National Park Service
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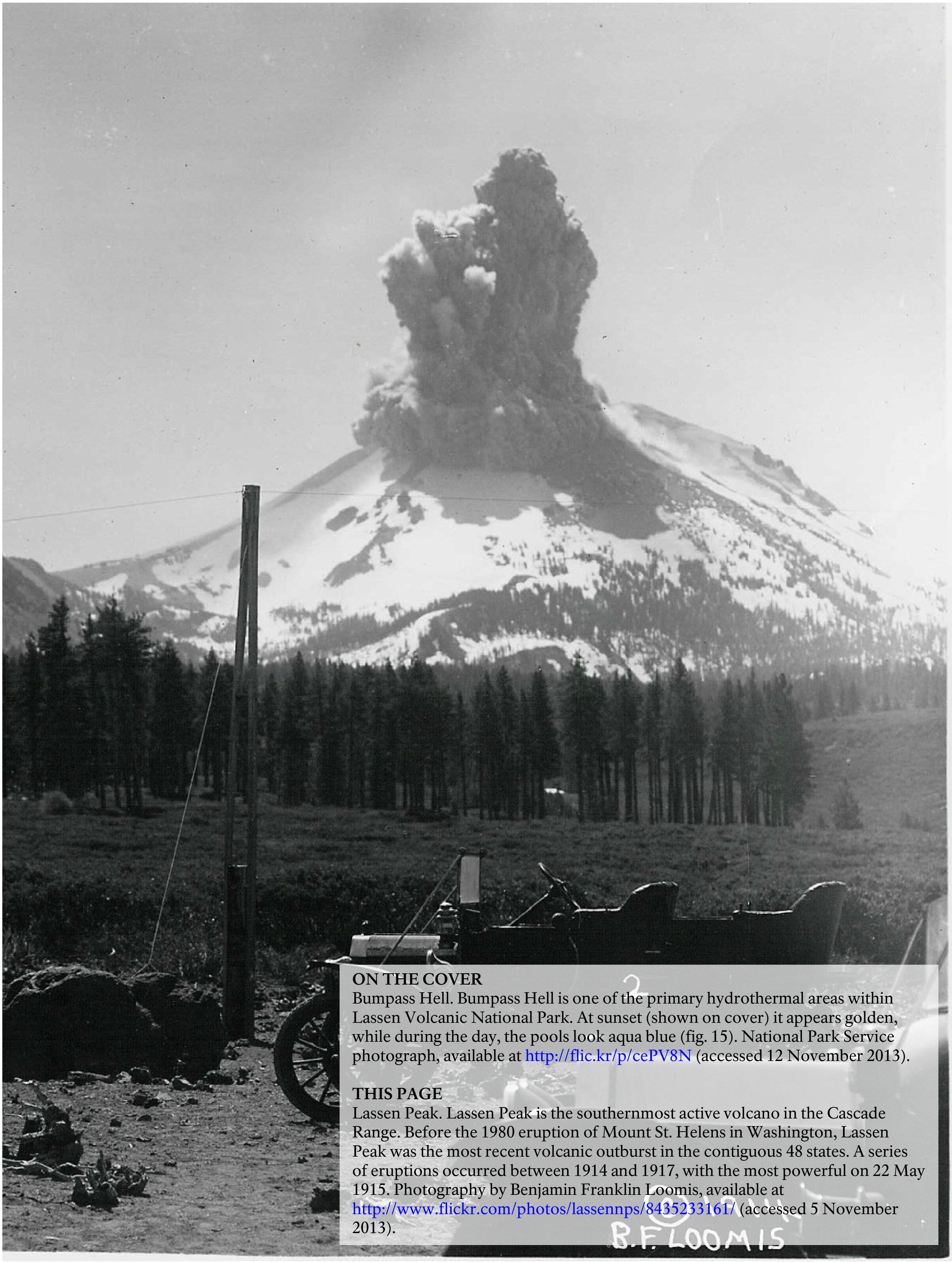
Natural Resource Stewardship and Science

Lassen Volcanic National Park

Geologic Resources Inventory Report

Natural Resource Report NPS/NRSS/GRD/NRR—2014/755



ON THE COVER
Bumpass Hell. Bumpass Hell is one of the primary hydrothermal areas within Lassen Volcanic National Park. At sunset (shown on cover) it appears golden, while during the day, the pools look aqua blue (fig. 15). National Park Service photograph, available at http://flic.kr/p/cePV8N (accessed 12 November 2013).

THIS PAGE
Lassen Peak. Lassen Peak is the southernmost active volcano in the Cascade Range. Before the 1980 eruption of Mount St. Helens in Washington, Lassen Peak was the most recent volcanic outburst in the contiguous 48 states. A series of eruptions occurred between 1914 and 1917, with the most powerful on 22 May 1915. Photography by Benjamin Franklin Loomis, available at http://www.flickr.com/photos/lassennps/8435233161/ (accessed 5 November 2013).

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National Park Service
Geologic Resources Division
PO Box 25287
Denver, CO 80225

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US Department of the Interior
National Park Service
Natural Resource Stewardship and Science
Fort Collins, Colorado

The National Park Service, Natural Resource Stewardship and Science office in Fort Collins, Colorado, publishes a range of reports that address natural resource topics 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.

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Contents

List of Figures

List of Tables

Executive Summary

The Geologic Resources Inventory (GRI) is one of 12 inventories funded by the National Park Service (NPS) Inventory and Monitoring Program. The NPS Geologic Resources Division held a GRI scoping meeting for Lassen Volcanic National Park in California on 1 March 2004 and a follow-up conference call on 8 April 2013 to discuss geologic resources, the status of geologic mapping, and resource management issues and needs. This report synthesizes those discussions and is a companion document to the previously completed GRI digital geologic map data.

This Geologic Resources Inventory (GRI) report was written for resource managers at Lassen Volcanic National Park to assist in science-informed decision making; it may also be useful for interpretation. It was prepared using available geologic information. The NPS Geologic Resources Division did not conduct any new fieldwork in association with report preparation. The various sections of the report discuss distinctive geologic features and processes within the park, highlight geologic issues facing park resource managers, describe the geologic history leading to the park's present-day landscape, and provide information about the GRI geologic map data. Clynne and Muffler (2010, geologic map) and Muffler et al. (2010, database) were the sources of these data. The GRI team converted the source map data to the GRI data model. The geologic map graphic (map 1, in pocket) illustrates these data, and the Map Unit Properties Table (in pocket) summarizes report content for each map unit.

Geologic features and processes of particular significance for resource management include:

- Volcanic Features. Few places in the world have such a diversity of volcanic landforms in such a relatively small area as Lassen Volcanic National Park. The park contains the four primary types of volcanoes (composite volcanoes, shield volcanoes, cinder cones, and lava domes), as well as lava flows, pyroclastic flows (density currents of volcanic gases, ash, and rock), and tephra (deposits of volcanic material ejected from a volcano). Before the eruption of Mount St. Helens in 1980, Lassen Peak was the only Cascade volcano to have erupted in the 20th century. The currently active volcanic center, the "Lassen volcanic center," of which Lassen Peak is a part, is within the park. This center is superimposed upon a volcanic platform created by regional volcanoes, which in addition to the volcanic center also occur in the park. Over its 825,000-year lifespan, the Lassen volcanic center has consisted of a collapsed caldera complex filled by the now much–eroded Brokeoff Volcano and the Lassen domefield. Three eruptions have occurred at the Lassen volcanic center in the last 1,050 years, the most recent in 1914–1917.
- Geothermal and Hydrothermal Systems. A deep, geothermal heat source—probably a body of hot or molten rock beneath Lassen Peak—drives the Lassen hydrothermal system, which underlies most of the southern half of the park. The heat source is about 8–10 km (5–6 mi) below the surface and is related to recent volcanism. A long-held model interprets the Lassen hydrothermal system as consisting of a central vapor-dominated reservoir (or reservoirs) underlain by a reservoir of hot water discharging at lower elevations. Using seismic and geothermal data, investigators recently refined this model by including two separate hydrothermal cells. One cell originates as precipitation on the southwestern flank of Lassen Peak and the remnant topography of Brokeoff Volcano and discharges at Growler and Morgan hot springs south of the park. A second cell originates on the southeastern flank of Lassen Peak and Reading Peak and discharges as steam at Drakesbad and Terminal Geyser.
- Hydrothermal Features. Lassen Volcanic National Park contains the most extensive, intact network of hydrothermal features in the Cascade Range. These features—including fumaroles (vents from which steam and volcanic gases issue), hot springs (thermal springs with water temperatures higher than that of the human body), and mud pots (hot springs containing boiling mud)—are the surface manifestation of ongoing volcanism. The main hydrothermal areas within the park are Sulphur Works, Little Hot Springs Valley, Bumpass Hell, Devils Kitchen, Boiling Springs Lake, and Terminal Geyser.
- Glacial Features. Although no glaciers exist in the park today, glaciers and volcanoes in tandem created the present landscape. During the Pleistocene ice ages, glaciers deepened major valleys, removed bedrock from large parts of the landscape, and created or enlarged hundreds of lake basins. Glacial and volcanic debris is commonly intercalated and reworked in mudflows, lahars, landslides, and moraines. Till (material directly deposited from glacial ice) often covers lava flows.
- Lakes. Lassen Volcanic National Park contains more than 200 lakes. Most of these are small, glacial lakes, but exceptions include lakes dammed by lava flows, lahars, and slope deposits, and those in tectonically down-dropped basins.
- Meadows. Lakes are ephemeral features and serve as "traps" for stream-delivered sediment, organic materials provided by plants and animals, and dust from atmospheric deposition. They ultimately fill in

becoming meadows. Meadows in the park that were once lakes include upper Kings Creek Meadow and the meadow adjacent to (west of) Horseshoe Lake. Dersch, Cameron, and Lower Kings Creek meadows also were probably once lakes.

- Streams and Waterfalls. Lassen Volcanic National Park is in the Sacramento River watershed. Numerous tributaries flow within the park boundaries, which in the rugged terrain are generally down-cutting and far from a steady state condition. Despite relief and ample streamflow, few sizable waterfalls occur within the park, but two notable examples are Mill Creek and Kings Creek falls. These waterfalls flow over resistant layers of Brokeoff Volcano rocks.

Geologic issues of particular significance for resource management were identified during the 2004 scoping meeting and a 2013 conference call include:

