits (HPEl) that represent former shorelines and the bed of ancient Tule Lake. Where molten lava flowed into or erupted beneath the lake, distinctive features such as pillow lava, littoral cones, and palagonite tuff formed.
- Glacial Outwash Deposits. At the southern end of Lava Beds National Monument, two deposits of gravel (PEg) record past glacial activity. This gravel is outwash material, deposited by glacial meltwater beyond the ice margins.
- Geologic Features with Cultural Significance. Geologic features used during the Modoc War (1872–1873) include Captain Jacks Stronghold, Gillem Bluff, Hospital Rock, and the volcanic ridges at Thomas-Wright Battlefield. These features help convey an understanding of the events that led to and unfolded during the war. The basalt of Prisoners Rock (PEbp) is the backdrop for Petroglyph Point, where more than 5,000 individual rock carvings were inscribed into the cliff face and record a history that extends back to the early Holocene Epoch (11,700 years ago).

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

- Cave Management. An active cave management program has been in place at Lava Beds National Monument since the adoption of the 1990 cave management plan. Caves at the monument are susceptible to threats such as modifications to entrances and passages; impacts on fragile cave features as a result of unintentional carelessness and intentional vandalism; and impacts from overlying or adjacent surface development, including the disturbance of cave environments by audible engine noise and exhaust odors. Another serious threat is white-nose syndrome, an infectious disease affecting bats that is associated with the fungus *Pseudogymnoascus destructans*. One of the largest future impacts on cave environments may be global climate change. Since 1990, monument staff has documented the loss of cave ice, which may be a result of climate change.
- Recreational Impacts on Geologic Features. The volcanic features at Lave Beds National Monument are significant geologic resources, and only new volcanic eruptions can create new features. Thus, once damaged, these distinctive geologic resources are unlikely to be replenished by natural processes in the near future. Presently, the absence of a formal message and orientation about the conservation of volcanic features, the lack of visitor management in sensitive geologic areas (e.g., lack of group size limit and supervision, and uninhibited access), and poorly defined infrastructure on particular trails have had significant and lasting impacts. Black Crater and Fleener Chimneys are the two most prominent examples of threatened geologic features in the monument.
- Wind Erosion at Petroglyph Point. Before the early 1900s, when Tule Lake was drained for agricultural purposes, Prisoners Rock was most practically reached by boat. Today, however, an unpaved road leads to Prisoners Rock and its wall of petroglyphs at Petroglyph Point. Scoping participants hypothesized that the exposed road surface provided material (dust and sand) for aeolian transport and erosion. A wave-cut bench at the base of Prisoners Rock also provides such material. Thus wind erosion ("sand blasting") may be erasing the petroglyphs; however, no study has been conducted to test this hypothesis. Monument staff installed a metal shield to protect the rock art and is considering other means of preservation.
- Abandoned Mineral Lands. The National Park Service is currently conducting an inventory and assessment of its abandoned mineral lands (AML). The NPS Geologic Resources Division administers this inventory and maintains a database of sites and features. As of April 2014, the AML database listed 23 features at 16 quarry sites in Lava Beds National Monument. These sites are no longer used and are being systematically restored; some sites are revegetating naturally.
- Rockfall and Roof Collapse. Freeze-thaw processes, storm events, and seismic activity induce rockfall, with fragments commonly deposited on roads within Lava Beds National Monument. Steep cliff faces, such as Gillem Bluff, and cave entrances are prone to rockfall. Many caves within the monument contain areas of rockfall, called "collapse rubble" or "breakdown." These areas, mapped by Waters et al. (1990), could serve as starting points for further surveys and monitoring of cave areas susceptible to rockfall. A potentially greater problem at the monument is the possible collapse of roads and other infrastructure into subsurface voids. Rockfall within caves and cave-roof collapse are ongoing public safety concerns.
- Earthquakes. Six significant earthquake events, occurring in 1978, 1981, 1988, 1989, 1993, and 1996, have been documented in the vicinity of Medicine Lake volcano. The events in 1988, 1989, and 1996—occurred directly beneath the volcano edifice; the events in 1978, 1981, and 1993 occurred in the nearby region. Seismic stations were sparse in the region

before about 1980, and earlier earthquakes may have gone undetected. Currently, the Medicine Lake volcano network includes two seismic stations and three Global Positioning System receivers.

- Volcano Hazards. Medicine Lake volcano will likely erupt again, although the probability of an eruption is very small, that is, one in 3,600 chances in the next year. The most likely future eruption would be a small effusion of basaltic lava, which could occur anywhere on the volcano. Also possible is an explosive eruption of silicic lava, including rhyolite and dacite, which would likely occur near the summit. Silicic eruptions are characterized by the production of prolific amounts of tephra (e.g., volcanic ash), which could impact Klamath Falls, Oregon (the largest nearby city), nearby local communities, Lava Beds National Monument, roads and highways, and the utility corridor that crosses the eastern and southern sides of the volcano. The opening of a volcanic vent under Medicine Lake would almost certainly cause phreatomagmatic (steam) eruptions. The intrusion of magma into the hydrothermal system beneath the volcano might cause hydrothermal explosions at the surface, in which hot water "flashing" to steam breaks rocks and throws them into the air.
- Geothermal Features and Development. Medicine Lake volcano hosts a large, active, high-temperature, geothermal system fueled by a deeper zone of magma. At the surface, the geothermal system is delineated as the Glass Mountain Known Geothermal Resource Area, a federally designated geothermal lease area south of the monument. In the early 1980s, geothermal exploration companies targeted Medicine Lake volcano; the Calpine Corporation proposed the development of two geothermal projects—Fourmile Hill and Telephone Flat—by 2004 and 2005, respectively. Development apparently was not economically viable under existing market conditions, and the projects remain "on hold."

Products and Acknowledgements

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

GRI Products

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

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

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

Additional information regarding the GRI, including contact information and current status, is available at http://www.nature.nps.gov/geology/inventory/.

Acknowledgements

The GRI team would like to thank the 2004 scoping meeting participants and other scoping contributors, who are listed in Appendix A, including Sid Covington (NPS Geologic Resources Division; geologist, now retired), who wrote the scoping summary. We also thank Julie Donnelly-Nolan (US Geological Survey, Volcano Science Center, research geologist), for answering questions, reviewing this report, providing photographs, and, of course, mapping Lava Beds National Monument with her colleague Duane E. Champion. In addition, Shane Fryer, the former physical scientist at Lava Beds National Monument, provided input on resource management issues, and Katrina Smith (Lava Beds National Monument, physical science technician) gathered and provided information about paleontological and cultural resources. Jessica Middleton (Lava Beds National Monument, cultural resource manager) provided information for the "Geologic Features with Cultural Significance" section. John Burghardt (NPS Geologic Resources Division, AML coordinator) provided updated information about abandoned mineral lands. Julia Brunner (NPS Geologic Resources Division, policy and regulatory specialist) reviewed the geothermal section. Thanks to Kenneth Ingham for making his excellent cave photographs available. Also, this report benefited from the code-writing "magic" of Mike Cox (Colorado State University, former research associate), who helped to streamline the creation of the Map Unit Properties Table.

Author

Katie KellerLynn (Colorado State University)

Review

Julie M. Donnelly-Nolan (US Geological Survey)
Jason Kenworthy (NPS Geologic Resources Division)
Nancy Nordensten (Lava Beds National Monument)
Dale Pate (NPS Geologic Resources Division)
Vincent Santucci (NPS Geologic Resources Division)
Katrina Smith (Lava Beds National Monument)

Editing

Jennifer Piehl (Write Science Right)

Source Maps

Julie Donnelly-Nolan (US Geological Survey)
Duane Champion (US Geological Survey)
D. W. Ramsey, T. J. Felger, E. Lougee, and P. E. Bruggman (US Geological Survey)

GRI Digital Geologic Data Production

Greg Mack (NPS Pacific West Regional Office)
Andrea Croskrey (NPS Geologic Resources Division)
Stephanie O'Meara (Colorado State University)

GRI Geologic Map Graphic Design

Max Jackl (Colorado State University)

GRI Geologic Map Graphic Review

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

Geologic Setting and Significance

This section describes the regional geologic setting of Lava Beds National Monument, as well as summarizes connections between geologic resources and other park resources and stories.

Lava Beds National Monument is in northeastern California, about 50 km (30 mi) south of Klamath Falls, Oregon, and 100 km (60 mi) northeast of Mount Shasta (the town and volcano; fig. 1). Established by presidential proclamation in 1925, the monument was initially administered by the Forest Service as part of Modoc National Forest, but was transferred to the National Park Service (NPS) in 1933. Lava Beds Wilderness was designated in 1972 and encompasses 11,496 ha (28,460 ac) or 61% of the monument's total land area of 18,843 ha (46,560 ac).

The Petroglyph Section of the monument is a separate, 80-ha (200-ac) area approximately 4 km (3 mi) northeast of the main unit (fig. 2). The cliff face of Petroglyph Point displays more than 5,000 individual petroglyphs. This abundance of rock carvings makes Petroglyph Point one of the most extensive representations of American Indian rock art in California (National Park Service 2007b). The monument also includes the sites of many important battles of the Modoc War.

The monument's landscape is dominated by the lava beds and broad shield form of Medicine Lake volcano (figs. 3 and 4), which erupted during 208 recorded events (Donnelly-Nolan 2010). The views are dominated by the iconic Mount Shasta stratovolcano, Medicine Lake volcano's towering volcanic neighbor to the southwest (fig. 5). At 4,303 m (14,117 ft) above sea level, Mount Shasta is the highest Cascade volcano. Volumetrically, Medicine Lake volcano (600 km^3 [150 mi^3]) surpasses Mount Shasta (450 km^3 [110 mi^3]) and is the largest Cascade volcano by volume (Heiken 1978; Donnelly-Nolan 1988, 2010; Hildreth 2007).

Newberry Volcano—another broad, shield-shaped volcano—is the largest Cascade volcano by area (Donnelly-Nolan et al. 2011). Its extensive apron of lava flows covers nearly 3,100 km^2 (1,200 mi^2) in central Oregon. By comparison, the areal extent of Medicine Lake volcano's lava flows is approximately 2,200 km^2 (850 mi^2); the maximum extent of lava is about 80 km (50 mi) north–south by 50 km (30 mi) east–west (Donnelly-Nolan et al. 2008).

Only about 10% of the voluminous Medicine Lake volcano occurs within the monument. Most of the eastern half of the volcano and its caldera, which contains Medicine Lake, are south of the monument in Modoc National Forest. Klamath National Forest contains the northwestern side of the volcano, and Shasta-Trinity National Forest hosts the southwestern side (figs. 1 and 2).

The lava flows that make up Medicine Lake volcano range in composition from rhyolite to basalt, with basalt predominating (fig. 6). The oldest lava of Medicine Lake volcano consists of the basalt of Hovey Point (map unit PEbhp), which has an argon-40 (^{40}Ar)/argon-39 (^{30}Ar) age of 445,000 ± 25,000 years ago (Donnelly-Nolan and Lanphere 2005; Donnelly-Nolan 2010). This flow is in the monument. The youngest lava flow in the monument consists of the basaltic andesite of Callahan Flow (Hmcf), which has a calibrated radiocarbon age of 1,120 years before present (BP) (Donnelly-Nolan et al. 2007; Nathenson et al. 2007). Radiocarbon ages are recorded as years BP, with "present" being 1950 CE (Common Era; preferred to "AD"). Thus, the Callahan Flow is about 1,180 years old. The most recently erupted lava from the volcano—rhyolite of Glass Mountain (Hrgm; 890 years BP)—does not occur within the monument.

The largest lava flow in Lava Beds National Monument is composed of basalt of Mammoth Crater (PEbmc), which erupted from its namesake crater and other nearby vents at the monument's southern boundary. The basalt of Mammoth Crater spread south to north across the landscape about 35,000 years ago; the unit has an ^{40}Ar/^{30}Ar age of 36,000 ± 16,000 years (Donnelly-Nolan and Lanphere 2005; Donnelly-Nolan 2010). The magnitude of material, covering about 70% of the monument, is notable, representing one of the largest lava flows of Medicine Lake volcano. The basalt of Mammoth Crater hosts most of the more than 700 known caves within the monument (National Park Service 2012).

Faulting at Gillem Bluff brought a few older volcanic units to the surface at the monument. These Pliocene and early Pleistocene (fig. 7) flows predate Medicine Lake volcano. The older tuff of Gillem Bluff (PLotg), which sits atop this feature, is the oldest dated rock unit exposed in the monument (^{40}Ar/^{30}Ar age, 2.023 ± 0.020 million years). Thus, lavas under this tuff, such as the older basaltic andesite in western Lava Beds National Monument (PLomw), are older.

Various field guides (e.g., Donnelly-Nolan et al. 1981; Donnelly-Nolan 1987; Muffler et al. 1989) provide road logs indicating geologic points of interest in Lava Beds National Monument and on other parts of Medicine Lake volcano. Recreation in the monument provides opportunities to explore and enjoy many geologic features associated with the volcano. The monument contains 12 hiking trails, the most popular of which are short and lead to interesting historic sites and geologic features (National Park Service 2007c). They include the Thomas-Wright Battlefield Trail, which crosses Black

Crater; the Gillem Bluff Trail, which ascends 170 m (550 ft) to the top of the bluff, providing a view of Gillems Camp and the surrounding landscape; two self-guiding trails through Captain Jacks Stronghold—the heart of the Modoc's wartime defenses in the basalt of Mammoth Crater; the Petroglyph Point Trail, which provides access to the rock art carved into the Prisoners Rock tuff cone; and the trail to the fire lookout at Schonchin Butte. The basalt of Devils Homestead (PEbdh) and its vents at Fleener Chimneys are also easily accessible. The monument's "Things to Do" webpage provides additional information (http://www.nps.gov/labe/planyourvisit/things2do.htm).

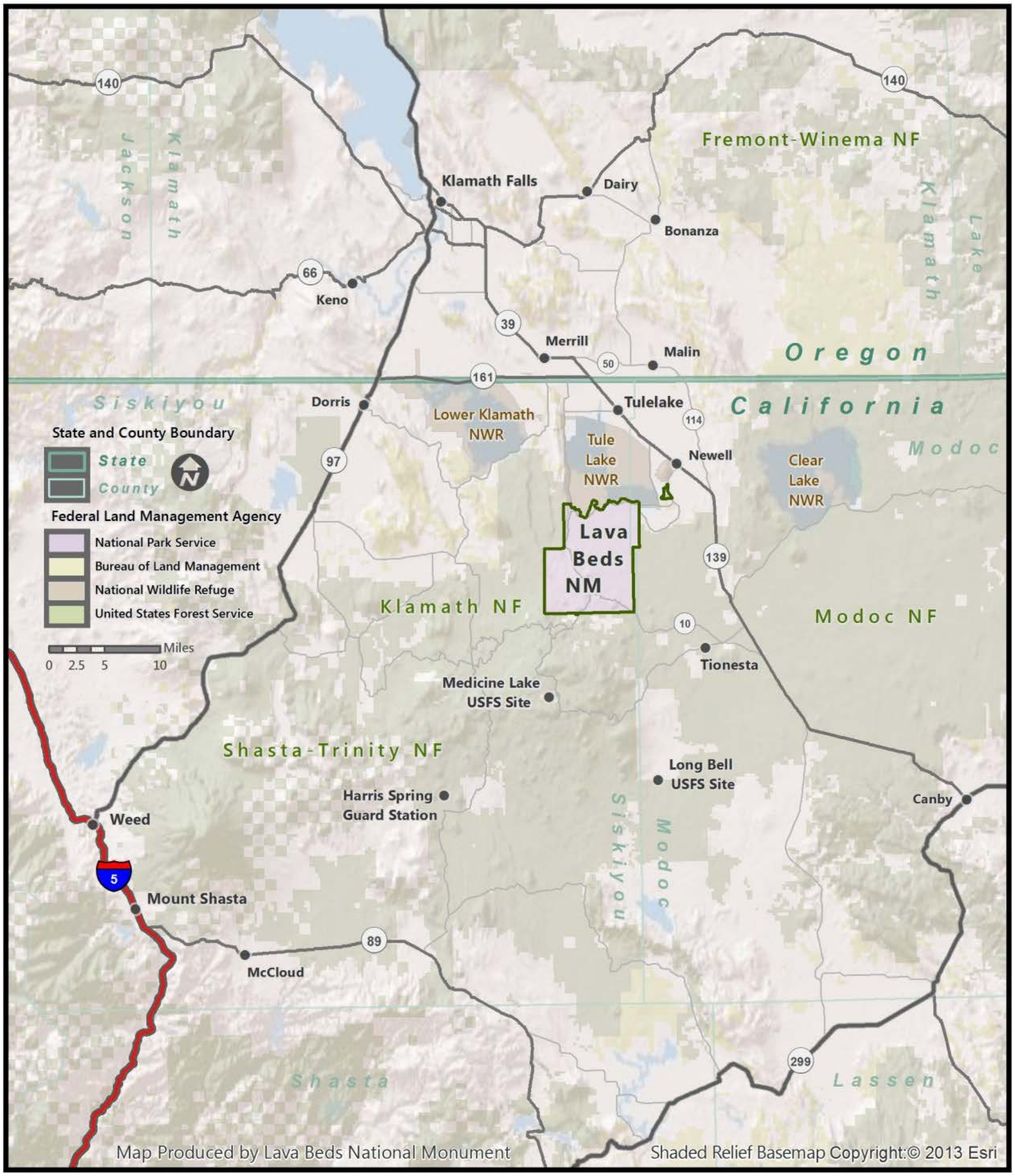

Figure 1. Regional map. Most of Lava Beds National Monument is in Siskiyou County; about 6% is in Modoc County. The monument is bordered by the Modoc and Klamath national forests, the Lower Klamath and Tule Lake national wildlife refuges, and Bureau of Land Management and private lands. National Park Service graphic.

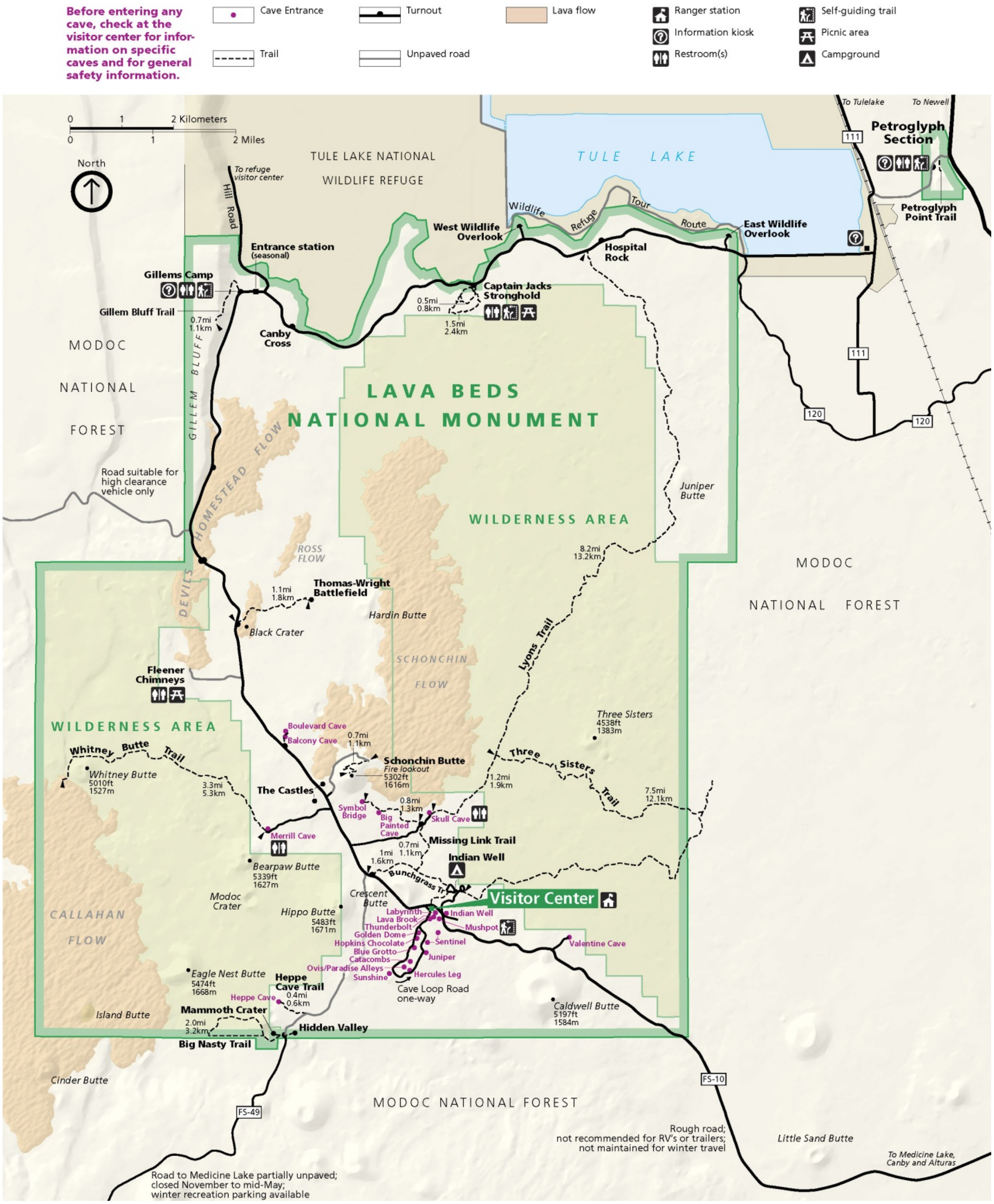

Figure 2. Map of Lava Beds National Monument. The monument is on the northern flank of Medicine Lake volcano, which last erupted 890 years BP or about 950 calendar years ago. Two thirds of the monument is covered by the basalt of Mammoth Crater (not labeled), which flowed from south to north across the landscape about 35,000 years ago, extruding from Mammoth Crater and other nearby vents. Many geologic features with cultural significance, including Captain Jacks Stronghold, are part of this lava flow. With the exception of Valentine Cave, all of the 22 visitor-use caves (labeled in pink) are in the basalt of Mammoth Crater. National Park Service graphic, available online http://www.nps.gov/hfc/cfm/carto-detail.cfm?Alpha=LABE (accessed 11 April 2014).

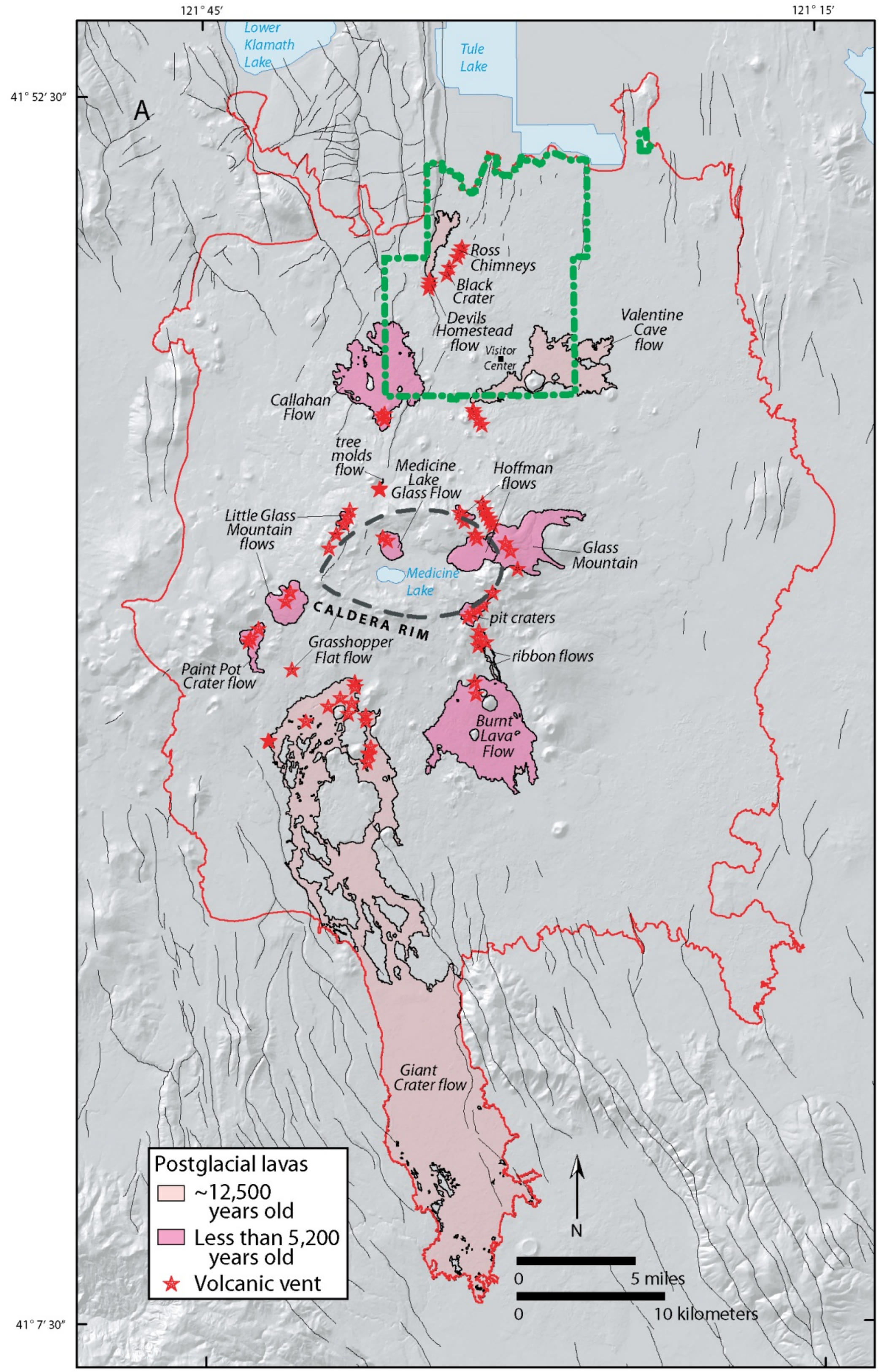

Figure 3. Map of Medicine Lake volcano. Lava Beds National Monument (green outline) is on the northern flank of Medicine Lake volcano (red outline). Note the postglacial lava flows (light-pink shading), the flows less than 5,200 years old (dark-pink shading), such as the Callahan Flow at Lava Beds National Monument, and the vents from which these flows extruded (red stars). Also note the limited number of faults (gray lines) located directly on the volcano edifice, but prolific faulting north and south of the volcano. Faults on the volcano are probably buried by younger lavas. Graphic extracted from Donnelly-Nolan et al. (2007, figure 3) with modification to the monument boundary.

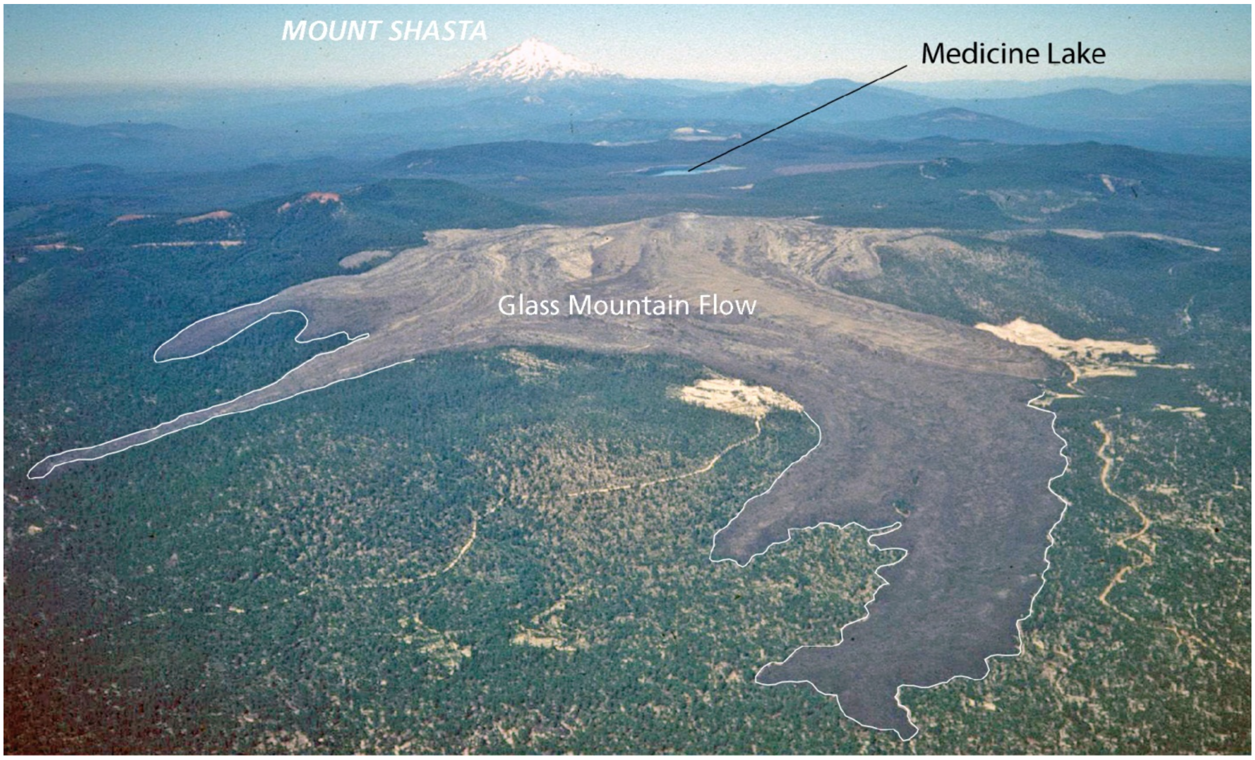

Figure 4. Medicine Lake volcano. An aerial view west across the upper part of Medicine Lake volcano toward Mount Shasta (on the horizon) highlights extensive lava flows. Medicine Lake volcano's youngest lava flow—the Holocene Glass Mountain Flow (foreground)—is treeless and drapes over the volcano's eastern side. The northeastern tongue of this flow extends nearly to the bottom of the photograph. This flow is not within Lava Beds National Monument. Medicine Lake is in the volcano's caldera. US Geological Survey photograph by Julie M. Donnelly-Nolan.

Figure 5. Mount Shasta. A view southwest across Lava Beds National Monument to Mount Shasta encompasses Tule Lake and some lava flows, including the basalts of Mammoth Crater (PEbmc) and Devils Homestead (PEbdh), as well as Hovey Point and Gillem Bluff. National Park Service photograph, available at http://www.nps.gov/labe/photosmultimedia/photogallery.htm (accessed 8 August 2013).

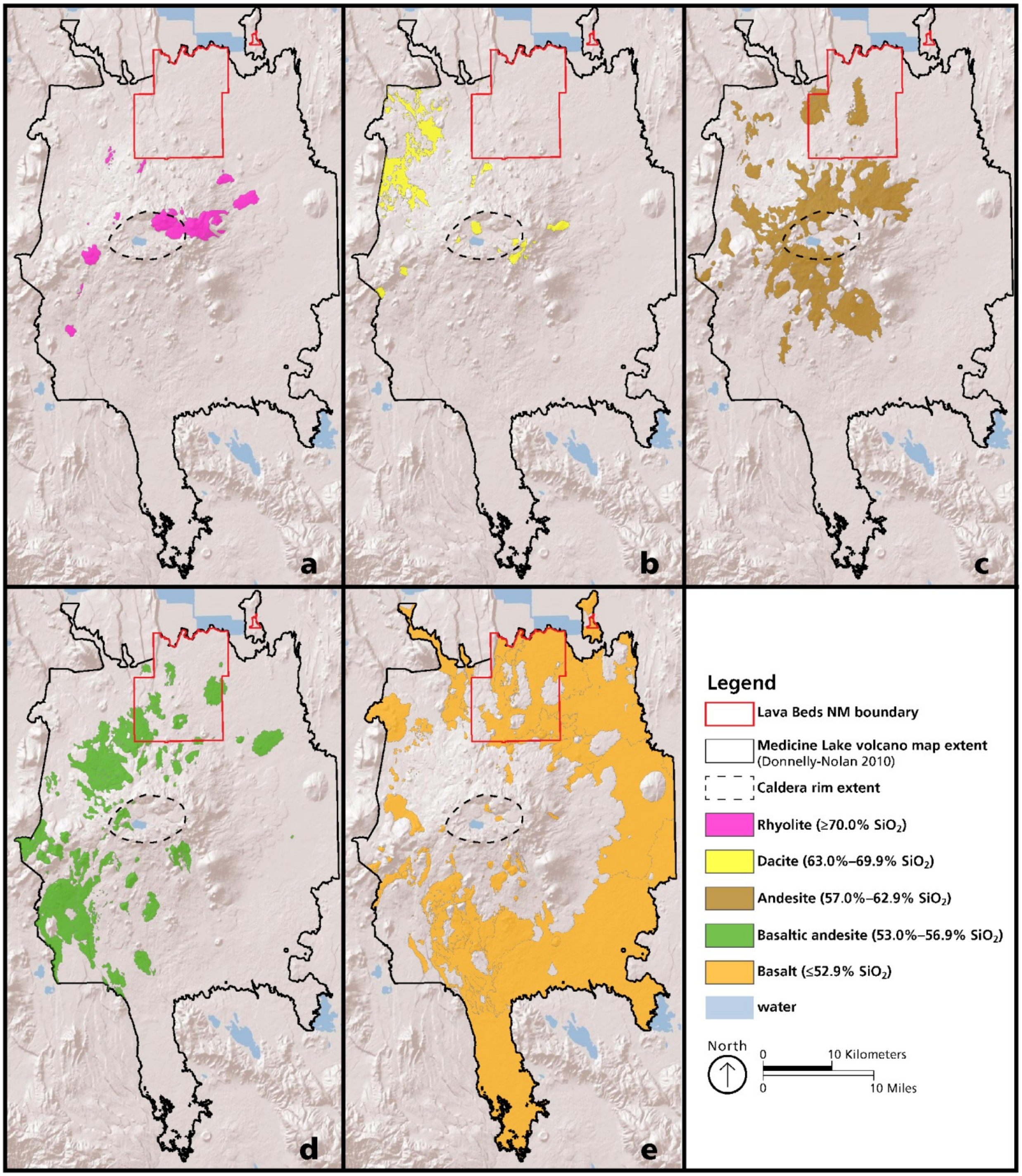

Figure 6. Types of lava at Medicine Lake volcano. Black outlines delineate the extent of Medicine Lake volcano mapped by Donnelly-Nolan (2010). Dashed lines indicate the location of the caldera rim. Red outlines approximate the boundary of Lava Beds National Monument. Panels a–e show areas of Medicine Lake volcano covered by five types of lava, grouped by percentage of silica (SiO_2): rhyolite (a, pink) and dacite (b, yellow) each cover about 3% of the volcano's edifice, andesite (c, brown) covers about 15%, basaltic andesite (d, green) covers about 13%, and basalt (e, orange) covers about 66%. Percentages of silica are from Donnelly-Nolan (2010). Graphic after Donnelly-Nolan et al. (2008, figure 6) by Jason Kenworthy (NPS Geologic Resources Division) using GRI data after Ramsey et al. (2010). Base map is World Shaded Relief layer by ESRI.