- Hydrothermal Hazards. Hydrothermal features such as hot springs and fumaroles are a major visitor attraction at the park; they are also one of the main hazards. High-temperature fumaroles and mud pots pose potential burn hazards to people who stray from trails and boardwalks, and thin surface crusts are susceptible to collapse under the weight of people walking on them. Hydrothermal features, which are high-temperature and highly acidic, result in the alteration of volcanic rocks and the alteration of anthropogenic features such as boardwalks and roads. A primary area of concern is Sulphur Works, where migrating fumarolic activity is impacting the park road (California Highway 89).
- Volcano Hazards. The most common volcanic activity in the Lassen area consists of small to moderate-sized, mafic (low silica, gas-poor) eruptions from regional volcanoes. Many of these volcanoes occur in the vicinity of the park, and some occur within the park. Future regional volcanism would produce effusive, nonexplosive outpourings of lava. These eruptions could build a new cinder or spatter cone, produce modest ash fallout downwind from a vent, and emit lava flows that spread a few kilometers from a vent. With respect to the Lassen volcanic center, the most likely type of eruption would be explosive, starting with intermittent steam explosions that eject rocks near the vent and emit ash clouds, followed by explosive silicic (higher silica, gas-rich) lava flows. Also, lahars (highly mobile, fast-moving debris flows composed mostly of volcanic materials) are a significant hazard in the drainages originating on Lassen Peak.
- Seismic Activity. The Lassen area experiences tectonic, volcanic, and hydrothermal earthquakes. Tectonic earthquakes occur because the Lassen volcanic center is located along the western edge of the Basin and Range physiographic province, which contains many closely spaced normal faults. Volcanic earthquakes are generally interpreted as reflecting movement of mafic magma into the deep crust below an active volcanic area. Hydrothermal earthquakes are a result of movement of hydrothermally altered rocks and brittle failure of rock in the Lassen hydrothermal system.
- Slope Movements. Steep-sided volcano edifices like those within the park are inherently unstable and susceptible to slope movements such as landslides, rockfall, debris avalanches, and debris flows. Covering an area of 7 km^2 (3 mi^2), Chaos Jumbles is a notable debris-avalanche deposit within the park. It formed when dome C of Chaos Crags partially collapsed. Also, landslides and rockfalls are significant hazards in the hydrothermally altered core of Brokeoff Volcano, in particular at Brokeoff Mountain and Pilot Pinnacle.
- Geothermal Development. Two instances of geothermal exploration have had the potential to impact the hydrothermal features at the park—a geothermal well on an inholding near Terminal Geyser, and proposed leasing for energy development on Forest Service lands adjacent to the park. As a result of the Geothermal Steam Act, the Bureau of Land Management established a buffer zone in Lassen National Forest south of the park, where no geothermal energy production is to take place.
- Abandoned Mineral Lands (AML). A servicewide AML database maintained by the NPS Geologic Resources Division lists eight surface mines within Lassen Volcanic National Park. In 1999, resource specialists from the Geologic Resources and Water Resources divisions made an assessment of disturbed lands (22 sites), including abandoned mineral lands, within the park. The connection between these sites and those listed in the AML database is unknown, but the AML inventory of National Park System units in California is underway and will provide an updated inventory of mineral lands within the park.
- Disturbed Lands Restoration. Disturbed lands within Lassen Volcanic National Park include roads, dams, stream channel modifications, and drained wetlands. Recent restoration efforts removed an earthen dam at Dream Lake, which was constructed in 1932 for recreational purposes at the Drakesbad Guest Ranch. This effort helped to restore Drakesbad Meadow to a wet meadow–fen complex in the Warner Valley. The wetland had been drained in the early 1900s to provide better pasture for domestic livestock.
- Manzanita Lake Dam. In 1911 the Northern California Power Company constructed a dam at Manzanita Lake to enlarge the natural feature and increase water supply to a downstream power plant. Ownership of the dam and reservoir was transferred to the federal government and incorporated into Lassen Volcanic National Park in 1931. The impoundment remains, and the lake is a scenic and popular visitor attraction. Dam failure would impact downstream infrastructure, in particular a segment of California Highway 44. Also, Forest Service Road 17 would likely be washed out. Whenever rainfall exceeds 5 cm (2 in) in a 24-hour period and after significant storms, the National Park Service inspects the dam and would initiate an established emergency response plan in the eventuality of dam failure. The National Park Service also conducts an annual inspection of the dam. In the event of an earthquake greater than magnitude (M) = 5.4, the National Park Service would also inspect the dam.

Acknowledgements

The GRI is administered by the Geologic Resources Division of the Natural Resource Stewardship and Science Directorate.

The NPS Geologic Resources Division relies on partnerships with institutions such as Colorado State University and other universities, the US Geological Survey, state geological surveys, and museums to develop products for the Geologic Resources Inventory.

The GRI team would like to thank the participants at the 2004 scoping meeting, who are listed in Appendix A, including Sid Covington (NPS Geologic Resources Division; geologist, now retired), who wrote the scoping summary. Also, thanks to Janet Coles, formerly with Lassen Volcanic National Park and currently chief of Resource Management at Guadalupe Mountain National Park, who reviewed and provided input for the "Disturbed Lands Restoration" section of this report. Julia Brunner (NPS Geologic Resources Division, policy and regulatory specialist) provided input for the "Geothermal Development" section. Also, this report benefited from the code-writing "magic" of Mike Cox (former Colorado State University, research associate). His know-how saved the author hours of time compiling the Map Unit Properties Table. And last, but certainly not least, thanks very much to Michael A. Clynne (US Geological Survey, research geologist) and L. J. Patrick Muffler (US Geological Survey, scientist emeritus) for answering questions, providing background information, clarifying specific points of interest, reviewing this report, and of course, mapping Lassen Volcanic National Park. Without them, this report would not have been properly completed.

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Introduction

This section briefly describes the National Park Service Geologic Resources Inventory Program and the regional geologic setting and history of Lassen Volcanic National Park.

Geologic Resources Inventory Program

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

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

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

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

Park Setting

Lassen Volcanic National Park contains 430 km^2 (170 mi^2) of volcanic landforms, glacially sculpted terrain, and spectacular thermal features (map 2, in pocket). Lassen Peak, and ultimately the park, took their name from Peter Lassen, one of the first white settlers in the northern Sacramento Valley and a discoverer of a route, the "Lassen Trail," through the mountains.

Interest in preserving the geologic and scenic wonders of the Lassen area as a national park and protecting them from commercial development arose in the early 1900s. Initially, two smaller national monuments—Cinder Cone and Lassen Peak—were designated by President Theodore Roosevelt in 1907. The eruptions of Lassen Peak, starting in 1914, inspired renewed efforts for the establishment of a national park, which had languished since the smaller monuments' designations in 1907. In 1916, Congress established Lassen Volcanic National Park by combining the previously designated national monuments.

Figure 1. Lassen Peak. The summit of Lassen Peak is 3,187 m (10,457 ft) above sea level. Volcanism started building the volcano edifice about 27,000 years ago. The most recent eruption occurred less than 100 years ago. The mountain is a lava dome composed of dacite (64%–65% silica; see table 1). National Park Service photograph by Amanda Sweeney.

Geologic Setting

Lassen Peak is the southernmost active volcano in the Cascade Range (figs. 1 and 2). Mount Meager in British Columbia, Canada, marks the northernmost summit of Cascade volcanism. Before the 1980 eruption of Mount St. Helens in Washington, Lassen Peak was the most recent volcanic outburst in the contiguous 48 states. During a series of eruptions starting in 1914, Lassen Peak erupted explosively on 22 May 1915. Pyroclastic flows, debris avalanches, debris flows, and associated flood waters devastated nearby areas, and volcanic ash fell across hundreds of miles to the east. Other historic eruptions in the Cascade Range include Mount St. Helens (mid-1800s; 1980–1986; 2004–2008) and Cinder Cone (1666), and possible historic eruptions at Mount Shasta (1786), Mount Baker (mid-1800s), Mount Hood (mid-1800s), and Mount Rainier (mid-1800s).

Lassen Peak and the other volcanoes of the Cascade Range are part of the Cascade volcanic arc, which extends from southern British Columbia to northern California (fig. 2). The volcanic arc is a result of oblique subduction of the Explorer, Juan de Fuca, and Gorda plates on the western edge of the continent. Commonly, the Explorer and Gorda plates, north and south, respectively, of the Juan de Fuca plate, are considered “subplates” of the larger plate (fig. 2). Landward from the plunging tectonic plates, magma has worked its way to the surface and built a series of conspicuous volcanic landscapes, ranging in age from Miocene to Holocene (fig. 3). Subduction, and resulting volcanoes and earthquakes, inspired the collective name “Ring of Fire” for the circle of volcanoes that surround the Pacific Ocean (fig. 4). Cascade arc volcanoes, including Lassen Peak, make up a segment of this ring.

The heat source (magma chamber) of active volcanism at the park yields remarkable hydrothermal features, including roaring fumaroles, mud pots, boiling pools, and thermal ground. These features are indicators of the ongoing potential for future volcanic eruptions in the Lassen volcanic center.

Although the park is noted primarily for its volcanic terrain and associated hydrothermal features, volcanism and glaciation have gone hand in hand in the creation of the park’s landscape. Large ice caps covered the mountainous terrain several times during ice ages of the recent geologic past (fig. 3). Glacial landforms such as moraines and outwash deposits “overprint” much of the volcanic foundation. The alteration of volcanic rocks by hydrothermal processes facilitated glacial erosion, and glacially eroded features such as cirques and arêtes occur throughout the park.

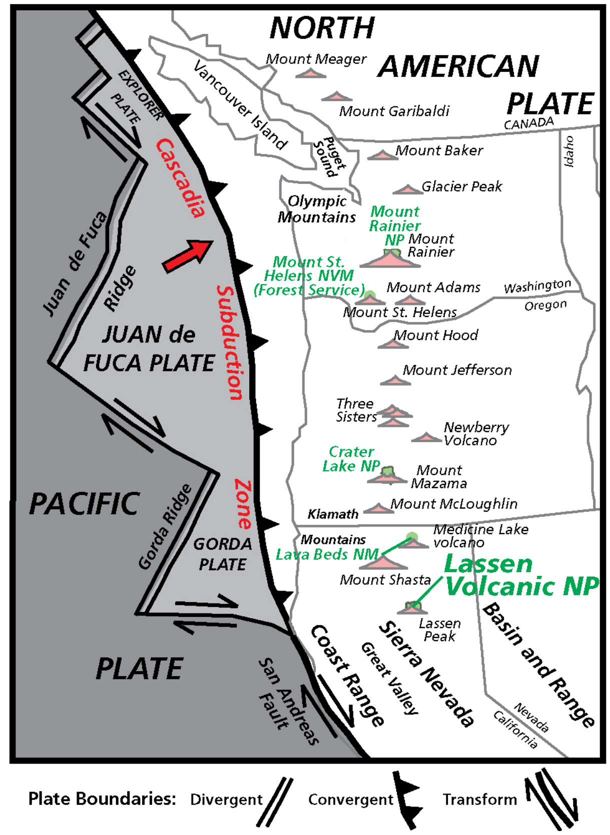

Figure 2. Cascade volcanic arc. Volcanism at Lassen Volcanic National Park is a result of the Gorda oceanic plate—commonly considered a “subplate” and the southernmost part of the Juan de Fuca plate—subducting under the North American continental plate. The Gorda plate is part of the Cascadia subduction zone, which created the Cascade volcanic arc. This arc of volcanoes runs from northern California to southern Canada and includes 16 major volcanoes, four of which are within the National Park System: Lassen Peak in Lassen Volcanic National Park, Medicine Lake volcano in Lava Beds National Monument, Mount Mazama in Crater Lake National Park, and Mount Rainier in Mount Rainier National Park. Mount St. Helens National Volcanic Monument is under the stewardship of the Forest Service. Transform plate boundaries are north and south of the convergent plate boundary of the Cascadia subduction zone. The well-known San Andreas Fault is a transform plate boundary south of the Cascadian subduction zone. The Queen Charlotte Fault is a transform plate boundary north of the Cascadia subduction zone. National Park Service graphic by Jason Kenworthy (NPS Geologic Resources Division) after Lillie (2005, figure 5.5).

Eon	Era	Period	Epoch	MYA	Age	Life Forms	North American Events
Phanerozoic	Cenozoic (CZ)	Quaternary (Q)	Holocene (H)	0.01	Age of Mammals	Extinction of large mammals and birds Modern humans	Ice ages; glacial outburst floods Cascade volcanoes (W)
			Pleistocene (PE)	2.6			
		Tertiary (T): Neogene (N)	Pliocene (PL)	5.3		Spread of grassy ecosystems	Linking of North and South America (Isthmus of Panama) Columbia River Basalt eruptions (NW) Basin and Range extension (W)
			Miocene (MI)	23.0			
		Tertiary (T): Paleogene (PG)	Oligocene (OL)	33.9			
			Eocene (E)	56.0			Laramide Orogeny ends (W)
			Paleocene (EP)	**66.0**		Early primates Mass extinction	
	Mesozoic (MZ)	Cretaceous (K)		145.0	Age of Reptiles	Placental mammals Early flowering plants	Laramide Orogeny (W) Western Interior Seaway (W) Sevier Orogeny (W)
		Jurassic (J)		201.3		Dinosaurs diverse and abundant	Nevadan Orogeny (W) Elko Orogeny (W)
		Triassic (TR)		**252.2**		Mass extinction First dinosaurs; first mammals Flying reptiles Mass extinction	Breakup of Pangaea begins Sonoma Orogeny (W)
	Paleozoic (PZ)	Permian (P)		298.9	Age of Amphibians		Supercontinent Pangaea intact
		Pennsylvanian (PN)		323.2		Coal-forming swamps Sharks abundant First reptiles	Ouachita Orogeny (S) Alleghany (Appalachian) Orogeny (E) Ancestral Rocky Mountains (W)
		Mississippian (M)		358.9			
		Devonian (D)		419.2	Fishes	Mass extinction First amphibians First forests (evergreens)	Antler Orogeny (W) Acadian Orogeny (E-NE)
		Silurian (S)		443.4		First land plants	
		Ordovician (O)		485.4	Marine Invertebrates	Mass extinction Primitive fish Trilobite maximum Rise of corals	Taconic Orogeny (E-NE)
		Cambrian (C)		**541.0**		Early shelled organisms	Extensive oceans cover most of proto-North America (Laurentia)
Proterozoic		Precambrian (PC, X, Y, Z)		2500		Complex multicelled organisms Simple multicelled organisms	Supercontinent rifted apart Formation of early supercontinent Grenville Orogeny (E) First iron deposits Abundant carbonate rocks
Archean				4000		Early bacteria and algae (stromatolites)	*Oldest known Earth rocks (~3.96 billion years ago)*
Hadean				4600		Origin of life Formation of the Earth	*Oldest moon rocks (4–4.6 billion years ago)* *Formation of Earth's crust*

Figure 3. Geologic time scale. The divisions of the geologic time scale are organized stratigraphically, with the oldest at the bottom and youngest at the top. GRI map abbreviations for each geologic time division are in parentheses. The most significant geologic events at Lassen Volcanic National Park took place during the Holocene (H) and Pleistocene (PE) epochs. A few Pliocene (PL) units occur within the park, primarily from the Maidu and Dittmar volcanic centers. Major North American life history and tectonic events are included. Compass directions in parentheses indicate the regional locations of events. Bold horizontal lines indicate major boundaries between eras; boundary ages are millions of years ago (MYA). Graphic design by Trista Thornberry-Ehrlich (Colorado State University) and Rebecca Port (NPS Geologic Resources Division), using dates published by the International Commission on Stratigraphy (http://www.stratigraphy.org/index.php/ics-chart-timescale; accessed 23 September 2013).

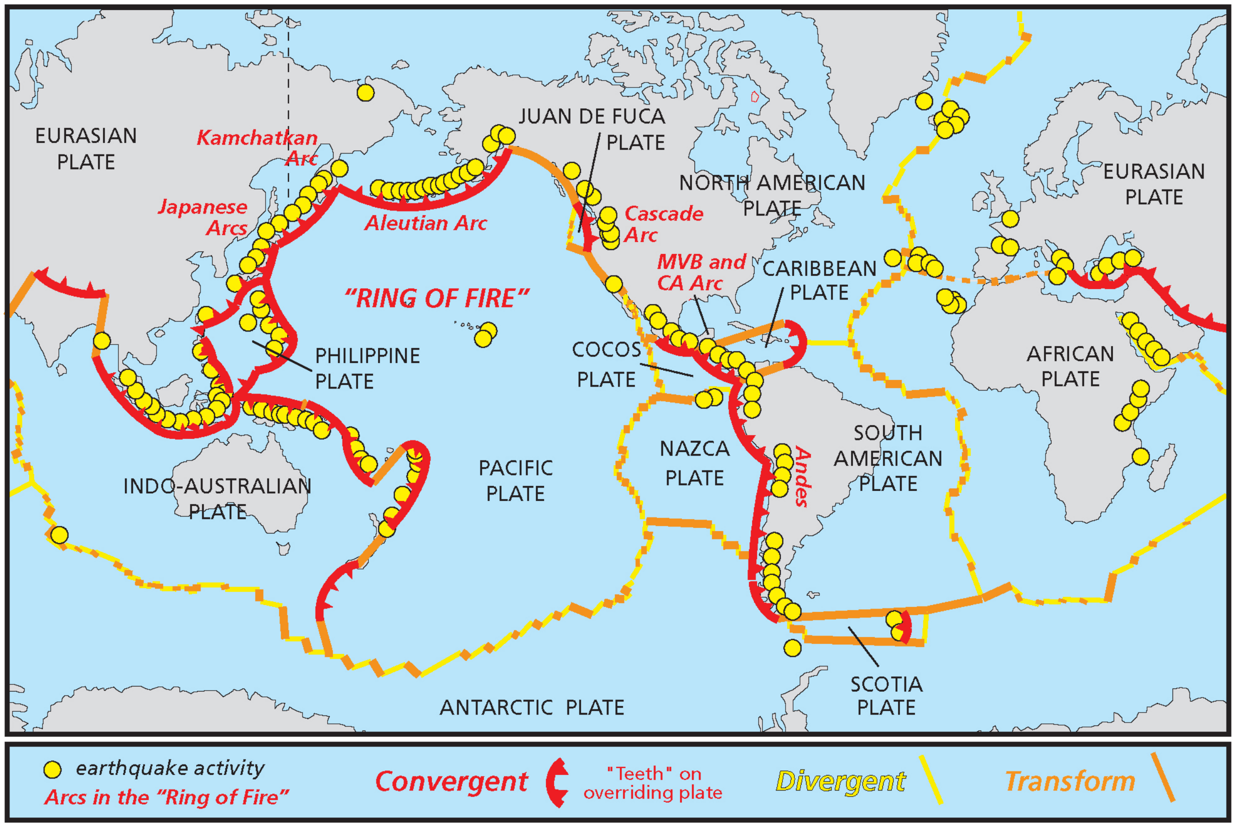

Figure 4. Active volcanoes, tectonic plates, and the "Ring of Fire." Cascade-arc volcanoes are part of the "Ring of Fire" around the Pacific Ocean. The ring is composed of active volcanoes over subducting plates, and delimited by intense earthquake activity (yellow circles). "MVB" refers to the Mexican Volcanic Belt. "CA Arc" refers to the Central American Arc. National Park Service graphic by Jason Kenworthy (NPS Geologic Resources Division), modifying a base map from Lillie (2005) with information from Simkin et al. (2006) and Michael A. Clynne and Patrick Muffler (US Geological Survey, written communications, 25 July 2013).

Geologic Features and Processes

Geologic resources underlie park ecosystems and geologic processes shape the landscape of every park. This section describes the most prominent and distinctive geologic features and processes in Lassen Volcanic National Park.

During the 2004 scoping meeting and 2013 conference call, participants (see Appendix A) identified the following distinctive geologic features and processes:

- Volcanic Features
- Geothermal and Hydrothermal Systems
- Hydrothermal Features
- Glacial Features
- Lakes
- Meadows
- Streams and Waterfalls

Volcanic Features

Few places in the world have such a diversity of volcanic features in such a relatively small area as Lassen Volcanic National Park. The park contains lava flows, pyroclastic flows, tephra deposits, and of course, volcanoes. All four primary types of volcanoes (cinder cones, shield volcanoes, lava domes, and composite volcanoes) occur in the park (map 2, in pocket; and fig. 5). These categories provide a system for classification and thus a means for understanding and communication. In reality, however, volcanoes occur in a continuum of sizes and shapes and have a variety of origins. For example, Raker Peak has characteristics of both shield (its shape) and composite (its history) volcanoes, and is more accurately described as a "lava cone" (Michael Clynne, US Geological Survey, research geologist, written communication, 21 November 2013). Its edifice consists of a cone of andesite (PEarp), which erupted about 270,000 years ago, and an underlying steep-sided lava dome composed of rhyolite (PErr), which extruded when the Rockland caldera complex was active 825,000–609,000 years ago (fig. 6).

Volcanic Rocks

Geologists use silica (silicon dioxide, SiO_2) content as a means for classifying volcanic rocks. The term "mafic" refers to rocks with lesser amounts of silica, such as basalt and basaltic andesite (table 1). "Mafic" is a term derived from ***ma**gnesium + **f**err**ic*** to describe an igneous rock having abundant dark-colored, magnesium- or iron (chemical symbol, Fe)–rich minerals. Mafic lavas tend to erupt effusively as lava flows. The term "silicic" refers to rocks with higher amounts of silica, for instance, dacite, rhyodacite, and rhyolite (table 1). Andesite has more silica than basalt and basaltic andesite (mafic rocks), but it is not necessarily considered silicic. Although there is no firm agreement among petrologists, a silicic rock is usually said to have at least 65% silica (Neuendorf et al. 2005).

The percentage of silica controls many properties of magma, including viscosity and explosiveness. In general, lavas with more silica are more viscous and explosive (table 1). There are exceptions, of course, for example, the silica content of the 18 May 1980 eruption of Mount St. Helens was the same as the dome-building events that followed in 2004–2008. The difference was the volatile component (water or carbon dioxide) in the magma. The volatile component, in this case water, had a sufficiently high vapor pressure to be concentrated in a gaseous phase. Rapid ascent of magma from depth meant that the volatile component could not separate from the magma. Thus, when it reached a certain overpressure near the surface, it "exploded" in a violent eruption. The same magma ascending slowly has time to "lose its gas" and erupt passively as a dome (Michael Clynne, US Geological Survey, research geologist, written communication, 19 July 2013).

Table 1. Volcanic rocks

Name	Percentage Silica (SiO_2)*	Viscosity	Explosiveness
Rhyolite	>72%	High	Very
Rhyodacite	68%–72%	↓	↑
Dacite	63%–68%	↓	↑
Andesite	57%–63%	↓	↑
Basaltic andesite	53%–57%	↓	↑
Basalt	<53%	Low	Less

From Clynne and Muffler (2010).

Examples of well-known volcanoes help to illustrate the influence of silica on volcanic activity: Hawaiian volcanoes produce basalt (low silica) that erupts effusively as lava flows (see GRI reports by Thornberry-Ehrlich 2009, 2011 for summaries). The lava flows of Medicine Lake volcano in Lava Beds National Monument provide a Cascade example of this type of eruption (see GRI report by KellerLynn 2014 for a summary). Stepping up in explosiveness, Lassen Peak erupted dacite (fig. 7). Mount Mazama, which climactically exploded and formed Crater Lake caldera in Oregon, erupted rhyodacite (see GRI report by KellerLynn 2013 for a summary). Finally, deposits of rhyolite represent the most explosive volcanoes on Earth. After a rhyolite eruption, volcano edifices often do not look like volcanoes because the eruptions are so explosive that the volcano ends up collapsing in on itself. The Yellowstone caldera in Yellowstone National Park erupted rhyolite. Large calderas such as Yellowstone represent "supervolcanoes"—a popular term for the largest volcanoes on Earth.

Figure 5. Types of volcanoes. Lassen Volcanic National Park is known for its diversity of volcanic features. Four primary types of volcanoes occur wihtin the park: composite volcano (upper left; Brokeoff Mountain, which is a remnant of Brokeoff Volcano), cinder cone (upper right; Cinder Cone; in the background is the Lassen Peak lava dome), shield volcano (lower left; Prospect Peak), and lava dome (lower right; the domes of Chaos Crags). See map 2 (in pocket) for the locations of these and other volcanoes in the park. US Geological Survey photographs by Michael A. Clynne (upper and lower left) and Patrick Muffler (upper and lower right

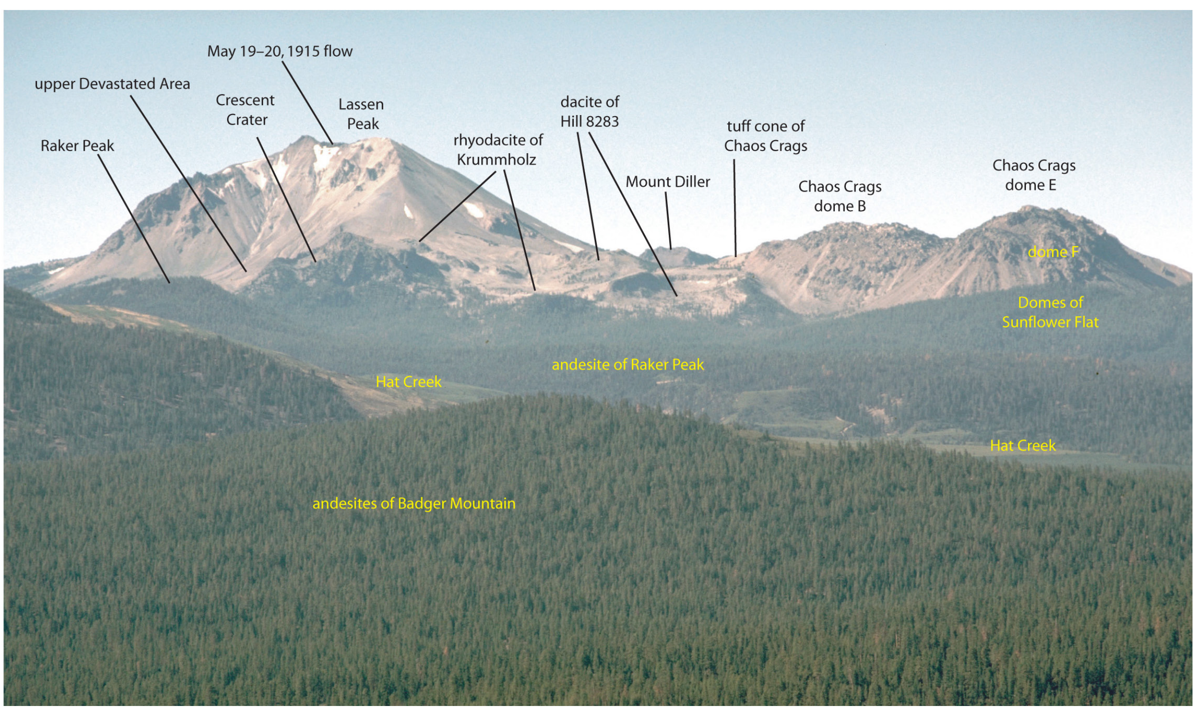

Figure 6. Lassen domefield. The four general types of volcanoes are composite, shield, cinder cone, and lava dome. Lassen Peak and Chaos Crags, which are part of the Lassen domefield, are lava domes. Mount Diller (in the middle background of the photograph) is a remnant of the Brokeoff Volcano—a composite volcano that dominated the Lassen landscape between 590,000 and 385,000 years ago. Raker Peak (below and left of Lassen Peak) is a "lava cone," having characteristics of both shield and composite volcanoes. US Geological Survey photograph by Patrick Muffler.