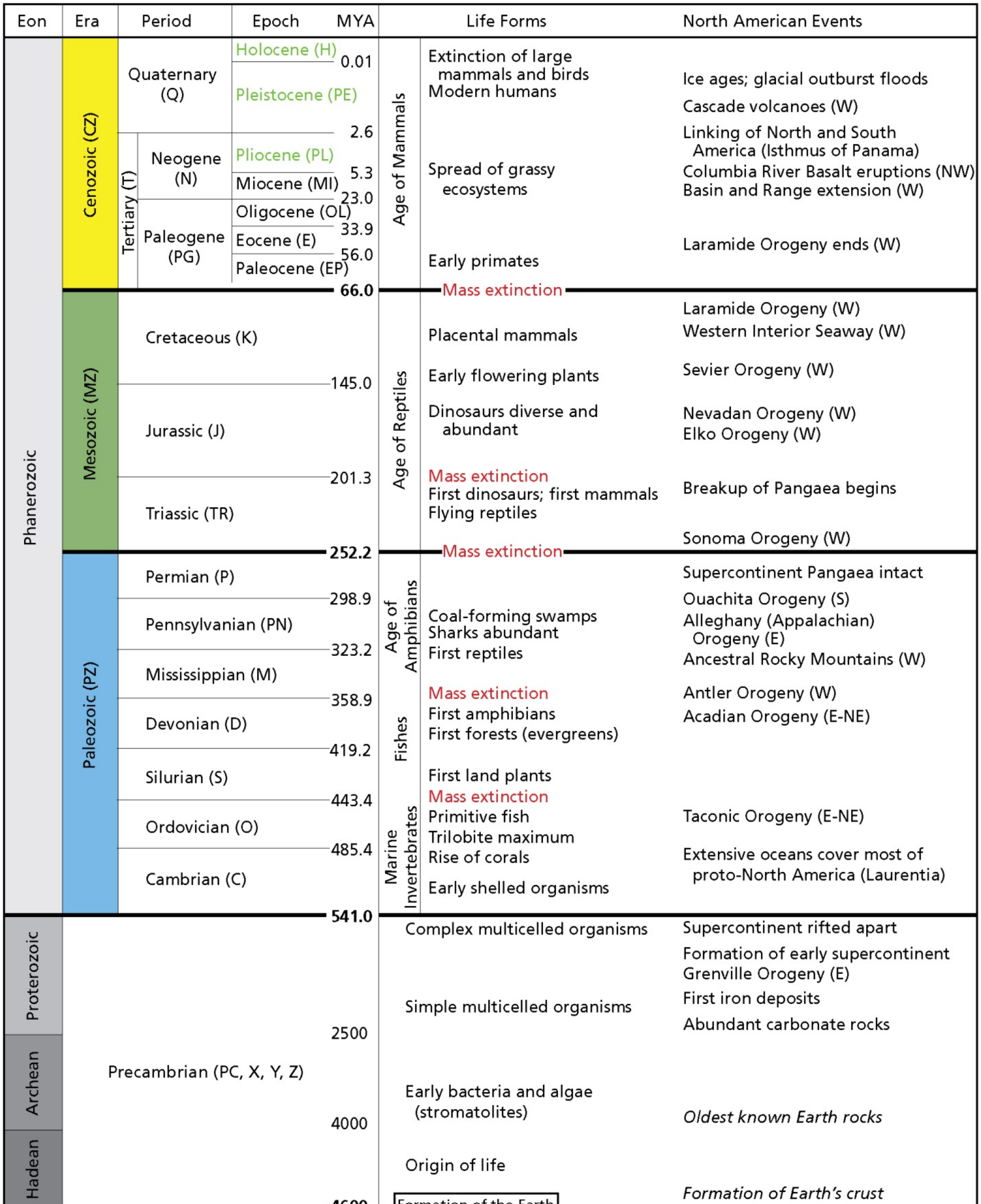

Figure 7. Geologic time scale. The divisions of the geologic time scale are organized stratigraphically, with the oldest divisions at the bottom and the youngest at the top. GRI map abbreviations for each time division are in parentheses. Lava Beds National Monument contains rocks from the Pliocene (PL), Pleistocene (PE), and Holocene (H) epochs (shown in green on the time scale). Compass directions in parentheses indicate the regional locations of events. Boundary ages are millions of years ago (MYA). National Park Service graphic using dates from the International Commission on Stratigraphy (http://www.stratigraphy.org/index.php/ics-chart-timescale; accessed 10 January 2014).

Geologic Features and Processes

This section describes noteworthy geologic features and processes in Lava Beds National Monument.

The land protected by Lava Beds National Monument has been the site of geological and historical turmoil. Over the past 500,000 years, eruptions of Medicine Lake volcano have created a rugged landscape consisting of diverse volcanic features and caves. Some lava flows host fossils. Volcanic features are also the foundation for American Indian rock art and the sites of battles during the Modoc War.

The following geologic features and processes are discussed in this section:

- Medicine Lake Volcano
- Volcanic Features in Lava Beds National Monument
- Lava Tubes
- Tectonic Features
- Paleontological Resources
- Lake Deposits
- Glacial Outwash
- Geologic Features with Cultural Significance

Medicine Lake Volcano

Most of Lava Beds National Monument is covered by lava flows that erupted from Medicine Lake volcano. Viewed from the ground, this volcano forms a broad, seemingly nondescript highland (fig. 8). From the air, however, the volcano's extensive edifice, consisting of hundreds of lava flows, becomes apparent (fig. 9). For a sense of scale, this huge volcano covers all or part of 27 US Geological Survey (USGS) topographic quadrangle maps.

The name "Medicine Lake" was used to denote the lake at the center of the volcano (fig. 10) on maps as early as 1890. In his classic study, C. A. Anderson (1941) used the terminology "Medicine Lake Highland." Mertzman (1977) was the first to apply the term "volcano." The name "Medicine Lake volcano" conveys the idea of a single large volcanic center, rather than a set of overlapping smaller volcanoes (Donnelly-Nolan 2010).

Figure 8. Medicine Lake volcano. This view of Medicine Lake volcano from the northeast shows its broad shield shape. US Geological Survey photograph by Julie M. Donnelly-Nolan.

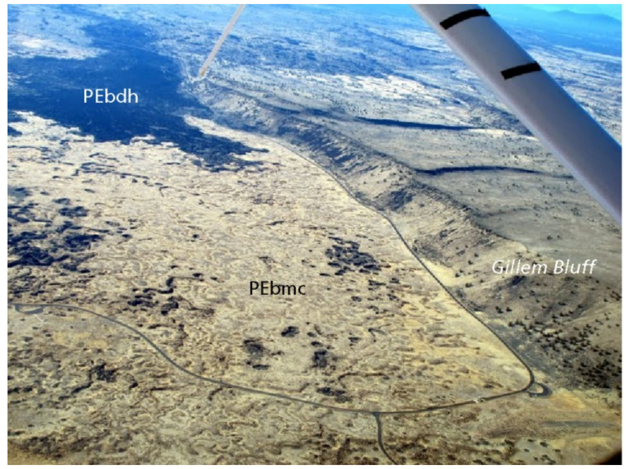

Figure 9. Northwestern corner of Lava Beds National Monument. This aerial view of the volcanic terrain of the monument shows the basalt of Mammoth Crater (PEbmc), which is mantled by windblown sediments and grass and appears yellowish in the photograph. The more rugged and much younger basalt of Devils Homestead (PEbdh; 12,320 years BP) is dark black. Looking south, Gillem Bluff rises to the west (right side of photograph). The northern entrance station is in the horseshoe bend in the road. At least 15 m (50 ft) of displacement has occurred on the Gillem fault since the basalt of Mammoth Crater flowed against it about 35,000 years ago. National Park Service photograph, available at http://www.nps.gov/labe/photosmultimedia/photogallery.htm (accessed 1 May 2013).

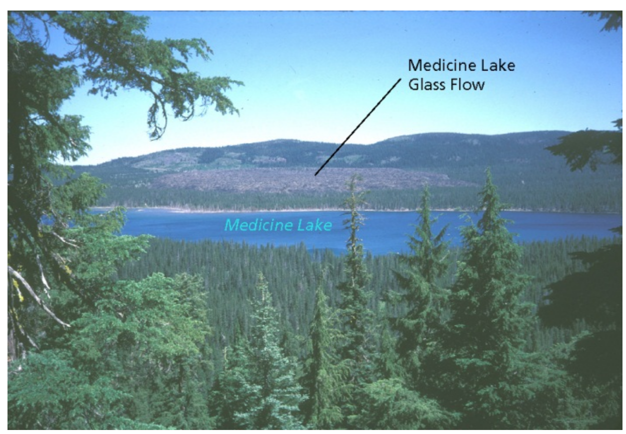

Figure 10. Medicine Lake. Nestled within the pines on the floor of Medicine Lake caldera, Medicine Lake (viewed here from the southern caldera rim) is 2,036 m (6,680 ft) above sea level. The lake is small, (area, 165 ha [408 ac]) and relatively shallow (average depth, 7 m [24 ft]). The nearly treeless Medicine Lake Glass Flow, which consists of dacite (63.0%–69.9% SiO_2), lies between the lake and the northern caldera rim. US Geological Survey photograph by Julie M. Donnelly-Nolan.

The rim of Medicine Lake volcano rises 1,300 m (4,265 ft) above the adjacent plain. Its summit caldera is a shallow basin, elongated east to west. The flanks of the volcano, which are dotted with cinder cones, slope gently upward to the caldera rim. The highest point on the rim is Mount Hoffman, which lies 2,412 m (7,913 ft) above sea level. Drill-hole data indicate that the center of the plateau surface underlying the volcano has been downwarped by 0.5 km (0.3 mi). Thus, the volcano may be even larger than the estimated 600 km^3 (150 mi^3) (US Geological Survey 2012b).

Medicine Lake volcano consists of 208 volcanic rock units: 13 rhyolites, 11 dacites, 39 andesites, 63 basaltic andesites, and 82 basalts. The types of lava that make up the volcano are categorized based on silica (SiO_2) content (fig. 6); many properties of magma, including viscosity and explosiveness, generally increase with SiO_2 content. Medicine Lake volcano lava ranges from basalt with 47.2% SiO_2 content to rhyolite with 77.1% SiO_2 content (Donnelly-Nolan 2010).

Basalt and basaltic andesite dominate the lower flanks of the volcano (fig. 6). These two "mafic" (derived from ***ma***gnesium + ***f***err***ic***, for magnesium- and iron-rich, respectively) lavas contain less SiO_2 and are generally less viscous and less gas-rich than magmas with more SiO_2. Mafic lavas tend to erupt effusively as flows. Higher on the volcano, mafic lavas are mostly absent and andesite (57.0%–62.9% SiO_2) dominates. Although it contains more SiO_2 than mafic rocks, andesite is not necessarily considered "silicic," which describes rocks with greater SiO_2 content, such as dacite and rhyolite. A silicic rock is usually said to contain at least 65% SiO_2, although amounts vary among petrologists (Neuendorf et al. 2005). High-silica lava such as rhyolite occurs higher on the volcano. Drill-hole data revealed the presence of a greater volume of rhyolite than indicated by surface mapping (US Geological Survey 2012c).

A depression in the summit area of the volcano marks the caldera, which is 7 × 12 km (4 × 7 mi) wide. Unlike the well-known Crater Lake caldera, which contains iconic Crater Lake (see GRI report by KellerLynn 2013), the caldera at Medicine Lake volcano was not formed in a single large eruption. The only volcanic material indicative of a caldera-forming explosion is the dacite tuff of Antelope Well (map unit PEdta; see "Geologic History" section), but the eruption represented by this material, which occurred 180,000 years ago, was too small to fully account for the formation of the caldera. Geologic evidence indicates that Medicine Lake caldera exists primarily because of subsidence in response to the repeated extrusion of mostly mafic lava (Donnelly-Nolan et al. 2008).

Volcanic Features in Lava Beds National Monument

Lava Beds National Monument contains abundant, well-preserved volcanic features that illustrate the powerful geologic story of Medicine Lake volcano (see "Geologic History" section). This volcano has the most vents among Cascade volcanoes (Hildreth 2007); 132 of its 521 vents, mapped at a scale of 1:50,000 (Donnelly-Nolan 2010), are within the monument. Not all vents are shown on the Medicine Lake volcano map, as many have been buried by younger lava (Julie M. Donnelly-Nolan, US Geological Survey, research geologist, written communication, 17 October 2013).

Most mapped units of Medicine Lake volcano consist of lava flows associated with one or more vents s that spawned the flows; these vents are commonly marked by cinder or spatter cones (Donnelly-Nolan 2010). Cinder cones are steep, conical hills ranging in height from tens to hundreds of meters (US Geological Survey 2013a), that are formed by the accumulation of solidified lava fragments around a vent. The rock fragments contain numerous gas bubbles that were "frozen" in place as magma exploded into the air and then quickly cooled, typically deposited during a single basaltic or andesitic eruption. The steepness of the slopes depends on factors such as coarseness of the cinders, height of the eruption, and wind velocity, but slopes typically exceed 10° (Neuendorf et al. 2005). By contrast, most spatter cones are small, usually no more than 10 m (30 ft) high. Spatter cones commonly form in linear groups along a fissure. Like cinder cones, spatter cones are steep sided, but they are constructed of agglutinate (lava bombs fused together while hot and viscous), rather than smaller solidified cinders (US Geological Survey 2013a).

During Medicine Lake volcano eruptions, cinder cones commonly formed before lava flows, suggesting an early explosive period, possibly resulting from the release of confined volatiles (Donnelly-Nolan and Champion 1987). Lavas with greater SiO_2 content, such as basaltic andesite (53.0%–56.9% SiO_2) and andesite (57.0%–62.9% SiO_2), typically erupted from cinder cones, whereas lavas containing less than 53.0% SiO_2 produced spatter cones or small shields with pit craters (Donnelly-Nolan and Champion 1987).

Although most lava flows in the monument issued from and are associated with nearby cinder or spatter cones, some "isolated" cones are not correlated with flows (see "Isolated Cinder Cones" section). In the GRI data set for Lava Beds National Monument, the symbols representing isolated cinder cones indicate their age (PE for Pleistocene), composition ("b" for basalt, "m" for basaltic andesite, and "a" for andesite), and relative location (numbers increase from north to south). Hence, Island Butte (PEa3) is a Pleistocene (PE) andesite (a) cone located farther south than Red Butte (PEa2).

Lava Flows and Associated Vents

Of the 208 volcanic units that make up Medicine Lake volcano, 36 are within the monument—17 basalts, 10 basaltic andesites, and 9 andesites (see Geologic Map Graphic and Map Unit Properties Table, in pocket). Distinctive geographic features and landmarks in the monument are composed of these volcanic units. Features highlighted in this section are listed from oldest to youngest. Seven of these features have been isotopically dated; the oldest dates are about 114,000 years ago and associated with Eagles Nest and Bearpaw buttes (table 1).

Table 1. Isotopically dated volcanic features

Feature	Age	Method
Callahan Flow	1,120 years BP	Calibrated radiocarbon age
Black Crater and Ross Chimneys	3,080 years BP	
Basalt of Valentine Cave	12,260 years BP	
Basalt of Devils Homestead	12,320 years BP	
Basalt of Mammoth Crater	36,000 ± 16,000 years	$^{39}Ar/^{40}Ar$
Schonchin Flow	65,000 ± 23,000 years	
Eagles Nest and Bearpaw buttes	114,000 ± 10,000 years	

Sources: Donnelly-Nolan and Lanphere (2005), Donnelly-Nolan et al. (2007), Nathenson et al. (2007), and Donnelly-Nolan (2010).

Juniper Butte

Basaltic andesite of Juniper Butte (PEmj; 53.8% SiO_2) makes up an eroded palagonite tuff ring in the northeastern part of the monument. By definition, palagonite tuff consists of angular fragments of hydrothermally altered or weathered basaltic glass (Neuendorf et al. 2005). Juniper Butte probably formed by the eruption of lava into ancient Tule Lake during the Middle Pleistocene Epoch, between 300,000 and 180,000 years ago; individual clasts in this unit are mud coated (Donnelly-Nolan 2010).

Semi Crater

The basaltic andesite of Semi Crater (PEmsc; 55.0%–55.5% SiO_2) erupted from cinder and spatter cones. The unit currently covers approximately 3 km^2 (1 mi^2), but it was probably at least twice that size before being buried by younger flows (Donnelly-Nolan and Champion 1987). C-shaped Semi Crater is separated from the main exposure of the flow on the north by a lava flow composed of the basalt of The Castles (PEbc). This basalt surrounds the vent area of Semi Crater on three sides. Additionally, a tongue of andesite of Schonchin Butte (PEasb) invaded the vent area from the east. To the north, the larger exposed area of basaltic andesite of Semi Crater apparently moved over the basalt of Canby Bay (PEbcb).

Donnelly-Nolan and Champion (1987) described the rugged basaltic andesite of Semi Crater as aa (pronounced "ah-ah"; basaltic lava with a rough, jagged, or clinkery surface). The Thomas-Wright Battlefield is located on this flow (see "Geologic Features with Cultural Significance" section).

Whitney Butte

Whitney Butte is a 1,527-m- (5,010-ft-) tall cinder cone with two summit craters located at the northern edge of the Callahan Flow (Hmcf). The vent marked by the butte erupted andesite that has one of the highest SiO_2 contents (58.3%) among lavas at the monument. Andesite of Whitney Butte (PEawb) flowed north about 6 km (4 mi) from this feature's vent. The lava flow is rugged and composed of aa; some of it occurs west and north of the monument. The flow is cut by north- and northeast-oriented normal faults with offsets whose downward sides are more commonly to the east than to the west. These faults expose flow thicknesses of at least 10 m (30 ft) (Donnelly-Nolan 2010).

Visitors can hike around Whitney Butte by starting at Merrill Cave (fig. 2). The trail curves around the butte and crosses the western part of Lava Beds Wilderness. The trail provides impressive views of Mount Shasta and the Callahan Flow (fig. 11). The edge of the Callahan Flow near Whitney Butte has a 9-m- (30-ft-) high flow front of block lava (Waters et al. 1990), which occurs in lava flows with high SiO_2 content and is made up of rock fragments greater than 26 cm (10 in) in diameter. Aa and block lava are similar, but the rock fragments in block lava are more regular in shape, somewhat smoother, and less vesicular ("bubbly") than those in aa (Neuendorf et al. 2005).

Figure 11. Whitney Butte Trail. A trail starting at Merrill Cave leads to Whitney Butte—a cinder cone at the northern edge of the Callahan Flow. Note the abrupt change from dark lava to vegetation in the photograph. Visitors can hike around Whitney Butte and across the western part of Lava Beds Wilderness along the trail, which provides impressive views of Mount Shasta and the Callahan Flow. The slope of Whitney Butte is on the left side of the photograph. Cinder Butte is in the distance. View is to the southwest. US Geological Survey photograph by Julie M. Donnelly-Nolan.

Eagle Nest and Bearpaw Buttes

Eagle Nest and Bearpaw buttes, located in the southwestern part of the monument, appear as separate, isolated cones, but are now known to have formed during the same eruption of basaltic andesite 114,000 ± 10,000 years ago (Donnelly-Nolan and Lanphere 2005; Donnelly-Nolan 2010). Donnelly-Nolan and Champion (1987) considered Eagle Nest Butte to be an "isolated cinder cone" and Bearpaw Butte to be part of the basalt of Mammoth Crater (PEbmc). However, Donnelly-Nolan (2010) remapped these buttes and two other exposures farther north as part of the basaltic andesite of Eagle Nest Butte (PEmen).

The SiO_2 content of this unit ranges from 52.4% to 53.8%, with an average of 53.2% from 10 samples. The vents are marked by Eagle Nest and Bearpaw buttes, which are separated by the basalt of Mammoth Crater (PEbmc) and many other units (e.g., PEmhi, PEbdh, Hbrr, and Hbcf; discussed below). These flows overlie lava associated with Eagle Nest and Bearpaw buttes and cause the apparent patchiness of the unit.

Hippo Butte

The Hippo Butte cinder cone rises 1,671 m (5,483 ft) above sea level and has three craters (vents), denoted by stars on the geologic map (see Geologic Map Graphic, in pocket). Basaltic andesite of Hippo Butte (PEmhi; 54.4%–56.1% SiO_2) erupted from the main cone (Hippo Butte) and a smaller cone south of Mammoth Crater (Donnelly-Nolan 2010). Part of the unit is northwest of Hippo Butte, but is separated from the butte by basalt of Mammoth Crater (PEbmc) and Bearpaw Butte, which is composed of basaltic andesite (PEmen). About 35,000 years ago, the basalt of Mammoth Crater flowed around the existing Hippo Butte cinder cone, separating it from the western part of its flow. The vent at Bearpaw Butte erupted before Hippo Butte.

Schonchin Flow

Andesite of Schonchin Butte (PEasb) makes up a prominent lava flow that covers approximately 14 km^2 (5 mi^2) at the center of the monument. Lava and tephra (pyroclastic material ejected from a volcano) erupted from a vent at Schonchin Butte, which is one of the largest cinder cones and a distinctive, lookout-topped landmark in the monument (fig. 12).

The Schonchin Flow has among the greatest SiO_2 contents (57.2%) of lavas in the monument. This content accounts for the blocky nature of the flow, including a relatively rough surface morphology and steep flow front, as well as density and glassiness. Glassier lavas, such as the andesite of Schonchin Butte, do not form lava tubes. As a result, no cave occurs within this flow. Only lava containing less than about 53% SiO_2 had the viscosity necessary to form lava tubes at Medicine Lake volcano (Donnelly-Nolan and Champion 1987).

Because of its rugged surface morphology, the Schonchin Flow appears to be very young. However, the $^{40}Ar/^{39}Ar$ age of 65,000 ± 23,000 years indicates that it is older than all units surrounding it, with the exception of the basaltic andesite of Semi Crater (PEmsc).

The National Park Service maintains a steep, 1.1-km- (0.7-mi-) long hiking trail that leads to the historic Schonchin Butte Lookout. The Civilian Conservation Corps (CCC) built this trail between 1939 and 1941, then hand-carried all of the materials needed to build the lookout atop the butte. The Schonchin Butte Lookout is listed on the National Register of Historic Places and is a functioning fire lookout. The first lookout ranger began duty in 1941 (Bowling 2009).

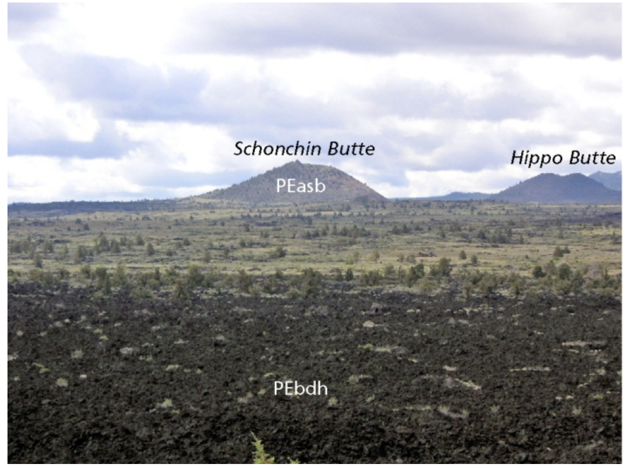

Figure 12. Schonchin Butte. This landmark in Lava Beds National Monument is composed of andesite of Schonchin Butte (PEasb). In the foreground is the basalt of Devils Homestead (PEbdh), which erupted farther south at the Fleener Chimneys spatter vents. A trail from the base of the cinder cone leads to the historic fire lookout. The cone to the right of Schonchin Butte is Hippo Butte. View is to the southeast. US Geological Survey photograph by Julie M. Donnelly-Nolan, available at http://pubs.usgs.gov/sim/2927/sim2927_data/site/photos.html (accessed 7 November 2013).

Three Sisters

The basaltic andesite of Three Sisters (PEmts) erupted from several cinder cones, including the three north–south-aligned cones of Three Sisters in the eastern part of the monument. Two additional vents lie slightly north-northwest of the three main cones, and two others are to the northwest and northeast, respectively. The basaltic andesite covers an area of 11 km^2 (4 mi^2), with about 0.2 km^3 (0.05 mi^3) of lava. Lava moved in all directions, but predominantly northward on nearly flat terrain, partly burying the cinder cones. The morphology of the flow ranges from aa to pahoehoe (pronounced “pah-hoy-hoy”; basaltic lava with a smooth, hummocky, or ropy surface), with block lava built up around the cinder cones.

The Three Sisters vents are atypical for Lava Beds National Monument in that they show no apparent alignment (Donnelly-Nolan 2010); most multiple vents in the monument have strong alignments between N30°W and N30°E (see Geologic Map Graphic, in pocket). The Three Sisters cones may have erupted along intersecting northeasterly and northwesterly alignments (Donnelly-Nolan 2010).

Basalt of Mammoth Crater

Basalt of Mammoth Crater (PEbmc) covers two-thirds of the monument, with a total area of about 250 km^2 (100 mi^2). Volumetrically, it is among the largest flows of Medicine Lake volcano (about 5 km^3 [1 mi^3]). Many distinctive landmarks of the monument, including Mammoth and Modoc craters, Hospital Rock, Captain Jacks Stronghold, and Gillems Camp, are associated with this basalt (fig. 2). The majority of the monument’s lava tubes are also contained within it (see “Lava Tubes” section).

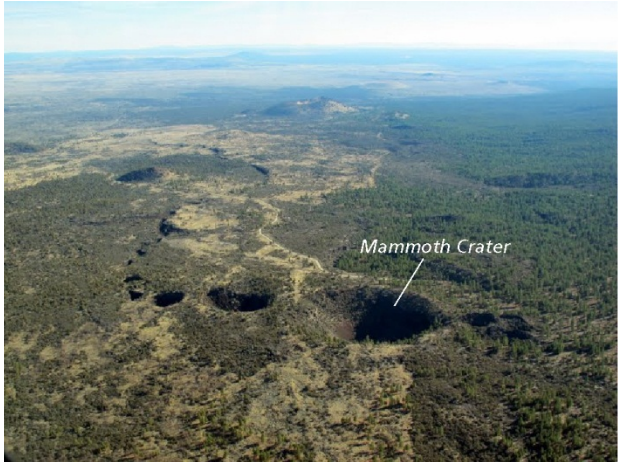

Figure 13. Basalt of Mammoth Crater. This basalt erupted from several vents, including Mammoth Crater (the largest pictured here) and other pit craters and spatter vents. A widespread lava-tube system distributed the basalt primarily to the north and northeast within Lava Beds National Monument, and to the northwest and east outside the monument. National Park Service photograph, available at http://www.nps.gov/labe/photosmultimedia/photogallery.htm (accessed 8 August 2013).

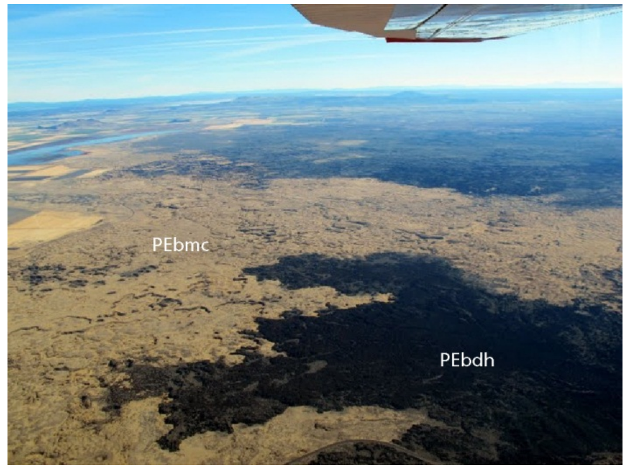

Figure 14. Basalt of Devils Homestead. Looking northeast from over Gillem Bluff, grasslands burned by the 2008 Jack Fire lie beyond the prominent (black) Devils Homestead basalt flow (PEbdh). The basalt of Mammoth Crater (PEbmc), which covers the majority of Lava Beds National Monument, underlies much of the brown-colored grasslands. Part of Tule Lake is visible in the distance. National Park Service photograph, available at http://www.nps.gov/labe/photosmultimedia/photogallery.htm (accessed 8 August 2013).

According to Larson (1992b), six lava tubes served as conduits for the basalt, distributing the molten material to the flow's front, as far as 25 km (15 mi) from the vent at Mammoth Crater (fig. 13). Lava also erupted from several other nearby vents, including Modoc Crater and Bat Butte, as well as a spatter rampart on the northern side of Bearpaw Butte and other north- and northwest-aligned pit craters and spatter vents. The basalt has an $^{40}Ar/^{39}Ar$ age of 36,000 ± 16,000 years (Donnelly-Nolan and Lanphere 2005; Donnelly-Nolan 2010). All sampled areas of this basalt have yielded the same remnant paleomagnetic direction, indicating that it flowed north across the monument area in a geologically brief period of time, probably less than 100 years (Donnelly-Nolan and Champion 1987). Although the unit is primarily basalt, it is compositionally variable, with SiO_2 content ranging from 48.4% to 55.9% (average, 52.3%).

The Castles

The basalt of The Castles (PEbc) contains numerous vents, indicated by stars on the geologic map (see Geologic Map Graphic, in pocket). Vents occur at The Castles and numerous other spatter cones farther north and northeast, including some vents that erupted on the eastern side of the Schonchin Flow. One major vent is the lava lake west of Semi Crater. Most vents are aligned north-northeast, but some are oriented north-northwest to northwest. All of these features, including those at The Castles, erupted fluid basalt (48.6% SiO_2) and produced pahoehoe flows. This type of lava is commonly distributed by lava tubes; the basalt of The Castles contains these features, but development of major lava tubes did not occur in this flow (Donnelly-Nolan and Champion 1987; Donnelly-Nolan 2010).

Basalt of Devils Homestead and Fleener Chimneys

The basalt of Devils Homestead (PEbdh; about 51.4% SiO_2) erupted from spatter vents known as Fleener Chimneys in the western part of the monument. Aa characterizes the eruption, but much of the lava near the vents, such as that under the tables at the Fleener Chimneys picnic area, is pahoehoe (Donnelly-Nolan 2010; Julie M. Donnelly-Nolan, US Geological Survey, research geologist, written communication, 17 October 2013).

During the eruption of this unit 12,320 years ago (Donnelly-Nolan et al. 2007; Nathenson et al. 2007), globs of molten lava piled up, creating a 15-m- (50-ft-) deep conduit for this material (National Park Service 2007d). These vents are located on Gillem fault and oriented N30°E, marking a bend in the north–south-oriented fault to the northeast in this location. Some of the lava flowed west, but most traveled northward, following a topographic low along the base of Gillem Bluff (fig. 14).

Basalt of Valentine Cave

The basalt of Valentine Cave (PEbvc) flowed 12,260 years BP (Donnelly-Nolan et al. 2007; Nathenson et al. 2007) from a northwest-oriented linear array of spatter cones on the northern flank of Medicine Lake volcano. The eruption created the Valentine Cave basalt flow, which covers most of the southeastern corner of the monument. The source vents (spatter cones)—Tickner Chimneys—lie just south of the monument. Nearly all of this basalt erupted from Tickner Chimneys, although additional, numerous, aligned vents uphill to the southeast produced a separate small flow of the same lava (Donnelly-Nolan 2010).

Most lava tubes in the monument occur in the basalt of Mammoth Crater (PEbmc), but the basalt of Valentine Cave also contains these features, including the much-visited Valentine Cave in the southeastern corner of the monument. The unit has an average SiO_2 content of 53.0%, slightly higher than that of the basalt of

Mammoth Crater, and one sample contained 53.4% SiO_2. Lava tubes are unusual in flows with such high SiO_2 content at Medicine Lake volcano, and their presence in the basalt of Valentine Cave may be related to the lava's high iron and titanium contents, which apparently lowered its viscosity (Donnelly-Nolan 2010).

The basalt of Valentine Cave overlies and encloses a deposit of glacial outwash gravel (PEg) about 0.5 km (0.3 mi) east of Caldwell Butte. The gravel from this deposit was formerly quarried (see "Glacial Outwash" section).

Black Crater and Ross Chimneys

The basalt of Black Crater and Ross Chimneys (Hbbr) makes up the second youngest lava flow in the monument; it has a calibrated radiocarbon age of 3,080 years BP (Donnelly-Nolan et al. 2007; Nathenson et al. 2007). A fissure on the lower, northern flank of Medicine Lake volcano erupted basaltic lava and formed the small, surface-fed flows of the unit. The eruption likely lasted only a few days. A linear array of spatter vents marks the fissure in two areas in the west-central part of the monument. Spectacular, open ground cracks with the same orientation as the vents extend north toward the boundary of the monument and may have opened during this eruption (Donnelly-Nolan and Champion 1987).

The vents knows as Ross Chimneys (fig. 15) extruded basalt containing 48.3%–49.6% SiO_2 at the more northerly, but topographically lower, patch of lava (Ross Flow). Vents for the more southerly, upper patch of lava at Black Crater erupted basalt containing 49.2%–50.6% SiO_2. In general, SiO_2 content decreases with elevation in these two features; lava from the Black Crater vents overlies that from the Ross Chimneys vents, suggesting that lava with greater SiO_2 content erupted after that with lesser SiO_2 content (Donnelly-Nolan 2010).

Figure 15. Ross Chimneys. Small spatter vents of Ross Chimneys erupted basalt of Black Crater and Ross Chimneys (Hbbr) about 3,000 years ago. The numerous spatter vents are aligned north–northeast in the northern part of Lava Beds National Monument. The view is to the south. The upper part of Medicine Lake volcano is visible on the horizon. US Geological Survey photograph by Julie M. Donnelly-Nolan, available at http://pubs.usgs.gov/sim/2927/sim2927_data/site/photos.html (accessed 7 November 2013).

Callahan Flow

Basaltic andesite of Callahan Flow (Hmcf) makes up the youngest lava flow in the monument (fig. 16) and one of the youngest of Medicine Lake volcano. A calibrated radiocarbon age of 1,120 years BP (Donnelly-Nolan et al. 2007; Nathenson et al. 2007) was based on three ages obtained from one of several tree remnants at the eastern edge of the flow, west of Mammoth Crater (Donnelly-Nolan et al. 1990).

Based on 40 samples, this unit's SiO_2 content averages 55.1% and is thus called "basaltic andesite." However, the unit is compositionally variable, ranging between 51.8% and 57.8% and consisting of basalt, basaltic andesite, and andesite (Donnelly-Nolan 2010). Morphologically, the flow varies from aa to block lava, with pahoehoe occurring near the vent (Kinzler et al. 2000).

Only part of the Callahan Flow occurs in the monument. The vent that fed it—marked by Cinder Butte, a cinder cone with an elevation of 1,813 m (5,948 ft) above sea level—is just south of the monument boundary (fig. 17). Most of the lava flowed north, and the vent at Cinder Butte is 7 km (4 mi) from the northern terminus of the flow (Donnelly-Nolan and Champion 1987).

Figure 16. Cinder and Island buttes. These buttes rise above the Callahan Flow near the southwestern corner of Lava Beds National Monument. The view is to the north-northwest. Cinder Butte (south of the monument) is the main vent for the basaltic andesite of Callahan Flow (Hmcf), which has a calibrated radiocarbon age of 1,120 years BP. Island Butte (PEa3) is an isolated cinder cone that has not been isotopically dated. National Park Service photograph, available at http://www.nps.gov/labe/photosmultimedia/photogallery.htm (accessed 8 August 2013).

Figure 17. Callahan Flow. The Callahan Flow appears rugged but surface morphology varies from aa to block lava to pahoehoe (near the vent at Cinder Butte). Cinder Butte is just south of the Lava Beds National Monument boundary. US Geological Survey photograph by Tanya Blacic, available at http://pubs.usgs.gov/sim/2927/sim2927_data/site/photos.html (accessed 6 November 2013).

Isolated Cinder Cones

As discussed in the "Lava Flows and Associated Vents" section, many of the named buttes in the monument are cinder cones associated with particular lava flows, but isolated cones are also present. The flows associated with these cones have likely been buried by lava from younger eruptions (Donnelly-Nolan 2010).

Isolated cinder cones in the monument include (from oldest to youngest) the basaltic andesite spatter vent west-northwest of Harden Butte (PEb1), Red Butte (PEa2), Island Butte (PEa3), the basalt cone southeast of Mammoth Crater (PEb5), Caldwell Butte (PEb4), Crescent Butte (PEm2), the andesite cone west of Crescent Butte (PEa1), and Bat Butte (PEm1). The ages of isolated cones are poorly constrained, and none has been numerically dated (Donnelly-Nolan 2010). Furthermore, the temporal relationship between the andesite cone west of Crescent Butte (PEa1) and the Crescent Butte cinder cone (PEm2), located a short distance northwest of the visitor center, is unknown (see Geologic Map Graphic, in pocket).

Lava Tubes

Lava tubes are conduits for molten lava. Nine major lava-tube systems originate in or pass through Lava Beds National Monument (Larson 1992b); six are in the basalt of Mammoth Crater (PEbmc) and one each is in the basalts of Valentine Cave (PEbvc), Caldwell Ice Caves (PEbci), and The Castles (PEbc).

The most extensive lava tubes in the monument are in the basalt of Mammoth Crater (fig. 18). About 35,000 years ago, lava conduits originating at Mammoth Crater and other nearby vents created a broad fan of interlacing tubes. Most of the lava was transported beneath a congealing surface of basalt. In some cases, tubes delivered lava 25 or 30 km (15 or 20 mi) from a source vent. This tube-fed basalt covers roughly two-thirds of the monument and an equal area outside of it. Most caves in the monument are segments of lava tubes formed within this flow (Larson 1992b). The caves are tunnel-like openings that remain after eruption has ceased and lava has stopped flowing through these distributary conduits.

According to the resource stewardship strategy (National Park Service 2012), the monument contains 777 known caves in lava tubes. However, this number may not be accurate because the monument's cave database and GIS are in need of thorough updating and revision. The current database problematically counts multiple entrances to the same cave as different caves, thereby inflating the count. Also, several newly discovered caves have not been added to the database/GIS (Katrina Smith, Lava Beds National Monument, physical science technician, written communication, 11 December 2013). Nevertheless, the 700 or more caves at the monument constitute the greatest concentration of these features in the continental United States (National Park Service 2012).