Figure 7. Volcanic rock at Lassen Peak. Lassen Peak is composed of 27,000-year-old dacite (map unit PEdl)—a silica-rich volcanic rock. The explosive eruption of the volcano in 1915 also erupted dacite (Hd4), which contains conspicuous phenocrysts (white specks, shown here) up to 12 mm (0.5 in) in diameter. National Park Service photograph.

With respect to viscosity (internal friction), low-silica basalts form fast-moving, fluid, lava flows that spread out in broad, thin sheets up to several kilometers wide. In contrast, flows of andesite and dacite tend to be thick and sluggish, traveling only short distances from a vent. Dacite and rhyodacite lavas often squeeze out of a vent to form irregular mounds or lava domes. In this way, the viscosity of magma determines the type of volcano edifice built by an eruption. The variety of magma types in the Lassen volcanic center led to the variety of volcano types in the park.

Regional Volcanoes

Geologists often separate the volcanoes of the Cascade arc into two broad categories—regional volcanoes and volcanic centers. Hundreds of closely spaced, small, short-lived, regional volcanoes (cinder cones and shield volcanoes; see descriptions below) make up much of the Cascade arc (Clynne and Muffler 2010). These volcanoes are mafic in composition (table 1). Moreover, these volcanoes are usually monogenetic; that is, they typically erupt only once for a brief period (weeks to a few years). Once a given mafic eruption has run its course, subsequent eruptions typically issue from new vents. Over tens to hundreds of thousands of years, these short-lived eruptions build broad platforms consisting of many extinct volcanoes (Clynne and Muffler 2010).

In the case of shield volcanoes, prolonged basaltic volcanism at a single site may produce a sizeable edifice, such as the broad, relatively flat Prospect Peak (fig. 5) and Sifford Mountain (fig. 26) in the park. Shield volcanoes are active for longer periods (centuries to a few millennia) than smaller cinder cones. Both types of volcanoes are "regional volcanoes."

In the vicinity of Lassen Volcanic National Park, regional volcanism occurs mainly along chains of vents aligned in a north or northwest direction, parallel to regional faults. For example, the regional volcanoes that make up the Caribou volcanic field on the eastern side of the park and in the Caribou Wilderness tend to erupt as groups in linear arrays or chains. Faults, which serve as pathways for ascending magma, control the locations of these volcanoes (Clynne and Muffler 2010). The best-documented of these chains is the Poison Lake Chain, just northeast of the park (Muffler et al. 2011).

Cinder Cones

Cinder cones are piles of vesicular ("bubbly") fragments of lava called cinders or scoria. Cinder cones form during a mildly explosive eruption of relatively fluid, gas-rich basalt-to-andesite magma that is thrown out of a vent and piled up around it. Lava may also erupt from fissures around the base of a cone. Cinder cones rarely exceed 300 m (1,000 ft) in height and typically have only a short period of activity.

Cinder cones dot the landscape in the park and are representative of regional volcanism. For example, Red Cinder Cone (PEmrc) is a notable landmark on the eastern side of the park. The cone, marked by two vents, is geographically and geologically part of the Caribou volcanic field.

Although cinder cones typify regional volcanism, many of the cinder cones at the park are part of the Lassen domefield within the Lassen volcanic center, including Hat Mountain (PEah), Fairfield Peak (PEmfp), and Crater Butte (PEac). The most prominent cinder cone in the park is Cinder Cone (Hmfci). Cinder Cone is a major attraction and textbook example of this type of volcano (figs. 5, 8, and 13). It stands 215 m (700 ft) above its base and has a maximum diameter of 0.8 km (0.5 mi). Its summit crater is 72 m (240 ft) deep and 305 m (1,000 ft) across.

Figure 8. Cinder Cone. Located in the northeastern corner of Lassen Volcanic National Park, Cinder Cone is a major attraction and a textbook example of this type of volcano. Note the oxidized ash in the Painted Dunes area in the mid-ground of the photograph. National Park Service photograph, available at http://www.flickr.com/photos/61860846@N05/8368095135/ (accessed 12 April 2013).

Shield Volcanoes

Shield volcanoes are shaped like an inverted shield and form where relatively mafic (basalt to andesite) lava erupts effusively and flows far from a vent. Multiple shield volcanoes will often overlap to form a lava plain. The shield volcanoes at the park occur near the boundaries (map 2, in pocket). Table Mountain (PEat) and Prospect Peak (PEap; fig. 5) are on the north. Sifford Mountain (PEbsm; fig. 26) and Mount Harkness (PEamh) are on the south. Compared to Hawaiian shield volcanoes (see GRI reports by Thornberry-Ehrlich 2009, 2011 for summaries), the shield volcanoes in the park are small and have a variety of compositions (basalt, basaltic andesite, and andesite).

Volcanic Centers

Volcanic centers—which are focused sites of long-lived, voluminous volcanic activity—are intercalated with regional volcanoes. Five volcanic centers occur in the vicinity of the park: Latour, Yana, Dittmar, Maidu, and Lassen. The park contains rocks from two of these centers—Dittmar and Lassen. On the geologic map graphic (map 1, in pocket), these rocks are shown as unit PEPL-D (for the Pliocene [PL] and Pleistocene [PE] rocks of the Dittmar [D] volcanic center) and seven units for the sequences of the Lassen volcanic center (see "Geologic History" section).

Each volcanic center had a distinctive history from the others, but all generally consisted of an initial phase of silicic volcanism followed by construction of a large, andesitic composite volcano flanked by a variety of younger more silicic rocks such as dacite. Late in the history of a volcanic center, an acidic hydrothermal system, driven by heat from silicic magma bodies, altered permeable rocks of the composite volcano to clay minerals and silica, thus facilitating later fluvial and glacial erosion. The outcome is selective preservation of a central rim of thick cone-building lava flows, composed of basaltic andesite to andesite, around a central depression flanked by andesitic to silicic rocks (Clynne 1990).

The Lassen volcanic center, which is within the park, is the current active volcanic center in the Lassen area. The center consists of widely distributed vents that extend more than 20 km (12 mi) north–south and 25 km (15 mi) east–west, mingling with nearby regional volcanoes. The Lassen volcanic center consists of the following features: (1) the Rockland caldera complex, (2) a composite volcano (Brokeoff Volcano); and (3) the Lassen domefield, which is composed of small, closely spaced, silicic lava domes and flows. These three components of the Lassen volcanic center formed sequentially—caldera, composite volcano, then the domefield—from a single evolving magmatic system (Clynne and Muffler 2010). The most recent volcanic eruptions took place in the domefield (fig. 6).

Lava Domes

Lava domes (also called "plug domes") form when gas-poor, dacite-to-rhyolite magma piles up over a vent because it is too viscous to flow away. More than any other type of volcano, lava domes characterize the Lassen landscape (Kane 1980). Lava domes have steep sides and come in a range of sizes. Lassen Peak is the world's largest lava dome and reaches 3,187 m (10,457 ft) in elevation (US Geological Survey 2003). Lassen Peak began as a volcanic vent on Brokeoff Volcano's northern flank and now rises 610 m (2,000 ft) from its base. Other lava domes in the park cluster around Lassen Peak and include the six domes at Chaos Crags (domes A–F, Hrca–Hrcf; figs. 5 and 6), Crescent Crater (PEdc), Reading Peak (PEdr), Bumpass Mountain (PEdb), Eagle Peak (PEre), Vulcans Castle (PEdv), Loomis Peak (PErlm), and the rhyodacite domes at Sunflower Flat (PErsf).

Composite Volcanoes

When most people think of a volcano, they probably envision a composite volcano, also referred to as a "stratovolcano." The iconic summits of Mount Fuji in Japan and Mounts Shasta (see fig. 10) and Rainier in the Cascade Range are composite volcanoes. Unlike the other three general types of volcanoes (cinder cones, shield volcanoes, and lava domes), a representative of this type is not easily recognizable at the park (fig. 5). Once upon a time, however, an impressive composite volcano—Brokeoff Volcano—existed (fig. 9). This volcano was eroded, primarily by glaciers, so that only remnants remain. The surviving portions of the central rim include Brokeoff Mountain (fig. 5), Mount Diller (fig. 6), Mount Conrad, and Pilot Pinnacle. During its heyday Brokeoff Volcano occupied the entire southwestern part of what is now Lassen Volcanic National Park and would have dominated the skyline. The volcano was an estimated 20 km (12 mi) in diameter and rose about 1,800 m (6,000 ft) above the landscape to an elevation of 3,300 m (11,000 ft) (Kane 1980).

In contrast to regional volcanoes, composite volcanoes are large, long-lived features that erupt episodically for tens to hundreds of thousands of years from the same or closely spaced vents. Moreover, they are thousands of meters high and display a wide range of eruptive and explosive styles—andesite, dacite, rhyodacite, and rhyolite. Brokeoff Volcano erupted primarily andesite.

Lava Flows

In the same way that volcanoes in the Lassen area are divided into "regional" and "volcanic centers," so are lava flows. Mafic lava is vented from regional volcanoes, such as those in the eastern part of the park and Caribou Wilderness. Andesitic to silicic lava flows erupted within the Lassen volcanic center.

Mafic Lava Flows

The most common volcanic feature on the Lassen landscape is mafic (low silica, low viscosity) lava flows associated with cinder cones (Clynne and Muffler 2010). Mafic lava flows are generally small—typically limited to a few kilometers in length—and cover an area of a few square kilometers. In the last 100,000 years, 54 eruptions built cinder cones and/or emitted mafic lava flows in the Lassen area (Clynne and Muffler 2010; Clynne et al. 2012). Of these, the basalt and basaltic andesite flows of the regional volcanoes of the Caribou volcanic field, in particular the Red Cinder chain (see Map Unit Properties Table), are notable for the park.

The largest mafic lava flows in the Lassen area are fluid basalt flows associated with Basin and Range volcanism and designated as "tholeiitic basalts" (Clynne and Muffler 2010; Clynne et al. 2012). None of this type of mafic flow occurs at the surface of the park, but two

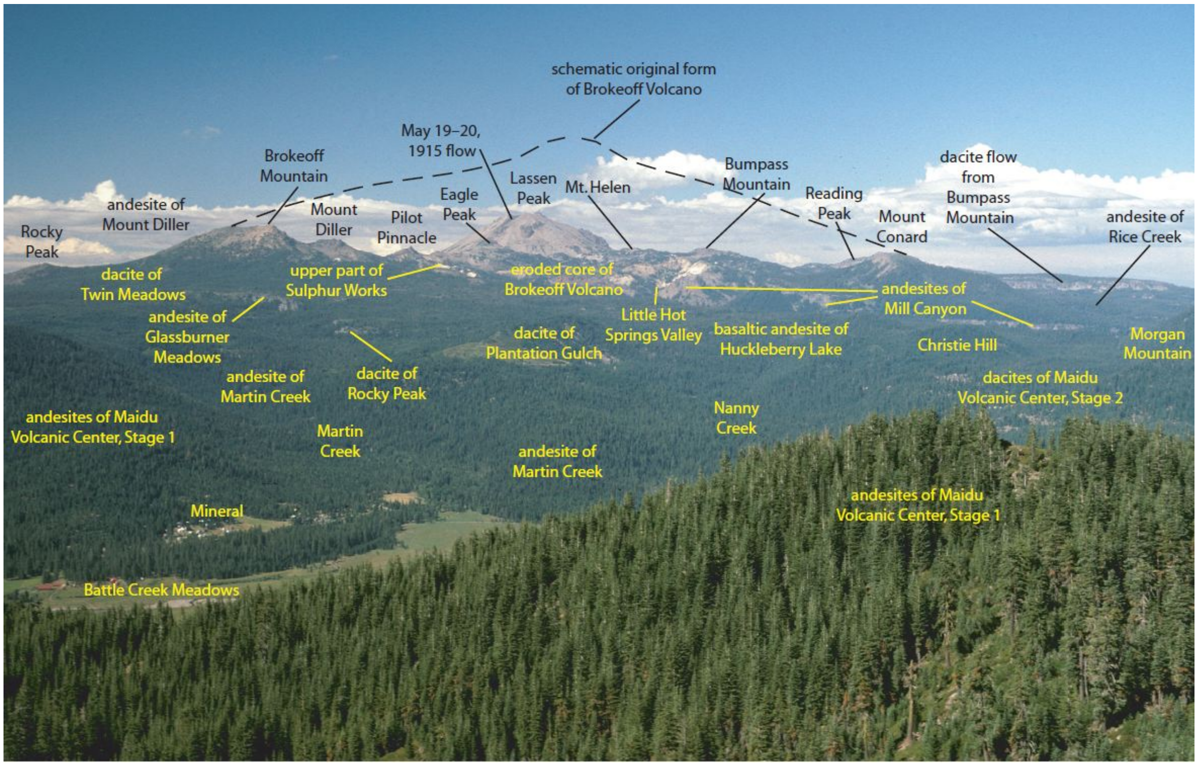

Figure 9. Brokeoff Volcano. Before hydrothermal alteration weakened and glacial advances eroded its edifice, Brokeoff Volcano was a large composite volcano, rising 3,400 m (11,000 ft) above sea level. The hypothesized height would have exceeded that of present-day Lassen Peak. US Geological Survey photograph by Michael A. Clynne.

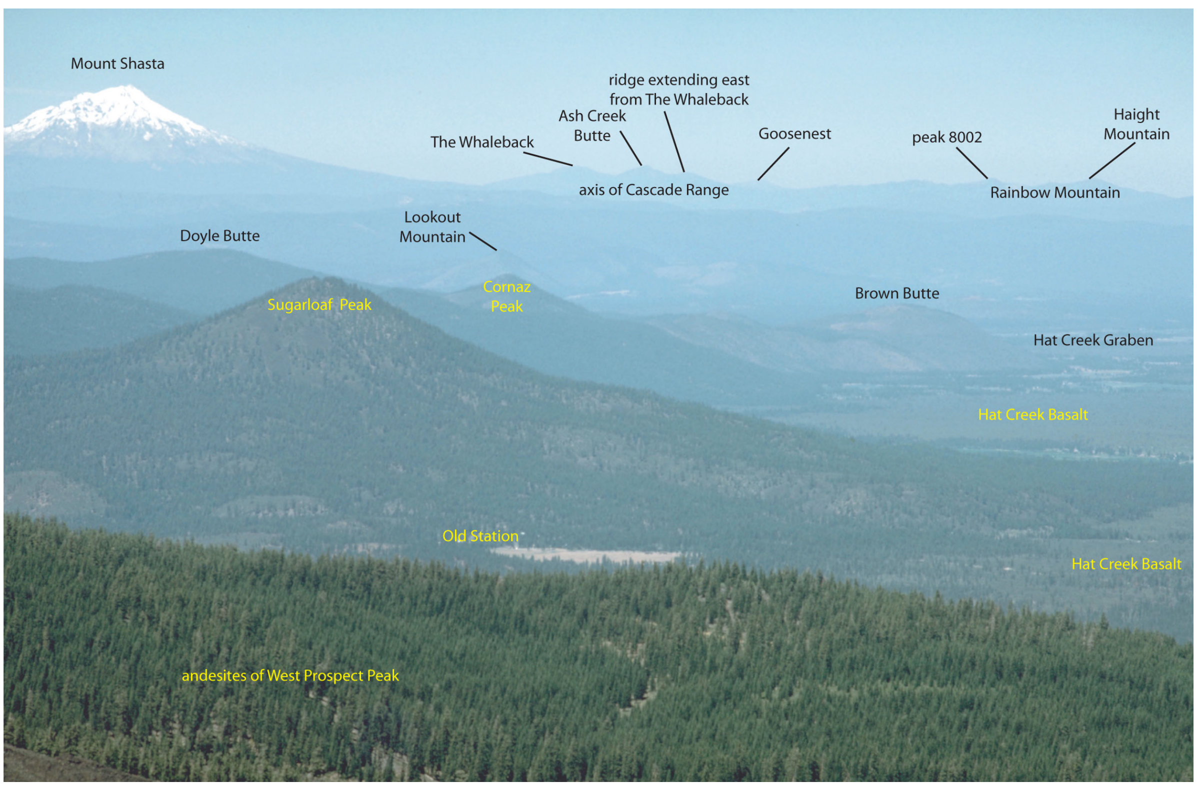

Figure 10. Hat Creek Basalt. This 330° view from Prospect Peak in the park shows a segment of the axis of the Cascade Range and includes many Cascade-arc volcanoes. Mount Shasta, in the background, is a young composite volcano north of the park and west of the Cascade-arc axis. The largest mafic lava flows in the Lassen area are fluid basalt flows associated with Basin and Range volcanism and designated as "tholeiitic basalts." The tholeiitic Hat Creek Basalt (map unit PEbhc) floors the Hat Creek graben. It is the nearest and youngest flow of this type to Lassen Volcanic National Park. US Geological Survey photograph by Patrick Muffler.

probably occur in the subsurface—tholeiitic basalts of Nobles Trail (PEbn) and Warner Valley (PEbwv); these are now buried by younger rocks (Patrick Muffler, US Geological Survey, scientist emeritus, written communication, 17 July 2013). Units of tholeiitic basalt are included in the GRI data set (see "Geologic Map Data" section and accompanying digital geologic data). The nearest and youngest of this type of flow to the park is the 24,000-year-old Hat Creek Basalt (PEbhc; Turren et al. 2007) to the north (fig. 10). This flow erupted from a fissure vent just south of Old Station. In the Lassen area, this type of flow most commonly erupted slightly east of the main Cascade-arc axis. These fluid flows erupted from fissures with little associated ash, and the lava was generally distributed via lava tubes.

Andesitic to Silicic Lava Flows

Andesitic to silicic lava flows and domes are common eruptive features within the park. Silicic flows surround Lassen Peak and Chaos Crags in the western part of the park, and thick, andesitic lava flows form the eastern part of the Lassen domefield. Typically, these flows are much thicker and tend to have larger volumes than mafic lava flows.

Four andesite lava-flow complexes have been emplaced on the Lassen domefield in the past 100,000 years: the andesites of Crater Butte (PEac), Eagle Peak (PEae), Hat Mountain (PEah), and hill 7416 (PEa74) (Clynne and Muffler 2010). The largest of these, Hat Mountain (PEah), covers nearly 100 km^2 (40 mi^2) and has a volume of about 5 km^3 (1 mi^3). The others are smaller, but still substantial and cover a combined area of approximately 40 km^2 (15 mi^2).

Pyroclastic Flows

Pyroclastic flows are masses of hot, dry, rock fragments mixed with hot gases. Pyroclastic flows travel rapidly (tens of meters per second) away from a volcanic vent or collapsing flow front, and typically exceed 800°C (1,500°F) in temperature. They are extremely hazardous because of their high speeds and high temperatures (see "Volcano Hazards" section).

A particularly significant pyroclastic flow for Lassen's recent volcanic past was the "glowing avalanche" that flowed down Lassen Peak on 22 May 1915. This pyroclastic flow came from a single vent that had been plugged. The bottleneck created by the plug caused a tremendous buildup of gas pressure in the rising magma. Eventually, and violently, the magma found an exit and blasted vertically while simultaneously spilling down the volcano's slope. This particular pyroclastic flow (Hpw2) created "one of the park's most awesome sites" (Kane 1980, p. 34)—the scarred landscape referred to as the "Devastated Area" (fig. 11).

Tephra

Tephra is the general term for all pyroclastic material ejected out of a volcano. The size of erupted debris ranges from fine dust to blocks a meter or more in diameter (Crandell and Mullineaux 1970). The force of a pyroclastic eruption may hurl tephra many thousands—or even tens of thousands—of meters into the air.

Pumice

Pumice is a common tephra type in the park. Pumice is violently erupted magma full of stretched voids that contained magmatic gas, making it more easily carried long distances by wind. Deposits of pumice accumulate as fragments that settle more or less vertically out of the air. Pumice tends to form a continuous mantle over the affected topography, rather than being confined to valleys like lava flows. Pumice commonly has the composition of rhyolite (table 1). At the park, the rhyodacites of Chaos Crags (Hpc), Kings Creek (PEpk), Sunflower Flat (PEpsf), and Eagle Peak (PEpe) contain pumice.

Painted Dunes Ash

The Painted Dunes area in the park has a distinctive tephra deposit, informally called the "Painted Dunes ash" (fig. 12). This material, which is as much as 2 m (8 ft) thick, was deposited during the eruption of Cinder Cone in 1666 (Sheppard et al. 2009) (fig. 13). Heiken (1978) measured and described the tephra, and divided it into three numbered units. Units 1 and 2 erupted from an older, remnant cinder cone (Hmpci), and are

Figure 11. Devastated Area. During the most recent volcanic eruption of Lassen Peak, magmatic activity was confined to the period from about 14 to 22 May 1915 and affected primarily the northeastern flank and slope of the mountain, which is now referred to as the "Devastated Area," as well as the valleys of Lost and Hat creeks as far as about 50 km (30 mi) downstream. US Geological Survey photograph by Michael A. Clynne.

Figure 12. Painted Dunes. The Painted Dunes area in the park is covered by an ash deposit of the Cinder Cone eruption sequence. The ash—informally known as "Painted Dunes ash"—became brightly oxidized when it landed on still-hot lava flows. National Park Service photograph by I-Ting Chiang, winner of the Lassen Volcanic National Park 2012 photo contest.

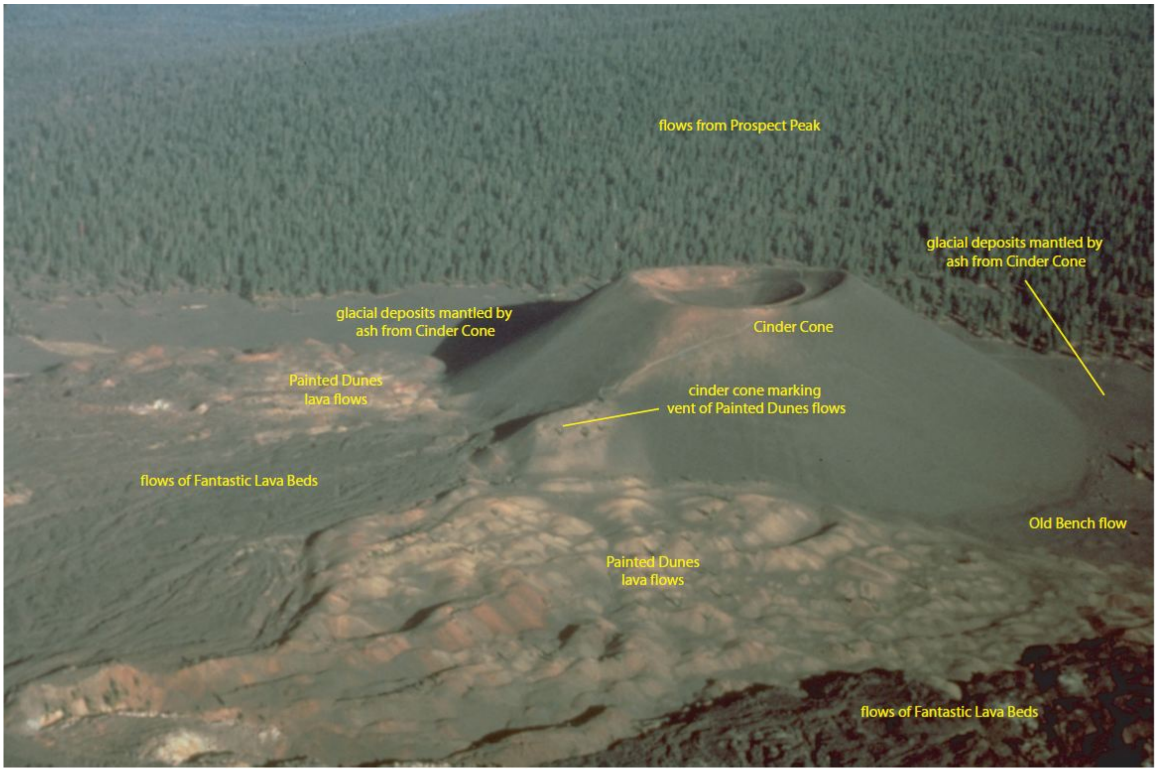

Figure 13. Cinder Cone, lava flows, and ash. Painted Dunes ash covers the Old Bench flow and Painted Dunes flows at Cinder Cone. Red and tan "bumpy" patches in the foreground and middle ground of the photograph indicate ash-covered lava flows. The gray area between these flows and the dark area at the lower right corner of the photograph are the ash-free Fantastic Lava Beds flows. Cinder Cone is 215 m (705 ft) high from base to summit. National Park Service photograph with annotations from Clynne et al. (2012).