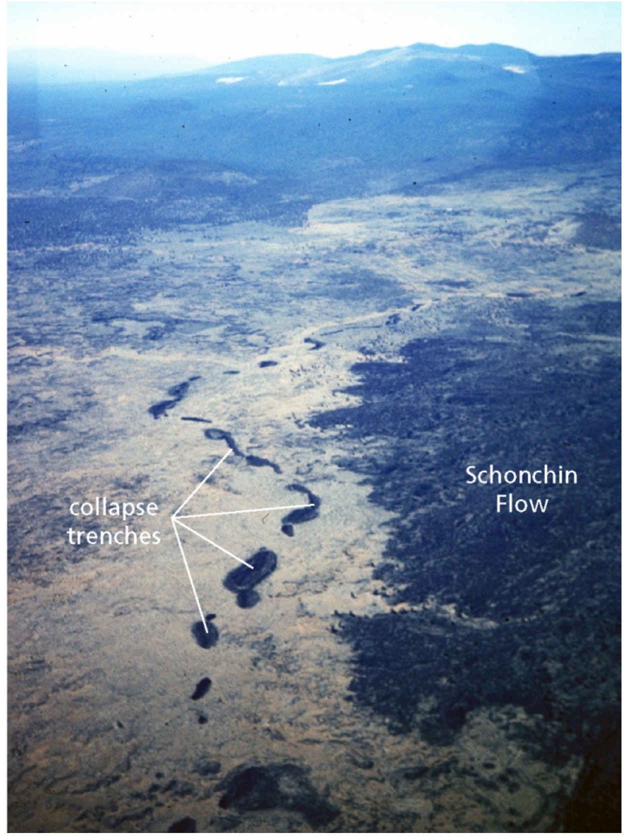

Figure 18. Lava tube. This south-southeast view across central Lava Beds National Monument shows dark-colored collapse trenches along a trace of the lava tube that carried lava from Modoc Crater, one of the vents for the basalt of Mammoth Crater (PEbmc). To the right of the lava tube is the eastern edge of the Schonchin Flow, which was deposited before the basalt of Mammoth Crater. Andesite of Schonchin Butte (PEasb) makes up the lava flow and namesake butte. US Geological Survey photograph by Julie M. Donnelly-Nolan, available at http://pubs.usgs.gov/sim/2927/sim2927_data/site/photos.html (accessed 7 November 2013).

Twenty-two of these caves are "visitor-use caves" (see table 2 and "Cave Management" section).

Lava tubes are a significant part of the rich cultural history of the monument (National Park Service 2012). The Modoc Indians occupied the landscape for thousands of years and extensively used the caves, which served as sources of water, spiritual and ceremonial destinations, and protection from attacking forces (see "Geologic Features with Cultural Significance" section). Archeological material, as well as Pleistocene fossils and the Holocene remains of extirpated species, has been recovered from the caves (see "Paleontological Resources" section).

Individual caves are as much as 30 m (100 ft) across (fig. 19) and more than 4 km (2 mi) long. According to present statistics, the longest cave in the monument is South Labyrinth, 4.20 km (2.61 mi) long. The continuous South Labyrinth cave system includes South Labyrinth, Mitertite Hall, Balcony Chamber, Blue Grotto, Hopkins Chocolate, and Golden Dome (Katrina Smith, Lava Beds National Monument, physical science technician, written communication, 11 December 2013). Tubes are

Table 2. Visitor-use caves at Lava Beds National Monument (continued on next page)

Name	Length	Recreation Level*	Features**
Caves in the Headquarters Area (listed alphabetically)			
Indian Well	91 m (300 ft)	Moderately challenging—pathway changes to loose rock in first half of cave. High ceilings.	Historically contained a pool of water, hence its designation as a "well;" seasonal water now. Ice formations in winter. Balcony. Breakdown.
Labyrinth–Lava Brook (fig. 23)	1,506 m (4,942 ft)	Most challenging—two caves connected by a twisting segment requiring crawling. Ceilings generally low throughout. As the name "Labyrinth" suggests, visitors must pay attention to the route to avoid getting lost. Visitors may exit at one of three locations: Labyrinth, Lava Brook, or Thunderbolt entrances.	The "lava brook" pattern was left on the floor of one passage by the last lava flow. Pahoehoe, including frothy. Benches. Breakdown. Dripstone. Floor jam. High-lava marks. Lava cascades. Lavacicles. Lava pool. Pillars. Pull outs. Rafted blocks.
Mushpot	235 m (770 ft)	Least challenging—developed cave with interpretive signs and lighting.	The "mushpot" is a small rounded mound of smooth lava with a hole in the top; sticky lava emerged from the hole and spread radially, building up a low cone. Balcony. Breakdown. Dripstone. High-lava marks. Lava block jam. Lavacicles. Pahoehoe. Pillars.
Thunderbolt	781 m (2,561 ft)	Most challenging—crawling required in downstream portions, where it connects to Labyrinth and Lava Brook caves. A few tight areas upstream (right) from the entrance; one is 15 cm (6 in) wide at knee level. Some stooping required before ceiling height allows upright walking.	Benches. Breakdown. Floor jam. High-lava marks. Lava cascades. Lava pool. Pahoehoe, including frothy. Rafted blocks. Tube-in-tube.
Caves along Cave Loop (listed in order around one-way road)			
Golden Dome (fig. 27)	679 m (2,229 ft)	Moderately challenging—requires stooping and crawling. "Headache Rock" is a notable feature near the entrance. Rear section, where "Golden Dome" is located, has a figure-eight pattern that requires attention to avoid going in circles.	"Golden Dome" (hydrophobic bacteria). Breakdown. Benches. High-lava marks. Lava cascade. Lava pool. Pahoehoe, including frothy and ropy. Pillar. Rafted blocks.
Hopkins Chocolate	519 m (1,702 ft)	Most challenging—stooping required; one passage has a ceiling height of 0.9 m (3 ft), which requires "duck walking" (i.e., ducking while walking).	Named by E. L. Hopkins for the rich brown lava that coats the ceiling and walls. Contains historical graffiti by J. D. Howard and E. L. Hopkins. Benches. Displays of hydrophobic bacteria. Floor jam. High-lava marks. Lava cascades. Lava pool. Pahoehoe, including frothy.
Blue Grotto	470 m (1,541 ft)	Moderate—high ceilings throughout but rough floors.	Named for the pale blue-gray portions of ceiling. Benches. Floor jam. Lava cascade. Natural bridge and arch. Pahoehoe, including frothy. Rafted blocks.
Catacombs (fig. 19)	2,571 m (8,436 ft)	Most challenging—very long cave that is easily entered but gradually increases in difficulty. Possible to walk upright for approximately 240 m (800 ft) to the stairway, after which the ceiling height rarely exceeds 0.9 m (3 ft) and is less than 30 cm (12 in) in some areas. Multiple levels and numerous side passages. Not recommended for inexperienced cavers.	Balcony. Benches. Breakdown. Lava cascades and falls. Lava pool. Pahoehoe, including frothy. Pillars. Rafted blocks.
Ovis	59 m (194 ft)	Least challenging—commonly explored with Paradise Alleys, to which it is connected by a small opening near a steep drop off, but can be explored safely on established trails. Ceiling heights exceed 8 m (25 ft), and some outside light is visible throughout.	Contained 36 bighorn skulls when it was discovered in the 1890s. Breakdown. High-lava marks.
Paradise Alleys	327 m (1,074 ft)	Least challenging—commonly explored with Ovis Cave, to which it is connected by a small opening near a steep drop off, but can be explored safely on established trails. Smooth floors and ceiling heights exceeding 2 m (7 ft) throughout.	Balconies. Benches. Block jam. Breakdown. High-lava marks. Lava cascades. Lava pools. Natural bridge. Rafted blocks coated with lavacicles.

Table 2. Visitor-use caves at Lava Beds National Monument (continued).

Name	Length	Recreation Level*	Features**
Caves along Cave Loop (listed in order around one-way road, continued)			
Sunshine	142 m (466 ft)	Moderately challenging—stooping required in main passage. Rear section has floors that are steep, very rough, and sometimes wet.	Abundant vegetation where two collapses allow sunlight to enter the cave. Beautiful hydrophobic bacteria coatings and icicles (in winter) adorn rear ceiling.
Hercules Leg–Juniper	1,728 m (5,670 ft)	Most challenging—a single, long excursion through Hercules Leg and Juniper caves involves crossing rocky floors with a passage height of 0.8 m (2.5 ft) and several low sections thereafter. Many skylights and entrances along the way. Hercules Leg portion has generally high ceilings and smooth floors.	Balcony. Benches. Breakdown. Dripstone. Floor jam. High-lava marks. Lava cascades and falls. Lavacicles. Lava pool. Pahoehoe. Rafted blocks.
Sentinel	740 m (2,428 ft)	Least challenging—developed cave with two entrances. Requires no stooping or ducking.	Balconies. Benches. Breakdown. Lava fall. Natural bridge. Pahoehoe, including pulled. Tube-in-tube.
Cave East of Cave Loop			
Valentine (fig. 20)	650 m (2,135 ft)	Least challenging—named for the day it was discovered in 1933. Large main passages with smooth floors and walls.	Occurs in basalt of Valentine Cave (PEbvc); only visitor-use cave not in the basalt of Mammoth Crater (PEbmc). Benches. High-lava marks. Lava cascade. Lavacicles. Lava-covered breakdown. Lava pool. Pillars. Pahoehoe, including pulled between cascades and frothy. Rafted blocks.
Cave West of Cave Loop			
Heppe (fig. 47)	52 m (170 ft)	Least challenging—twilight-lit cave with high ceilings.	Breakdown. Cinders exposed by collapse in cave walls. In wetter years, contains small pool of water. Seasonal ice and water.
Caves North of Cave Loop (listed alphabetically)			
Balcony	885 m (2,903 ft)	Moderately challenging—commonly explored with Boulevard Cave. Sections of low ceilings. Optional crawl up onto a lava balcony.	Balcony. Benches. Breakdown. Natural bridge.
Big Painted	81 m (266 ft)	Least challenging—commonly explored with Symbol Bridge Cave.	Faint American Indian pictographs in entrance area. Breakdown.
Boulevard	231 m (759 ft)	Moderately challenging—commonly explored with Balcony Cave. Sections of low ceilings. Named for the smooth floor created by a lava cascade.	Bench. Floor jam. High-lava marks. Lava falls. Natural bridge. Rafted plates. Tube-in-tube.
Merrill	198 m (650 ft)	Least challenging—relatively high ceiling and smooth, flat floor.	Visitors once skated by lantern light on an enormous ice floor at the bottom of this cave. Today, only small areas of ice remain. Breakdown. Benches. Peeling lava. Tube-in-tube.
Skull	177 m (580 ft)	Least challenging—accessible via a smooth trail down a metal stairway to a platform. Ceiling heights of 14–18 m (45–60 ft) on the upper level. Wide-open feel, thus good for first-time cavers.	Named for the mammal bones, including two human skeletons, discovered here. Remnants of three very large stacked lava tubes. Year-round ice floor on lower level. Balcony. Benches. Breakdown. High-lava marks. Lava falls. Slides of red lapilli and scoria on floor.
Symbol Bridge (fig. 45)	45 m (148 ft)	Least challenging—commonly explored with Big Painted Cave.	Prominent American Indian pictographs in entrance area. Breakdown.

Sources: Waters et al. (1990), National Park Service (2013a), and Katrina Smith (Lava Beds National Monument, physical science technician, written communication, 11 December 2013).

****From National Park Service (2013a). "Least challenging" caves have relatively high ceilings and relatively smooth floors or trails. "Moderately challenging" caves have low sections that may involve stooping and/or rough floors. "Most challenging" caves have very low sections that require crawling; orientation may be challenging and map use is recommended.***

*****Features are described in the "Primary Cave Features," "Collapse Features," and "Secondary Features" sections.***

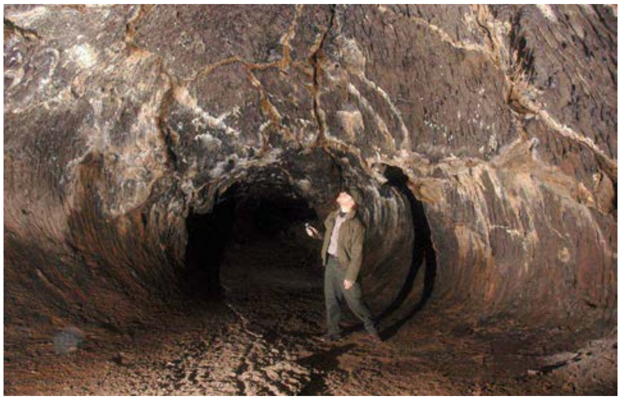

Figure 19. Catacombs Cave. This 2,571-m- (8,436-ft-) long cave with numerous side passages and multiple levels is among the most challenging caves to explore, requiring stooping, "duck walking" (ducking while walking), and crawling. National Park Service photograph.

at the surface and as much as 45 m (150 ft) below it (Larson 1992a). Some are multilevel (Knox 1959) and others are horizontally complex, with many interconnected branches (Larson 1992a).

Primary Cave Features

Hot gases and flowing, dripping, splashing, accreting, and pulling lava created many interesting features within the caves at the monument. Table 2 lists the 22 visitor-use caves at the monument and highlights features found therein. Molten or partially solidified lava formed the following features.

- Bench or balcony—when lava flows constantly for a considerable period of time at a single high level within a tube, congealing of a lava surface from the walls toward the center of the tube may build a lava balcony. When constant flow or ponding occurs lower on the walls, a lava bench may form (fig. 20).
- Dripstone—undamaged parts of most tube walls in the monument have dripstone linings (Waters et al. 1990). These features retain the forms taken by congealing lava as it splashed against or dripped off the walls of a tube (fig. 21).
- High-lava marks—like the high-water mark of a river at flood stage, high-lava marks record the high-stage position of a lava stream on the walls of a tube.
- Lava cascade or fall—where lava moves down-gradient in a tube or drops into a lower tube, a cascade or fall may form as the material solidifies. These features were named for their resemblance to a frozen waterfall or river (Larson 1990).
- Lavacicles—intact parts of the ceilings of most caves in the monument show fine displays of lavacicles (Waters et al. 1990). As the name implies, these features resemble icicles, but were formed as molten lava dripped from the roof of a tube (fig. 22).
- Lava pool—a lava pool may form as flowing lava "ponds" in a flat area of a tube. The smooth, thin, partly congealed "skin" on the surface of the molten liquid commonly has a glassy sheen, adding to the pool-like appearance of these features. Fluctuating pools of lava can create high-lava marks.

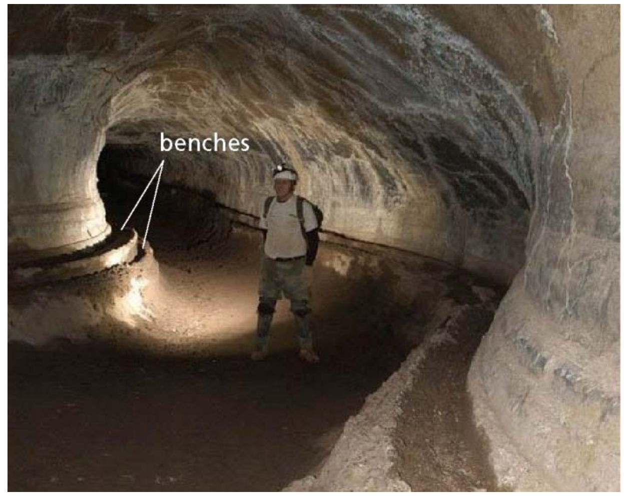

Figure 20. Valentine Cave. Like high-water marks during a flood, high-lava marks record "flood positions" of a lava stream on the walls of a lava tube. Where lava flowed constantly or pooled, benches formed. National Park Service photograph, available at http://www.nps.gov/labe/photosmultimedia/photogallery.htm (accessed 5 November 2013).

Figure 21. Dripstone. As molten lava drips down the wall of a lava tube and congeals, dripstone is created. This dripstone is covered by secondary mineralization; its location in the monument is uncertain. National Park Service photograph.

Figure 22. Lavacicles. These icicle-like features form as molten lava drips from the roof of a lava tube. Fine examples occur in the caves at Lava Beds National Monument. Although their location in the monument is uncertain, the lavacicles pictured here may be in Catacombs Cave, based on a similar photograph in Waters et al. (1990). National Park Service photograph by Dale Pate (NPS Geologic Resources Division).

- Pahoehoe, aa, and pahoehoe–aa transitions—the smooth to ropy (pahoehoe) surface of lava on the floor of a lava tube may change gradually to a very rough surface composed of bubble-filled loose blocks of aa lava. The release of water vapor and other gases produces bubbles and blisters in molten lava. Lava may froth when pressure drops as magma rises to the surface or where lava tumbles turbulently over a lava cascade. Frothy pahoehoe is a distinctive feature in many caves in the monument (table 2).
- Pillars—tall pillars (or columns) of lava form where molten rock pouring through a hole in a cave roof or from an adjacent tube cools in place (Hill and Forti 1997).
- Pull outs—pull outs form where dripping "plaster" of a final coat of lava sags down, peels away, or sloughs off from a tube's wall. These features expose another layer of lava, possibly dripstone, on the wall.
- Rafted blocks and floor jams—large blocks of lava may tumble from the roof of a tube and then raft downstream as part of a molten flow. A floor jam may form when many blocks or plates become rafted together. Some caves, such as Juniper Cave, contain avalanche-like lobes of floor-jam blocks.
- Stacked tubes—where flowing lava is building a pair of benches from opposing walls, a crust of congealed lava may extend completely across the tube. A two-storied tube forms when the molten lava flowing beneath this crust drains out.
- Tube-in-tube—a tube-in-tube forms when a small lobe of new lava invades an older, larger, open tube and drains out soon thereafter, leaving a thin, encircling, solidified crust. A few flow surges of diminishing size can produce a succession of tube-in-tubes resembling nested concrete culverts.

Collapse Features

Caves at the monument commonly contain collapsed rubble that has fallen from the roof. Huge piles of angular broken rock, called "collapse rubble" or "breakdown," may cover a cave floor. Breakdown is indicative of collapse that occurred as a tube cooled and contracted (Waters et al. 1990) or in response to some later event (Julie M. Donnelly-Nolan, US Geological Survey, research geologist, written communication, 17 October 2013). It is commonly stacked so tightly that it prevents further exploration of a cave passage.

Bridges form between collapse trenches on the surface. Inside a tube, a natural bridge or arch is a remnant of rock that spans a tube from wall to wall.

Many of the visitor-use caves are entered through a collapsed portion of a former lava tube (fig. 23). In some cases, collapse of a tube's roof provides a large entrance through which visitors can walk with ease (Waters et al. 1990) (fig. 24).

Figure 23. Entrance to Labyrinth Cave. Some visitor-use caves, such as this one, are entered through collapse openings in the lava tubes' roofs. As the name of this cave suggests, attention must be paid to the route to avoid getting lost. Explorers may exit at one of three locations: Labyrinth, Lava Brook, or Thunderbolt entrances. National Park Service photograph by Dale Pate (NPS Geologic Resources Division).

Figure 24. Collapse trench. Collapse of the roofs of lava tubes creates open trenches and entrances to caves. Cave entrances are prone to rockfall, particularly as a result of earthquake activity. National Park Service photograph, available at http://www.nps.gov/labe/photosmultimedia/photogallery.htm (accessed 18 December 2013).

Secondary Minerals and Cave Deposits

Caves in lava tubes contain a variety of secondary minerals formed by seepage waters that extract components from the overlying soil and basalt and deposit them in the underlying tubes as crusts, crystals, and small speleothems (White 2010). These features add interest and color to the cave environment (fig. 25).

Oxides of iron appear as red-stained coatings that contrast with black and gray basalts (fig. 26). White deposits—consisting of a coating of calcium carbonate, soluble salt, or clay—are formed by the seepage of rain or melting snow into a cave, wetting the surface of a lavacicle or dripstone (fig. 21) before evaporating. Cave walls that are completely covered by this material can show a silver or pale-blue sheen when wet. This phenomenon is the source of the name "Blue Grotto" (Waters et al. 1990). Some of these deposits are quite ornate and lacelike; excellent examples occur in Mushpot Cave.

Figure 25. Secondary mineralization. Seeping water deposits minerals on lavacicles in Mammoth Cave in Modoc National Forest, south of Lava Beds National Monument (upper photograph). Water seeping through soil and basalt incorporates minerals and then deposits them as crusts, crystals, and small speleothems. These speleothems in an unnamed cave in the monument (lower photograph) are mineral-coated coralloids—a catchall term for a variety of nodular, globular, and coral-like speleothems. National Park Service photographs by Katrina Smith (Lava Beds National Monument).

Figure 26. Secondary mineralization and cave ice. Coatings of iron oxide provide color in cave environments. White and blue cave ice also adds interest to Crystal Ice Cave. Photograph by Kenneth Ingham (copyright 2011, used by permission).

Secondary cave deposits may also be pale buff, tan, or chocolate brown, depending on the concentrations of clay, humic acids (from soil), and hydrous iron-oxide stains. Bacterial growth on moist cave walls creates a golden appearance when a light is cast on it; water droplets on the bacteria shimmer like polished gold. This "false gold" is sometimes visible in wet areas of Mushpot Cave and is beautifully displayed on the moist roof and walls of Golden Dome (fig. 27), Hopkins Chocolate, and Valentine caves (Waters et al. 1990).

Figure 27. Golden Dome. Bacterial growth on moist cave walls creates a golden appearance when a light is cast on it. This "false gold" is beautifully displayed on the moist roof and walls of Golden Dome. Photograph by Kenneth Ingham (copyright 2011, used by permission).

Another interesting, albeit uncommon, secondary phenomenon is a flickering greenish glow visible in near-surface caves with wet floors. The color and intensity of the glow appear to change as light plays on it. This effect is the result of phosphorescence derived from the decay of animal droppings. Valentine Cave is a notable location where this phenomenon can be observed (Waters et al. 1990).

Tectonic Features

Medicine Lake volcano lies in a transitional zone between the Cascade volcanic arc and the Basin and Range physiographic province (fig. 28). The volcano is east of the axis of the Cascade volcanic arc, which formed at the surface above the Cascadia subduction zone. The Cascade arc of volcanoes extends from the Garibaldi volcanic belt in southern British Columbia to the Lassen volcanic center in northern California

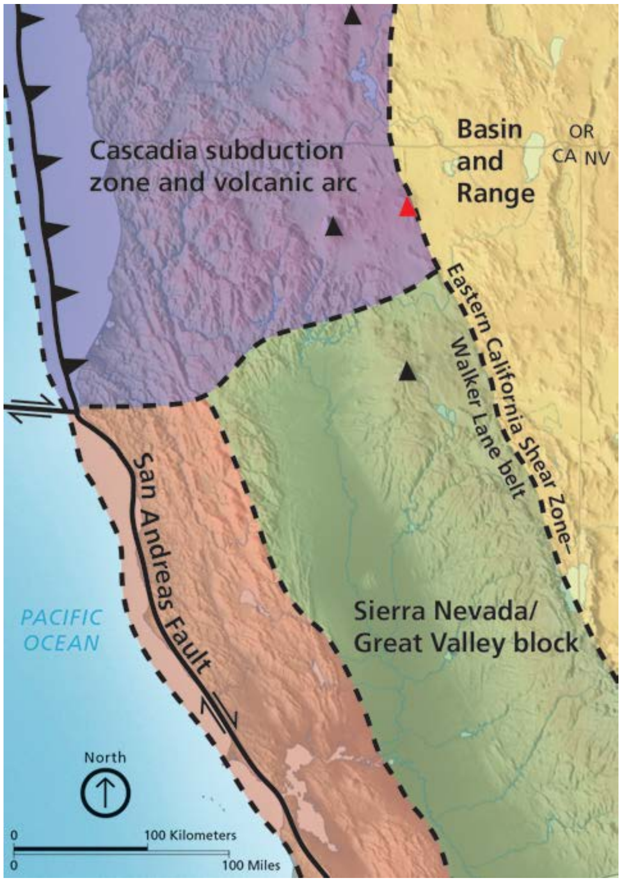

Figure 28. General tectonic provinces of northern California. Seismic activity beneath and in the vicinity of Medicine Lake volcano (red triangle) is influenced by the surrounding tectonic provinces, in particular, the Basin and Range (yellow) and Cascadia subduction zone and volcanic arc (purple). Movement in other regional provinces also influences the area's seismic activity. These provinces are the San Andreas Fault zone (orange),Sierra Nevada/Great Valley block (green), and the Eastern California Shear Zone–Walker Lane belt, which separates the Basin and Range and Sierra Nevada/Great Valley block. Individual black triangles mark volcanoes of the Cascade volcanic arc. Arrows show relative motions along transform faults. The chain of triangles along the Cascadia subduction zone indicates the area of subduction and direction of thrusting. Graphic by Trista Thornberry-Ehrlich (Colorado State University) after Poland et al. (2006, figure 1).

(summarized in the GRI report about Lassen Volcanic National Park by KellerLynn 2014). It is characterized by a north–northwest-oriented linear array of stratovolcanoes (also called "composite volcanoes"), cinder cones, and shield volcanoes, including Medicine Lake volcano. The arc is the result of oblique subduction of the Juan de Fuca oceanic plate, and associated Gorda and Explorer plates, beneath the North American continental plate.

Medicine Lake volcano also lies on the western margin of the Basin and Range physiographic province, an area of active rifting (pulling apart) of Earth's crust. Normal faults—located north and south of the volcano and presumably under its edifice (Donnelly-Nolan 1988; Jennings 1994; Blakely et al. 1997)—are indicative of Basin and Range rifting at Medicine Lake volcano (fig. 3).

Distinctive tectonic features in Lava Beds National Monument and vicinity are an outcome of this tectonic setting and include Gillem Bluff and fault, north–south-oriented faults and ground cracks, and subsidence of the Medicine Lake caldera.

Gillem Bluff

The fault scarp at Gillem Bluff, which forms the western margin of Tule Lake basin, is the major structural feature of Medicine Lake volcano (Donnelly-Nolan and Champion 1987). Gillem fault exposes much older rocks than are seen in the rest of the monument. Fault movement brought Pliocene rocks to the surface, including older basaltic andesite (PLomw and PLomg), older basalt (PLobg), and older tuff (PLotg). Some of these units show considerable evidence of interaction with ancient Tule Lake (Donnelly-Nolan and Champion 1987). Older basaltic andesite in western Lava Beds National Monument (PLomw) is the oldest rock unit in the monument. It is not dated, but underlies older tuff of Gillem Bluff (PLotg), which has an $^{40}Ar/^{39}Ar$ age of 2.023 ± 0.020 million years. All units with "older" in their names predate the eruption of Medicine Lake volcano.

At Gillem Bluff, vertical offset on the fault is at least 160 m (530 ft). At Fleener Chimneys, where vents for the Pleistocene basalt of Devils Homestead (PEbdh) are located on the fault, offset is less than 30 m (100 ft). Farther south, ground cracks that appear to trend into and join the fault do not occur on the Holocene Callahan Flow (Hmcf). Thus, the fault terminates or is buried under younger flows in the southern part of the monument (Donnelly-Nolan and Champion 1987).

At least 15 m (50 ft) of displacement, up to the west, has occurred on this fault since the 35,000-year-old basalt of Mammoth Crater (PEbmc) flowed against the fault scarp. The fault is not known to be seismically active, but such activity may be episodic (Donnelly-Nolan and Champion 1987).

Faults and Ground Cracks

The orientation of faults on Medicine Lake volcano is similar to that of volcanic vents. Both are controlled by external (regional east–west extension) and internal (caldera-related) stress (Donnelly-Nolan 2002).

Faults on the volcano edifice are limited in number and extent (fig. 3). Many faults are likely buried by younger lavas. Regional, dominantly north–south-oriented, Basin and Range faults with normal offsets project directly under Medicine Lake volcano. No lateral motion has been documented on these faults (Donnelly-Nolan 2002).

Open ground cracks are common on the lower northern and eastern flanks of Medicine Lake volcano. Some cracks probably opened 3,080 years ago, during the fissure eruption of Black Crater and Ross Chimneys. East–west extension is indicated by offset features on opposite sides of some of these open cracks (Donnelly-Nolan 2002). In addition, numerous north–northwest- to north–northeast-oriented faults, including open ground

Figure 29. Big Crack. This feature has an overall north–south orientation and is located in the northeastern part of Lava Beds National Monument. The fault has no apparent vertical offset and is a result of regional east–west extension associated with the Basin and Range physiographic province. The view is to the south. US Geological Survey photograph by Julie M. Donnelly-Nolan, available at http://pubs.usgs.gov/sim/2927/sim2927_data/site/photos.html (accessed 7 November 2013).

cracks such as Big Crack (fig. 29), cut the basalt of Mammoth Crater (PEbmc; Donnelly-Nolan 2010).

Open ground cracks, including those associated with the basalt of Black Crater and Ross Chimneys (Hbbr), are indications of Holocene faulting. The 10-m (30-ft) vertical offset of the 12,500-year-old Giant Crater lava south of the monument is an obvious indication of recent faulting (Donnelly-Nolan et al. 2007). In general, however, documented seismicity at Medicine Lake volcano is rare (Dzurisin et al. 1991), suggesting that extension and accompanying seismic activity are episodic and intermittent (Donnelly-Nolan et al. 2008; see "Earthquakes" section).

Caldera Subsidence

With respect to the outer margin of the volcano edifice, the center of the Medicine Lake caldera is currently subsiding at a rate of 8.6 mm (0.34 in) per year (Dzurisin et al. 2002). With respect to the caldera rim, subsidence of the center of the caldera is occurring at a rate of 4.9 mm (0.19 in) per year. Subsidence is a result of east–west regional extension of the Basin and Range and the weight of the large volcano edifice on a hot, weak crust (Dzurisin et al. 1991, 2002), combined with the cooling (and contraction) of hot rock beneath the volcano (Poland et al. 2006). This rate of subsidence is too rapid to be sustained for thousands of years and is probably temporary (Poland et al. 2006; Donnelly-Nolan et al. 2008).

Paleontological Resources

The paleontological resources at Lava Beds National Monument document a long history of flora and fauna, as well as climate change. They occur as tree molds in lava flows; mammal remains and packrat middens in caves; and diatoms, pollen, and ostracodes in lake deposits.

All paleontological resources are nonrenewable and subject to science-informed inventory, monitoring, protection, and interpretation as outlined in the 2009 Paleontological Resources Preservation Act (see Appendix B). As of January 2014, regulations associated with this act were being developed. Paleontological resources at the monument are scarce, fragile, and scientifically valuable (National Park Service 2010). In a chapter in *Geological Monitoring*, Santucci et al. (2009) described five methods and vital signs for monitoring in situ paleontological resources: (1) erosion (geologic factors), (2) erosion (climatic factors), (3) catastrophic geohazards, (4) hydrology/bathymetry, and (5) human access/public use. Smith (2012) provided a method for rating the vulnerability and significance of paleontological resources at the monument.

Tree Molds

Several lava flows at the monument contain tree molds. These are trace fossils, which preserve evidence of an organism's life activities, rather than the organism itself; they form where molten lava surrounds a tree or engulfs a forest, but the tree or trees are not immediately consumed by the heat. Upon contact with a lava flow, a tree's moisture content is released as steam, accelerating

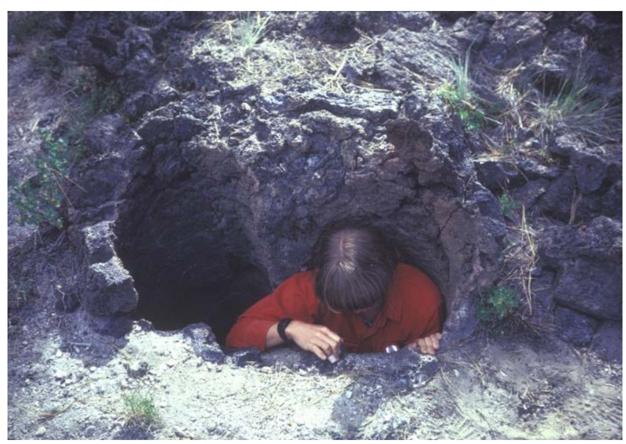

Figure 30. Tree molds at Medicine Lake volcano. Tree molds are trace fossils that develop when trees engulfed by molten lava are not immediately consumed by the heat. In Lava Beds National Monument, the Valentine Cave, Black Crater, and Callahan flows contain tree molds. The molds shown here occur south of the monument in Klamath National Forest. US Geological Survey photograph by Julie M. Donnelly-Nolan.

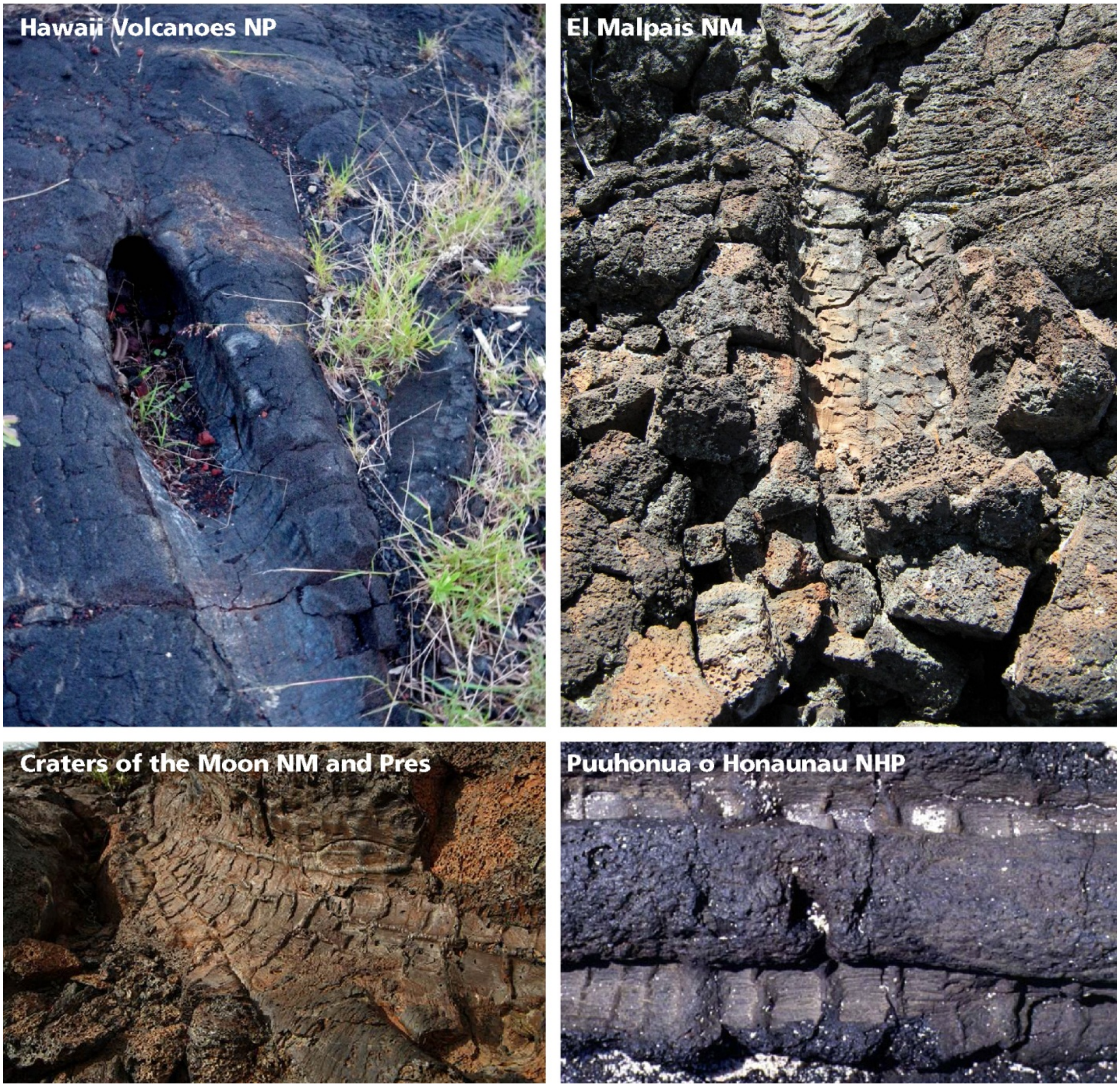

Figure 31. Tree molds in the National Park System. Lava Beds National Monument is one of five units in the National Park System that contains tree molds. The other units are Hawaii Volcanoes National Park in Hawaii (upper left), Craters of the Moon National Monument and Preserve in Idaho (lower left), El Malpais National Monument in New Mexico (upper right), and Puuhonua o Honaunau National Historical Park in Hawaii (lower right). National Park Service photographs from Santucci et al. (2012).

cooling and allowing time for the formation of an impression of the tree in the lava. Surface details such as bark patterns are sometimes preserved (Santucci et al. 2012).

Santucci et al. (2012) reported that Lava Beds National Monument is one of five units in the National Park System with tree molds (figs. 30 and 31). The other units are Craters of the Moon National Monument and Preserve in Idaho, El Malpais National Monument in New Mexico (see GRI report by KellerLynn 2012), and Hawaii Volcanoes and Puuhonua o Honaunau national parks in Hawaii (see GRI reports by Thornberry-Erhlich 2009, 2011).

The following units at Medicine Lake volcano contain tree molds: basalt of Valentine Cave (PEbvc), which has a calibrated radiocarbon age of 12,260 years BP; basalt of Black Crater and Ross Chimneys (Hbbr), dated to 3,080 years BP; and basaltic andesite of Callahan Flow (Hmcf), with an age of 1,120 years BP. Notably, tree molds in these flows were the sources of charcoal or charred wood used for radiocarbon dating (Donnelly-Nolan et al. 1990; Nathenson et al. 2007). Known tree molds in the basalt of Valentine Cave occur outside the monument (Julie M. Donnelly-Nolan, US Geological Survey, research geologist, written communication, 17 October 2013).

Pleistocene and Holocene Mammals

Paleontological resources discovered within the monument provide evidence for a time when mastodon (*Mammut americanum*), camel (*Camelops hesternus*), bear (*Ursid* sp.), jaguar (*Panthera onca*), and bison (*Bison* sp.) roamed the landscape. In the 1930s, F. P Cronemiller and W. S. Brown found the remains of mastodon (dentary fragment with two partial molars; fig. 32), camel (two teeth), and bear (one tooth) apparently embedded in lava in a cave in the basalt of Mammoth Crater (PEbmc). Thus, these animals may have inhabited the land that is now Lava Beds National Monument at the same time that Medicine Lake volcano was extruding this basalt, about 35,000 years ago. However, the association of these fossils with volcanic material raises questions about how the specimens survived destruction by high-temperature lava (Santucci et al. 2001). A more likely interpretation is that this bone material exhibits a "patina" that superficially resembles the surrounding lava (fig. 32; Santucci and Kenworthy 2009). R. M. Bushey discovered jaguar (tooth) and bison (tooth) remains in 1934. Secondary cave mineralization—calcite or cristobalite—encrusts these specimens.

The Museum of Paleontology, University of California–Berkeley, holds the specimens found by Cronemiller and Brown. The Lava Beds National Monument collection retains the specimens found by Bushey; it also contains nine mastodon specimens of unknown provenience (Santucci and Kenworthy 2009).

More recently, during the Holocene Epoch (fig. 7), bighorn sheep (*Ovis canadensis*) (fig. 33) roamed the area encompassing the monument. In the 1890s, E. L. Hopkins found 36 bighorn skulls in what became known as Ovis Cave, in the basalt of Mammoth Crater (PEbmc). The age of these skulls is unknown, but Kast (2008) reported radiocarbon ages of 6,370, 4,800, and 3,700 years BP for three bighorn sheep specimens, which provide a general timeframe of occupation by the species. Additional radiocarbon ages extended this range to 1,780 years BP; a few samples yielding dates of 100 years BP were likely from the reintroduction population or from animals that lived just before the historic die-off (Katrina Smith, Lava Beds National Monument, physical science technician, written communication, 11 December 2013). Bighorn sheep inhabited the Lava Beds area until about 1910, when they were extirpated as a result of unrestricted hunting practices (Smith 2012).

Figure 32. ***Mammut americanum*** **molar. Collections of the Museum of Paleontology at the University of California–Berkeley contain a partial molar from a mastodon that was discovered in Lava Beds National Monument. A thick, dark patina coats part of the tooth's surface and is similar to secondary mineralization on the floor of the cave. National Park Service photograph.**

Figure 33. ***Ovis canadensis*** **skull. Smith (2012) documented the results of a paleontological survey of bighorn sheep in Lava Beds National Monument. Investigators surveyed 42 caves, 25 of which contained the remains of bighorn sheep. National Park Service photograph by Katrina Smith (Lava Beds National Monument).**

In the 1960s, K. A. Howard found bone material that is likely modern, including a bobcat mandible and tibia and a deer rib. C. Roundtree found bone material at nine sites in the same cave in 2001 (Santucci and Kenworthy 2009).

Packrat Middens

Packrat (*Neotoma* spp.) middens are important tools for the reconstruction of late Pleistocene and Holocene paleoecology and climate in western North America. They are collections of plant material, food waste, coprolites, bones, and other biological materials, which are commonly well preserved in arid, protected settings, such as caves and rock shelters. They document the environment within the builder's foraging range.

Tweet et al. (2012) provided an inventory of packrat middens in 33 National Park System units, including Lava Beds National Monument. Packrat middens occur in caves at the monument. Mehringer and Wigand (1984, 1987) described these features and reported dates from seven middens, ranging from 5,265 ± 75 to 1,260 ± 80 years BP. The studies by Mehringer and Wigand (1984, 1987) focused on the prehistoric distribution of western juniper (*Juniperus occidentalis*). However, the middens at the monument yielded fossils of a variety of trees, forbs, grasses, and mosses (Mehringer and Wigand 1987).

Diatoms, Pollen, and Ostracodes

Although lava tubes have been the primary focus of past paleontological surveys at the monument, lake deposits (PEHl) have also yielded paleontological material (see "Lake Deposits" section). For example, Adam et al. (1989) observed diatoms, pollen, and ostracodes in a 334-m- (1,096-ft-) long Tule Lake sediment core extracted in the town of Tulelake, near the center of the lake basin. The base of the core tapped 3-million-year-old sediments (see "Geologic History" section).

Diatoms (microscopic, single-celled aquatic plants) are present throughout this core, indicating the presence of a shallow, saline lake (Adam et al. 1989). Pollen is also present in most of the core, and changes in pollen abundance and species represent responses of the regional vegetation to climactic changes. The algae record is more directly related to lake behavior, including responses to tectonic or volcanic events, rather than climate (Adam et al. 1989).

Ostracodes are present in high-carbonate (>10% $CaCO_3$) intervals of the core, indicating that Tule Lake contained slightly saline, carbonate-enriched waters in the past. Lakes with this chemical characteristic are common in areas where evaporation exceeds precipitation, including the Tule Lake region today. Ostracode preservation in the core appears to be associated with a dry climate or a groundwater regime mimicking a dry climate, such as a hydrologically closed basin (Forester 1987; Adam et al. 1989). The modern-day Tule Lake sump contains very abundant ostracode fauna (Adam et al. 1989).

Lake Deposits

Today, farmland laced with irrigation and drainage ditches covers the area at the northern edge of Lava Beds National Monument. In the not-so-distant past, however, the waters of Tule Lake lapped against the steep, lava-flow front at Captain Jacks Stronghold (Waters 1981, 1992), which is composed of basalt of Mammoth Crater (PEbmc). Between 1906 and 1918, Tule Lake shrank as a result of the diversion of Lost River to irrigate lands farther west. Once drained, the volcanic silt and sands of the lakebed, fortified with organic matter from the tule (bulrush) swamps, became rich farmland (Waters 1981, 1992).

Donnelly-Nolan (2010) correlated lake deposits (PEHl) with volcanism occurring during eruptive stages 3 (180,000–100,000 years ago), 4 (100,000–13,000 years ago), and 5 (13,000 years ago to present) of Medicine Lake volcano (see "Geologic History" section). Pockets of the former lakebed occur among lava at the northern edge of the monument, and include deposits of sand, gravel, and clay west and northwest of Prisoners Rock and along Gillem Bluff. Donnelly-Nolan and Champion (1987) noted distinctive lake deposits of fine gravel, sand, and clay at the northern limit of the basalt of Mammoth Crater where it flowed into Tule Lake, although these

Figure 34. Pillow lava. Ellipsoidal pillows of lava formed when the basalt of Mammoth Crater (PEbmc) flowed into ancient Tule Lake about 35,000 years ago. US Geological Survey photograph by Julie M. Donnelly-Nolan.

deposits were too thin or small to map at a scale of 1:24,000. Additionally, where lava interacted with the waters of ancient Tule Lake, pillows (ellipsoidal mounds of lava) formed by repeated oozing and quenching of hot basalt under water (fig. 34). Between Captain Jacks Stronghold and the northeastern corner of the monument, pillow basalt is visible in small quarries at the edge of the flow (see "Abandoned Mineral Lands" section).

Although larger in extent than today, Tule Lake must have been shallow when the basalt of Mammoth Crater flowed into it because the upper surface of the flow shows no sign of interaction with water, except for the thin deposits noted above (Adam et al. 1989). The presence of diatom species in the lake deposits provides further evidence that the lake was shallow and periodically saline at the time of eruptions (Adam et al. 1989).

During the last 3 million years, Tule Lake basin and other basins of the upper Klamath River received runoff from the surrounding volcanic highlands. Thus, these basins are rich in dissolved silica (from volcanic rocks), and were able to support abundant diatom populations during the Pleistocene ice ages, which were wetter. As a result, much of the sediment in these basins is rich in biogenic opaline silica (diatomite). In addition, these basins are downwind of many Cascade volcanoes and have been blanketed by volcanic ash, both as tephra layers deposited by airfall and as reworked layers of volcanic ash brought in by streams (Adam et al. 1989). Interestingly, some tephra in the Tule Lake–basin record erupted from volcanoes in other national parks, such as the 620,000-year-old Lava Creek ash from Yellowstone National Park, the 609,000-year-old Rockland tephra from Lassen Volcanic National Park (see GRI report by KellerLynn 2014), and the 7,700-year-old Llao Rock pumice from Crater Lake National Park (see GRI report by KellerLynn 2013).

Glacial Outwash

Donnelly-Nolan (2010) mapped gravel and sand deposits (PEg), interpreted as glacial outwash (sand and gravel deposited by glacial meltwater streams), at two locations in Lava Beds National Monument. One area of glacial outwash gravel was mapped east of Caldwell Butte, and was formerly exposed in a quarry east of the monument road. The quarry was used as a landfill after mining ceased and later filled. The outwash was covered as a result of quarry filling (Donnelly-Nolan 2010). The basalt of Valentine Cave (PEbvc) surrounded but did not cover this deposit; as such, the deposit was a notable feature of volcanic landscapes called a “kipuka” (an area surrounded by a lava flow). The gravel’s stratigraphic position indicated that it was deposited by glacial meltwater before the basalt of Valentine Cave erupted from Tickner Chimneys and other vents 12,260 years ago. Abundant white pebbles of pumice in the glacial outwash are compositionally identical to the rhyolite of Mount Hoffman (Hrmh; see GRI information on the attached CD), which erupted 28,000 ± 5,000 years ago on the northeastern caldera rim (Donnelly-Nolan and Lanphere 2005; Donnelly-Nolan 2010).

The second area of glacial outwash gravel covers the floor of Hidden Valley—an elongated, amphitheater-shaped enclosure east of Mammoth Crater (fig. 35). As in the other deposit, rounded pebbles of rhyolite of Mount Hoffman occur in this gravel. Apparently, the gravel was transported by meltwater down a channel later filled by the postglacial basalt of Valentine Cave.

Figure 35. Hidden Valley. This valley is one of two areas in Lava Beds National Monument that Donnelly-Nolan (2010) mapped as containing glacial outwash gravel. Hidden Valley is an elongated, amphitheater-shaped enclosure at the southern boundary of the monument. National Park Service photograph, available at http://www.nps.gov/labe/photosmultimedia/photogallery.htm (accessed 1 May 2013).

Geologic Features with Cultural Significance

Geologic features at Lava Beds National Monument have influenced human occupation and activities for thousands of years (National Park Service 2010). The significance of past human events can be fully realized through a geologic perspective, with the landscape described “through the eyes of a geologist.” As a notable example of this geohistorical approach, Waters (1981, 1992) described Captain Jacks Stronghold, the geologic events that created this natural fortress, and the role that geology played in the Modoc War of 1872–1873. This section highlights the stronghold and other geologic features associated with the Modoc War, as well as the geology of culturally significant Petroglyph Point.

Modoc War Sites

The Modoc Lava Beds Archeological District, listed on the National Register of Historic Places in 1991, includes 221 significant sites throughout Lava Beds National Monument (National Park Service 2010). Sites along the historic shore of Tule Lake are particularly significant because they represent sites in the Tule Lake basin unaltered by modern agricultural activity (National Park Service 2010).

In the mid-19th century, pressures from immigrating European Americans drove the Modoc Indians from their home along the shores of Tule Lake. The US government transferred the Modoc to Oregon, where they shared a reservation with the Klamath Indians. In November 1872, a band of Modoc warriors, women, and children led by Kientpoos, also known as Captain Jack, left the Klamath Reservation and headed back to the Lost River Valley and Lava Beds. US troops and volunteers were organized to capture this group of Modoc people and return them to the reservation. Raids and killings poisoned chances for a peaceful resolution, and full-scale war ensued (Vesilind 2001).

Volcanic activity created the rough terrain that was the setting for the Modoc War. At first glance, the landscape appears to be relatively flat, with undulating low hills bordered on the west by the high Gillem Bluff. However, sagebrush and grasses obscure a rocky landscape, created by volcanic activity and dominated by lava flows and ridges, ground cracks, and lava tubes (fig. 36). Modoc warriors, who were familiar with the landscape, used the rough terrain to their advantage, while the US Army greatly underestimated the difficulties that the landscape would present in capturing the Modoc men, women, and children (National Park Service 2005). Every change in topography provided an opportunity for defensive and offensive strategies used by both sides during the war (National Park Service 2005).

Access to a reliable water source was another significant factor during the war. High water levels of Tule Lake at this time brought the shoreline up to the northern edges of Captain Jacks Stronghold, Gillems Camp, and Hospital Rock (National Park Service 2005), and lake access was critical for the survival of all parties involved in the war.

Captain Jacks Stronghold

Captain Jack and his followers found refuge in the basalt of Mammoth Crater (PEbmc) near the shores of Tule Lake (fig. 37). This area, known as Captain Jacks Stronghold, is cut by lava cracks and dotted with small habitable caves, creating a natural fortress with a seemingly endless variety of places through which to move unnoticed (National Park Service 2007a). Windblown dust had partially filled many of the lava cracks, building natural pathways (Knox 1959).

Figure 36. Terrain at Lava Beds National Monument. The terrain in the monument is deceiving, as the apparently flat landscape is replete with rocky outcrops, collapse trenches, and cave openings, as is evident in this photograph (note the cave opening in the upper right corner). During the Modoc War of 1872–1873, Modoc warriors used the rough terrain to their advantage, while US Army soldiers greatly underestimated the difficulties that the landscape would present in capturing the Modoc band of men, women, and children. National Park Service photograph, available at http://www.nps.gov/labe/photosmultimedia/photogallery.htm (accessed 8 August 2013).

Field skirmishes were fought in the lava crevices surrounding the stronghold. Hundreds of defensive rock walls, constructed from lava blocks, are the primary built features remaining from these skirmishes (National Park Service 2005).

The basalt of Mammoth Crater proved an imposing barrier to the US Army. For five months, about 170 Modoc men, women, and children held out against a US Army force that eventually numbered 600. The choice of location gave the Modoc band enough advantage to withstand a long siege against incredible odds—in terms of numbers of people and through the harsh winter season (National Park Service 2005). When the US Army ultimately surrounded the stronghold on three sides, cutting off access to Tule Lake, the Modoc band used their knowledge of the lava flow in conjunction with the cover of night to escape to the south undetected.

Waters (1981, 1992) discussed the influence of the volcanic terrain on various assaults during the war and the Modoc's escape route at its end, and provided a map showing the geologic features and fortifications of Captain Jacks Stronghold. These geologic features, including schollendomes, collapse basins, collapse pits, and natural defense trenches, were originally mapped by D. Kimbrough and A. C. Waters in 1976. Since that time, other investigators have clarified the genesis of these features. Schollendomes are now understood to be tumuli, created where pressure of slow-moving molten lava within a flow swells or pushes the overlying crust upward. The surfaces of pahoehoe lava flows on flat or gentle slopes commonly exhibit these domed structures (US Geological Survey 2013a). The axial cracks in tumuli at the stronghold were created when lava encountered the waters of Tule Lake, stopped, and inflated. These cracks provided sheltered pathways for Modoc warriors (Julie M. Donnelly-Nolan, US Geological Survey, research geologist, written communication, 17 October 2013).

Figure 37. Captain Jacks Stronghold. In the upper photograph, cave openings punctuate the surface of the basalt of Mammoth Crater (PEbmc) and appear much as they did during the Modoc War. Since the war, sagebrush has grown on the basalt, obscuring a Modoc breastwork (a stacked rock wall used for defense). In the lower photograph, a crack cuts the surface of the basalt. Modoc warriors likely used this and other cracks as defensive points against the US Army. Photographs from National Park Service (2005).

Inflation of basalt is an important process that Waters (1981, 1992) did not recognize. Only since the late 1980s and early 1990s has the term "inflated lava" begun to appear on geologic maps (e.g., Kuntz et al. 1988) and been used widely by geologists and volcanologists (Chitwood 1994). Inflation features are areas of pahoehoe flows that have swelled as a result of lava injection beneath the flow's surface crust. Classic inflation features include inflation mounds and pits. Commonly, these mounds have distinctive cracks that formed when the brittle crust cracked as additional lava inflated from below. Most features called "collapse pits" or "collapse basins," including those denoted by Waters (1981, 1992) at Captain Jacks Stronghold, are now interpreted as inflation pits; rather than being areas of collapse, they are areas that did not inflate (Chitwood 1994). Thus, the "collapse pits" mapped by Waters (1981, 1992) are actually non-inflation pits. This distinction is important for understanding the Modoc War and movement within the stronghold. Non-inflation pits were not connected to lava tubes that carried the inflating lava, and thus were not connected to caves that provided cover and shelter for the Modoc people.

Gillems Camp

Gillems Camp stood on an uneven platform of the basalt of Mammoth Crater (PEbmc) at the base of the steep Gillem Bluff. Movement along Gillem fault (see "Tectonic Features" section) created the bluff and exposed much older rocks than are seen elsewhere in the monument. Vertical offset on the fault is at least 160 m (520 ft).

The US Army selected this site because of access to water and proximity to a prominent lookout from which to survey the landscape below. Partway up the slope of Gillem Bluff, Signal Rock provided unobstructed views of Hospital Rock, allowing signals to be passed between the two US Army camps and coordination of attacks on the stronghold using flags (Murray 1959). Soldiers used this vantage point to monitor Modoc activity, especially during the four months of attempted peace negotiations; to communicate with troops in the field; and to plan mortar and howitzer fire (Murray 1959; National Park Service 2005).

Hospital Rock

The US Army encampment at Hospital Rock was less than 3 km (2 mi) northeast of Captain Jacks Stronghold. This site was chosen for its proximity to the stronghold and its natural defensive advantage, views, and access to water (Tule Lake). This rock outcropping provided 360° views of the surrounding terrain (fig. 38), including those toward Captain Jacks Stronghold and to Gillems Camp (National Park Service 2005).

Hospital Rock marks the site of three littoral cones that formed explosively where a lava tube transporting basalt of Mammoth Crater (PEbmc) emptied directly into ancient Tule Lake (Donnelly-Nolan and Champion 1987; Donnelly-Nolan 2010). A littoral cone is similar in appearance to a small cinder cone, but formed by steam explosions where lava entered the lake. These distinctive littoral cones at Hospital Rock are marked on the digital geologic map (see Geologic Map Graphic, in pocket).

Canby Cross

The current site of Canby Cross rests on basalt of Mammoth Crater (PEbmc). This occurrence is more of a coincidence than a geologic connection that influenced human actions. Nevertheless, the basalt underlies the spot where Modoc warriors murdered General Canby and Reverend Eleazer Thomas during attempted peace negotiations. In 1873, US soldiers erected a simple cross to mark the location. Later, perhaps during the CCC era, the cross was enlarged and set upon a mortared rock base.

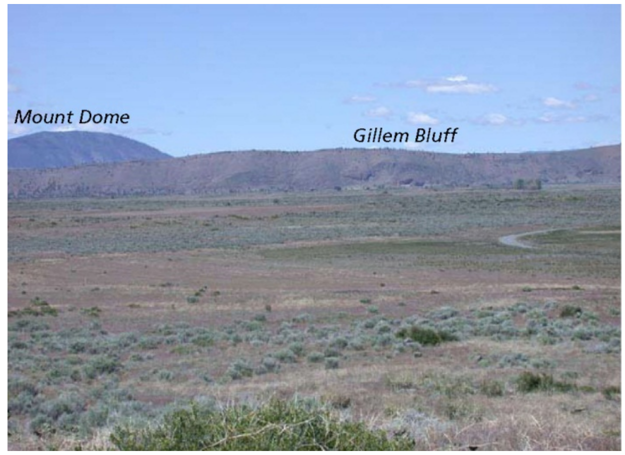

Figure 38. Terrain between Hospital Rock and Gillem Bluff. From Hospital Rock looking southwest toward Gillem Bluff, the topography appears deceptively flat, but is actually rocky and difficult to traverse. Mount Dome is in the distance. Photograph from National Park Service (2005).

Water Resources

The lack of water in the lava flows made Tule Lake a critical resource for survival. Toward the end of the war, the Modoc band was cut off from Tule Lake, their only reliable water source. Surrounded by the US Army on the western, northern, and eastern sides of Captain Jacks Stronghold, the Modoc band planned a nighttime escape and fled southward across the relatively smooth, inflated surface of the basalt of Mammoth Crater to the Schonchin Flow (composed of the andesite of Schonchin Butte, PEasb), where they made a camp near small water pools (location unknown; National Park Service 2005). When this source of water was depleted, they moved to ice caves familiar to Modoc hunters, enabling the group to postpone their surrender for a while longer. According to Murray (1959), the Modoc band used water available in Captain Jacks Ice Cave, Frozen River Cave, and Caldwell Cave. Captain Jacks Ice Cave and Frozen River Cave lie east of the Schonchin Flow in basalt of Mammoth Crater (PEbmc). Caldwell Cave lies farther south, in the basalt of Caldwell Ice Caves (PEbci).

Thomas-Wright Battlefield

After the Modoc's nighttime escape toward the Schonchin Flow, a decisive battle was fought at what is now known as the Thomas-Wright Battlefield (fig. 39). Basaltic andesite of Semi Crater (PEmsc) underlies this site. Lava formed a large bowl-shaped depression surrounded by ridges with small rock outcroppings. A patrol led by Captain Evan Thomas was en route from Gillems Camp to Hardin Butte (PEb1) in search of the Modoc band when they stopped to rest in this natural depression. First Lieutenant Thomas F. Wright was one of four officers who accompanied Captain Thomas and

Figure 39. Thomas-Wright Battlefield. At noon on 26 April 1873, US troops rested in a depression in basaltic andesite of Semi Crater (PEmsc) west of Hardin Butte (PEb1). The troops were attacked by Modoc warriors from the surrounding higher ground of lava ridges and suffered many casualties. Photograph from National Park Service (2005).

59 enlisted men. They were unaware that Modoc warriors were following them. Initially hidden from view by the surrounding ridges, the warriors surprised the soldiers and were able to inflict the largest number of casualties in a single day during the war (National Park Service 2005).

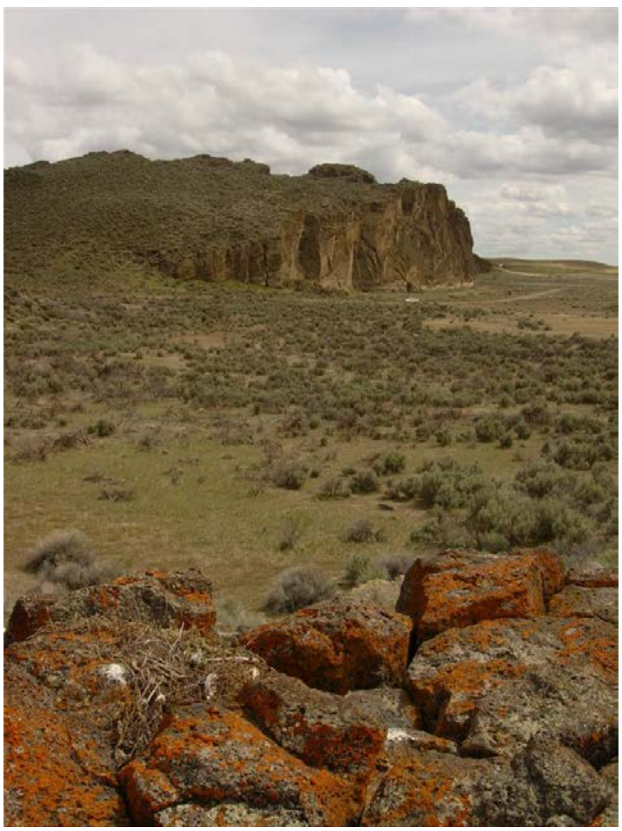

Figure 40. Petroglyph Point. American Indian rock art is preserved on the basalt of Prisoners Rock (PEbp) at Petroglyph Point. National Park Service photograph, available at http://www.nps.gov/labe/photosmultimedia/photogallery.htm (accessed 3 September 2013).

Petroglyph Point

With more than 5,000 individual carvings, Petroglyph Point is one of the most extensive representations of American Indian rock art in California (National Park Service 2007b) (fig. 40). The site was listed in the National Register of Historic Places in 1975. Geometric patterns dominate the rock art, though anthropomorphs (human), zoomorphs (animal), and other figures appear to be represented (fig. 41). Some researchers have classified the petroglyphs at Lava Beds National Monument as representative of the Great Basin Style, whereas others have interpreted them as unique to the area (National Park Service 2007b).

Figure 41. Petroglyphs. Petroglyph Point—a cliff wall covered by more than 5,000 individual petroglyphs, including those pictured here—is on the Prisoners Rock tuff cone. Petroglyph Point was listed in the National Register of Historic Places in 1975. National Park Service photographs, available at http://www.nps.gov/labe/photosmultimedia/photogallery.htm (accessed 3 September 2013).

Serving as the backdrop for Petroglyph Point, Prisoners Rock is a distinctive landmark in a series of two tuff cones and one tuff ring that rise 50–250 m (160–820 ft) above the ground surface (fig. 42). The other two members of this volcanic trilogy, which formed along north- and northwest-oriented faults, are The Peninsula tuff cone and North Crater tuff ring, north of Prisoners Rock (Lavine and Aalto 2002). All three of these features developed during a single volcanic event 273,000 ± 18,000 years ago, when rising basaltic magma encountered the waters of Tule Lake (Donnelly-Nolan and Lanphere 2005; Donnelly-Nolan 2010). The interaction of magma and water resulted in

Figure 42. Prisoners Rock. The tuff cone on which Petroglyph Point is located, in the Petroglyph Section of Lava Beds National Monument, formed when lava erupted through ancient Tule Lake about 275,000 years ago. American Indians carved petroglyphs into the soft rock on its steep western face (right side of photograph). This aerial view looks southeast. US Geological Survey photograph by Julie M. Donnelly-Nolan, available at http://pubs.usgs.gov/sim/2927/sim2927_data/site/photos.html (accessed 7 November 2013).

phreatomagmatic (steam) eruptions: as magma superheated the water, violent explosions ensued, fracturing the surrounding rocks. During hundreds to thousands of eruptive pulses, clouds of steam and volcanic ash carrying pieces of subsurface rocks, were blown into the air to heights of up to 5 km (3 mi) (Lavine 1994). Ash and other volcanic material falling from the sky built up in layers, creating cones and a ring around the vents (Lavine 1994). Prevailing southwesterly winds at the time of the explosions created thicker tuff deposits east and northeast of the vents, resulting in the asymmetrical shapes of Prisoners Rock, The Peninsula, and North Crater (Lavine and Aalto 2002). Wave activity in Tule Lake eroded these features, almost completely eroding the North Crater tuff ring (Lavine and Aalto 2002). Well-exposed wave-cut benches along the western and eastern sides of Prisoners Rock provide evidence of past lacustrine activity (Donnelly-Nolan 2010).

Depositional layers that form Prisoners Rock, The Peninsula, and North Crater generally show a decrease in water–magma interaction with time, transitioning from hydrovolcanic tuff to spatter to lava (Lavine and Aalto 2002). Following these interactions and prior to the lithification of tuff, lava filled the crater at The Peninsula, creating a lava lake that flowed over the crater rim to the west and southwest. The exposures of basalt north and south of Prisoners Rock consist of this lava-lake material, and a small spatter cone near the center of The Peninsula crater probably marks its vent (Lavine 1994).

As mapped by Donnelly-Nolan (2010), a single unit—basalt of Prisoners Rock (PEpb)—encompasses this hydrovolcanic episode and consists of lava flows, spatter vents, tuff cones, and dikes (fig. 43). Lavine and Aalto (2002) mapped the specific volcanic, hydrovolcanic, and lacustrine deposits, and delineated the crater rims of the tuff cones and ring, providing greater detail (fig. 44).

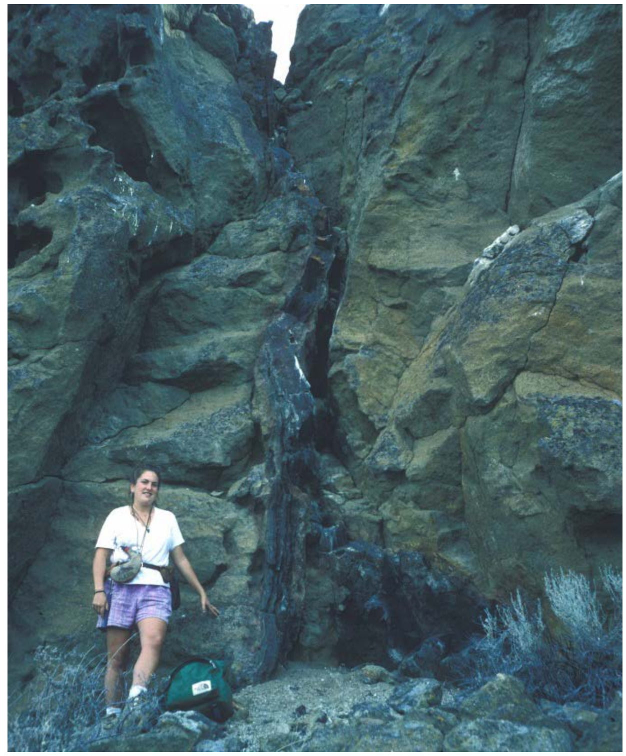

Figure 43. Igneous dike. Magmatic activity continued at the Prisoners Rock tuff cone after water–magma interactions ceased, forming basalt flows, dikes (shown here), spatter cones, and a lava lake. US Geological Survey photograph by Julie M. Donnelly-Nolan.

Drilling between Prisoners Rock and The Peninsula tuff cones has shown that phreatomagmatic tuff extends 45 m (150 ft) below the present ground surface. The tuff overlies lake deposits that were at the surface at the time of the eruptions (Hotchkiss 1968; Lavine 1992). Thus, Prisoners Rock was an island for much of its existence, and historic lake levels were up to 7 m (23 ft) above the present ground surface (Cleghorn 1959). Between the tuff cone's formation about 270,000 years ago and the early 1900s, when Tule Lake was drained for agricultural purposes, lake waves cut the previously mentioned benches and significantly eroded the sides of Prisoners Rock and The Peninsula, undercutting hydrovolcanic deposits, which broke along fracture surfaces and formed cliff faces, including Petroglyph Point.

Thus, Prisoners Rock was most practically reached by boat before Tule Lake was converted to cropland. Researchers studying evidence of climate change believe that the cliff face on which the petroglyphs are located was above water only during certain drier periods, which delimit the times at which people could have made the carvings at each level. These dry periods are believed to have occurred between 6,400 and 5,700 years ago, between 4,500 and 2,600 years ago, and within the last 500 years (National Park Service 2007b).

Other American Indian rock art is found at Symbol Bridge (fig. 45), Big Painted Cave, and Fern Cave. These features are pictographs—pictures painted on rocks—which, like petroglyphs, link geology and archeology.

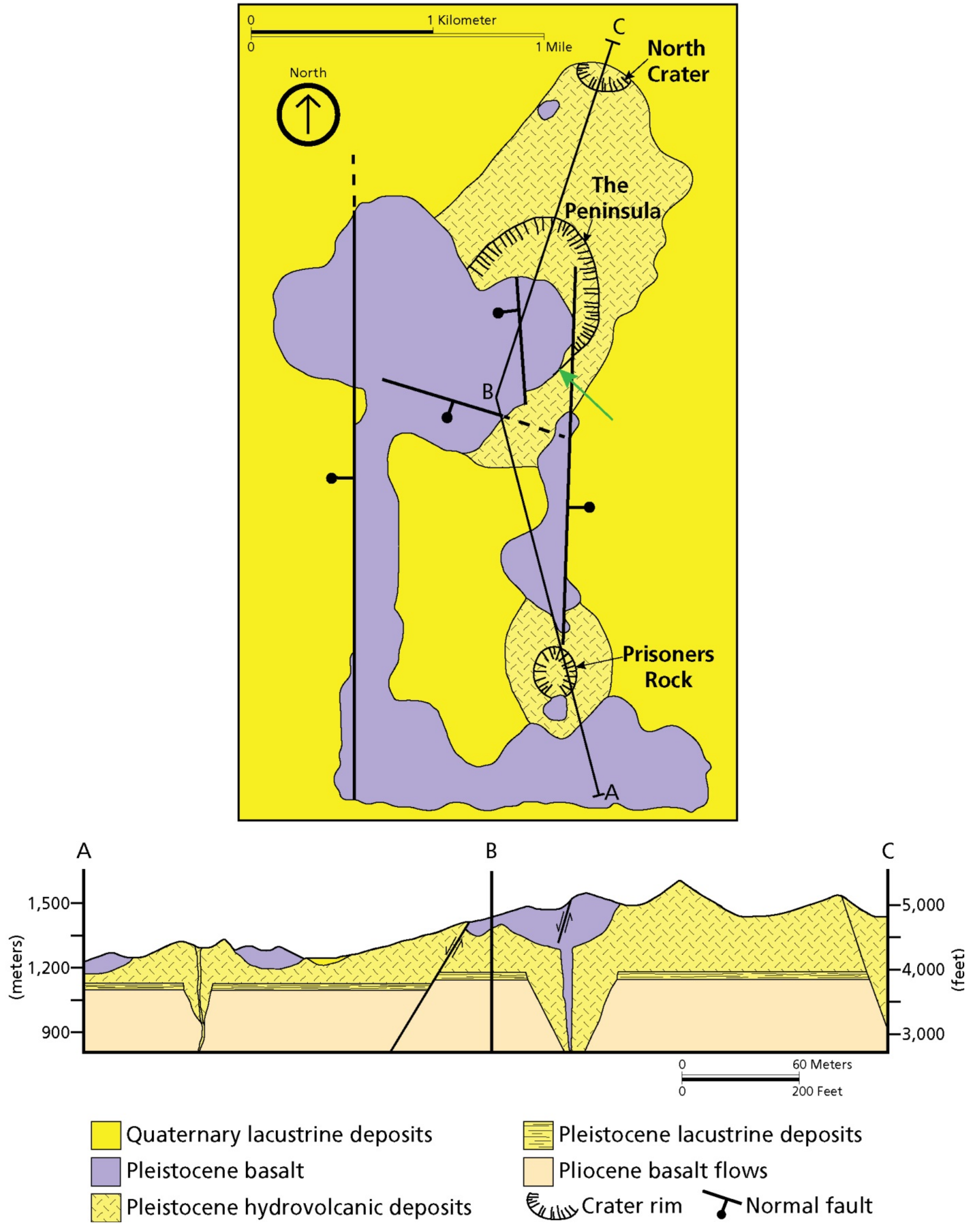

Figure 44. Petroglyph Section geologic map and cross section. The Peninsula tuff cone is the central and largest of three edifices in and near the Petroglyph Section of Lava Beds National Monument. The other two are the Prisoners Rock tuff cone and North Crater tuff ring. The green arrow points to the outcrop of the lava lake margin of The Peninsula. The cross section shows subsurface units, as inferred from drill holes and country rock inclusions in the tuff cones. Graphic after Lavine and Aalto (2002, figure 2) by Trista Thornberry-Ehrlich (Colorado State University).