lithologically similar to the Painted Dunes flows (Hmp1 and Hmp2). However, most Painted Dunes lava erupted as the tephra fall was waning (Clynne and Bleick 2011). Unit 3 erupted from Cinder Cone (Hmfci), and is lithologically similar to the Fantastic Lava Beds flows (Hmf1 and Hmf2). Minimal amounts of ash were erupted during or after the time that the Fantastic Lava Beds flows were emplaced, and these flows' surfaces are nearly ash free. Ash covers the Old Bench flow (Hmo)—with only a few lava pinnacles of the Old Bench flow poking through the ash—and the Painted Dunes flows (Hmp1 and Hmp2).

A distinctive feature of the Painted Dunes ash deposit is its color (fig. 12). The brightly oxidized ash demonstrates that the Old Bench and Painted Dunes lava flows were still hot when ash fell on them. Additionally, the ash deposit is cemented in places by opal (Finch and Anderson 1930), which adds further color to the Painted Dunes area.

Geothermal and Hydrothermal Systems

Following Neuendorf et al. (2005), this report uses the term "geothermal" to describe Earth as a heat source (e.g., geothermal gradient) or Earth's heat when it is harnessed for use (e.g., geothermal exploration, development, reservoir, and resources; see "Geothermal Development" section). By contrast, the term "hydrothermal" pertains to hot water and its actions and products (e.g., hydrothermal water, alteration, deposit, feature, and eruption). Additionally, a hydrothermal system is a groundwater system that has a source (or area) of recharge, a source (or area) of discharge, and a heat source. This usage conforms to that provided in Heasler et al. (2009) in *Geological Monitoring* (see "Geologic Issues" section). The terms "geothermal" and "hydrothermal" may be used differently in other publications, however.

The Lassen hydrothermal system underlies most of the southern half of the park. White et al. (1971) originally suggested a model for vapor-dominated systems, such as the Lassen hydrothermal system. At Lassen, a deep, geothermal heat source, 8–10 km (5–6 mi) below the surface, drives the system. The source of heat is probably a body of hot or molten rock beneath Lassen Peak (Clynne et al. 2003). Water from rain and snow that falls on Lassen Peak and other high-elevation areas in the park peculates down to this geothermal source where it is heated and as a result rises to 1–2 km (0.6–1.2 mi) below the surface, forming a reservoir of near neutral pH, chloride-bearing, hot water at a temperature of approximately 240°C (460°F). This part of the system is referred to as the "liquid-dominated zone" (fig. 14). Above the liquid-dominated zone, lower pressure allows rising hot water to boil in what is referred to as the "vapor-dominated zone." As steam rises through the vapor-dominated zone to feed higher elevation thermal features in the park, gas–depleted hot water flows laterally along permeable pathways from the liquid-dominated zone. This water reaches the surface at lower elevations—about 1,500 m (5,000 ft) above sea level—

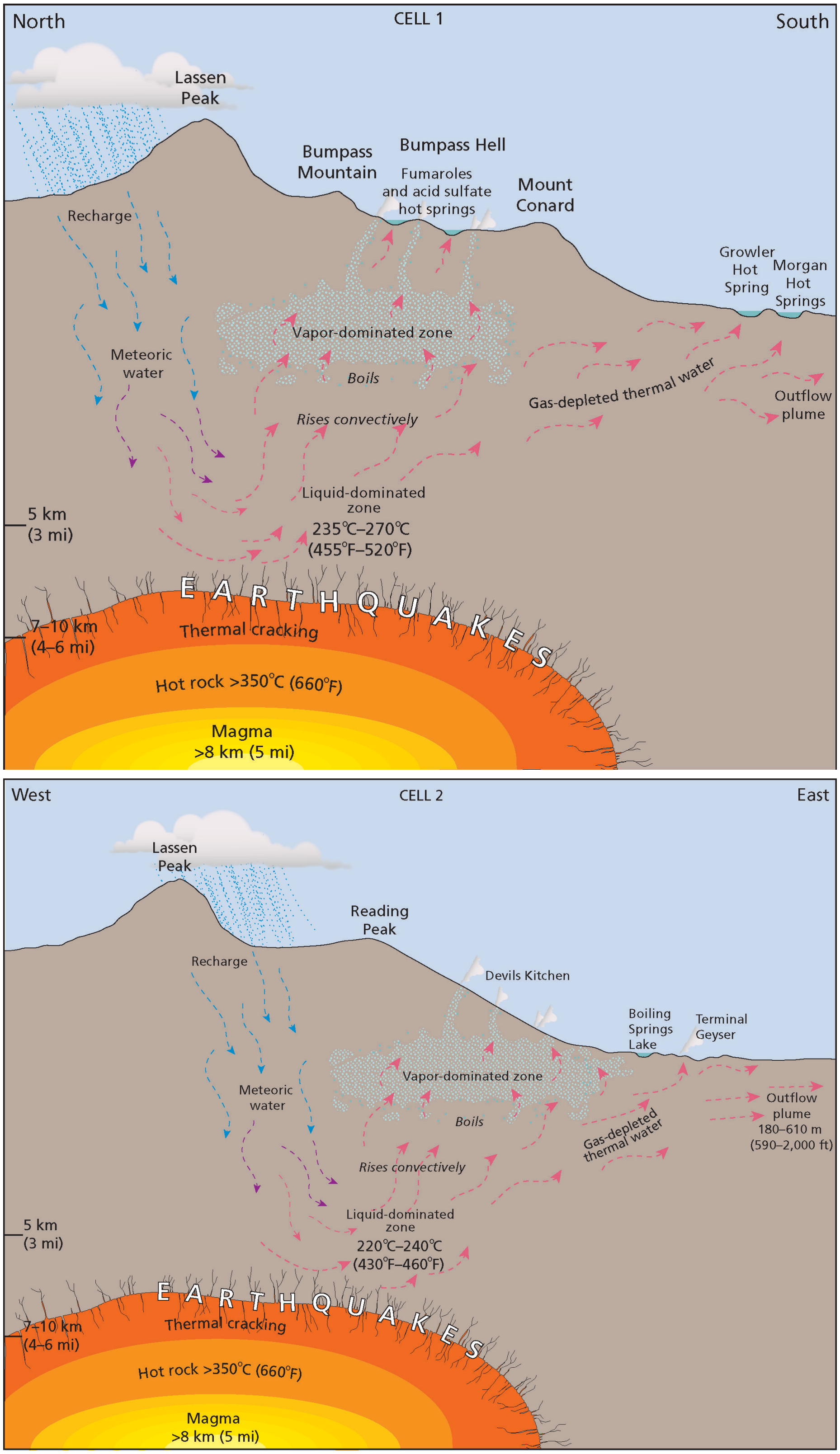

Figure 14. Lassen hydrothermal system. Recharge of the Lassen hydrothermal system starts at high elevations. The upper image illustrates circulation in cell 1 of Janik and McLaren (2010): the lower image illustrates circulation in cell 2 of Janik and McLaren (2010). In both cells meteoric water percolates to a depth limited by a zone of hot rock overlying a magma body. Hot water rises convectively along favorable flow paths and boils in response to decreasing pressures to form a vapor-dominated zone that releases steam and gases to surface fumaroles and acidic hot springs. The residual thermal water flows laterally down gradient and emerges as hot springs south of the park (cell 1) or continues to flow downward into the subsurface (cell 2). Graphic by Trista Thornberry-Ehrlich (Colorado State University) with information from Clynne et al. (2003), Janik and McLaren (2010), and Michael A. Clynne and Patrick Muffler (US Geological Survey, written communication, 30 September 2013).

south of the park, forming Growler and Morgan hot springs (Muffler et al. 1982; Ingebritsen and Sorey 1985; Clynne et al. 2003; Janik and McLaren 2010).

Using seismic and geothermal data obtained since 1982, Janik and McLaren (2010) refined the long-standing model for Lassen (Muffler et al. 1982), and showed that the flow of water is limited by a zone of hot rock overlying the Lassen magma body. Earthquakes occur in this hot rock in response to changing hydrostatic and fluid pressures in pores and fractures, and to local tectonic stresses. Janik and McLaren (2010) refined the model to include two separate hydrothermal cells (fig. 14). Meteoric water originating on the southwestern flank of Lassen Peak and other high-elevation areas, such as the remnant topography of Brokeoff Volcano, is incorporated into “cell 1” and discharges at Growler and Morgan hot springs south of the park. Cell 1, which has a fluid reservoir at 235°C–270°C (455°F–518°F), “fuels” Little Hot Springs Valley, Bumpass Hell, Sulphur Works, and Pilot Pinnacle. Little Hot Springs Valley and Bumpass Hell are above the greatest upflow (with respect to volume and ascent rate) from the thermal reservoir. Sulphur Works and Pilot Pinnacle are on the western margin of the reservoir where upflow is less.

Meteoric water originating on the southeastern flank of Lassen Peak and Reading Peak forms “cell 2” of Janik and McLaren (2010) and discharges as steam at Terminal Geyser and thermal water at Drakesbad. Outflow of this cell was intercepted by the Walker O well (see “Geothermal Development” section) and continues in a south–southeast direction at 180–610 m (590–2,000 ft) depth toward the North Fork Feather River drainage (Janik and McLaren 2010). Cell 2 incorporates a reservoir of hot fluid, 220°C–240°C (428°F–464°F), which rises and boils to form small parasitic vapor zones that feed steam to Devils Kitchen and Boiling Spring Lake.

Hydrothermal Features

The Lassen volcanic center hosts far and away the most extensive hydrothermal system in the Cascade arc (Clynne et al. 2012). Lassen Volcanic National Park contains the surface manifestation of the Lassen hydrothermal system at (listed in order of size, table 2) Little Hot Springs Valley, Sulphur Works, Bumpass Hell (fig. 15), Devils Kitchen (fig. 16), Boiling Springs Lake (fig. 17), Drakesbad, Pilot Pinnacle, and Terminal Geyser (fig. 18). These areas contain many thermal vents that form superheated fumaroles from which gases are emitted (fig. 19), hot springs where water temperatures are higher than that of the human body, mud pots that range in temperature from boiling to near ambient (fig. 20), and warm to hot ground commonly covered with orange and yellow sulfates. In addition, the slow seepage of cold CO_2—one of the prominent gases emitted from the system—occurs beneath water in a few places and causes bubbling in Soda Lake and Cold Boiling Lake (Kane 1980). Extensive areas of hydrothermally altered rocks are a further surface expression of hydrothermal activity and indicate that the hydrothermal system moves around with time.

Figure 15. Bumpass Hell. A boardwalk provides passage through Bumpass Hell. The area was named for Kendall Vanhook Bumpass, an explorer and mountain man who fell into a boiling mud pot in 1865 and had to have his leg amputated. US Geological Survey photograph, available at http://volcanoes.usgs.gov/volcanoes/lassen_volcanic_center/lassen_volcanic_center_gallery_4.html (accessed 20 November 2013).

Figure 16. Devils Kitchen. Devils Kitchen—a bubbling cauldron—is accessible via a hiking trail in the Warner Valley. Hydrothermal features at Devils Kitchen include steam vents, mud pots, and boiling pools. National Park Service photograph, available at http://flic.kr/s/aHsjEjhdH8 (accessed 12 November 2013).