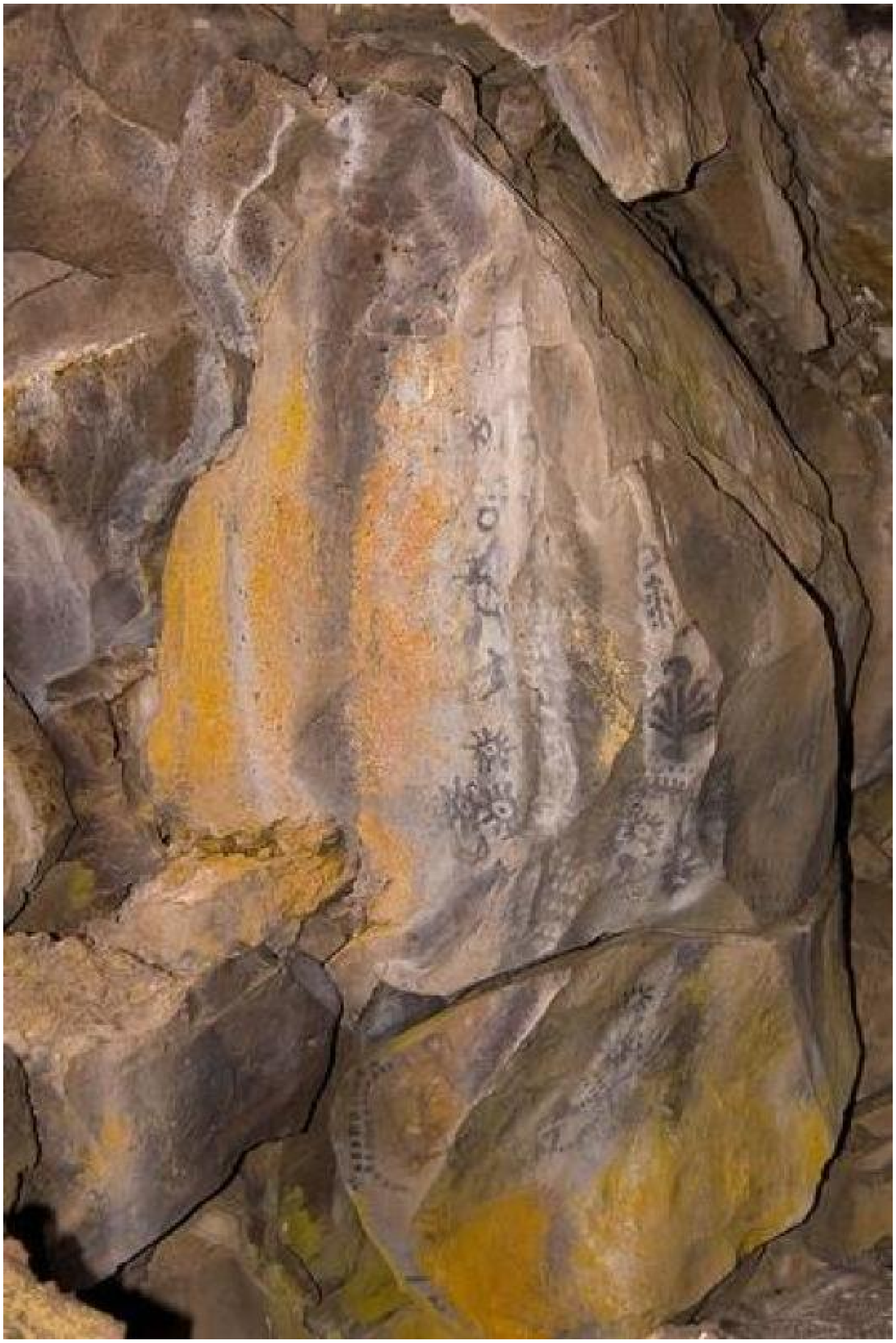

Figure 45. Symbol Bridge pictographs. In addition to petroglyphs, Lava Beds National Monument contains another type of American Indian rock art—pictographs (images painted on rocks). Excellent examples of pictographs can be seen at Symbol Bridge, a cave located north of Cave Loop. National Park Service photograph, available at http://www.nps.gov/media/photo/gallery.htm?id=C333EE50-155D-4519-3E2AEF2EBB151E60 (accessed 3 September 2013).

Geologic Resource Management Issues

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

Discussions during a GRI scoping meeting (4 March 2004) and a post-scoping, follow-up call (20 June 2013) identified the following geologic issues:

- Cave Management
- Recreational Impacts on Geologic Features
- Wind Erosion at Petroglyph Point
- Abandoned Mineral Lands
- Rockfall and Roof Collapse
- Earthquakes
- Volcano Hazards
- Geothermal Features and Development

Resource managers may find *Geological Monitoring* (Young and Norby 2009) useful for addressing these geologic resource management issues. This book provides guidance in the monitoring of vital signs—measurable parameters of the overall condition of natural resources. Each chapter covers a different geologic resource and includes detailed recommendations for resource managers and suggested methods of monitoring. Information about monitoring in situ paleontological resources is discussed in the “Paleontological Resources” section of this report.

Cave Management

Caves are premiere resources at Lava Beds National Monument (see “Lava Tubes” section). To protect them, an active cave management program has been in place since the adoption of a cave management plan in 1990 (National Park Service 2012). A significant future activity for the cave management program at the monument is completion of an updated cave management plan, which will propose management strategies and potential “protected areas” (e.g., natural areas or areas used only for research) to address current threats to cave resources (National Park Service 2012). Moreover, a major planned activity for the cave management program is the initiation of a long-term cave monitoring protocol developed through the Klamath Network. This protocol will focus on seven parameters: cave climate, cave ice, cave visitation, bats, invertebrates, nutrient input (scat and visible organics), and cave-entrance vegetation (National Park Service 2012). *Geological Monitoring* (Young and Norby 2009) may be useful for this endeavor. In 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.

A significant part of cave management at the monument is monitoring visitation, which is concentrated in 22 visitor-use caves. These caves contain infrastructure such as stairs, platforms, and developed trails; associated parking areas and access trails are located outside many of them. About 80,000 visitors enter the caves annually (Shane Fryer, Lava Beds National Monument, physical scientist, telephone communication, 20 June 2013). Cave-visitation monitoring is accomplished via voluntary cave registers and infrared trail counters placed at cave entrances (National Park Service 2012).

Recreation is an acceptable use of caves within the monument. However, not all caves are open to this activity. To help US Department of the Interior and US Department of Agriculture (Forest Service) managers protect caves and the fragile resources found within them, the Federal Cave Resources Protection Act of 1988 (US Congress 1988) and associated regulations (see Appendix B) do not allow the National Park Service to release cave location data unless the authorized officer (superintendent) determines that disclosure will not create a substantial risk to cave resources due to theft or vandalism. Most non–visitor-use caves in the monument are in remote backcountry or wilderness areas that are difficult to access, resulting in minimal visitation to many caves, which helps to maintain relatively pristine cave environments.

Visitor-use caves may be temporarily closed, for example, to protect maternity colonies of Townsend’s big-eared bats (*Corynorhinus townsendii*), which are listed as a species of special concern in California. Closures are posted on the Lava Beds National Monument website, http://www.nps.gov/labe/planyourvisit/index.htm. Resource management and law enforcement staff members work together to enforce cave closures.

The decision to temporarily close a cave is the result of a resource-protection or public-safety concern. For example, Fern Cave is gated, with limited visitation offered in summer during ranger-guided tours. This restricted access allows for the protection of cultural and natural resources, including pictographs, ferns and associated plant communities, and a population of Pacific tree frogs (*Pseudacris regilla*). Similar to Fern Cave, Crystal Ice Cave is gated, with visitation restricted to ranger-guided tours during winter, which is necessary to protect ice formations (fig. 46) and ice floors (figs. 26 and 47). Visitation is allowed only during winter when the cave's temperature is at or below freezing, so that a group's body heat will only minimally impact ice resources. The lower level of Skull Cave is gated to protect an ice floor. Visitors are able to view the ice floor through the gate, but are prevented from entering to minimize foot traffic, which would introduce particulates and heat that could potentially accelerate melting. In response to numerous impacts and repeated misuse, Post Office Cave was gated in 1998 (Sowers 2000). This cave is located near a high-use area and for years received unregulated visitation that resulted in a significant amount of prohibited activities. Restoration efforts have been ongoing since the closure to remove impacts associated with previous abuses (National Park Service 2012).

Threats

Caves and their unique subterranean environments are extremely fragile resources. Caves at the monument are highly susceptible to a range of threats, including modifications to cave entrances and passages. Entrance enlargement or the addition of poorly designed infrastructure potentially disrupts airflow patterns, changes the extent of the twilight zone, and alters natural meteorological conditions maintained within cave ecosystems (National Park Service 2012). In contrast to cave entrances, the morphology of cave passages in the monument is fairly resistant to impacts. However, fragile cave features, such as lavacicles (fig. 22) and secondary mineralization (fig. 25), are nonrenewable resources that can be permanently destroyed by carelessness or intentional vandalism. Unintentional impacts on cave resources include accidental dropping of litter, deposition of lint, deterioration of the substrate by trampling, crushing of difficult-to-see invertebrates, and damage of cave features through inadvertent head bumping and hand/knee placement. Unauthorized impacts are the result of illegal actions, usually committed intentionally, that destroy or damage cave resources. Although uncommon, these acts do occur and include vandalism, graffiti, theft, closure violations, smoking, and deposition of trash and human excrement.

Figure 46. Cave ice. Some caves in Lava Beds National Monument contain notable displays of cave ice. Entrance into these caves is restricted to ranger-guided tours during winter to protect these fragile features. National Park Service photographs by Dale Pate (NPS Geologic Resources Division) (Crystal Ice Cave) and Katrina Smith (Lava Beds National Monument) (Indian Well). Lower right photograph by Kenneth Ingham (copyright 2011, used by permission).

Figure 47. Ice floor. These distinctive features occur in several caves at Lava Beds National Monument, including Heppe Cave, shown here (see also fig. 26). National Park Service photograph, available at http://www.nps.gov/labe/photosmultimedia/photogallery.htm (accessed 1 May 2013).

A single unauthorized incident can have a greater impact than years of visitation (National Park Service 2012). Monument staff has made considerable effort to remove human waste, litter/debris, and graffiti from caves. In 2010, staff and volunteers removed 150 kg (330 lbs) of trash from 32 of the monument's most frequently visited caves (National Park Service 2012).

Another form of impact on caves may result from adjacent or overlying development. The hydrology of caves in the monument is limited primarily to the infiltration of surface moisture, which can be affected by the presence of roadways or parking areas that introduce or divert runoff. Runoff that is transported into caves through cracks and fractures in overlying basalt can introduce contaminants, such as petrochemicals, which accumulate on paved surfaces and wash off in concentrated amounts during or following precipitation events. The presence of vehicular traffic in the monument adds to the potential for disturbance of cave environments through audible engine noise and exhaust odors (National Park Service 2012).

At present, monument staff screens visitors to minimize threats from white-nose syndrome—an infectious disease affecting bats that is associated with the fungus *Pseudogymnoascus destructans* (National Park Service 2013b). This syndrome is a relatively new and serious threat to cave wildlife. Discovered in winter 2006 in a cave with hibernating bats in New York, white-nose syndrome has spread to 22 states and five Canadian provinces, causing the death of millions of bats (US Geological Survey 2013b). Whether the spread of white-nose syndrome will continue and how many species of bats are susceptible to the disease are unknown. However, the monument is home to 14 species of bats and protects the largest and most significant bat populations in California and the Pacific Northwest. Thus, the potential introduction of white-nose syndrome represents a serious threat (National Park Service 2012). At the monument, visitors pass though decontamination stations before entering caves. An unintended positive outcome of white-nose syndrome and the screening process has been the opportunity for monument staff to interact with visitors and deliver a conservation message (Shane Fryer, Lava Beds National Monument, physical scientist, telephone communication, 20 June 2013). Visitor-use impacts can be minimized through increased education, contact with monument staff, and the requirement that visitors receive a conservation message about the fragility of cave resources before they enter a cave (National Park Service 2012).

Global climate change is potentially among the largest impacts on cave environments (National Park Service 2012). Since 1990, monument staff has observed the loss of cave ice in regularly visited caves, which may be a result of climate change. Because ice floors act as temperature buffers, temperatures are likely to fluctuate over a broader range as ice declines, which may in turn affect other physical and biological processes. Ice floors in caves also serve as water sources for diverse wildlife, from cave-obligate species such as bats to terrestrial birds and mammals. The loss of or changes in these water sources could severely impact the future of wildlife habitat at the monument (National Park Service 2012).

Additional information about climate change and the National Park Service, including the NPS Climate Change Response Strategy, is provided by the NPS Climate Change Response Program (see "Additional References" section). Furthermore, Karl et al. (2009) summarized climate change impacts by region across the United States, and Loehman (2010) provided talking points to understand the science of climate change and its impacts on arid lands.

Recreational Impacts on Geologic Features

Although the landscape of Lava Beds National Monument may appear resilient and lasting, undirected human use is impacting geologic features (National Park Service 2012). Only new volcanic eruptions can create new features, thus distinctive geologic resources such as Fleener Chimneys and Schonchin Butte are unlikely to be "replenished" by natural processes in the near future (see "Volcanic Hazards" section).

The lava flows that dominate the monument's landscape are highly resistant to natural forms of erosion, but are easily crushed and can collapse under foot. Footfalls can cause slopes of cinders to avalanche down the side of a cinder cone, making cinder cones and spatter cones some of the most delicate geologic features within the monument. Off-trail travel on these features triggers cascades, disrupting cinders that have rested at a cone's angle of repose for thousands of years. Such activity also is a visitor-safety concern. Furthermore, the resulting impact leaves lasting and visible scars. Previous impacts to these features occurred from mining activities (see "Abandoned Mineral Lands" section). Cinder extraction in the monument ended in the 1960s (National Park Service 2012).

Presently, the absence of a formal message and orientation about the conservation of volcanic features, the lack of visitor management in sensitive geologic areas (e.g., unregulated group size, lack of supervision, and uninhibited access), and poorly defined infrastructure have led to significant and lasting impacts on geologic features at the monument (National Park Service 2012). The two most prominent examples of threatened geologic features in the monument are Black Crater and Fleener Chimneys. The areas surrounding these features have been extensively impacted by social trails. The monument's dry environment limits water erosion and biological weathering (e.g., via the invasion of plant roots), but allows for long-term scarring from social trails and increases the difficulty of restoration (National Park Service 2012). The proliferation of social trails is an issue for the preservation of scenic views and cultural landscapes (Shane Fryer, Lava Beds National Monument, physical scientist, telephone communication, 20 June 2013).

Many trails in the monument are along a single track of an abandoned two-track/bulldozed road. Where these tracks end, visitors continue in the direction of a particular feature, thereby creating a system of social trails. Thus, the current trail system at the monument is poorly designed for the protection of geologic features and enhancement of the visitor experience (National Park Service 2012). A recommended enhancement is the redesign of current trails to create "loop" trails with interpretive wayside exhibits, thereby providing improved enjoyment and resource education.

The development of a trail management plan is a primary concern for the monument (Shane Fryer, Lava Beds National Monument, physical scientist, telephone communication, 20 June 2013). Such a plan would be guided by the general management plan (National Park Service 2010) and include collaboration among divisions (National Park Service 2012). It would address impacts associated with social trails and define areas where activities such as bouldering would be acceptable. Bouldering is rock climbing without ropes or harnesses on small outcrops or large boulders that are usually less than 6 m (20 ft) high. Overall, the geologic setting of the monument is not conducive to bouldering because lava is commonly fragile and sharp to the touch. However, the rock-climbing community has expressed an interest in conducting this activity in the monument. The Schonchin Flow might be an appropriate location (Julie M. Donnelly-Nolan, US Geological Survey, research geologist, written communication, 17 October 2013). No bouldering would be allowed in caves (Shane Fryer, telephone communication, 20 June 2013).

Following the completion of a trail management plan, the restoration of geologic features and development of sustainable management practices for them will be resource management priorities. Site monitoring would follow restoration, starting with Fleener Chimneys and Black Crater (National Park Service 2012). Restoration of other features may be attempted, depending on need and available staff and funding.

In the development of best management practices and restoration of geologic resources, monument staff will identify potential partnerships with other NPS units or offices (National Park Service 2012). The NPS Geologic Resources Division is a likely partner. Also, the Forest Service has completed extensive restoration efforts at Newberry National Volcanic Monument in central Oregon, which may serve as a model for Lava Beds National Monument (Shane Fryer, telephone communication, 20 June 2013).

Wind Erosion at Petroglyph Point

In the past, Prisoners Rock was an island in Tule Lake (see "Petroglyph Point" section). Waves cut benches into the base of this tuff cone and facilitated the development of the cliff face at Petroglyph Point (fig. 48). Today, an unpaved road leads to Prisoners Rock and the wall of petroglyphs at Petroglyph Point, and wave-cut benches form the parking area (Julie M. Donnelly-Nolan, US Geological Survey, research geologist, written communication, 17 October 2013). The exposed road and parking area surfaces provide ample material (dust and sand) for wind transport. Scoping participants hypothesized that wind erosion ("sand blasting") may be erasing the petroglyphs from the nearby cliff face (Covington 2004). However, no study has confirmed this hypothesis (Katrina Smith, physical science technician, and Nancy Nordensten, chief of Natural Resources; Lava Beds National Monument, written communication 13 December 2013).

Figure 48. Wave-cut benches. Wave activity on ancient Tule Lake eroded benches (arrow) into the tuff cones at Prisoners Rock and The Peninsula (in the distance). The exposed benches now supply dust and sand for aeolian transport. These tuff rings are part of the basalt of Prisoners Rock (PEbp) and represent the most northeastern extent of Medicine Lake volcanism. US Geological Survey photograph by Julie M. Donnelly-Nolan, available at http://pubs.usgs.gov/sim/2927/sim2927_data/site/photos.html (accessed 7 November 2013).

To mitigate the effects of wind erosion, monument staff installed a metal shield to protect the rock art. However, the road, parking lot, and exposed wave-cut benches continue to supply material. As of summer 2013, monument managers were developing a site strategy for Petroglyph Point (Shane Fryer, Lava Beds National Monument, physical scientist, telephone communication, 20 June 2013).

In *Geological Monitoring*, Lancaster (2009) described the following methods and vital signs for monitoring aeolian features and processes: (1) frequency and magnitude of dust storms, (2) rate of dust deposition, (3) rate of sand transport, (4) wind erosion rate, (5) changes in total area occupied by sand dunes, (6) areas of stabilized and active dunes, (7) dune morphology and morphometry, (8) dune field sediment state (supply, availability, and mobility), (9) rates of dune migration, and (10) erosion and deposition patterns on dunes. Although not all these vital signs are applicable to Lava Beds National Monument, monument managers may find this discussion useful in defining and potentially mitigating the effects of sand and dust transport and erosion.

Abandoned Mineral Lands

The NPS Geologic Resources Division is currently (April 2014) finalizing an inventory and assessment of its abandoned mineral lands (AML). An interim report was completed in 2013 excepting National Park System units in California, which contain approximately 80% of documented AML features in the system (Burghardt et al. 2013). The NPS Geologic Resources Division may be consulted for assistance, guidance, or additional information about AML sites in Lava Beds National Monument, which include gravel pits and rock quarries that provided raw materials for construction and maintenance (fig. 49 and table 3). After extraction ceased, some pits and quarries were used as staging or maintenance areas, or as dump sites (Ziegenbein et al. 2006).

As of April 2014, the AML inventory of Lava Beds National Monument listed 23 features at 16 quarry sites that primarily targeted cinders and pumice (John Burghardt, NPS Geologic Resources Division, AML program coordinator, written communication, 10 April 2014). An earlier report listed 14 pits and one dump site in the monument, based primarily on work by Ziegenbein et al. (2006). The National Park Service is systematically reclaiming these sites, many of which have been inactive for more than 30 years (Ziegenbein et al. 2006), and some are revegetating naturally (Covington 2004). Twelve of those features have proposed reclamation projects totaling approximately $215,000 (J. Burghardt, written communication, 10 April 2014). As of June 2013, past restoration at Crescent Butte “looked good,” whereas restoration at Caldwell Butte “needed more work” (Shane Fryer, Lava Beds National Monument, physical scientist, telephone communication, 20 June 2013). Ziegenbein et al. (2006) provided site descriptions and recommendations for restoration of 15 sites.

During geologic scoping in 2004, Julie Donnelly-Nolan (US Geological Survey) expressed an interest in keeping portions of one AML site—the upper part of the pit east of Caldwell Butte, referred to as “Closed Dump Pit” by Ziegenbein et al. (2006)—open and available for geologic study and interpretation (Covington 2004; Julie M. Donnelly-Nolan, US Geological Survey, research geologist, written communication, 17 October 2013). Because the site exposed glacial outwash gravel, it may have been of interest for the interpretation of past glacial activity and the effects of climate change. However, this exposure apparently was covered during restoration of the pit, sometime between 2004 and 2010 (see “Glacial Outwash” section).

Figure 49. Caldwell Pit. This cinder quarry is on the side of Caldwell Butte; its high, nearly vertical cut slope has some deeply incised gullies and talus deposits. Of geologic interest, the quarry exposed the internal structure of this cinder cone (PEb4). National Park Service photograph by Katrina Smith (Lava Beds National Monument).

Rockfall and Roof Collapse

In *Geological Monitoring*, Wieczorek and Snyder (2009) described five vital signs useful for understanding and monitoring slope movements, such as fall, topple, slide, spread, and flow, can involve a variety of materials and degrees of slope. Rockfall from steep slopes is the primary type of slope movement at Lava Beds National Monument. Rockfall debris is commonly deposited onto roads in the monument as a result of freeze-thaw processes (Covington 2004). Storm events also induce rockfall, and staff must often remove debris from the road after storms (Shane Fryer, Lava Beds National Monument, physical scientist, telephone communication, 20 June 2013). Additionally, Donnelly-Nolan et al. (2007) noted that seismic activity could induce rockfall from steep bluffs in the monument, potentially depositing debris across the main road.

Gillem Bluff is a primary location for potential slope movements in the monument. Talus, which is indicative

Table 3. Abandoned mineral lands at Lava Beds National Monument

Map Unit	Site Name	Area
Gravel (PEg)*	Closed Dump Pit	1.42 ha (3.50 ac)
Basalt of Mammoth Crater (PEbmc), littoral cones	Hospital Rock Pits (two pits)	0.30 ha (0.73 ac)
Basalt of Mammoth Crater (PEbmc)	Brass Cap Pit	5.22 ha (12.90 ac)
	East Lyons Road Pit	1.78 ha (4.40 ac)
	[Dump] Site 14 of Ziegenbein et al. (2006)	0.36 ha (0.90 ac)
	Old Shoreline Pit	1.94 ha (4.80 ac)
	Sump Pump Pit	0.95 ha (2.34 ac)
	West Lyons Road Pit	0.28 ha (0.68 ac)
Andesite cone west of Crescent Butte (PEa1)	Burn Pit	1.25 ha (3.09 ac)
	West Crescent Butte Pit	0.19 ha (0.48 ac)
Basaltic andesite of Crescent Butte (PEm2)	Crescent Butte Pit	0.23 ha (0.56 ac)
Basalt of Canby Bay (PEbcb)	Sheepherder Tank Pits (four pits)	0.16 ha (0.39 ac)
Basalt of Caldwell Butte (PEb4)	Caldwell Pit (pits A and B)	1.65 ha (4.07 ac)
Basalt of Hardin Butte (PEb1)	Harden Butte Pit	0.56 ha (1.38 ac)
Unit unknown, possibly PLomw, PLobg, PEadh, or PEbgf exposed along Gillem Bluff	Gillem Bluff Pit	0.34 ha (0.85 ac)
	Total area	**16.62 ha (41.06 ac)**

Source: Ziegenbein et al. (2006). *See "Glacial Outwash" section.

of rockfall processes, covers much of the outcrop and obscures contacts among units on the face of Gillem Bluff. Based on variations in the amount of vegetative cover, talus deposits appear to be of different ages, and probably began to accumulate after activation of the Gillem fault during the Pleistocene Epoch (fig. 7) (Donnelly-Nolan and Champion 1987).

In addition to inducing rockfall from steep slopes, seismic activity could loosen blocks on cave roofs and at cave entrances (fig. 24), endangering visitors and staff who are exploring these features. The rockfall deposit near the entrance of Valentine Cave is evidence of such an event (Donnelly-Nolan et al. 2007). NPS staff initially asked Aaron Waters to survey and map the caves at the monument for this reason (Julie M. Donnelly-Nolan, US Geological Survey, research geologist, written communication, 17 October 2013).

As part of a survey of lava tubes in and near the monument, Waters et al. (1990) mapped many areas of rockfall, called "collapse rubble" or "breakdown," within caves (see "Collapse Features" section). Some of this material was deposited when molten lava was flowing through the lava tubes and yields an easily decipherable record of collapse events, which may provide an interesting interpretive story for visitors. However, much of the material was deposited after volcanism ceased, with large parts of most cave roofs falling in and creating collapse rubble. Plates 1–6 in USGS Bulletin 1673 (Waters et al. 1990) show the locations of these deposits and may be of use in surveys or for the development of a rockfall monitoring program within the caves at the monument.

A potentially greater problem at the monument is the possibility that roads and other infrastructure will collapse into subsurface voids (Covington 2004). Roads cross all of the four map units that contain caves (PEbmc, PEbvc, PEbgc, and PEbci; see Geologic Map Graphic, in pocket), rendering the potential for collapse an ongoing public-safety concern. In the early 2000s, managers initiated a study of subsurface voids through the Federal Highway Administration. The study established weight limits for vehicles using roads in the monument (Covington 2004). During geologic scoping in 2004, participants discussed the process of coring to better define voids, but the National Park Service would prefer a less disruptive and damaging method. Scoping participants noted that the US Geological Survey conducted a magnetometer survey to detect subsurface voids at Hawai'i Volcanoes National Park (see GRI report by Thornberry-Ehrlich 2009), which may be an option for Lava Beds National Monument. As of February 2014, no such study had been conducted.

Earthquakes

Seismic activity in the Medicine Lake volcano region is a consequence of interactions between the compressional setting of the Cascadia subduction zone and extensional setting of the Basin and Range physiographic province (fig. 28). Six earthquake episodes have been documented in this region in 1978, 1981, 1988, 1989, 1993, and 1996. No record of significant seismic activity exists prior to 1978, but it may not have been detected because seismic stations were sparse in the region before about 1980 (Dzurisin et al. 1991, 2002). Three earthquake events (1988, 1989, and 1996) occurred beneath Medicine Lake volcano; the other three (1978, 1981, and 1993) occurred in the nearby region.

The first documented seismic event occurred in 1978 near Stephens Pass, between Medicine Lake volcano and Mount Shasta. All earthquakes were shallow and occurred on a north-oriented fault zone with an eastward dip, similar to other normal faults in the region. The largest event of the swarm occurred on 1 August 1978; its magnitude (M) was 4.6 (Patton and Zandt 1991).

In 1981, an episode of shallow seismicity was recorded 10 km (6 mi) north of Stephens Pass near the town of Tennant, again along a north-oriented fault. The largest earthquake of this swarm was M = 4.1.

Another swarm of earthquakes, with the largest measured at M = 4.1, began in late September 1988. This swarm occurred at shallow depth under the Medicine Lake caldera and was followed by smaller earthquakes in subsequent months. Walter and Dzurisin (1989) interpreted this event as tectonic (resulting from breakage and associated movement of Earth's crust), rather than volcanic (resulting from magma moving through Earth's crust).

Two long-period (seismic activity of more than 6 seconds' duration) earthquakes have been detected beneath Medicine Lake volcano—on 1 December 1989 at a depth of 15 km (9 mi) and on 14 October 1996 at an unknown depth. These earthquakes may indicate magma migration at depth (Pitt et al. 2002).

To the north of Medicine Lake volcano, along the projection of faults that emerge from beneath the northern side of the edifice (fig. 3), an earthquake swarm took place in 1993 west of Klamath Falls, Oregon. The two largest earthquakes were M = 6.0, indicating that damaging seismic activity can occur in the region. Similar activity can be expected in the future (Donnelly-Nolan et al. 2007).

The California Volcano Observatory posts monthly updates of seismic activity at Medicine Lake volcano at http://volcanoes.usgs.gov/activity/status.php (accessed 3 September 2013). The seismic network at Medicine Lake volcano includes two seismic stations and three Global Positioning System (GPS) receivers. USGS scientists installed the network in 1978 and added the most recent instrument in 2009 (http://volcanoes.usgs.gov/volcanoes/medicine_lake/medicine_lake_monitoring_12.html; accessed 4 November 2013).

In *Geological Monitoring*, Braile (2009) described the following methods and vital signs useful for understanding earthquakes and monitoring seismic activity: (1) earthquake monitoring, (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.

Volcano Hazards

Medicine Lake volcano has erupted nine times in the past 5,200 years, more frequently than any other Cascade arc volcano except Mount St. Helens (Donnelly-Nolan 2010). In addition, Medicine Lake volcano has erupted hundreds of times during its 500,000-year history (Donnelly-Nolan 2010), a record that represents one of the highest eruptive frequencies among Cascade volcanoes (Donnelly-Nolan et al. 2007). The documented behavior of Medicine Lake volcano indicates that once the volcano becomes active, it could continue to erupt for decades, or even erupt intermittently for centuries, and very likely from multiple vents scattered across the edifice (Donnelly-Nolan et al. 2007).

Given its long eruptive history and frequent eruptions in recent geologic time, Medicine Lake volcano will erupt again (Donnelly-Nolan et al. 2007). In addition to these factors, the volcano's proximity to regional infrastructure led the USGS National Volcano Early Warning System to assess Medicine Lake volcano and deem it a "high threat." A fact sheet describing this assessment system is available at http://pubs.er.usgs.gov/publication/fs20063142 (accessed 6 September 2013). Despite this high threat, the probability that Medicine Lake volcano will erupt in any given year is very small (one chance in 3,600) (Donnelly-Nolan et al. 2007).

Basaltic Eruptions

The most likely future eruption at Medicine Lake volcano would be a small effusive eruption of basaltic lava, which could occur anywhere on the volcano (fig. 50). This type of eruption would build a cinder or spatter cone, eject hot blocks of rock on ballistic trajectories near the vent, and produce small lava flows (a few kilometers long). Lava flows do not move very quickly and can be outrun easily, but they would damage or destroy any infrastructure in their path. During dry or windy weather, the advancing front of a lava flow on the volcano would likely cause fires (US Geological Survey 2012d).

Silicic Eruptions

An explosive eruption of silicic lava, including rhyolite and dacite, is also possible. This type of eruption would likely occur near the summit. The two most recent eruptions, which expelled the rhyolites of Glass Mountain (Hrgm) and Little Glass Mountain (Hrlg), were of this type. These explosive events sent ash tens of kilometers downwind before extruding thick, glassy lava flows (obsidian). Neither of these volcanic units occurs within Lava Beds National Monument, but ash and pumice deposits from these explosions with thicknesses of up to about 0.3 m (1 ft) are present on the eastern edge of the Callahan Flow (Julie M. Donnelly-Nolan, US Geological Survey, research geologist, written communication, 17 October 2013).

In addition to prolific amounts of ash and pumice (see "Tephra" section below), silicic eruptions are

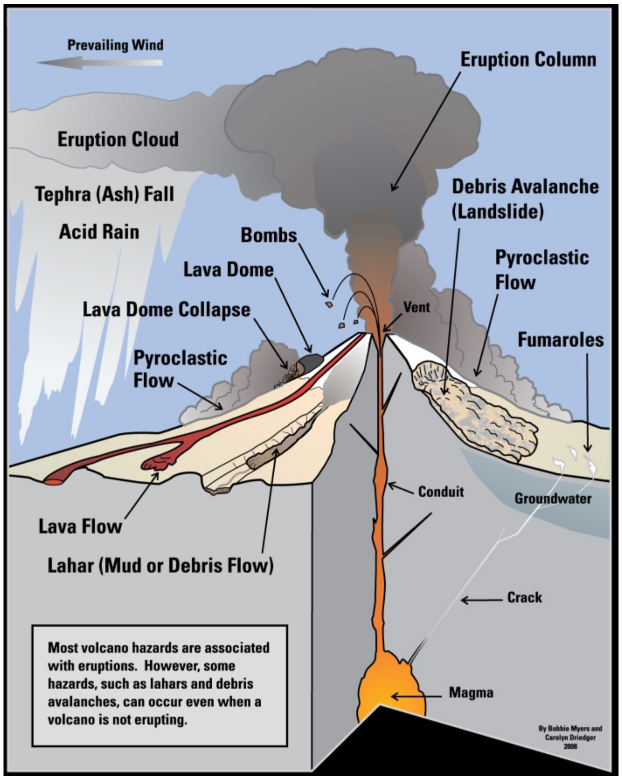

Figure 50. Volcano hazards. This graphic illustrates hazards associated with volcanic eruptions in the Cascade Range. Not all of these hazards are expected to occur during an eruption at Medicine Lake volcano. During a basaltic eruption, a cinder cone could be built and lava flows could occur anywhere on the volcano. During a silicic eruption, which would occur near the summit, profuse emission of tephra, pyroclastic flows, and the building of lava domes followed by collapse could occur. Graphic modified from Myers and Driedger (2008, 1 sheet).

characterized by pyroclastic flows and surges (discussed below), lava flows, and the growth of lava domes, possibly followed by dome collapse and transport of hot avalanche-debris flows (fig. 50). Silicic domes and flows are not likely to extend more than a few kilometers from their vents (Donnelly-Nolan et al. 2007).

A pyroclastic flow is a hot—typically more than 800°C (1,500°F)—chaotic mixture of rock fragments, gas, and ash that travels rapidly (tens of meters per second). Pyroclastic flows are extremely hazardous because of their high speeds and high temperatures (Clynne et al. 2012). An eruption generating a large pyroclastic flow at Medicine Lake volcano is very unlikely, but not unprecedented. One such eruption—of dacite tuff of Antelope Well (PEdta)—took place at the center of the volcano about 180,000 years ago. Exposures of the tuff occur close to the monument boundary west of Devils Homestead, providing evidence that a pyroclastic flow could reach and cover parts of the monument. Interestingly, the rock beneath the picnic tables at Fleener Chimneys is dacite tuff of Antelope Well (Julie M. Donnelly-Nolan, US Geological Survey, research geologist, written communication, 17 October 2013). This eruption contributed to the formation of a summit caldera and produced highly mobile, volatile-rich pyroclastic flows down the flanks of the volcano. An eruption producing a pyroclastic flow would destroy everything in its path, but the probability of such a high-consequence event at Medicine Lake volcano is negligible (US Geological Survey 2012f).

Small, local pyroclastic flows could occur on the upper parts of the volcano during emplacement of silicic lava flows. Most silicic eruptions would be near the center of the volcano, and associated pyroclastic flows would likely travel only short distances, probably no more than 1 km (0.6 mi), from the vents or collapsing flow fronts (US Geological Survey 2012f).

Tephra

"Tephra" is a general term referring to all pyroclastic material ejected into the air by a volcano, ranging in size from fine dust to blocks with diameters of 1 m (3 ft) or more (Crandell and Mullineaux 1970). Tephra accompanying silicic eruptions at Medicine Lake volcano could be regionally widespread, and fallout could cause short-term disruption of activities in Klamath Falls, Oregon (the largest nearby city). Local communities, Lava Beds National Monument, roads and highways, and the utility corridor that crosses the eastern and southern sides of the volcano would probably be affected for days or weeks (US Geological Survey 2012a). Near-vent accumulations of tephra as a result of a silicic eruption could be many meters thick. Tephra from the Glass Mountain eruption is more than 9 m (30 ft) thick near its vents, thinning abruptly to less than 1 cm (0.4 in) within about 10 km (6 mi) of the vents (Ramsey et al. 2009). By contrast, mafic eruptions are much less likely to produce large volumes of tephra, which would only extend a few kilometers from the source (US Geological Survey 2012a).

At Medicine Lake volcano, the probability of an eruption producing enough tephra to accumulate 1 cm (0.4 in) thickness in any given year is one in 5,000. Experience with the eruption of Mount St. Helens indicates that as little as 0.5 cm (0.2 in) of ash is sufficient to slow vehicle traffic to a crawl and close businesses for one to two weeks (US Geological Survey 2012a). Aircraft could be affected by any eruption generating tephra that rose sufficiently high into the atmosphere to disrupt flight paths (US Geological Survey 2012a).

Phreatomagmatic Eruptions

If a vent were to open under Medicine Lake in the caldera, phreatomagmatic eruptions would almost certainly occur. These eruptions involve magma and water, which typically interact explosively, leading to the concurrent ejection of steam and pyroclastic fragments. Such eruptions would deposit wet, muddy tephra over the immediate area, covering campgrounds and cabins near Medicine Lake, and perhaps over much of the caldera.

Hydrothermal Explosions

If magma intruded into the shallow hydrothermal system (see "Geothermal Features and Development" section), hydrothermal explosions might occur at the surface (US Geological Survey 2012a). This type of explosion occurs when hot water in a volcano's hydrothermal (hot-water) system flashes to steam, breaking rocks and throwing them into the air.

Toxic Gases

During volcanic eruptions—as well as before and during magmatic intrusions—gases, including carbon dioxide, sulfur dioxide, and hydrogen sulfide, can be transported to the surface. The closed topography formed by the rim around the Medicine Lake caldera could allow toxic gases to pond during periods of calm wind conditions, potentially resulting in asphyxiation (US Geologic Survey 2012c).

Volcano Monitoring

Volcanic eruptions are typically preceded over periods of days to years by precursory phenomena related to the rise of magma toward the surface, including heightened earthquake activity and ground deformation. Published rates of magma ascent in volcanoes range from 0.01 to 2 m (0.03 to 7 ft) per second and are based on a variety of data, including seismic monitoring of eruptions in Iceland and at Mount St. Helens (Rutherford and Gardner 2000; Buck et al. 2006). Geophysical and petrologic data from Medicine Lake volcano indicate that a magma reservoir probably exists at a depth of 3–7 km (2–4 mi). Magma rising from a depth of 6 km (4 mi) at a rate of 0.01 m (0.03 ft) per second would arrive at the surface in about seven days, whereas that traveling from a depth of 3 km (2 mi) at a rate of 2 m (7 ft) per second would reach the surface in less than 30 minutes (Donnelly-Nolan et al. 2007).

Given the probable shallow depth of magma, possible short times of ascent to the surface, and frequency of eruptive and intrusive events at Medicine Lake volcano, the establishment of monitoring instruments before signs of actual eruptive activity would be prudent (Ewert et al. 2005). Adequate real-time monitoring at Medicine Lake volcano would involve 12–20 seismic stations and 12–17 continuous GPS stations, as well as airborne gas surveys and the application of remote sensing techniques (Ewert et al. 2005; Donnelly-Nolan et al. 2007). USGS scientists would evaluate the data generated by these monitoring techniques to identify any change. Monitoring would involve personnel at the USGS California Volcano Observatory in Menlo Park, California (see http://volcanoes.usgs.gov/observatories/calvo/; accessed 3 September 2013).

Monitoring of changes in seismic activity (see "Earthquakes" section), ground deformation (see Dzurisin et al. 1991, 2002; Poland et al. 2006), and gaseous emissions (see "Toxic Gases" section) provides an opportunity to forecast expected hazards (Donnelly-Nolan et al. 2007). In *Geological Monitoring*, Smith et al. (2009) described six vital signs and methodologies useful for understanding and monitoring volcanoes: (1) earthquake activity, (2) ground deformation, (3) emission at ground level, (4) emission of gas plumes and ash clouds, (5) hydrologic activity, and (6) slope instability. Ground deformation monitoring by GPS might provide earlier indications of a change in the magma system, such as inflation of the caldera area in contrast to ongoing subsidence (Donnelly-Nolan et al. 2007). The US Geological Survey provides further information about volcano monitoring at http://volcanoes.usgs.gov/About/What/Monitor/monitor.html (accessed 4 September 2013).

Geothermal Features and Development

Medicine Lake volcano has a large, active, high-temperature (up to 290°C [550°F]), geothermal system fueled by a deeper zone of magma (Iovenitti and Hill 1997; Barger 2001; US Geological Survey 2012e). Despite its size and high temperature, however, this geothermal system has almost no active surface expression (Hulen and Lutz 1999). A small area of heated ground, referred to as the "Hot Spot," west of Glass Mountain is the sole, obvious surface indication of the large, concealed, active system (fig. 51). At this location, gases discharge from two distinct vents with diameters of 0.3–0.5 m (1–1.5 ft) (Schneider and McFarland 1996). A large area (90 × 150 m [300 × 500 ft]) surrounding the vents lacks vegetation, and the ground surface is covered with pumice. Elevated temperatures occur 5–8 cm (2–3 in) below the ground surface throughout this area (Hulen and Lutz 1999).

Figure 51. The "Hot Spot." Steam emerges from the only fumarole at Medicine Lake volcano. This sole expression of geothermal activity occurs west of Glass Mountain. The margin of the Glass Mountain Flow is in the background. US Geological Survey photograph by Julie M. Donnelly-Nolan, available at http://pubs.usgs.gov/sim/2927/sim2927_data/site/photos.html (accessed 7 November 2013).

Hydrothermally altered rocks crop out in at least two other locations on the volcano—near Schonchin Spring and Crystal Springs in the caldera (Donnelly-Nolan 2010). Hydrothermal alteration occurs where steam and volcanic gases issue from vents (i.e., fumaroles). However, these rocks are not obviously associated with active thermal phenomena (Hulen and Lutz 1999).

Due to recent volcanism, geologists and geothermal exploration companies view Medicine Lake volcano as a possible resource for geothermal energy (energy derived from Earth's heat). This kind of energy is harnessed from underground hot fluids that are commonly associated with active volcanic regions. These naturally occurring, hydrothermal fluids are extracted and used to produce electricity.

At the surface, the Medicine Lake volcano geothermal system is delineated as the Glass Mountain Known Geothermal Resource Area (KGRA), which is located adjacent to (south of) the monument and is a federally designated geothermal lease area. In 2004, scoping participants suggested that geothermal energy development in the Glass Mountain KGRA could result in drawdown of the groundwater table. Also, drilling rigs and support activities in a developed geothermal field could cause vibrations and disturbances. In addition, steam plumes and gases from geothermal power plants would be significant visual impacts (Covington 2004). Such concerns can be raised during the environmental review process for proposed projects.

In the early 1980s, geothermal exploration companies targeted Medicine Lake volcano primarily on the basis of abundant Holocene felsic volcanics, which were thought to provide evidence for a still-cooling plutonic heat source (Smith and Shaw 1979; Richards et al. 1998). In the early 2000s, Calpine Corporation proposed two geothermal energy development projects in the Glass Mountain KGRA at Telephone Flat and Fourmile Hill. Both projects were to include production wells, injection wells, a steam power plant, cooling tower, and emission control system (Calpine Corporation 2006).

The Calpine Corporation had proposed that the Fourmile Hill project would be online by December 2004, and the Telephone Flat project would be online by December 2005 (Sass and Priest 2002). However, development apparently was not economically viable under existing market conditions, and the projects remain "on hold" (Shane Fryer, Lava Beds National Monument, physical scientist, telephone communication, 20 June 2013).

In June 2013, monument staff expressed some concern regarding the Enhanced Geothermal System (EGS)—a form of geothermal engineering that relies on artificial fracturing of rocks to produce energy. This procedure—referred to as "hydro-shearing," perhaps to differentiate it from "hydraulic fracturing," commonly known as "fracking," which is an equivalent and controversial procedure in the oil and gas industry—is occurring at Newberry Volcano in central Oregon. However, EGS is not applicable at Medicine Lake volcano because, unlike Newberry Volcano, it has a known hot-water resource (Julie M. Donnelly-Nolan, US Geological Survey, research geologist, written communication, 17 October 2013). With traditional geothermal development, water and steam are tapped from naturally occurring hydrothermal reservoirs. With EGS, artificial hydrothermal reservoirs are created by pumping millions of gallons of water into hot rock at depth to create new fractures or deepen existing ones. Theoretically, the result is a manufactured, underground system ("boiling pot") that can be harnessed for energy.

Geologic History

This section describes the chronology of geologic events that formed the present landscape of Lava Beds National Monument.

Some rocks exposed in Lava Beds National Monument (aged 2 million years or more) predate the existence of Medicine Lake volcano and were brought to the surface by faulting at Gillem Bluff. For the past 500,000 years, however, Medicine Lake volcanism has dominated the scene. The volcano's eruptive history can be divided into five stages (Donnelly-Nolan et al. 2008; Donnelly-Nolan 2010), each of which is represented by rocks in the monument. During the Pleistocene Epoch (fig. 7), glaciers covered the Medicine Lake caldera and flowed away from it. Under these wetter climatic conditions, a large pluvial lake filled the Tule Lake basin, coinciding with Medicine Lake volcanism (Lavine 1994). The volcano continued to erupt during and after the time of glacial activity, approximately 13,000 years ago. Eruptions as recent as 1,120 years BP in the monument, and 890 years BP at the summit, foreshadow future volcanic activity.

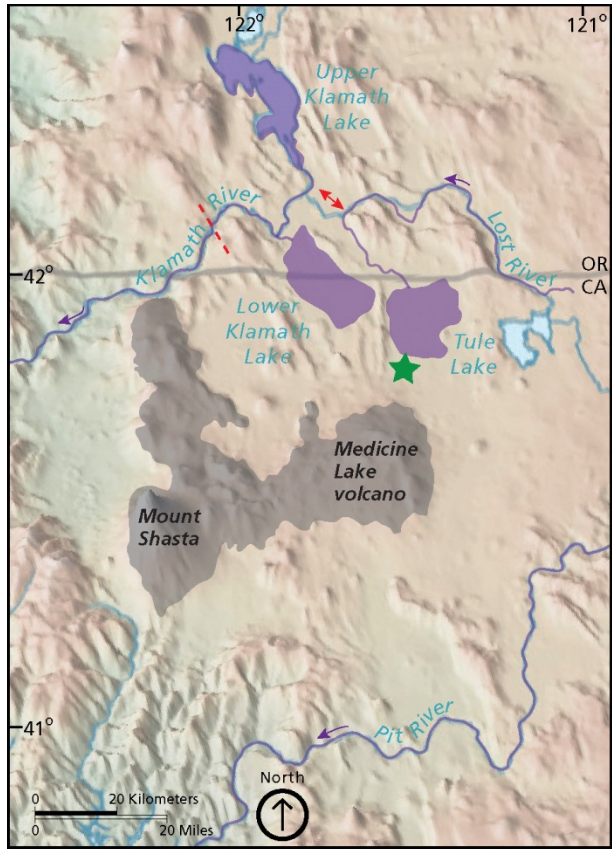

Figure 52. Lost and Klamath river drainages. During the Pleistocene ice ages, when the climate was wetter than today, large pluvial lakes occupied the basins of the upper Klamath River. Drainage of water to the south from ancient Tule Lake into the Pit River was interrupted by the growth of Medicine Lake volcano. The double-headed arrow indicates the bidirectional flow at the divide between the Lost and Klamath river drainages. The dotted line across the Klamath River indicates the probable location of the divide over which the ancient lake system first spilled into the Klamath drainage. The lightly shaded area indicates elevations in the vicinity of Medicine Lake volcano and Mount Shasta above 1,500 m (5,000 ft). Graphic by Trista Thornberry-Ehrlich (Colorado State University) after Adam et al. (1989, figure 1). Basemap by Tom Patterson (National Park Service), available online: http://www.shadedrelief.com/physical/index.html (accessed 10 April 2014).

Pre–Medicine Lake Volcano History

Volcanism has been long lived and relatively continuous in northeastern California (Donnelly-Nolan 2010). Rock units in the northwestern part of Lava Beds National Monument record the activity of Pliocene and early Pleistocene (fig. 7) volcanoes that predate Medicine Lake volcano. These units include older tuff (PLotg), older basaltic andesites (PLomw and PLomg), and older basalts (PLobg and PEobp) at Gillem Bluff. The tuff unit (PLotg) has an $^{40}Ar/^{39}Ar$ age of 2.023 ± 0.020 million years (Donnelly-Nolan and Lanphere 2005; Donnelly-Nolan 2010). Although not numerically dated, the oldest unit predating Medicine Lake volcano (and the oldest in the monument) is the older basaltic andesite in western Lava Beds National Monument (PLomw). This rock is exposed on the face of Gillem Bluff.

Lake History

Older basalt of Gillem Bluff (PLobg) contains pillow lavas, showing that this lava flow entered water, presumably an ancient Tule Lake (Donnelly-Nolan and Champion 1987), whose sedimentary record of basin deposits extends back 3 million years (Adam et al. 1989). Throughout the late Pliocene and Pleistocene epochs (fig. 7), a large pluvial lake covered much of southeastern Oregon and northeastern California, including the Tule Lake basin. Lavine (1994) referred to this lake as "Lake Modoc." Drainage from the basin was to the south into the ancestral Pit River (fig. 52), but was ultimately interrupted by the formation of Medicine Lake volcano (Adam et al. 1989). Ponding of this southwestern drainage formed a large lake (ancestral to Tule and Lower Klamath lakes) that eventually became deep enough to spill westward into the Klamath River drainage, downcutting the divide that separates the two basins (fig. 52). The divide is very low near Klamath Falls. Water has flowed across it in both directions at different times (Clapp et al. 1912). Most water flowing through the combined system presently bypasses the Tule Lake basin and flows down the Klamath River (Adam et al. 1989). Today, Tule Lake is a sump for the Lost River.

Medicine Lake Volcano History

The Medicine Lake shield volcano built up in five major stages (Donnelly-Nolan et al. 2008; Donnelly-Nolan 2010). The complete suite of lava consists of basalt, basaltic andesite, andesite, dacite, and rhyolite (fig. 53). Almost all lava types have been present throughout the

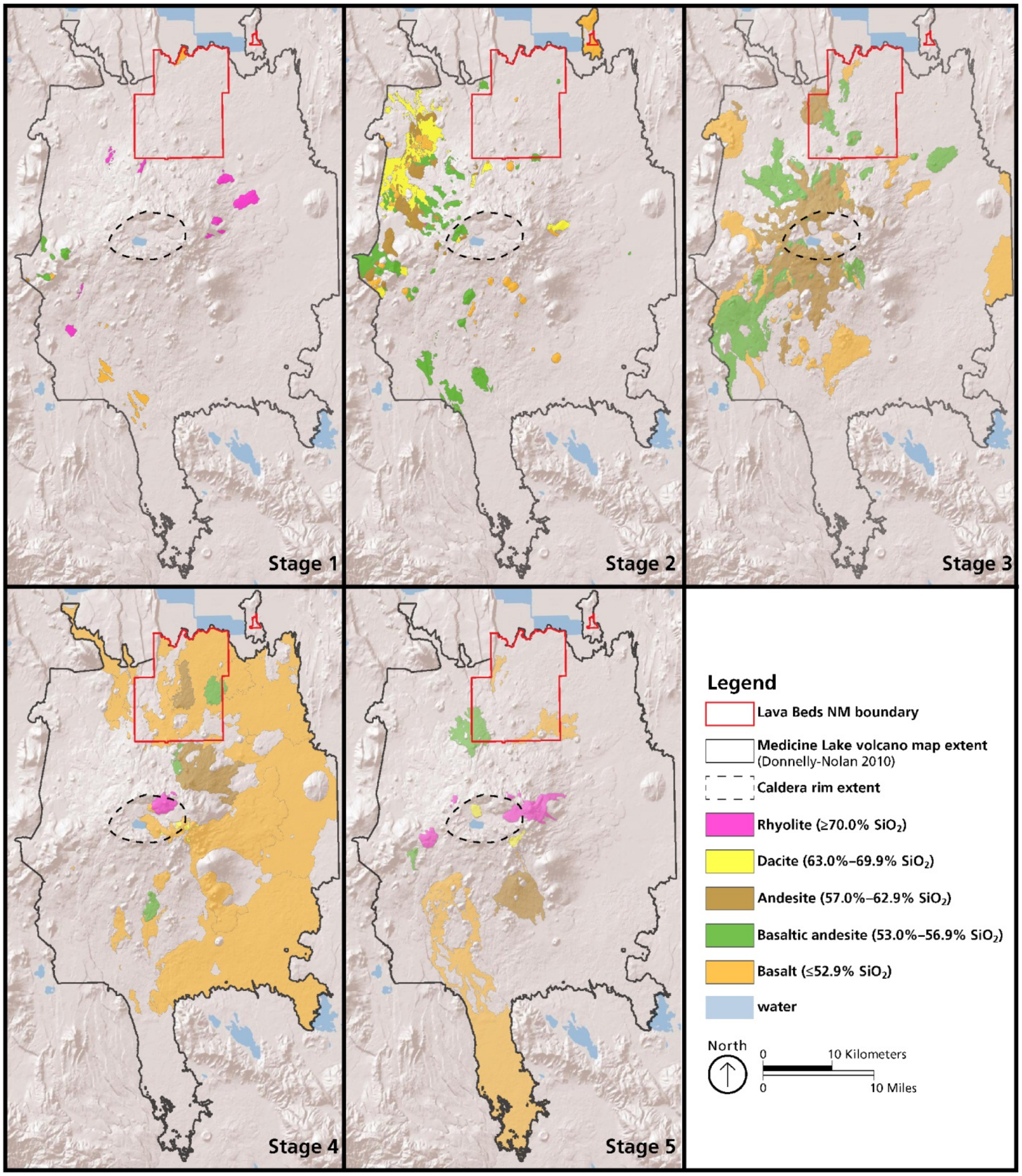

Figure 53. Eruptive stages of Medicine Lake volcano. The volcano built up in five stages over its 500,000-year lifespan. Lava compositions range from basalt with 47.2% silica (SiO_2) to rhyolite with 77.1% SiO_2. Percentages of silica on the legend are from Donnelly-Nolan (2010). Note the basalt of Hovey Point (orange area at the northern edge of Medicine Lake volcano) in stage 1 this is the oldest unit of Medicine Lake volcanism in Lava Beds National Monument. Stage 2 culminated with the eruption of dacite tuff of Antelope Well (note yellow area on the stage 2 panel). Volcanism during stage 3 was profuse; more than 80 volcanic units are part of this stage. The largest individual eruptions of Medicine Lake volcano were basaltic flows, which spread across the landscape during stage 4. Some of these flows have volumes as much as 5 km^3 (1 mi^3), such as the basalt of Mammoth Crater (PEbmc). Note the extensive coverage of basalt (orange area) in stage 4. During stage 5, basalt and basaltic andesite, including basaltic andesite of Callahan Flow (Hmcf) about 1,120 years ago, erupted in Lava Beds National Monument. Graphic after Donnelly-Nolan et al. (2008, figure 7) by Jason Kenworthy (NPS Geologic Resources Division) using GRI data after Ramsey et al. (2010). Base map is World Shaded Relief layer by ESRI.

volcano's history. Significant amounts of silicic volcanism characterized the volcano before 300,000 years ago, with predominantly mafic lava thereafter (Donnelly-Nolan et al. 2008).

Eruptive Stage 1: Early Silicic Volcanism

Medicine Lake volcano began erupting about 500,000 years ago. Silicic domes and flows dominated eruptive stage 1 (approximately 500,000–300,000 years ago), although mafic lavas such as the basalt of Hovey Point (PEbhp; $^{40}Ar/^{39}Ar$ age, 445,000 ± 25,000 years) also erupted (Donnelly-Nolan and Lanphere 2005; Donnelly-Nolan 2010). This unit occurs within the monument at the southern edge of Tule Lake (fig. 5). The lava flow is adjacent to lake deposits that have served as farmland since the early 1900s. Hovey Point lava was inundated by ancient Tule Lake, and its original flow surface was considerably mantled and modified (Donnelly-Nolan and Champion 1987).

Eruptive Stage 2: Lead-Up to the Eruption of Dacite Tuff of Antelope Well

Eruptive stage 2 of Medicine Lake volcano (approximately 300,000–180,000 years ago) is represented by six eruptions and corresponding units in the monument—three basaltic andesites (PEmj, PEmc, and PEmni), two basalts (PEbp and PEb1), and one andesite (PEa2). Many isolated cinder cones have also been assigned to this stage, including Hardin Butte (PEb1) and Red Butte (PEa2) within the monument. Basaltic andesite of Juniper Butte (PEmj) also erupted at this time, likely into ancient Tule Lake (Donnelly-Nolan 2010).

Dacite tuff of Antelope Well (PEdta) represents the culminating event of this eruptive stage (fig. 54). It is Medicine Lake volcano's only ash-flow tuff—a chaotic mixture of pumice, ash, and gas that travels rapidly (as fast as tens of meters per second) away from a volcanic vent during an explosive eruption. On a volcano where even voluminous lava flows are typically confined to limited radial sectors, the tuff's occurrence in multiple sectors is distinctive. This unit was buried by younger lava flows and is not exposed at the surface in the monument.

Figure 54. Dacite tuff of Antelope Well. This unit (PEdta) is the only ash-flow tuff at Medicine Lake volcano. This exposure is on the lower northern flank of the volcano, just west of Lava Beds National Monument. It occurs in a shallow depression north of the road connecting the monument to Gold Digger Pass. US Geological Survey photograph by Julie M. Donnelly-Nolan, available at http://pubs.usgs.gov/sim/2927/sim2927_data/site/photos.html (accessed 7 November 2013).

Donnelly-Nolan et al. (2008, p. 318) called the dacite tuff of Antelope Well "the single most important stratigraphic unit at Medicine Lake volcano." The unit is isotopically dated and widespread, making it a stratigraphically important "marker bed." It has an $^{40}Ar/^{39}Ar$ age of 171,000 ± 43,000 years (Donnelly-Nolan and Lanphere 2005; Donnelly-Nolan 2010). However, stratigraphic relationships to other dated units, together with climate constraints, indicate that dacite tuff of Antelope Well must be between 185,000 and 180,000 years old, most likely the latter (Donnelly-Nolan 2010).

Tephra from the Antelope Well explosion was found in a quarry about 13 km (8 mi) north of Timber Mountain, just east of Highway 139 beyond the eastern edge of the area mapped by Donnelly-Nolan (2010). Furthermore, Sarna-Wojcicki et al. (1991) correlated distal tephra of the eruption to ash layer KK at Summer Lake, Oregon, and to ash found by Rieck et al. (1992) in a deep core in Tule Lake.

Another significant feature of the dacite tuff of Antelope Well is that the eruption took place when ice was present over the caldera (Donnelly-Nolan and Nolan 1986), allowing correlation with widely used marine oxygen-isotope records, which indicate the existence of cooler conditions about 180,000 years ago (Martinson et al. 1987; Bassinot et al. 1994; Worm 1997).

Eruptive Stage 3: Profuse Volcanism and Construction of the Caldera Rim

Approximately 180,000–100,000 years ago, during eruptive stage 3 of Medicine Lake volcano, extrusion of lava was prolific. More than 80 volcanic units (about 40% of the total) have been assigned to this stage. The documented eruption rate for this 80,000-year period is one per 1,000 years, which is more frequent than any other time period except eruptive stage 5. Eruptive activity was dominated by basalt and basaltic andesite, but 20 andesite units also erupted. Within the monument, 17 eruptions are recorded—six basalts (PEbgf, PEb5, PEb4, PEbcb, PEbnw, and PEbng), six andesites (PEa3, PEadh, PEanh, PEawf, PEa1, and PEawb), and five basaltic andesites (PEmsc, PEm2, PEm1, PEman, and PEmhi).

Additionally, the caldera rim developed during this stage. Unlike other Cascade calderas that formed via collapse, such as Crater Lake (summarized in the GRI report by KellerLynn 2013), the Medicine Lake caldera built via eruption of rim-forming lavas that presumably traveled up ring faults (arcuate pathways that define and control the existence of the central basin) (Donnelly-Nolan 2010). These faults were most likely created during the eruption of the dacite tuff of Antelope Well (PEdta) at the end of eruptive stage 2.

Eruptive Stage 4: Big Basalt

Medicine Lake volcano erupted far fewer times during stage 4 (approximately 100,000–13,000 years ago) than during stage 3. Only 24 eruptions took place during this 85,000-year period, compared to 80 eruptions during the previous 80,000 years. However, eruptions during this stage produced almost half of the volcano's volume, in particular, large basaltic lava flows, including Lake Basalt (PEbl) and basalt of Yellowjacket Butte (PEbyb) south of the monument. The Yellowjacket Butte flow covers an estimated 300 km^2 (120 mi^2), making it the largest single Medicine Lake volcano unit in terms of area (Donnelly-Nolan 2010). Another very large basalt flow, the basalt of Mammoth Crater (PEbmc), was erupted later in this stage, about 35,000 years ago. It covers roughly 250 km^2 (100 mi^2), including the majority of the monument. Many caves eventually formed in the extensive lava-tube system that distributed this basalt.

Only two andesite units were erupted during stage 4, which is one-tenth the amount erupted during stage 3. Both of these andesites occur in the monument on the northern and northeastern flanks of the volcano edifice. The older of the two flows is the andesite of Schonchin Butte (PEasb), which comprises distinctive features in the monument, including the Schonchin Flow and Schonchin Butte. This andesite has an $^{40}Ar/^{39}Ar$ age of 65,000 ± 23,000 years (Donnelly-Nolan and Lanphere 2005; Donnelly-Nolan 2010). The other andesite unit extruded during this stage was the andesite of Indian Butte (PEaib), with an $^{40}Ar/^{39}Ar$ age of 22,000 ± 13,000 years.

Eruptive Stage 5: Postglacial Volcanism

Eruptive state 5 encompasses volcanism since the retreat of the Pleistocene glaciers about 13,000 years ago (see "Glacial History" section). Medicine Lake volcano has produced at least 17 episodic eruptions from vents distributed widely across the volcano edifice during this stage (Donnelly-Nolan et al. 1990; Donnelly-Nolan 2010). Mafic eruptions began about 13,000 years ago, followed by silicic eruptions (e.g., dacite of Medicine Lake Glass Flow [Hdm], not in the monument) about 5,000 years ago, then basaltic and andesitic eruptions on the northern and southern flanks, respectively, about 3,000 years ago.

Stage 5 includes the most recent eruptions of Medicine Lake volcano—the rhyolites of Little Glass Mountain and Glass Mountain—and many notable flows in the monument, such as the basalts of Devils Homestead (PEbdh) and Valentine Cave (PEbvc). These lavas flowed across the landscape about 12,320 and 12,260 years ago, respectively (Donnelly-Nolan et al. 2007; Nathenson et al. 2007). Eruptions of basalt at Black Crater and Ross Chimneys (Hbbr) about 3,080 years ago and basaltic andesite of Callahan Flow (Hmcf) about 1,120 years ago followed. The Callahan Flow is the most recent to have moved across the landscape of the monument.

Glacial History

No glaciers occur on Medicine Lake volcano today, but during the Pleistocene Epoch, glaciers covered the caldera and flowed away from it. Anderson (1941) was the first to document modification of the upper parts of the volcano by ice, which left glacial striations and polish (fig. 55). These features are most noticeable on the dense, hard andesitic lavas of the caldera rim. In addition, glacial ice eroded the surfaces of lava flows on the flanks of the volcano and transported this material downslope. Donnelly-Nolan (2010) mapped the distribution of glacial features, particularly glacial till (PEt), composed of boulders, cobbles, gravel, and finer-grained material deposited directly by glaciers. These deposits are poorly exposed and limited in extent, and none occur within the monument. Glacial meltwater also transported material, but beyond the limit of glacial ice. Within the monument, Donnelly-Nolan (2010) mapped gravel (PEg) consisting of primarily glacial outwash. This material corresponds to eruptive stages 2, 3, and 4, although the specific beginning and ending dates are uncertain.

Figure 55. Glacial polish and striations. An outcrop of andesite of north rim (PEanr) of Medicine Lake volcano displays glacial polish and striations created as glacial ice moved across the surface. The rubbly lava surface was removed by glacial erosion. Ice covered the upper part of the volcano, including the caldera, during the last ice age. US Geological Survey photograph by Julie M. Donnelly-Nolan, available at http://pubs.usgs.gov/sim/2927/sim2927_data/site/photos.html (accessed 7 November 2013).

Holocene Epoch: Geology and Culture

As one of the longest continually occupied areas in North America (National Park Service 2014), the geologic history of Lava Beds National Monument readily blends with its rich cultural past. Petroglyphs (carved symbols) and pictographs (painted symbols) on rock surfaces document the earliest human occupation. In 1872–1873, the lava beds were the site of the Modoc Indian War when Indians made use of the lava flows for shelter and defense. This area, infused with the spirit of place, remains culturally and geologically important for many modern people.

Geologic Map Data

This section summarizes the geologic map data available for Lava Beds National Monument. The Geologic Map Graphic (in pocket) displays the map data draped over imagery of the park and surrounding area. The Map Unit Properties Table (in pocket) summarizes this report's content for each geologic map unit. Complete GIS data are included on the accompanying CD and are also available at the GRI publications website: http://go.nps.gov/gripubs.

Geologic Maps

Geologic maps facilitate an understanding of an area's geologic framework and the evolution of its present landscape. Using designated colors and symbols, geologic maps portray the spatial distribution of rocks and unconsolidated deposits on the landscape. Furthermore, geologic maps are distinguished from other types of maps in that they show the temporal relationships among map units.

Geologic maps can be divided into two primary types: surficial and bedrock. Surficial geologic maps typically encompass deposits that are unconsolidated and formed during the past 2.6 million years (the Quaternary Period; fig. 7). 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. Both bedrock and surficial geologic map data are provided for Lava Beds National Monument.

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

Source Maps

The GRI team converts digital and/or paper geologic source maps to GIS formats that conform to the GRI GIS data model. The GRI digital geologic map product also includes essential elements of the source map, such as a correlation chart of map units, unit descriptions, map legend, map notes, references, and figures. The GRI team used the following source map and digital data for the Lava Beds National Monument data set:

Donnelly-Nolan, J. M. 2010. Geologic map of Medicine Lake volcano, northern California (scale 1:50,000). Scientific Investigations Map 2927. US Geological Survey, Menlo Park, California. http://pubs.er.usgs.gov/publication/sim2927.

Ramsey, D. W., T. J. Felger, E. Lougee, P. E. Bruggman, and J. M. Donnelly-Nolan. 2010. Database for the geologic map of Medicine Lake volcano, northern California. *Data to accompany* J. M. Donnelly-Nolan, 2010. Geologic map of Medicine Lake volcano, northern California (scale 1:50,000). Scientific Investigations Map 2927. US Geological Survey, Menlo Park, California. http://pubs.usgs.gov/sim/2927/sim2927_data/index.html.

Donnelly-Nolan (2010), which covers the entire Medicine Lake volcano, is based on previous mapping by Donnelly-Nolan and Champion (1987), which covered Lava Beds National Monument. Both of these maps provided information for the "Geologic Features and Processes," "Geologic Issues," and "Geologic History" sections of this report.

In addition, the GRI data set includes the following information:

Donnelly-Nolan, J. M. 2006. Chemical analyses and K-Ar ages of samples from 13 drill holes, Medicine Lake volcano, California. Open-File Report 2006-1041. US Geological Survey, Volcano Hazards Program, Menlo Park, California. http://pubs.er.usgs.gov/publication/ofr20061041.

Donnelly-Nolan, J. M. 2008. Chemical analyses of pre-Holocene rocks from Medicine Lake volcano and vicinity, northern California. Open-File Report 2008-1094. US Geological Survey, Volcano Hazards Program, Menlo Park, California. http://pubs.er.usgs.gov/publication/ofr20081094.

Donnelly-Nolan, J. M., and M. A. Lanphere. 2005. Argon dating at and near Medicine Lake volcano, California: results and data. Open-File Report 2005-1416. US Geological Survey, Washington, DC. http://pubs.usgs.gov/of/2005/1416/.

Geologic GIS Data

The Lava Beds National Monument data set conforms to the GRI GIS data model that standardizes map deliverables. The data model is included on the enclosed CD and is also available at http://science.nature.nps.gov/im/inventory/geology/GeologyGISDataModel.cfm. This data model dictates GIS data structure, including layer architecture, feature attribution, and relationships within ESRI ArcGIS software. The GRI team digitized the data for Lava Beds National Monument using data model version 2.1.

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

The following components and geology data layers are part of the GRI data set for Lava Beds National Monument:

- Data in ESRI geodatabase and shapefile GIS formats
- Layer files with feature symbology (table 4)
- Federal Geographic Data Committee–compliant metadata
- An ancillary map information document (PDF) that contains other information captured from source maps, such as map unit descriptions, geologic unit correlation tables, legends, cross sections, and graphics
- An ESRI map document (.mxd) that displays the digital geologic data
- A KML/KMZ version of the data viewable in Google Earth (table 4)

Table 4. Geology data layers in the Lava Beds National Monument GRI GIS data set

Data Layer	Data Layer Code	On Geologic Map Graphic?	Google Earth Layer?
Geologic sample localities	labegsl	No	No
Geologic point features (springs)	labegpf	No	No
Drill holes	labedhp	No	No
Mine point features	labemin	No	No
Glacial feature lines (moraine crests)	labegfl	No	Yes
Volcanic point features (cones, vents)	labevpf	Yes	No
Volcanic line features (caldera boundary, internal flow contacts)	labevlf	No	Yes
Map symbology (fault symbols)	labesym	Yes	No
Faults	labeflt	Yes	Yes
Linear dikes	labedke	Yes	Yes
Geologic contacts	labeglga	Yes	Yes
Geologic units	labeglg	Yes, clipped to monument boundary	Yes

Map Unit Properties Table

The Map Unit Properties Table (in pocket) lists the geologic time division, map symbol, and a simplified description for each of the map units in Lava Beds National Monument. The accompanying GRI GIS data (on attached CD) provide descriptions of units not within the monument. Following the structure of the report, the Map Unit Properties Table summarizes the geologic features and processes, issues, and geologic history associated with each map unit.

The source map by Donnelly-Nolan (2010) delineated 237 units: Holocene and Pleistocene surficial deposits (4 types), volcanic rocks of Medicine Lake volcano (208 units), and units older than Medicine Lake volcano (2 surficial and 23 volcanic rocks). To provide a Map Unit Properties Table of reasonable size, only the 43 units (surficial deposits and volcanic rocks) that occur within the boundaries of the monument are included. For a list and description of all units in the GRI GIS data, refer to labe_geology.pdf on the attached CD.

Geologic Map Graphic

The Geologic Map Graphic (in pocket) displays the GRI digital geologic data draped over a shaded relief image of the monument and surrounding area. The graphic is clipped to the monument's boundary. For graphic clarity, not all GIS feature classes are visible on the map graphic (table 4). Geographic information and selected features have been added. Digital elevation data and added geographic information are not included with the GRI GIS data for Lava Beds National Monument, but are available online from a variety of sources.

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 on the information provided here. Please contact the NPS Geologic Resources Division with any questions.

Inaccuracies may exist regarding the locations of geologic features relative to other geologic or geographic features on the GIS data and Geologic Map Graphic, particularly if mapping was conducted prior to the widespread use of GPS, which is the case for Donnelly-Nolan and Champion (1987), and, therefore, Donnelly-Nolan (2010). Based on the source map's scale (1:50,000) and US National Map Accuracy Standards, geologic features represented in the GRI data set are within approximately 25 m (82 ft) of their true locations.

Glossary

This section contains brief definitions of selected geologic terms relevant to this report. Definitions are based on those in the American Geosciences Institute Glossary of Geology *(5th edition; 2005). Additional terms are defined at*

- *http://geomaps.wr.usgs.gov/parks/misc/glossarya.html*,
- *http://vulcan.wr.usgs.gov/Glossary/volcano_terminology.html, and*
- *http://volcanoes.usgs.gov/vsc/glossary.html#glnk-36*.

aa. A Hawaiian term for lava flows typified by a rough, jagged, or clinkery surface.

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

andesite. An extrusive (volcanic) igneous rock characteristically medium dark in color and containing approximately 57%–63% silica and moderate amounts of iron and magnesium.

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

basalt. An extrusive (volcanic) igneous rock that is characteristically dark in color (gray to black), contains 45%–53% silica, and is rich in iron and magnesium; more fluid than andesite or dacite, which contain more silica.

basaltic andesite. An extrusive (volcanic) igneous rock that is commonly dark gray to black and contains approximately 53%–57% silica.

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

bed. The smallest sedimentary stratigraphic unit, commonly ranging in thickness from about 1 cm (0.4 in) to 1 to 2 m (40 to 80 in) and distinguishable from beds above and below.

bedding. Depositional layering or stratification of sediments.

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

block (fault). A crustal unit bounded completely or partially by faults.

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

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

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

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

carbonate rock. A rock, for example, limestone, calcite, and dolomite, that consist primarily of carbonate minerals.

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

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

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

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

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

continental crust. Earth’s crust that is rich in silica and aluminum and underlies the continents and the continental shelves; ranges in thickness from about 25 km (15 mi) to more than 70 km (40 mi) under mountain ranges, averaging about 40 km (25 km) thick.

country rock. The rock surrounding an igneous intrusion or pluton; also, the rock enclosing or traversed by a mineral deposit.