Figure 17. Boiling Springs Lake. Boiling Springs Lake is a bubbling lake with a temperature around 52°C (125°F). The lake formed in a down-dropped basin in the basalt and basaltic andesite of Sifford Mountain (PEbsm). Mud pots and steam vents line part of the shore and drainage creeks. National Park Service photograph, available at http://flic.kr/p/e2RJcJ (accessed 12 November 2013).

Figure 18. Terminal Geyser. Terminal Geyser is not a true geyser, but spurting steam in the middle of a creek bed. Terminal Geyser is accessed from the Warner Valley trailhead and provides an impressive show for visitors. National Park Service photograph, available at http://www.nps.gov/media/photo/gallery.htm?id=C751AB55-155D-4519-3E6BF20C8E7253AE (accessed 12 November 2013).

Figure 19. Fumarole. A fumarole is a hole or vent in the ground from which gas is emitted. Lassen Volcanic National Park contains many exceptional examples of this feature type, such as this one at Sulphur Works. National Park Service photograph, available at http://flic.kr/p/e2RKJG (accessed 12 November 2013).

Figure 20. Mud pot. A mud pot is a type of hot spring that contains boiling mud. Mud pots are often sulfurous and multicolored; note the yellow coloration on nearby ground of this mud pot in Bumpass Hell. National Park Service photograph, available at http://flic.kr/p/e2L2De (accessed 12 November 2013).

Figure 21. Big Boiler. Measured temperatures of Big Boiler in Bumpass Hell have been as high as 161°C (322°F), making this fumarole one of the hottest in the world. National Park Service photograph, available at http://flic.kr/p/e2L5Ct (accessed 12 November 2013).

The boiling point of water varies with elevation but in general is about 95°C (203°F) at the park. Measured temperatures of hot springs range from 52°C to 97°C (126°F to 207°F) in the Lassen area (Clynne et al. 2003). Fumaroles have temperatures as high as 161°C (322°F) at Bumpass Hell, notably Big Boiler (fig. 21; Truesdell et al. 1983), and 147°C (297°F) at Little Hot Springs Valley (Janik and Bergfeld 2010).

The vigor of Lassen's hydrothermal features varies from season to season and year to year. In spring, when cool groundwater from snowmelt is abundant, the fumaroles and pools have lower temperatures, and mud pots are more fluid. In late summer and in drought years, the features become drier and hotter because less mixing occurs with shallow, cool groundwater. On a longer time scale, hydrothermal features may shift position, die out, or evolve into different types of features (see "Hydrothermal Hazards" section). For example, an area of steaming ground in upper Sulphur Works collapsed in the early 1980s, forming a huge, boiling mud pot (Clynne et al. 2003).

Table 2. Hydrothermal areas in Lassen Volcanic National Park

Name	Size
Little Hot Springs Valley	79,000 m^2 (850,000 ft^2)
Sulphur Works	58,000 m^2 (624,000 ft^2)
Bumpass Hell	46,000 m^2 (495,000 ft^2)
Devils Kitchen	40,900 m^2 (440,000 ft^2)
Boiling Springs Lake	14,300 m^2 (154,000 ft^2)
Drakesbad	10,000 m^2 (108,000 ft^2)
Pilot Pinnacle thermal area	7,500 m^2 (80,700 ft^2)
Terminal Geyser	900 m^2 (9,700 ft^2)

Source: Sorey and Colvard (1994); see map 2 (in pocket) for locations.

Hydrothermal Alteration, Minerals, and Thermophiles

Hot water at 240°C (460°F) in a deep reservoir provides the steam that feeds hydrothermal features at the surface in the park. This steam contains hydrogen sulfide (H_2S), which oxidizes in the near-surface environment to produce sulfuric acid. Sulfuric acid, in turn, reacts with near-surface volcanic rocks, altering them to soft, light-gray to white slopes composed primarily of opal (hydrous SiO_2) and kaolinite (a clay mineral). Where the acidity of the water is relatively high, nearly pure opal forms; lower acidity and lower temperatures produce mainly kaolinite (Kiver and Harris 1999).

Hydrothermal alteration is widespread in and around the thermal areas of the park (fig. 22). Hydrothermally altered rocks occur in active thermal areas (Hh) and in the hydrothermally altered core of Brokeoff Volcano (Hsh). Hydrothermally altered rocks are prone to slope movements (see "Slope Movements" section).

Figure 22. Hydrothermal alteration. Acidic hot water chemically changes minerals in volcanic rocks to white kaolinite (clay) and silica (including the mineral opal). This process is called "hydrothermal alteration," and this type of material is abundant at Bumpass Hell (shown here). The alteration process weakens rocks, making them more susceptible to erosion and slope movements. US Geological Survey photograph, available at http://pubs.usgs.gov/fs/2002/fs101-02/ (accessed 12 November 2013).

Many distinctive rocks and minerals form in the highly acidic, hydrothermal environment at the park. Pyrite (FeS_2) is common in many of the hot springs as linings of vents and discharge channels, scum floating on the surface of pools, and dispersions in gray or black mud pots (fig. 23). Additionally, native sulfur (S) often coats the walls of steam vents with yellow, whereas sulfates (SO_4) appear orange.

Springs depositing travertine (Hht, shown as part of unit Hh on map 1, in pocket) occur on the periphery of some of the steam-dominated thermal areas in Little Hot Springs Valley. Travertine is finely crystalline, white, tan, or cream-colored calcium carbonate ($CaCO_3$) formed by chemical precipitation from solution in surface water and groundwater. Clynne and Muffler (2010) mapped two travertine deposits in Little Hot Springs Valley, and located another deposit too small to show at map scale (1:50,000) on the south side of Hot Springs Creek about 240 m (800 ft) along trail from Warner Valley picnic area. In the 1970s and 1980s, Patrick Muffler mapped a third travertine deposit in Little Hot Springs Valley, but in 2004 could not relocate the deposit and its vent. It had apparently eroded away or been removed by a landslide (Patrick Muffler, US Geological Survey, scientist emeritus, written communication, 17 July 2013).

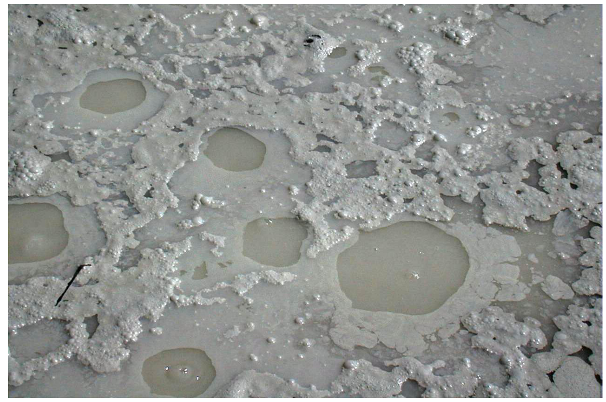

Figure 23. Boiling pool. This boiling pool of mud and water at Bumpass Hell contains pyrite (iron sulfide), known as "fool's gold." National Park Service photograph, available at http://flic.kr/p/e2L2Lg (accessed 26 March 2013).

Algal and bacteria colonies also lend color to Lassen's thermal areas (fig. 24). Called thermophilic (heat-loving) bacteria, these organisms are not true bacteria but belong to a group known as Archaea (relating to Archaean of geologic time; fig. 3), which survive at temperatures as high as 80°C (175°F). Investigators have found species of Archaea in many environments previously thought to be sterile, such as acid hot springs (Clynne et al. 2003). Some studies suggest that life on Earth may have sprung from microbes similar to modern Archaea. Thus, Lassen Volcanic National Park serves as a laboratory for studying very early life on Earth (Clynne et al. 2003). Work by Siering et al. (2006) characterized the microbial and geochemical diversity of hot acidic environments in the park. With temperatures ranging from 50°C to 115°C (122°F to 239°F) and pH from 0 to 3, hydrothermal features at the park represent some of the most extreme life-supporting environments on Earth (Siering et al. 2006).

Figure 24. Algal and bacterial mats. The hot, acid hydrothermal features in Lassen Volcanic National Park are not as lifeless as they might appear. Colorful algal and bacterial mats are prominent in the cooler parts of hot springs and outflow channels. As shown here, these life-forms cover a travertine deposit along the bank of West Sulphur Creek just below (south of) Sulphur Works. US Geological Survey photograph by Patrick Muffler, available at http://pubs.usgs.gov/fs/2002/fs101-02/ (accessed 15 November 2013).

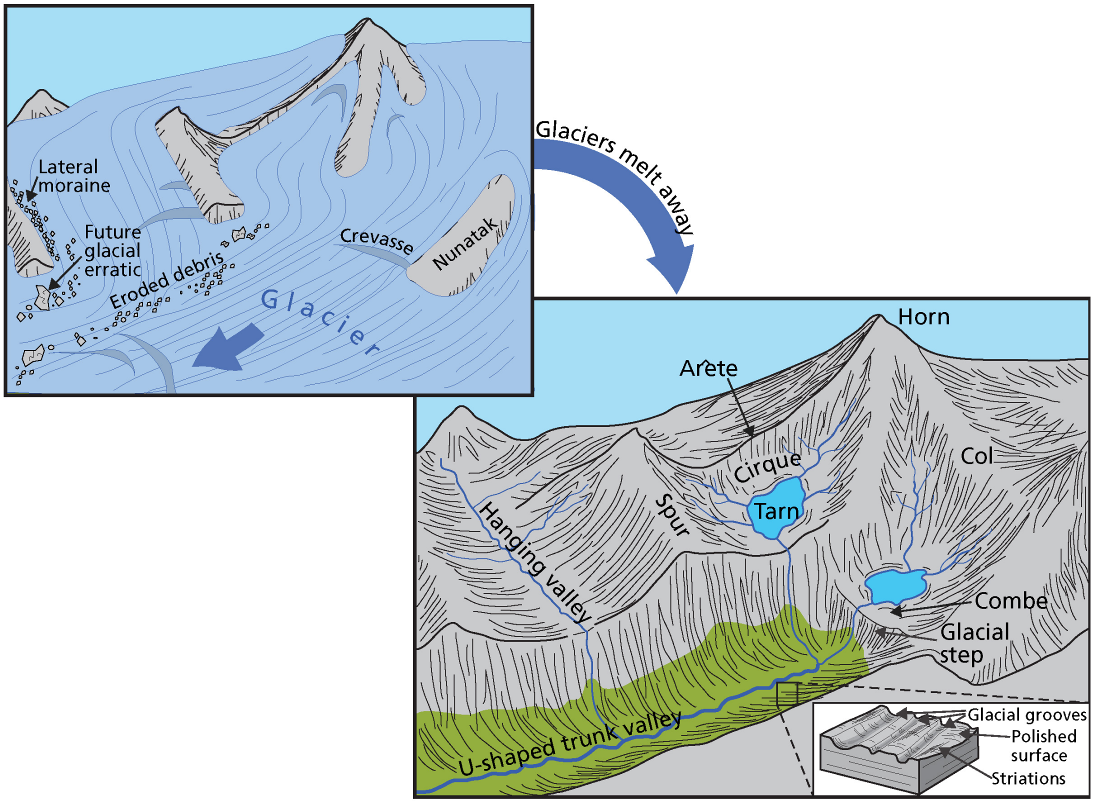

Figure 25. Glacial landforms. This schematic graphic illustrates "classic" landforms common to glaciated areas. Not every landscape contains examples of every feature. Many of these can be found within Lassen Volcanic National Park such as polish and striations, U-shaped valleys, and cirques. Graphic by Trista Thornberry-Ehrlich (Colorado State University).

Glacial Features

Although the park's landscape is devoid of glaciers today, glaciers advanced at least five times during the ice ages of the Pleistocene Epoch. Valley glaciers radiated out from the base and northeastern flank of Lassen Peak, and an ice cap was situated over the central plateau area of the park (Kane 1982; Turrin et al. 1998). Additionally, two small moraines near the base of Lassen Peak record early Holocene glacial activity, between about 8,000 and 12,000 years ago (Christiansen et al. 2002).

The main effects of Pleistocene glaciation in the park were erosional (fig. 25). Glaciers deepened major valleys (see "U-shaped Valleys" section), removed bedrock from large parts of the landscape (see "The Missing Summit of Brokeoff Volcano" section), and created or enlarged hundreds of lake basins (see "Lakes" section). Glaciers also polished and scratched striations and grooves on bedrock surfaces (see "Glacial Polish, Striations, and Grooves" section), and formed cirques and arêtes at high elevations (see "Cirques" and "Arêtes" sections), and roches moutonnées in valleys (see "Roches Moutonnées" section).