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

crust. Earth’s outermost layer or shell. Compare to “oceanic crust” and “continental crust.”

dacite. An extrusive (volcanic) igneous rock that is characteristically light in color and contains approximately 63%–68% silica and moderate amounts of sodium and potassium.

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

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

diatom. A microscopic, single-celled alga that secretes walls of silica, called frustules; lives in freshwater and marine environments.

diatomite. A light-colored, soft, silica-rich sedimentary rock consisting mostly of diatoms.

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

dome. Any smoothly rounded landform or rock mass; more specifically, an elliptical uplift in which rocks dip gently away in all directions.

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

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

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

drift. All rock material (clay, silt, sand, gravel, and boulders) transported and deposited by a glacier, or by running water emanating from a glacier.

dripstone. A mineral deposit formed in a cave by dripping water.

ductile. Describes a rock that is able to sustain deformation such as folding, bending, or shearing before fracturing.

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

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

extrusion. The emission of lava onto Earth's surface; also, the rock so formed.

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

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

feldspar. A group of abundant silicate (silicon + oxygen) minerals, comprising more than 60% of Earth's crust and occurring in all types of rocks. Compare to "alkali feldspar" and "plagioclase."

felsic. Derived from ***fel***dspar +***si***li***c***a to describe an igneous rock having abundant light-colored minerals such as quartz, feldspars, or muscovite; also, describes those minerals.

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

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

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

fracture. The breaking of a mineral other than along planes of cleavage. Also, any break in a rock such as a crack, joint, or fault.

freeze-thaw. The mechanical weathering process caused by alternate or repeated cycles of freezing and thawing water in pores, cracks, and other openings of rock and unconsolidated deposits, usually at the surface.

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

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

glassy. Describes the texture of certain extrusive (volcanic) igneous rocks that is similar to broken glass and developed as a result of rapid cooling of the lava, without distinctive crystallization. Synonymous with "vitreous."

graben. An elongated, downdropped trough or basin, bounded on both sides by high-angle normal faults that dip toward one another. Compare to "horst."

hanging wall. The upper wall of a fault. Compare to "footwall."

hyaloclastite. A deposit formed by the flow or intrusion of lava or magma into water, ice, or water-saturated sediment, which shatters the lava or magma into small angular fragments.

hydrogeology. The science that deals with subsurface waters and related geologic aspects of surface waters, including the movement of groundwater; the mechanical, chemical, and thermal interaction of groundwater with the porous medium; and the transport of energy and chemical constituents by the flow of groundwater. Synonymous with "geohydrology."

hydrology. The study of liquid and solid water properties, circulation, and distribution, on and under the Earth's surface and in the atmosphere.

hydrothermal. Of or pertaining to hot water, to the action of hot water, or to the products of this action, such as a mineral deposit precipitated from a hot aqueous solution, with or without demonstrable association with igneous processes; also, said of the solution itself.

hydrothermal water. Subsurface water whose temperature is high enough to make it geologically or hydrologically significant, whether or not it is hotter than the rock containing it.

igneous. Describes a rock or mineral that solidified from molten or partly molten material; also, describes processes leading to, related to, or resulting from the formation of such rocks.

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

ingrown meander. A continually growing or expanding incised meander formed during a single cycle of erosion by the enlargement of an initial minor meander while the stream was actively downcutting; exhibits a pronounced asymmetric cross profile (a well-developed, steep undercut slope on the outside of the meander, a gentle slip-off slope on the inside) and is produced when the rate of downcutting is slow enough to afford time for lateral erosion.

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

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

island arc. A offshore, generally curved belt of volcanoes above a subduction zone.

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

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

kipuka. An area surrounded by a lava flow.

lacustrine. Describes a process, feature, or organism pertaining to, produced by, or inhabiting a lake.

lag gravel. An accumulation of coarse material remaining on a surface after finer material has been blown or washed away.

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

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

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

lavacicle. A protrusion of lava that resembles an icicle in form, resulting from the dripping of lava into a lava tube.

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

lava lake. A lake of molten lava, usually basaltic, in a volcanic crater or depression; refers to solidified and partly solidified stages as well as the molten, active lava lake.

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

lithification. The conversion of sediment into solid rock.

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

littoral cone. A mound of hyaloclastic debris constructed by steam explosions at the point where lava enters the sea or other body of water. Littoral cones lack feeding vents connected to subsurface magma supplies.

mafic. Derived from ***ma***gnesium + ***f***err***ic*** (Fe is the chemical symbol for iron) to describe an igneous rock having abundant dark-colored, magnesium- or iron-rich minerals such as biotite, pyroxene, or olivine; also, describes those minerals.

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

magma reservoir. A chamber in the shallow part of the lithosphere from which volcanic materials are derived; the magma has ascended from a deeper source.

mantle. The zone of the Earth below the crust and above the core.

marker bed. A well-defined, easily identifiable stratum or body of strata that has sufficiently distinctive characteristics (such as lithology or fossil content) to facilitate correlation in field mapping or subsurface work. Also, a geologic formation that serves as a marker.

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

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

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

moraine. A mound, ridge, or other distinct accumulation of unsorted, unstratified glacial drift, predominantly till, deposited chiefly by direct action of a glacier, in a variety of topographic landforms that are independent of control by the surface on which the drift lies.

normal fault. A fault in which the hanging wall appears to have moved downward relative to the footwall; the angle of dip is usually 45°–90°.

numerical age. The geologic age of a fossil organism, rock, or geologic feature or event given in units of time, usually years. Commonly used as a synonym of "isotopic age," but may also refer to ages obtained from tree rings, varves, and other dating methods.

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

oceanic crust. Earth's crust that underlies the ocean basins and is rich in iron and magnesium; ranges in thickness from about 5 to 10 km (3 to 6 mi).

ostracode. Any aquatic crustacean belonging to the subclass Ostracoda, characterized by a two-valved (shelled), generally calcified carapace with a hinge along the dorsal margin. Range: Lower Cambrian to Holocene

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

outwash. Glacial sediment transported and deposited by meltwater streams.

pahoehoe. A Hawaiian term for a lava flow typified by a smooth, billowy, or ropy surface.

palagonite. An altered volcanic, specifically basaltic, glass that incorporate into pillow lavas or occurs in amygdules.

palagonite tuff. A pyroclastic rock consisting of angular fragments of hydrothermally altered or weathered palagonite, produced by explosive interaction of mafic magma and water.

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

phreatic. Of or relating to groundwater.

phreatic explosion. A volcanic explosion of steam, mud, or other material that is not incandescent (hot enough to glow); caused by the heating and consequent expansion of groundwater due to an underlying igneous heat source.

phreatic zone. The zone of saturation.

plagioclase. A silicate (silicon + oxygen) mineral of the feldspar group that contains both sodium and calcium ions that freely substitute for one another;

characterized by striations (parallel lines) in hand specimens.

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

platform. Any level or nearly level surface.

pluton. A deep-seated igneous intrusion.

plutonic. Describes an igneous rock or intrusive body formed at great depth beneath Earth's surface.

pluvial. Describes a geologic process or feature resulting from rain.

pumice. An extrusive (volcanic) igneous rock, composed of highly vesicular pyroclasts with very low bulk density and thin vesicle walls.

pumiceous. Describes a texture of volcanic rock consisting of tiny gas holes such as in pumice; finer than scoriaceous.

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

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

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

radiolarian. Any actinopod (protozoan) belonging to the subclass Radiolaria, characterized by a siliceous skeleton and a marine pelagic environment. Range: Cambrian to Holocene.

rhyodacite. An extrusive (volcanic) igneous rock that contains approximately 68%–72% silica and is intermediate in composition between rhyolite and dacite.

rhyolite. An extrusive (volcanic) igneous rock that is characteristically light in color, contains approximately 72% or more silica, and is rich in potassium and sodium.

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

rift valley. A depression formed by grabens along the crest of a mid-ocean ridge or in a continental rift zone.

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

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

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

sand. A clastic particle smaller than a granule and larger than a silt grain, with a diameter ranging from 1/16 to 2 mm (0.0025 to 0.08 in).

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

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

scoria cone. A conical volcanic feature formed by the accumulation of scoria and other pyroclasts, usually of basaltic or andesitic composition.

scoriaceous. Describes a texture of volcanic rock consisting of relatively large gas holes such as in vesicular basalt; coarser than pumiceous.

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

sedimentary. Pertaining to or containing sediment.

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

sequence. A succession of geologic events, processes, or rocks, arranged in chronologic order to show their relative position and age with respect to geologic history as a whole.

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

shear zone. A zone of rock that has been crushed and brecciated by many parallel fractures as a result of shearing.

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

shoal. A relatively shallow place in a stream, lake, sea, or other body of water.

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

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

silicic magma. Describes magma that contains more than 65% silica; generally viscous, gas-rich, and tends to erupt explosively.

silt. Clastic sedimentary material intermediate in size between fine-grained sand and coarse clay, 1/256 to 1/16 mm (0.00015 to 0.0025 in) across.

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

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

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

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

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

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

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

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

structural geology. The branch of geology that deals with the description, representation, and analysis of structures, primarily on a moderate to small scale. The subject is similar to tectonics, but the latter term is generally used for the analysis of broader regional or historical phases.

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

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

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

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

sump. An excavated area in which drainage water is collected for subsequent use in irrigation or wild-fowl conservation. Also, a dialect term for a swamp or morass, and for a stagnant pool or puddle of dirty water.

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

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

tectonics. The geologic study of the broad structural architecture and deformational processes of the lithosphere and asthenosphere.

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

thrust fault. A dip-slip fault with a shallowly dipping (less than 45°) fault surface where the hanging wall moves up and over relative to the footwall.

till. Unstratified drift deposited directly by a glacier without reworking by meltwater and consisting of a mixture of clay, silt, sand, gravel, and boulders ranging widely in size and shape.

tonalite. An intrusive (plutonic) igneous rock composed primarily of quartz and plagioclase with 10% or less alkali feldspar.

tongue. An extension, projection, or offshoot of a larger body of rock, commonly occurring as wedges that disappear away from the main body.

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

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

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

trend. The direction or bearing of an outcrop of a geologic feature such as an ore body, fold, or orogenic belt.

tuff. A fine-grained, extrusive (volcanic) igneous rock composed of consolidated volcanic ash.

tuffaceous. Describes non-volcanic, clastic sediments that contain ash-size pyroclasts.

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

twilight zone. The part of a cave where daylight penetrates and gradually diminishes to zero light.

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

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

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

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

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

volatile. Readily vaporizable.

volatile component. Material in magma, such as water or carbon dioxide, whose vapor pressures is sufficiently high to be concentrated as a gas.

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

volcanic arc. A large-scale (hundreds of kilometers) generally curved belt of volcanoes above a subduction zone.

volcanigenic. Formed by processes directly connected with volcanism.

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

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

Literature Cited

This section lists references cited in this report. Contact the Geologic Resources Division for assistance in obtaining these documents.

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Additional References

This section lists additional references, resources, and websites that may be of use to resource managers. Web addresses are valid as of January 2014. Refer to Appendix B for laws, regulations, and policies that apply to NPS geologic resources.

Geology of National Park Service Areas

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

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

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

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

NPS Resource Management Guidance and Documents

1998 National parks omnibus management act: http://www.gpo.gov/fdsys/pkg/PLAW-105publ391/pdf/PLAW-105publ391.pdf

Management Policies 2006 (Chapter 4: Natural resource management): http://www.nps.gov/policy/mp/policies.html

NPS-75: Natural resource inventory and monitoring guideline: http://www.nature.nps.gov/nps75/nps75.pdf

NPS Natural resource management reference manual #77: http://www.nature.nps.gov/Rm77/

Geologic monitoring manual (Young, R., and L. Norby, editors. 2009. Geological monitoring. Geological Society of America, Boulder, Colorado): http://nature.nps.gov/geology/monitoring/index.cfm

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

Climate Change Resources

NPS Climate Change Response Program Resources: http://www.nps.gov/subjects/climatechange/resources.htm

US Global Change Research Program: http://globalchange.gov/home

Intergovernmental Panel on Climate Change: http://www.ipcc.ch/

Geological Surveys and Societies

California Geological Survey: http://www.conservation.ca.gov/CGS/Pages/Index.aspx

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.agiweb.org/

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

US Geological Survey Reference Tools

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

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

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

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

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

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

Appendix A: GRI Scoping Participants

The following people contributed to the GRI scoping process for Lava Beds National Monument. Most attended the GRI scoping meeting on 4 March 2004; some only provided input to the scoping summary. Discussions during the scoping meeting supplied a foundation for this GRI report. The scoping summary document is available at the GRI publications website: http://go.nps.gov/gripubs.

Name	Affiliation	Position
Pete Biggam	NPS Natural Resources Information Division	Soil Scientist
Tim Connors	NPS Geologic Resources Division	Geologist
Sid Covington	NPS Geologic Resources Division	Geologist
Chris Currens	USGS Biological Resources Division	Aquatic Biologist
Marsha Davis	NPS Columbia Cascades Support Office	Geologist
Julie Donnelly-Nolan	USGS Geologic Division	Geologist
Dave Larsen	Lava Beds National Monument	Chief, Natural Resources
Ron Kerbo	NPS Geologic Resources Division	Cave Specialist
Anne Poole	NPS Geologic Resources Division	Geologist
Daniel Sarr	NPS Klamath Network	Network Coordinator
Bob Truitt	NPS Klamath Network	Data Manager
Hanna Waterstat	NPS Klamath Network	Data Miner

Appendix B: Geologic Resource Laws, Regulations, and Policies

The NPS Geologic Resources Division developed this table to summarize laws, regulations, and policies that specifically apply to National Park Service minerals and geologic resources. The table does not include laws of general application (e.g., Endangered Species Act, Clean Water Act, Wilderness Act, National Environmental Policy Act, or National Historic Preservation Act). The table does include the NPS Organic Act when it serves as the main authority for protection of a particular resource or when other, more specific laws are not available. Information is current as of January 2014. 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, 16 USC. § 5937** protects the confidentiality of the nature and specific location of cave and karst resources. **Lechuguilla Cave Protection Act of 1993, Public Law 103-169** created a cave protection zone (CPZ) around Lechuguilla Cave in Carlsbad Caverns National Park. Within the CPZ, access and the removal of cave resources may be limited or prohibited; existing leases may be cancelled with appropriate compensation; and lands are withdrawn from mineral entry.	**36 C.F.R. § 2.1** prohibits possessing/ destroying/disturbing…cave resources…in park units. **43 C.F.R. Part 37** states that all NPS caves are "significant" and 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, and minimize impacts. **Section 4.8.2** requires NPS to protect geologic features from adverse effects of human activity. **Section 4.8.2.2** requires NPS to protect caves, allow new development in or on caves if it will not impact cave environment, and to remove existing developments if they impair caves. **Section 6.3.11.2** explains how to manage caves in/adjacent to wilderness.

Resource	Resource-specific Laws	Resource-specific Regulations	2006 Management Policies
Paleontology	**National Parks Omnibus Management Act of 1998, 16 USC. § 5937** protects the confidentiality of the nature and specific location of paleontological resources and objects. **Paleontological Resources Preservation Act [PRPA] of 2009**, **16 USC. § 470aaa *et seq.*** provides for the management and protection of paleontological resources on federal lands.	**36 C.F.R. § 2.1(a)(1)(iii)** prohibits destroying, injuring, defacing, removing, digging, or disturbing paleontological specimens or parts thereof. **36 C.F.R. § 13.35** prohibition applies even in Alaska parks where the surface collection of other geologic resources is permitted. Regulations in association with 2009 PRPA are being finalized (December 2013).	**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 park managers to maintain confidentiality of paleontological information, and allows park managers to buy fossils only in accordance with certain criteria.
Rocks and Minerals	**NPS Organic Act**, **16 USC. § 1 *et seq.*** directs the NPS to conserve all resources in parks (including rock and mineral resources) unless otherwise authorized by law. **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, or Katmai) by non-disturbing methods (e.g., no pickaxes), which can be stopped by superintendent if collection causes significant adverse effects on park resources and visitor enjoyment.	**Section 4.8.2** requires NPS to protect geologic features from adverse effects of human activity.
Geothermal	**Geothermal Steam Act of 1970, 30 USC. § 1001 *et seq.*** as amended in 1988, states that -No geothermal leasing is allowed in parks. -"Significant" thermal features exist in 16 park units (the features listed by the NPS at 52 Fed. Reg. 28793-28800 [August 3, 1987], and 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	**Mining in the Parks Act of 1976, 16 USC. § 1901 *et seq.*** authorizes NPS to regulate all activities resulting from exercise of mineral rights, on patented and unpatented mining claims in all areas of the System, in order to preserve and manage those areas. **General Mining Law of 1872, 30 USC. § 21 *et seq.*** allows US citizens to locate mining claims on federal lands. Imposes administrative and economic validity requirements for "unpatented" claims (the right to extract federally owned locatable minerals). Imposes additional requirements for the processing of "patenting" claims (claimant owns surface and subsurface). Use of patented mining claims may be limited in wild and scenic rivers and Olympic, Glacier Bay, Coronado, Organ Pipe Cactus, and Death Valley. **Surface Uses Resources Act of 1955, 30 USC § 612** restricts surface use of unpatented mining claims to mineral activities.	**36 C.F.R. § 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 C.F.R. Part 6** regulates solid waste disposal sites in park units. **36 C.F.R. 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 C.F.R. 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 C.F.R. 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.
Park Use of Sand and Gravel	**Materials Act of 1947, 30 USC. § 601** does not authorize the NPS to dispose of mineral materials outside of park units. **Exception: 16 USC. §90c 1(b)** the non-wilderness portion of Lake Chelan, where sand, rock, and gravel may be made available for sale to the residents of Stehekin for local use as long as such sale and disposal does not have significant adverse effects on the administration of the national recreation area.	None applicable.	**Section 9.1.3.3** clarifies that only the NPS or its agent can extract park-owned common variety minerals (e.g., sand and gravel), and -Only for park administrative uses. -After compliance with the National Environmental Policy Act [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. -Park managers should use existing pits and create new pits only in accordance with park-wide borrow management plan. -Spoil areas must comply with Part 6 standards. -NPS must evaluate use of external quarries. Any deviation from this policy requires written waiver from the Secretary, Assistant Secretary, or Director.

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US Department of the Interior

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Geology of Lava Beds National Monument

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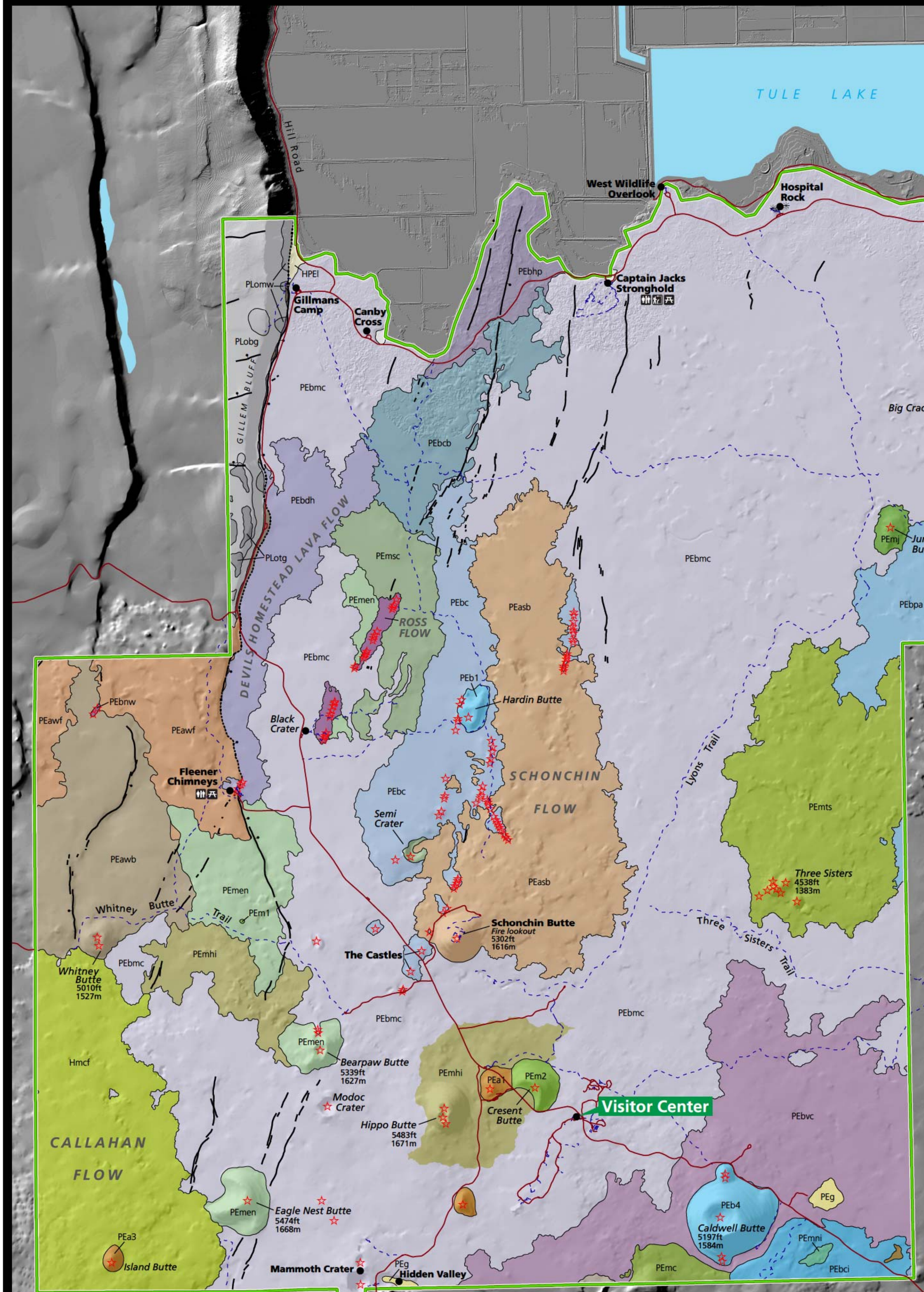
Geologic Resources Inventory



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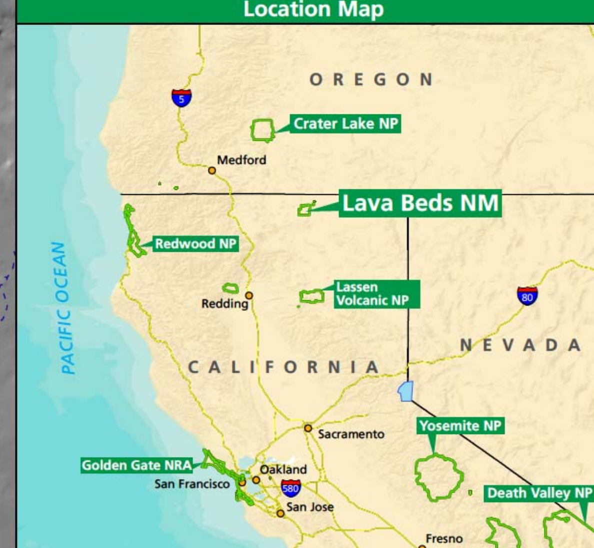
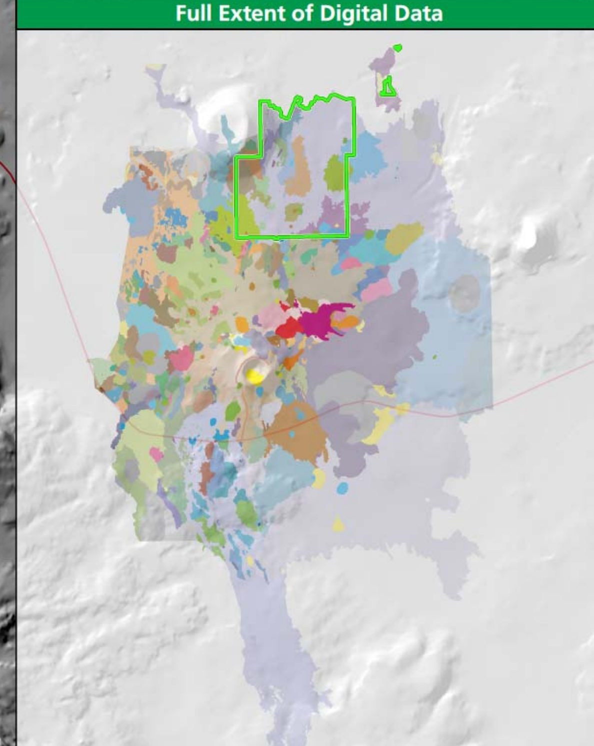


Full Extent of Digital Data



NPS Boundary

Infrastructure

- cities
- points of interest
- trails
- roads

Volcanic Point Feature

- littoral cone
- vent

Dike

- PEdike - Dike, known or certain

Fault

- unknown offset/displacement, known or certain
- normal fault, known or certain
- normal fault, concealed

Geologic Contacts

- known or certain
- concealed

Geologic mapping by Donnelly-Nolan and Champion (1987), as modified by Donnelly-Nolan (2010), delineated these 43 map units in Lava Beds National Monument. A full list and description of units of Medicine Lake volcano is on the attached CD (see labe_geology.pdf). That document also includes a link to the Correlation of Map Units figure from Donnelly-Nolan (2010).

Geologic Units

- Hmcf — Basaltic andesite of Callahan Flow (Holocene)
- Hbbr — Basalt of Black Crater and Ross Chimneys (Holocene)
- HPEl — Lake deposits (Holocene and Pleistocene)
- PEbvc — Basalt of Valentine Cave (late Pleistocene)
- PEbdh — Basalt of Devils Homestead (late Pleistocene)
- PEg — Gravel (Pleistocene)
- PEbgd — Basalt of Gold Digger Pass (late Pleistocene)
- PEbc — Basalt of The Castles (late Pleistocene)
- PEbmc — Basalt of Mammoth Crater (late Pleistocene)
- PEaib — Andesite of Indian Butte (late Pleistocene)
- PEbci — Basalt of Caldwell Ice Caves (late Pleistocene)
- PEmts — Basaltic andesite of Three Sisters (late? Pleistocene)
- PEasb — Andesite of Schonchin Butte (late Pleistocene)
- PEbpa — Basalt of The Panhandle (late Pleistocene)
- PEmhi — Basaltic andesite of Hippo Butte (late Pleistocene)
- PEmen — Basaltic andesite of Eagle Nest Butte (late Pleistocene)
- PEm1 — Basaltic andesite spatter vent west-northwest of Bat Butte (late or middle Pleistocene)
- PEawb — Andesite of Whitney Butte (middle Pleistocene)
- PEbng — Basalt northeast of Glass Mountain (middle? Pleistocene)
- PEa1 — Andesite cone west of Crescent Butte (middle? Pleistocene)
- PEawf — Andesite west of Fleener Chimneys (middle Pleistocene)
- PEm2 — Basaltic andesite of Crescent Butte (middle Pleistocene)
- PEbnw — Basalt north of Whitney Butte (middle Pleistocene)
- PEmsc — Basaltic andesite of Semi Crater (middle Pleistocene)
- PEanh — Andesite northeast of Mount Hoffman (middle Pleistocene)
- PEbcb — Basalt of Canby Bay (middle Pleistocene)
- PEb4 — Basalt of Caldwell Butte (middle? Pleistocene)
- PEadh — Andesite near Devils Homestead (middle Pleistocene)
- PEb5 — Basalt cone southeast of Mammoth Crater (middle? Pleistocene)
- PEa3 — Andesite of Island Butte (middle Pleistocene)
- PEbgf — Basalt west of Canby Cross at Gillem Fault (middle Pleistocene)
- PEmni — Basaltic andesite north of Indian Butte (middle Pleistocene)
- PEmc — Basaltic andesite south and southwest of Caldwell Butte (middle Pleistocene)
- PEa2 — Andesite of Red Butte (middle Pleistocene)
- PEb1 — Basalt of Hardin Butte (middle Pleistocene)
- PEbp — Basalt of Prisoners Rock (middle Pleistocene)
- PEmj — Basaltic andesite of Juniper Butte (middle Pleistocene)
- PEbhp — Basalt of Hovey Point (middle Pleistocene)
- PEobp — Older basalt on west side of Gillem Fault (early Pleistocene)
- PLotg — Older tuff of Gillem Bluff (Pliocene)
- PLomg — Older basaltic andesite of Gillem Bluff (Pliocene)
- PLobg — Older basalt of Gillem Bluff (Pliocene)
- PLomw — Older basaltic andesite in western Lava Beds National Monument (Pliocene)

This map graphic was produced by Max Jackl (Colorado State University) in June 2013 from the folllowing sources:

Donnelly-Nolan, J.M. 2010. Geologic Map of Medicine Lake volcano, northern California (scale 1:50,000). Scientific Investigations Map 2927. US Geological Survey, Menlo Park, California.

Ramsey, D.W., T.J. Felger, E. Lougee, P.E. Bruggman, and J.M. Donnelly-Nolan. 2010. Database for the geologic map of Medicine Lake volcano, northern California. Data to accompany J.M. Donnelly-Nolan, 2010. Geologic map of Medicine Lake volcano, northern California (scale 1:50,000). Scientific Investigations Map 2927. US Geological Survey, Menlo Park, California.

It is an overview of compiled data prepared as part of the NPS Geologic Resources Inventory. This map graphic is not a substitute for site-specific investigations.

As per source map scale and US National Map Accuracy Standards, geologic features represented here are within 25 m (83 ft) of their true location.

All digital geologic data and publications prepared as part of the Geologic Resources Inventory are available at the NPS Integrated Resource Management Applications Portal (IRMA): https://irma.nps.gov/App/Reference/Search. Enter “GRI” as the search text and select a park from the unit list.

Map Unit Properties Table: Lava Beds National Monument

Geologic mapping by Donnelly-Nolan and Champion (1987), as modified by Donnelly-Nolan (2010), delineated these 43 map units in Lava Beds National Monument. A full list and description of units of Medicine Lake volcano is on the attached CD (see labe_geology.pdf). That document also includes a link to the Correlation of Map Units figure from Donnelly-Nolan (2010). Bold text indicates report sections.

Age	Map Unit (symbol)	Geologic Description	Geologic Features and Processes	Geologic Resource Management Issues	Geologic History
HOLOCENE	Basaltic andesite of Callahan Flow (Hmcf)	Compositionally variable (51.8%–57.8% silica [SiO_2]; average [avg.] of 40 [samples] = 55.1%), blocky lava flow consisting of basalt, basaltic andesite, and andesite. Estimated area: 24 km^2 (9 mi^2). Estimated volume: 0.33 km^3 (0.08 mi^3).	**Volcanic Features**—youngest lava flow in Lava Beds National Monument. Erupted from Cinder Butte and adjacent smaller vents 7 km (4 mi) from northern terminus of flow. **Paleontological Resources**—contains tree molds.	**Volcano Hazards**—the most likely future eruption at Medicine Lake volcano would be a small effusive eruption of basaltic lava, which could occur anywhere on the volcano. Tephra emitted during a silicic eruption (near the summit) could affect Lava Beds National Monument.	**Medicine Lake Volcano History—** eruptive stage 5 (approximately 13,000 years ago to present). Calibrated radiocarbon age: 1,120 years before present (BP).
HOLOCENE	Basalt of Black Crater and Ross Chimneys (Hbbr)	Basalt (48.3%–50.6% SiO_2; avg. of 21 = 49.5%). Estimated area: 0.45 km^2 (0.17 mi^2). Estimated volume: 0.001 km^3 (0.0002 mi^3).	**Volcanic Features**—erupted from numerous north–northeast-oriented spatter cones that form en echelon linear arrays. Black Crater and Ross Chimneys mark vents. **Tectonic Features**—open ground cracks, which have the same orientation as vents, extend north toward Lava Beds National Monument boundary and may have opened during this eruption. **Paleontological Resources**—contains tree molds.	**Recreational Impacts to Geologic Features**—Black Crater and Ross Chimneys are popular visitor attractions and very susceptible to recreational impacts. **Volcano Hazards**—the most likely future eruption at Medicine Lake volcano would be a small effusive eruption of basaltic lava, which could occur anywhere on the volcano. Tephra emitted during a silicic eruption (near the summit) could affect Lava Beds National Monument.	**Medicine Lake Volcano History—** eruptive stage 5 (approximately 13,000 years ago to present). Calibrated radiocarbon age: 3,080 years BP.
HOLOCENE AND PLEISTOCENE	Lake deposits (HPEl)	Fine-grained, water-laid sediments in low, flat areas scattered around Medicine Lake volcano.	**Paleontological Resources**—includes diatoms, pollen, and ostracodes that inhabited Tule Lake basin over the past 3 million years. **Lake Deposits**—include deposits from ancient Tule Lake, Tule Lake, and around Medicine Lake in the caldera.	**Volcano Hazards**—phreatomagmatic eruptions possible if vent were to open under Medicine Lake in the caldera.	**Medicine Lake Volcano History—** coincides with eruptive stage 5, although history of Tule Lake (and its predecessors?) extends back 3 million years.
LATE PLEISTOCENE	Basalt of Valentine Cave (PEbvc)	Basalt and basaltic andesite (52.9%, 52.9%, 53.4% SiO_2; avg. of 3 = 53.0%). Estimated area: 20 km^2 (8 mi^2). Estimated volume: 0.2 km^3 (0.05 mi^3).	**Volcanic Features**—lava flow erupted from northwest-oriented linear array of spatter cones at 1,650–1,700 m (5,400–5,600 ft) elevation on northern flank of Medicine Lake volcano, just south of Lava Beds National Monument. Nearly all of the lava was erupted from vents known as Tickner Chimneys, but separate vents uphill and to the southeast produced a very small lava flow. **Lava Tubes**—contains a lava-tube system. Main flow contains several caves, including Valentine Cave. These are the youngest caves in the monument. **Paleontological Resources**—contains tree molds. **Glacial Outwash**—overlies glacial outwash formerly exposed in quarry east of paved monument road, about 0.5 km (0.3 mi) east of Caldwell Butte.	**Cave Management**—contains much-visited Valentine Cave. **Rockfall and Roof Collapse**—the monument road traverses parts of **PEbvc**. Steep slopes prone to rockfall. Rockfall debris may accumulate on road and be a hazard to travelers. **PEbvc** contains caves. Cave roofs and entrances are prone to collapse. Infrastructure built over caves is susceptible to collapse into the opening below. **Volcano Hazards**—the most likely future eruption at Medicine Lake volcano would be a small effusive eruption of basaltic lava, which could occur anywhere on the volcano. Tephra emitted during a silicic eruption (near the summit) could affect Lava Beds National Monument.	**Medicine Lake Volcano History—** eruptive stage 5 (approximately 13,000 years ago to present). Calibrated radiocarbon age: 12,260 years BP. **Glacial History**—early postglacial flow (i.e., erupted soon after ice-age glaciers retreated from the area).

Geologic mapping by Donnelly-Nolan and Champion (1987), as modified by Donnelly-Nolan (2010), delineated these 43 map units in Lava Beds National Monument. A full list and description of units of Medicine Lake volcano is on the attached CD (see labe_geology.pdf). That document also includes a link to the Correlation of Map Units figure from Donnelly-Nolan (2010). Bold text indicates report sections.

Age	Map Unit (symbol)	Geologic Description	Geologic Features and Processes	Geologic Resource Management Issues	Geologic History
LATE PLEISTOCENE	Basalt of Devils Homestead (PEbdh)	Basalt (51.3%, 51.4% SiO_2). Estimated area: 4 km^2 (2 mi^2). Estimated volume: 0.04 km^3 (0.01 mi^3).	**Volcanic Features**—lava flow erupted from spatter vents known as Fleener Chimneys. Aa lava makes up rugged Devils Homestead lava flow, although much of the lava near the vent is pahoehoe. **Tectonic Features**—vents, located at bend along predominantly north–south-oriented Gillem fault, are aligned approximately N20°–25°E.	**Recreational Impacts to Geologic Features**—Fleener Chimneys is a popular visitor attraction and very susceptible to recreational impacts. **Rockfall and Roof Collapse**—the monument road traverses parts of **PEbdh**. Steep slopes prone to rockfall. Rockfall debris may accumulate on road and be a hazard to travelers. **Volcano Hazards**—the most likely future eruption at Medicine Lake volcano would be a small effusive eruption of basaltic lava, which could occur anywhere on the volcano. Tephra emitted during a silicic eruption (near the summit) could affect Lava Beds National Monument.	**Medicine Lake Volcano History—** eruptive stage 5 (approximately 13,000 years ago to present). Calibrated radiocarbon age: 12,320 years BP. Age is interpreted as postglacial on the basis of paleomagnetic data and morphologic comparison with other lava flows.
PLEISTOCENE	Gravel (PEg)	Includes boulders as much as 1 m (3 ft) across, but dominant size range is pebbles to small cobbles. Deposited in widely scattered areas on middle to lower flanks of Medicine Lake volcano.	**Volcanic Features**—white pebbles in glacial outwash gravel are pumice that is compositionally identical to the rhyolite of Mount Hoffman (**PErmh**) outside Lava Beds National Monument. **Glacial Outwash**—only two exposures of **PEg** occur in the monument.	**Abandoned Mineral Lands**—cinders and gravel extracted from Closed Dump Pit.	**Glacial History**—consists primarily of glacial outwash gravel associated with deglaciation, as well as gravels deposited by a flood that was generated when the dacite tuff of Antelope Well (**PEdta**; see GRI data on attached CD) erupted onto summit ice cap about 180,000 years ago.
LATE PLEISTOCENE	Basalt of Gold Digger Pass (PEbgd)	Basalt (49.6%–50.7% SiO_2; avg. of 8 = 50.4%) on lower northern flank of Medicine Lake volcano. Exposed flow length is approximately 11 km (7 mi).	**Volcanic Features**—flow has youthful, well-preserved morphology similar to the (underlying) basalt of Mammoth Crater (**PEbmc**). Vent area presumably buried by Callahan Flow (**PEmcf**) to the south. **Tectonic Features**—broken by northwest- and northeast-oriented faults.	**Volcano Hazards**—the most likely future eruption at Medicine Lake volcano would be a small effusive eruption of basaltic lava, which could occur anywhere on the volcano. Tephra emitted during a silicic eruption (near the summit) could affect Lava Beds National Monument.	**Medicine Lake Volcano History**—eruptive stage 4 (approximately 100,000–13,000 years ago).
	Basalt of The Castles (PEbc)	Basalt (48.6% SiO_2). Estimated area: 6.5 km^2 (2.5 mi^2), including one small 1.4-km (0.9-mi) × 0.3-km (0.2-mi) area on the eastern side of Schonchin Flow. Estimated volume: less than 0.05 km^3 (0.02 mi^2).	**Volcanic Features**—lava extruded from many tens of spatter cones, including The Castles near western base of Schonchin Butte. One major vent is the lava lake west of Semi Crater (**PEmsc**). **PEbc** is mostly located west of Schonchin Flow, but one area is located at its northeastern edge. **Lava Tubes**—contains a lava-tube system. Small surface tubes are common, but development of major lava tubes did not occur. **Tectonic Features**—most vents are aligned north-northeast, but some are oriented north-northwest to northwest.	**Cave Management**—contains small caves close to the surface. **Rockfall and Roof Collapse**—the monument road traverses parts of **PEbc**. Steep slopes prone to rockfall. Rockfall debris may accumulate on road and be a hazard to travelers. **PEbc** contains caves. Cave roofs and entrances are prone to collapse. Infrastructure built over caves is susceptible to collapse into the opening below. **Volcano Hazards**—the most likely future eruption at Medicine Lake volcano would be a small effusive eruption of basaltic lava, which could occur anywhere on the volcano. Tephra emitted during a silicic eruption (near the summit) could affect Lava Beds National Monument.	**Medicine Lake Volcano History**—eruptive stage 4 (approximately 100,000–13,000 years ago). Degree of spatter-vent breakdown indicates **PEbc** is not of Holocene age.

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Age	Map Unit (symbol)	Geologic Description	Geologic Features and Processes	Geologic Resource Management Issues	Geologic History
LATE PLEISTOCENE	Basalt of Mammoth Crater (PEbmc)	Compositionally variable (48.4%–55.9% SiO_2; avg. of 45 = 52.3%) basalt and basaltic andesite; predominantly basalt. Can sometimes be distinguished by reddish patina.	**Volcanic Features**—consists of widespread lava flow, covering 70% of Lava Beds National Monument. Fed by lava tubes as far as 25 km (16 mi) from vent area. Vents include Mammoth Crater, Modoc Crater, and Bat Butte, as well as a spatter rampart on the northern side of Bearpaw Butte and other north- and northwest-aligned pit craters and spatter vents. **Lava Tubes**—contains six lava-tube systems and the majority of caves in the monument. **Tectonic Features**—cut by numerous north–northwest- to north–northeast-oriented faults, including open ground cracks. **Paleontological Resources**—Pleistocene mammal fossils in caves; for example Ovis Cave is known for extirpated bighorn sheep remains. **Lake Deposits**—at its northeastern edge, **PEbmc** entered ancient Tule Lake and formed pillow lavas and littoral cones of Hospital Rock. **Glacial Outwash**—overlies **PEg**. **Geologic Features with Cultural Significance**—Captain Jacks Stronghold, Gillems Camp, and Hospital Rock. Modoc used water available in Captain Jacks Ice Cave and Frozen River Cave, which occur in **PEbmc**.	**Cave Management**—contains all caves along Cave Loop, and all visitor-use caves except Valentine Cave. **Recreational Impacts to Geologic Features**—contains distinctive and often-visited landmarks, such as Captain Jacks Stronghold. **Abandoned Mineral Lands**—contains numerous abandoned mineral land sites: volcanic clasts and soil quarried from West Lyons and East Lyons road pits; cinders and pumice quarried from Sump Pump, Old Shoreline, Brass Cap, and Hospital Rock pits. [Dump] site 14 of Ziegenbein et al. (2006) occurs in **PEbmc**. **Rockfall and Roof Collapse**—the monument road traverses parts of **PEbmc**. Steep slopes prone to rockfall. Rockfall debris may accumulate on road and be a hazard to travelers. **PEbmc** contains caves. Cave roofs and entrances are prone to collapse. Infrastructure built over caves is susceptible to collapse into the opening below. **Volcano Hazards**—the most likely future eruption at Medicine Lake volcano would be a small effusive eruption of basaltic lava, which could occur anywhere on the volcano. Tephra emitted during a silicic eruption (near the summit) could affect Lava Beds National Monument.	**Medicine Lake Volcano History**—eruptive stage 4 (approximately 100,000–13,000 years ago). Argon-40/argon-39 ($^{40}Ar/^{39}Ar$) age: 36,000 ± 16,000 years.
	Andesite of Indian Butte (PEaib)	Andesite and basaltic andesite (56.1%–59.5% SiO_2; avg. of 11 = 57.6%). Covers significant area on upper northeastern flank of Medicine Lake volcano.	**Volcanic Features**—erupted from Indian Butte, the adjacent cinder cone to the west, and additional cones farther north-northwest.	**Volcano Hazards**—the most likely future eruption at Medicine Lake volcano would be a small effusive eruption of basaltic lava, which could occur anywhere on the volcano. Tephra emitted during a silicic eruption (near the summit) could affect Lava Beds National Monument.	**Medicine Lake Volcano History**—eruptive stage 4 (approximately 100,000–13,000 years ago). $^{40}Ar/^{39}Ar$ age: 22,000 ± 13,000 years.
	Basalt of Caldwell Ice Caves (PEbci)	Basalt (52.8% SiO_2). Not distinguished from **PEbmc** in hand specimen, but lacks the reddish surface patina. Chemically distinguished from **PEbmc** by lower magnesium oxide and higher titanium dioxide contents.	**Lava Tubes**—contains a lava-tube system. Tube and flow directions indicate buried vent(s) to southwest. Contains the mostly collapsed lava tube of Caldwell Ice Caves near the southeastern corner of Lava Beds National Monument. These are the oldest caves in the monument. **Geologic Features with Cultural Significance**—Modoc used water available in Caldwell Ice Caves.	**Cave Management**—contains Caldwell Ice Caves. **Rockfall and Roof Collapse**—the monument road traverses parts of **PEbci**. Steep slopes prone to rockfall. Rockfall debris may accumulate on road and be a hazard to travelers. **PEbci** contains caves. Cave roofs and entrances are prone to collapse. Infrastructure built over caves is susceptible to collapse into the opening below. **Volcano Hazards**—the most likely future eruption at Medicine Lake volcano would be a small effusive eruption of basaltic lava, which could occur anywhere on the volcano. Tephra emitted during a silicic eruption (near the summit) could affect the monument.	**Medicine Lake Volcano History**—eruptive stage 4 (approximately 100,000–13,000 years ago).
LATE? PLEISTOCENE	Basaltic andesite of Three Sisters (PEmts)	Basaltic andesite (54.4% SiO_2) in eastern part of Lava Beds National Monument.	**Volcanic Features**—apparently erupted from cluster of small cones at southern part of lava flow. **Tectonic Features**—vents are atypical in that they show no apparent alignment, although cones may lie on intersecting northeasterly and northwesterly alignments.	**Volcano Hazards**—the most likely future eruption at Medicine Lake volcano would be a small effusive eruption of basaltic lava, which could occur anywhere on the volcano. Tephra emitted during a silicic eruption (near the summit) could affect Lava Beds National Monument.	**Medicine Lake Volcano History**—eruptive stage 4 (approximately 100,000–13,000 years ago).

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Age	Map Unit (symbol)	Geologic Description	Geologic Features and Processes	Geologic Resource Management Issues	Geologic History
LATE PLEISTOCENE	Andesite of Schonchin Butte (PEasb)	Andesite (56.8%–57.4% SiO_2; avg. of 3 = 57.2%), typically dense and glassy. Among the highest SiO_2 contents of units in Lava Beds National Monument. Estimated area: 14 km² (5 mi²). Estimated volume: 0.2 km³ (0.05 mi³).	**Volcanic Features**—block lava flow (Schonchin Flow) with steep margin, rugged morphology, and little vegetative cover. Also includes tephra erupted from Schonchin Butte, which is a prominent landmark. **Geologic Features with Cultural Significance**—band of Modoc men, women, and children fled toward the Schonchin Flow when US Army troops cut them off from their water source at Tule Lake.	**Recreational Impacts to Geologic Features**—popular trail to fire lookout traverses Schonchin Butte. **Volcano Hazards**—the most likely future eruption at Medicine Lake volcano would be a small effusive eruption of basaltic lava, which could occur anywhere on the volcano. Tephra emitted during a silicic eruption (near the summit) could affect Lava Beds National Monument.	**Medicine Lake Volcano History**—eruptive stage 4 (approximately 100,000–13,000 years ago). $^{40}Ar/^{39}Ar$ age: 65,000 ± 23,000 years.
LATE PLEISTOCENE	Basalt of The Panhandle (PEbpa)	Basalt (49.6%–51.0% SiO_2; avg. of 3 = 50.4%). Similar to basalt of Mammoth Crater (**PEbmc**), which overlies it.	**Volcanic Features**—vent for lava flow is unknown, but presumably located south or southwest of outcrop area. **Tectonic Features**—cut by open ground crack (Big Crack) that also breaks unit **PEbmc**. **Lake Deposits**—shows evidence at its northeastern margin of having flowed into ancient Tule Lake; this and its petrographic and morphologic similarity to overlying unit **PEbmc**, which also flowed into ancient Tule Lake, make the two units (**PEbpa** and **PEbmc**) difficult to distinguish in the field.	**Volcano Hazards**—the most likely future eruption at Medicine Lake volcano would be a small effusive eruption of basaltic lava, which could occur anywhere on the volcano. Tephra emitted during a silicic eruption (near the summit) could affect Lava Beds National Monument.	**Medicine Lake Volcano History**—eruptive stage 4 (approximately 100,000–13,000 years ago).
LATE PLEISTOCENE	Basaltic andesite of Hippo Butte (PEmhi)	Basaltic andesite (54.4%–56.1% SiO_2; avg. of 7 = 55.4%). Commonly has speckled appearance.	**Volcanic Features**—lava flows erupted from Hippo Butte cinder cone and from smaller cone south of Mammoth Crater.	**Rockfall and Roof Collapse**—the monument road traverses parts of **PEmhi**. Steep slopes prone to rockfall. Rockfall debris may accumulate on road and be a hazard to travelers. **Volcano Hazards**—the most likely future eruption at Medicine Lake volcano would be a small effusive eruption of basaltic lava, which could occur anywhere on the volcano. Tephra emitted during a silicic eruption (near the summit) could affect Lava Beds National Monument.	**Medicine Lake Volcano History**—eruptive stage 3 (approximately 180,000–100,000 years ago).
LATE PLEISTOCENE	Basaltic andesite of Eagle Nest Butte (PEmen)	Basaltic andesite (52.4%–53.8% SiO_2; avg. of 10 = 53.2%).	**Volcanic Features**—lava flow erupted from Eagle Nest Butte and Bearpaw Butte cinder cones.	**Volcano Hazards**—the most likely future eruption at Medicine Lake volcano would be a small effusive eruption of basaltic lava, which could occur anywhere on the volcano. Tephra emitted during a silicic eruption (near the summit) could affect Lava Beds National Monument.	**Medicine Lake Volcano History**—eruptive stage 3 (approximately 180,000–100,000 years ago). $^{40}Ar/^{39}Ar$ age: 114,000 ± 10,000 years.
LATE OR MIDDLE PLEISTOCENE	Basaltic andesite spatter vent west-northwest of Bat Butte (PEm1)	Basaltic andesite (53.0% SiO_2). Mostly oxidized.	**Volcanic Features**—single isolated spatter cone (not associated with a flow), approximately 1 km (0.6 mi) west-northwest of Bat Butte.	**Volcano Hazards**—the most likely future eruption at Medicine Lake volcano would be a small effusive eruption of basaltic lava, which could occur anywhere on the volcano. Tephra emitted during a silicic eruption (near the summit) could affect Lava Beds National Monument.	**Medicine Lake Volcano History**—eruptive stage 3 (approximately 180,000–100,000 years ago). Cone is broken down and mostly oxidized, suggesting that it is relatively old; however, it is the most recent isolated cone to erupt in Lava Beds National Monument.
MIDDLE PLEISTOCENE	Andesite of Whitney Butte (PEawb)	Andesite (58.4% SiO_2, among the highest in Lava Beds National Monument). Estimated area: 9 km² (3 mi²), some of which is west and north of the monument.	**Volcanic Features**—lava erupted from Whitney Butte at northern edge of the Callahan Flow (**PEmcf**). Composed of aa. Lava moved north about 6 km (4 mi) from its vent at the Whitney Butte cinder cone. Whitney Butte has two summit craters aligned about N5°W. **Tectonic Features**—cut by north- and northeast-oriented normal faults whose offsets are more commonly down to the east than to the west. Faulting has revealed flow thicknesses of at least 10 m (30 ft), although flow margins are typically 2–3 m (7–10 ft) high.	**Volcano Hazards**—the most likely future eruption at Medicine Lake volcano would be a small effusive eruption of basaltic lava, which could occur anywhere on the volcano. Tephra emitted during a silicic eruption (near the summit) could affect Lava Beds National Monument.	**Medicine Lake Volcano History**—eruptive stage 3 (approximately 180,000–100,000 years ago).

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Age	Map Unit (symbol)	Geologic Description	Geologic Features and Processes	Geologic Resource Management Issues	Geologic History
MIDDLE PLEISTOCENE	Basalt northeast of Glass Mountain (PEbng)	Basalt (48.4%–50.8% SiO_2; avg. of 6 = 49.4%).	**Volcanic Features**—primary vent(s) buried by younger lava flows above 1,500 m (4,900 ft) elevation on northeastern flank of Medicine Lake volcano. Two additional satellite vents, which erupted the basalt, are aligned northeast near the southeastern corner of Lava Beds National Monument.	**Volcano Hazards**—the most likely future eruption at Medicine Lake volcano would be a small effusive eruption of basaltic lava, which could occur anywhere on the volcano. Tephra emitted during a silicic eruption (near the summit) could affect Lava Beds National Monument.	**Medicine Lake Volcano History**—eruptive stage 3 (approximately 180,000–100,000 years ago).
MIDDLE? PLEISTOCENE	Andesite cone west of Crescent Butte (PEa1)	Andesite (57.4% SiO_2), mostly red, oxidized cinders and bombs.	**Volcanic Features**—makes up the isolated cinder cone adjacent to Crescent Butte (**PEm2**) and just northeast of Hippo Butte. Age relationship to Crescent Butte (**PEm2**) is unknown.	**Abandoned Mineral Lands**—cone has been quarried for cinders and pumice and contains Burn Pit and West Crescent Butte Pit. **Rockfall and Roof Collapse**—the monument road traverses parts of **PEal**. Steep slopes prone to rockfall. Rockfall debris may accumulate on road and be a hazard to travelers. **Volcano Hazards**—the most likely future eruption at Medicine Lake volcano would be a small effusive eruption of basaltic lava, which could occur anywhere on the volcano. Tephra emitted during a silicic eruption (near the summit) could affect Lava Beds National Monument.	**Medicine Lake Volcano History**—eruptive stage 3 (approximately 180,000–100,000 years ago).
MIDDLE PLEISTOCENE	Andesite west of Fleener Chimneys (PEawf)	Andesite (60.8% SiO_2). Glassy.	**Volcanic Features**—lava flow with highly irregular, blocky surface. Flow margin is 10–20 m (30–70 ft) high. Vent is buried by younger flows to the south.	**Volcano Hazards**—the most likely future eruption at Medicine Lake volcano would be a small effusive eruption of basaltic lava, which could occur anywhere on the volcano. Tephra emitted during a silicic eruption (near the summit) could affect Lava Beds National Monument.	**Medicine Lake Volcano History**—eruptive stage 3 (approximately 180,000–100,000 years ago). Dacite tuff of Antelope Well (**PEdta**) ash-flow tuff is absent on top of **PEawf**, but is found immediately to the north, farther from the vent area, indicating that **PEawf** overlies (and is younger than) the 180,000-year-old marker bed.
	Basaltic andesite of Crescent Butte (PEm2)	Basaltic andesite (54.5% SiO_2). Oxidized.	**Volcanic Features**—makes up isolated Crescent Butte cinder cone. Age relationship to adjacent isolated andesite cinder cone (**PEa1**) is unknown. Located northwest of Lava Beds National Monument visitor center.	**Abandoned Mineral Lands**—cone has been quarried for cinder and pumice and contains Crescent Butte Pit. **Volcano Hazards**—the most likely future eruption at Medicine Lake volcano would be a small effusive eruption of basaltic lava, which could occur anywhere on the volcano. Tephra emitted during a silicic eruption (near the summit) could affect Lava Beds National Monument.	**Medicine Lake Volcano History**—eruptive stage 3 (approximately 180,000–100,000 years ago).
	Basalt north of Whitney Butte (PEbnw)	Basalt (50.7% SiO_2).	**Volcanic Features**—makes up eroded, northeast-oriented set of small spatter cones; no lava flow visible. Underlies, and is nearly surrounded by, andesite of Whitney Butte (**PEawb**).	**Volcano Hazards**—the most likely future eruption at Medicine Lake volcano would be a small effusive eruption of basaltic lava, which could occur anywhere on the volcano. Tephra emitted during a silicic eruption (near the summit) could affect Lava Beds National Monument.	**Medicine Lake Volcano History**—eruptive stage 3 (approximately 180,000–100,000 years ago).
	Basaltic andesite of Semi Crater (PEmsc)	Basaltic andesite (55.0%, 55.5% SiO_2). Present extent is about 3 km^2 (1 mi^2), but was probably at least twice that originally.	**Volcanic Features**—makes up aa lava flows that were erupted from the partially buried cinder and spatter cone of Semi Crater, which is surrounded on three sides by basalt of The Castles (**PEbc**) and invaded on the east by a tongue of the Schonchin Flow (andesite of Schonchin Butte, **PEasb**). **Geologic Features with Cultural Significance**—Thomas-Wright Battlefield.	**Volcano Hazards**—the most likely future eruption at Medicine Lake volcano would be a small effusive eruption of basaltic lava, which could occur anywhere on the volcano. Tephra emitted during a silicic eruption (near the summit) could affect Lava Beds National Monument.	**Medicine Lake Volcano History**—eruptive stage 3 (approximately 180,000–100,000 years ago). May be younger than dacite tuff of Antelope Well (**PEdta**), which does not overlie this unit.

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Age	Map Unit (symbol)	Geologic Description	Geologic Features and Processes	Geologic Resource Management Issues	Geologic History
MIDDLE PLEISTOCENE	Andesite northeast of Mount Hoffman (PEanh)	Andesite (57.7%, 58.0% SiO_2). Glassy. Extends at least 11 km (7 mi) from northeastern edge of rhyolite of Mount Hoffman (**Hrmh**; see GRI data on attached CD), which directly overlies this unit.	**Volcanic Features**—exposed in three separate areas. Vent is not exposed and presumably is buried to south or southwest. **Tectonic Features**—cut by two small northeast-oriented faults.	**Volcano Hazards**—the most likely future eruption at Medicine Lake volcano would be a small effusive eruption of basaltic lava, which could occur anywhere on the volcano. Tephra emitted during a silicic eruption (near the summit) could affect Lava Beds National Monument.	**Medicine Lake Volcano History**—eruptive stage 3 (approximately 180,000–100,000 years ago).
	Basalt of Canby Bay (PEbcb)	Basalt (50.0% SiO_2). Morphologically similar to the overlying basalt of Mammoth Crater (**PEbmc**). Presently covers about 4 km^2 (2 mi^2); original extent unknown.	**Volcanic Features**—vent location is unknown, but presumably buried to the south under younger lava flows.	**Abandoned Mineral Lands**—quarried for cinder and pumice; contains Sheepherder Tank Pits. **Volcano Hazards**—the most likely future eruption at Medicine Lake volcano would be a small effusive eruption of basaltic lava, which could occur anywhere on the volcano. Tephra emitted during a silicic eruption (near the summit) could affect Lava Beds National Monument.	**Medicine Lake Volcano History**—eruptive stage 3 (approximately 180,000–100,000 years ago).
	Basalt of Caldwell Butte (PEb4)	Basalt (51.6% SiO_2).	**Volcanic Features**—basalt erupted from Caldwell Butte cinder cone and Caldwell Minor (satellite vent on northern flank of Caldwell Butte), which are isolated cinder cones. Lava flows, if present, are entirely buried by younger lavas.	**Abandoned Mineral Lands**—cone has been quarried for pumice and contains Caldwell Pit. **Rockfall and Roof Collapse**—the monument road traverses parts of **PEb4**. Steep slopes prone to rockfall. Rockfall debris may accumulate on road and be a hazard to travelers. **Volcano Hazards**—the most likely future eruption at Medicine Lake volcano would be a small effusive eruption of basaltic lava, which could occur anywhere on the volcano. Tephra emitted during a silicic eruption (near the summit) could affect Lava Beds National Monument.	**Medicine Lake Volcano History**—eruptive stage 3 (approximately 180,000–100,000 years ago).
	Andesite near Devils Homestead (PEadh)	Andesite (56.5%–57.8% SiO_2; avg. of 3 = 57.3%). Maximum exposed thickness of three flows is 10 m (30 ft).	**Volcanic Features**—lava flows exposed at and near the base of Gillem Bluff in the northwestern part of Lava Beds National Monument. Additional small patches of **PEadh** occur farther north along Gillem fault. Three flows are exposed at and near Devils Homestead Overlook. Vent location is unknown, but presumably buried farther south. **Tectonic Features**—lava flowed against existing fault scarp and was subsequently uplifted. See also unit **PEbgf**.	**Volcano Hazards**—the most likely future eruption at Medicine Lake volcano would be a small effusive eruption of basaltic lava, which could occur anywhere on the volcano. Tephra emitted during a silicic eruption (near the summit) could affect Lava Beds National Monument.	**Medicine Lake Volcano History**—eruptive stage 3 (approximately 180,000–100,000 years ago). $^{40}Ar/^{39}Ar$ age of uppermost flow: 171,000 ± 4,000 years.
MIDDLE? PLEISTOCENE	Basalt cone southeast of Mammoth Crater (PEb5)	Basalt (52.1% SiO_2).	**Volcanic Features**—isolated cinder cone. Located just southeast of Mammoth Crater, south of the southwestern end of Hidden Valley.	**Volcano Hazards**—the most likely future eruption at Medicine Lake volcano would be a small effusive eruption of basaltic lava, which could occur anywhere on the volcano. Tephra emitted during a silicic eruption (near the summit) could affect Lava Beds National Monument.	**Medicine Lake Volcano History**—eruptive stage 3 (approximately 180,000–100,000 years ago).
MIDDLE PLEISTOCENE	Andesite of Island Butte (PEa3)	Andesite (57.5% SiO_2).	**Volcanic Features**—Island Butte is an isolated cinder cone located at the southwestern corner of Lava Beds National Monument. It is entirely surrounded by the Callahan Flow (**PEmcf**).	**Volcano Hazards**—the most likely future eruption at Medicine Lake volcano would be a small effusive eruption of basaltic lava, which could occur anywhere on the volcano. Tephra emitted during a silicic eruption (near the summit) could affect Lava Beds National Monument.	**Medicine Lake Volcano History**—eruptive stage 3 (approximately 180,000–100,000 years ago).

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Age	Map Unit (symbol)	Geologic Description	Geologic Features and Processes	Geologic Resource Management Issues	Geologic History
MIDDLE PLEISTOCENE	Basalt west of Canby Cross at Gillem fault (PEbgf)	Basalt (51.4% SiO_2).	**Volcanic Features**—exposed in small outcrops at base of Gillem Bluff. **Tectonic Features**—lava flowed against existing Gillem fault, then was partly covered by andesite near Devils Homestead (**PEadh**); subsequently, both units (**PEbgf** and **PEadh**) were moved more than 10 m (30 ft) upward along the fault.	**Volcano Hazards**—the most likely future eruption at Medicine Lake volcano would be a small effusive eruption of basaltic lava, which could occur anywhere on the volcano. Tephra emitted during a silicic eruption (near the summit) could affect Lava Beds National Monument.	**Medicine Lake Volcano History**—eruptive stage 3 (approximately 180,000–100,000 years ago). Younger than Pliocene units **PLobg** and **PLomw** of Gillem Bluff; underlies unit **PEadh**. Older than basalt of Mammoth Crater (**PEbmc)**, which flowed against upfaulted outcrops of **PEbgf**.
	Basaltic andesite north of Indian Butte (PEmni)	Basaltic andesite (54.8%, 55.0% SiO_2).	**Volcanic Features**—lava flow exposed in three separate outcrop areas. Also includes vent cone at southern end of the largest exposure.	**Volcano Hazards**—the most likely future eruption at Medicine Lake volcano would be a small effusive eruption of basaltic lava, which could occur anywhere on the volcano. Tephra emitted during a silicic eruption (near the summit) could affect Lava Beds National Monument.	**Medicine Lake Volcano History**—eruptive stage 2 (approximately 300,000–180,000 years ago). May be younger than Caldwell Butte (**PEa4**), but older than surrounding basalt of Caldwell Ice Caves (**PEbci**) and Indian Butte (**PEaib**).
	Basaltic andesite south and southwest of Caldwell Butte (PEmc)	Basaltic andesite (56.1% SiO_2).	**Volcanic Features**—lava flow and small cinder cone at southern boundary of Lava Beds National Monument.	**Volcano Hazards**—the most likely future eruption at Medicine Lake volcano would be a small effusive eruption of basaltic lava, which could occur anywhere on the volcano. Tephra emitted during a silicic eruption (near the summit) could affect Lava Beds National Monument.	**Medicine Lake Volcano History**—eruptive stage 2 (approximately 300,000–180,000 years ago).
	Andesite of Red Butte (PEa2)	Andesite (59.1% SiO_2). Cone consists of oxidized bombs and cinders.	**Volcanic Features**—Red Butte cinder cone is an isolated cone (not associated with a flow) southwest of Lava Beds National Monument visitor center.	**Rockfall and Roof Collapse**—the monument road traverses parts of **PEa2**. Steep slopes prone to rockfall. Rockfall debris may accumulate on road and be a hazard to travelers. **Volcano Hazards**—the most likely future eruption at Medicine Lake volcano would be a small effusive eruption of basaltic lava, which could occur anywhere on the volcano. Tephra emitted during a silicic eruption (near the summit) could affect Lava Beds National Monument.	**Medicine Lake Volcano History**—eruptive stage 2 (approximately 300,000–180,000 years ago). Appears morphologically old, with no crater remaining. Underlies (is older than) surrounding basalt of Mammoth Crater (**PEbmc**).
	Basalt of Hardin Butte (PEb1)	Basalt (52.1% SiO_2). Cone is oxidized and partially buried.	**Volcanic Features**—Hardin Butte is the oldest isolated cinder cone in Lava Beds National Monument and is surrounded by the (younger) basalt of The Castles (**PEbc**). Several vents of **PEbc** are located on lower western flank of Hardin Butte (**PEb1**).	**Abandoned Mineral Lands**—cone has been quarried for cinder and pumice and contains Hardin Butte Pit. **Volcano Hazards**—the most likely future eruption at Medicine Lake volcano would be a small effusive eruption of basaltic lava, which could occur anywhere on the volcano. Tephra emitted during a silicic eruption (near the summit) could affect Lava Beds National Monument.	**Medicine Lake Volcano History**—eruptive stage 2 (approximately 300,000–180,000 years ago).
	Basalt of Prisoners Rock (PEbp)	Basalt (48.0%–49.5% SiO_2; avg. of 5 = 48.6%).	**Volcanic Features**—lies beyond northeastern margin of contiguous lavas of Medicine Lake volcano. Represents the most northeastern extent of Medicine Lake volcanism. Erupted from north- and northeast-oriented subaerial and subaqueous vents (including Prisoners Rock, The Peninsula, and North Crater) and formed lava flows and spatter vents in addition to tuff cones and ring. **Lake Deposits**—tuff rings were significantly eroded on western, northern, and eastern sides by Tule Lake before it was drained for farmland beginning in the early 1900s. Well-exposed wave-cut benches can be seen along western and eastern sides. **Geologic Features with Cultural Significance**—makes up Petroglyph Point, on which more than 5,000 petroglyphs are preserved.	**Wind Erosion at Petroglyph Point**—windblown sand and dust, made available on access road, parking area, and wave-cut benches, may be "sandblasting" the petroglyphs. **Volcano Hazards**—the most likely future eruption at Medicine Lake volcano would be a small effusive eruption of basaltic lava, which could occur anywhere on the volcano. Tephra emitted during a silicic eruption (near the summit) could affect Lava Beds National Monument.	**Medicine Lake Volcano History**—eruptive stage 2 (approximately 300,000–180,000 years ago). Potassium-Ar age: 273,000 ± 18,000 years.

Geologic mapping by Donnelly-Nolan and Champion (1987), as modified by Donnelly-Nolan (2010), delineated these 43 map units in Lava Beds National Monument. A full list and description of units of Medicine Lake volcano is on the attached CD (see labe_geology.pdf). That document also includes a link to the Correlation of Map Units figure from Donnelly-Nolan (2010). Bold text indicates report sections.

Age	Map Unit (symbol)	Geologic Description	Geologic Features and Processes	Geologic Resource Management Issues	Geologic History
MIDDLE PLEISTOCENE	Basaltic andesite of Juniper Butte (PEmj)	Basaltic andesite (53.8% SiO_2). Individual juvenile clasts are mud coated.	**Volcanic Features**—eroded palagonite tuff ring in northeastern part of Lava Beds National Monument. **PEmj** is nearly surrounded by overlying basalt of Mammoth Crater (**PEbmc**); remaining perimeter is overlain by basalt of The Panhandle (**PEbpa**). **Lake Deposits**—tuff ring probably formed by eruption through ancient Tule Lake.	**Volcano Hazards**—the most likely future eruption at Medicine Lake volcano would be a small effusive eruption of basaltic lava, which could occur anywhere on the volcano. Tephra emitted during a silicic eruption (near the summit) could affect Lava Beds National Monument.	**Medicine Lake Volcano History**—eruptive stage 2 (approximately 300,000–180,000 years ago).
	Basalt of Hovey Point (PEbhp)	Basalt (50.9% SiO_2).	**Volcanic Features**—occurs at northern edge of Lava Beds National Monument. Underlies basalt of Canby Bay (**PEbcb**) and basalt of Mammoth Crater (**PEbmc**), both of which are adjacent to **PEbhp**. Represents oldest eruption of Medicine Lake volcano in the monument. **Lake Deposits**—appears to have been inundated at some time by ancient Tule Lake.	**Rockfall and Roof Collapse**—the monument road traverses parts of **PEbhp**. Steep slopes prone to rockfall. Rockfall debris may accumulate on road and be a hazard to travelers. **Volcano Hazards**—the most likely future eruption at Medicine Lake volcano would be a small effusive eruption of basaltic lava, which could occur anywhere on the volcano. Tephra emitted during a silicic eruption (near the summit) could affect Lava Beds National Monument.	**Medicine Lake Volcano History**—eruptive stage 1 (approximately 500,000–300,000 years ago). $^{40}Ar/^{39}Ar$ age: 445,000 ± 25,000 years.
EARLY PLEISTOCENE	Older basalt on west side of Gillem fault (PEobp)	Basalt (52.2% SiO_2). Has many conspicuous crystals.	**Volcanic Features**—occurs in three small patches. Overlies Pliocene basalt (**PLobg**) that caps much of Gillem Bluff. Vent location is unknown.	**Abandoned Mineral Lands**—geologic location of Gillem Bluff Pit is unknown, but may be in **PEobp**. **Rockfall and Roof Collapse**—the monument road passes along the base of Gillem Bluff, which is prone to rockfall. Rockfall debris may accumulate on road and be a hazard to travelers.	**Pre–Medicine Lake Volcano History**—predates Medicine Lake volcano.
PLIOCENE	Older tuff of Gillem Bluff (PLotg)	Dacitic ash-flow tuff, welded and typically reddish. SiO_2 content determined from six pumice lumps (66.9%–69.3% SiO_2; avg. of 6 = 68.0%; one whole-rock analysis, 66.9% SiO_2).	**Volcanic Features**—exposed in four closely spaced outcrop areas, each a few meters thick, at top of Gillem Bluff. **Tectonic Features**—exposed in face of Gillem Bluff; uplifted along Gillem fault.	**Abandoned Mineral Lands**—geologic location of Gillem Bluff Pit is unknown, but may be in **PLotg**. **Rockfall and Roof Collapse**—the monument road passes along the base of Gillem Bluff, which is prone to rockfall. Rockfall debris may accumulate on road and be a hazard to travelers.	**Pre–Medicine Lake Volcano History**—predates Medicine Lake volcano. $^{40}Ar/^{39}Ar$ age: 2.023 million ± 0.020 million years (Donnelly-Nolan and Lanphere 2005).
	Older basaltic andesite of Gillem Bluff (PLomg)	Basaltic andesite (56.9% SiO_2).	**Volcanic Features**—lava flow remnants on Gillem Bluff. **Tectonic Features**—exposed in face of Gillem Bluff; uplifted along Gillem fault.	**Abandoned Mineral Lands**—geologic location of Gillem Bluff Pit is unknown, but may be in **PLomg**. **Rockfall and Roof Collapse**—the monument road passes along the base of Gillem Bluff, which is prone to rockfall. Rockfall debris may accumulate on road and be a hazard to travelers.	**Pre–Medicine Lake Volcano History**—predates Medicine Lake volcano.
	Older basalt of Gillem Bluff (PLobg)	Basalt (47.7%, 47.9% SiO_2).	**Volcanic Features**—forms rimrock that caps upthrown fault block at Gillem Bluff. **Tectonic Features**—exposed in face of Gillem Bluff; uplifted along Gillem fault. **Lake Deposits**—includes pillow lavas exposed in Gillem Bluff.	**Abandoned Mineral Lands**—geologic location of Gillem Bluff Pit is unknown, but may be in **PLobg**. **Rockfall and Roof Collapse**—The monument road passes along the base of Gillem Bluff, which is prone to rockfall. Rockfall debris may accumulate on road and be a hazard to travelers.	**Pre–Medicine Lake Volcano History**—predates Medicine Lake volcano. **Lake History**—lava flowed into ancient Tule Lake.
	Older basaltic andesite in western Lava Beds National Monument (PLomw)	Basaltic andesite (53.7% SiO_2). Has speckled appearance.	**Volcanic Features**—represents the oldest ancient volcano to erupt in the vicinity of Lava Beds National Monument. **Tectonic Features**—exposed in face of Gillem Bluff; uplifted along Gillem fault.	**Abandoned Mineral Lands**—geologic location of Gillem Bluff Pit is unknown, but may be in **PLomw**. **Rockfall and Roof Collapse**—the monument road passes along the base of Gillem Bluff, which is prone to rockfall. Rockfall debris may accumulate on road and be a hazard to travelers.	**Pre–Medicine Lake Volcano History**—predates Medicine Lake volcano.