Glacial deposition also helped to shape the Lassen landscape. Glaciers widely distributed till (a mixture of clay, silt, sand, gravel, and boulders), developed moraines (mounds or ridges of till; see "Till and Moraines" section), and deposited erratics (see "Glacial Erratics" section). Glacial meltwater deposited outwash (sand and gravel) beyond the margins of glacial ice (see "Outwash" section).

U-shaped Valleys

Mountain valleys cut by streams are characteristically V-shaped but become U-shaped if they are carved by repeated advances of glacial ice. As a glacier moves down a valley, it steepens the valley walls and broadens the floor, transforming the cross profile to resemble a "U."

Many valleys in the park exhibit U-shaped forms, including Mill Creek valley, which is best viewed from around Diamond Peak or Lake Helen; and the North Fork of Bailey Creek (Blue Lake Canyon), which is best viewed from Ski Heil. Profiles of U-shaped valley are also apparent across Warner Valley and the valley of Hot Springs Creek, though these particular valleys are bounded by faults, and tectonic down-dropping in addition to glacial scouring probably deepened these valleys. Kane (1982) estimated that glacial scouring deepened Mill Creek valley about 185 m (600 ft) and the North Fork of Bailey Creek by about 275 m (900 ft).

The Missing Summit of Brokeoff Volcano

The huge quantities of bedrock that glaciers scoured, plucked, and abraded from the Lassen landscape may be inferred not only from the results of valley deepening but from the "missing summit" of Brokeoff Volcano (fig. 26). Some investigations have attributed the missing summit

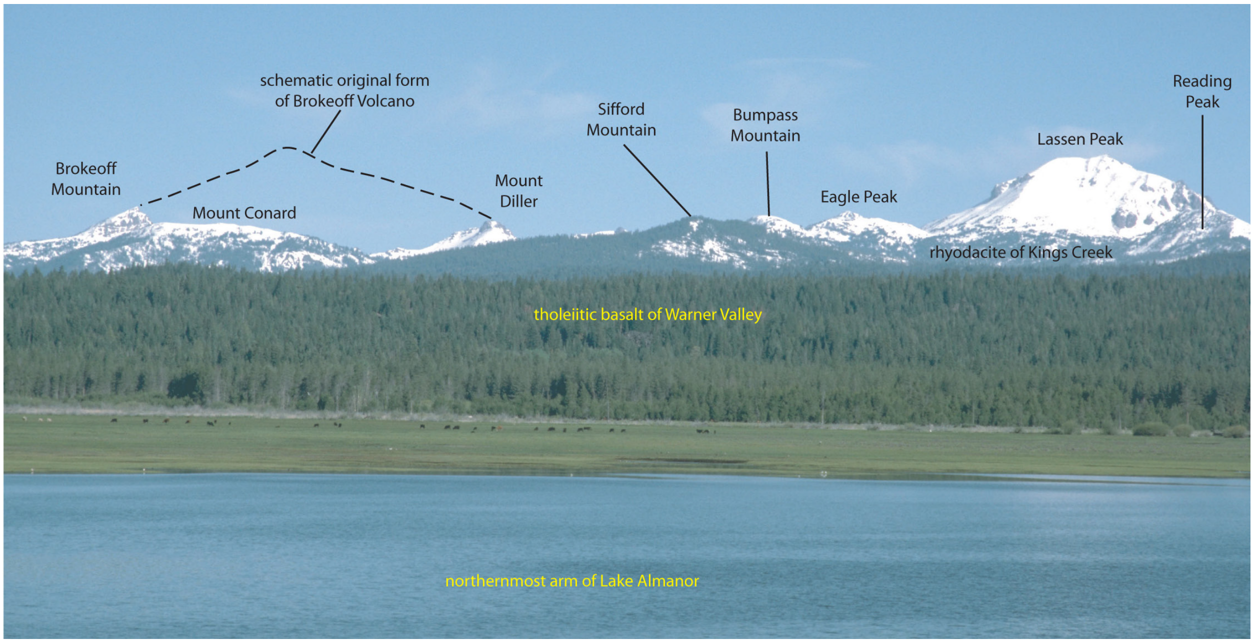

Figure 26. Missing summit of Brokeoff Volcano. Before glacial activity eroded the summit area of Brokeoff Volcano, it towered above the surrounding landscape. The present-day ridgeline contains glacial features such as cirques and arêtes. The photograph shows remnants of Brokeoff Volcano (i.e., Brokeoff Mountain, Mount Conrad, and Mount Diller), as well as the Sifford Mountain shield volcano and lava domes such as Bumpass Mountain, Eagle Peak, Lassen Peak, and Reading Peak. The forested slopes in the foreground are the tholeiitic basalt of Warner Valley (map unit PEbwv). US Geological Survey photograph by Patrick Muffler.

to partial collapse of the volcano into its magma chamber, but on a landscape covered by glacial deposits and wrought with classic, glacially eroded forms, glacial ice clearly played a significant role in the mountain's demise (Williams 1932). A reconstructed profile of the original volcano reveals that at least 90 m (300 ft) of rock have been eroded from the old volcano's flanks. Long-lived hydrothermal activity weakened the volcanic rocks, altering their mineralogies to clay and opal, which are more susceptible to erosion, including glacial erosion (Crowley et al. 2004; John et al. 2006, 2009).

Cirques

Cirques are a classic glacial landform consisting of a bowl-shaped, amphitheater-like hollow eroded into the side of a mountain. Cirques in the park are typically about 800 m (0.5 mi) across and set into a mountainside below a boulder-strewn headwall, 120–150 m (400–500 ft) high (Kane 1982). Most are closed depressions and contain small tarns (see "Lakes" section).

Many cirques occur on the flanks of the divide running between Brokeoff Mountain and Reading Peak (Kane 1982). A particularly nice example of this type of glacial landform lies on the northern side of the crest of Loomis Peak, overlooking Manzanita Lake (Schulz 1952). In addition, cirques occur just west of Lake Helen and on the northern side of Brokeoff Mountain. The cirque on Lassen Peak's northeastern flank was eroded by a glacier that extended 11 km (7 mi) down-valley (Clynne et al. 1999).

Arêtes

Mountains that are, or have been, surrounded by glaciers tend to have characteristic features derived from the fracturing and plucking action of ice. Resultant landforms are the steep rock walls at the heads of cirques and narrow serrate ridges, called "arêtes," between adjoining cirques. The large bowl-like depression contained within the Brokeoff Mountain–Mount Diller–Bumpass Mountain–Mount Conrad ridge exemplifies glacial erosion; the western part of this ridge is an arête, formed between the Bailey Creek cirques on the west and the Mill Creek cirque-like feature on the east (Kane 1982).

Roches Moutonnées

Roches moutonnées are asymmetrical, elongate knobs or hillocks of resilient bedrock that have been smoothed and scoured by moving ice on the up-glacier (stoss) side. On the down (lee) side, the rock is steep and hackly (jagged) from glacial quarrying. The term "roche moutonnée" may have come from the resemblance of this landform to the wigs ("moutonnées") worn in late-1700 Europe and by barristers and judges in British courts. The smooth bangs and curly backs of these wigs resemble this glacial form. The term may also be translated as "rock sheep;" the landform may have appeared as fleecy grazing sheep. In the park, roches moutonnées are present just west of the saddle between Lassen and Eagle peaks (Schulz 1952).

Glacial Polish, Striations, and Grooves

Rocks and sediment frozen to the base and sides of a glacier act like sandpaper and grind, scratch, and polish the bedrock over which they pass. Glacially transported rocks may also become smoothed and rounded. These features—called glacial polish, striations, and grooves—are abundant in Lassen's high country. Visitors can see excellent examples of scratched and polished dacite surfaces at the Lassen Peak trailhead and along the trail to Bumpass Hell (fig. 27).

Figure 27. Glacial erratic and polish. At the Bumpass Hell trailhead, a glacial erratic rests on glacially polished bedrock of Brokeoff Volcano (map unit PEad). A glacier carried and deposited this large block of dacite from Bumpass Mountain (PEdb), which remained at the edge of the canyon after the glacier had receded. National Park Service photograph ("Out of Place, Out of Time") by Barbara Matthews (submission in *Park Science* 2011 Wilderness Edition Photo Contest), available at http://www.nature.nps.gov/ParkScience/graphics/vol_28_3/PhotoContest/index.html (accessed 14 November 2013).

Till and Moraines

Till is the general term for the poorly sorted mixture of fine to coarse rock debris deposited directly from glacial ice. Clynne and Muffler (2010) mapped two broad units of till—younger (PEty) and older (PEto)—though no older till deposits (PEto) occur within the boundaries of the park. Glaciers laid down till while volcanoes erupted within the park. Till covers many lava flows (see Map Unit Properties Table, in pocket; and "Geologic History" section).

In the Lost, Hat, and Manzanita Creek drainages, Christiansen et al. (2002) mapped glacial features in greater detail (scale 1:24,000). The most important remaining geologic mapping problem in the Lassen area is the extension of the detailed glacial stratigraphy from these valleys to the rest of the park and beyond (Clynne and Muffler 2010). Christiansen et al. (2002) delineated six ages of glacial deposits that represent five Pleistocene glacial advances and one Holocene advance. From youngest to oldest, these units are (1) till of Badger Mountain (PEtb), (2) till of Raker Peak (PEtr), (3) post-maximum till of Raker Peak consisting of Lassen Peak avalanche debris (PEtrl), (4) till of Anklin Meadows (PEta), (5) late till of Anklin Meadows (HPEtal), and (6) till or protalus-rampart debris (Hth). The till of Badger Mountain (PEtb) is equivalent to the younger part of unit PEto (Clynne and Muffler 2010). The other tills—PEtr, PEtrl, PEta, PEtal, and Hth—are equivalent to the younger till unit (PEty). For a visual representation on the Lassen Volcanic National Park landscape, see map 1 (in pocket) where all till deposits are combined as unit HPEt.

Moraines are the most obvious landforms composed of till (figs. 28 and 29). These features can be undulating mounds or sharp ridges, depending on how long a glacier remained stable in a particular position or how much erosion and weathering have taken place in the intervening years between deposition and the present. In general, till from younger glaciations (PEty) has well-preserved moraines, whereas till from older glaciations (PEto) has only moderately to poorly preserved moraines (Clynne and Muffler 2010).

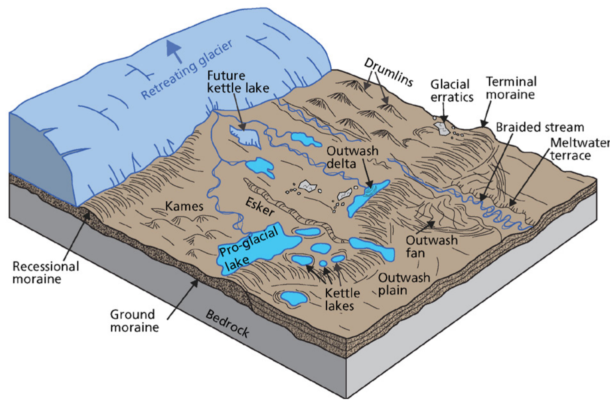

Figure 28. Glacial deposits. This schematic graphic illustrates deposits and features associated with glacial processes. Typically, glacial landscapes only preserve a fraction of the possible deposits. Till (generic term for material deposited by glacial ice) and moraines (composed of till) occur within Lassen Volcanic National Park (see fig. 29). Graphic by Trista Thornberry-Ehrlich (Colorado State University).

Lateral moraines form on the sides of glaciers and merge with end and terminal moraines, which are arc-like ridges of till that form at the terminus of glaciers. Terminal moraines mark the farthest point of a glacier's advance. Glaciers spilled down the valleys to elevations as low as 1,800 m (6,000 ft) (Kane 1982) and built terminal moraines as much as 8 km (5 mi) away (Kiver and Harris 1999). Most terminal and lateral moraines are beyond the park boundary (Kane 1982). Some recessional moraines occur in a few places at higher elevations within the park, such as in the area sweeping northeast from Reading Peak and enclosing Summit Lake, and in Cameron Meadow south of Mount Hoffman (Kane 1982).

Outwash

During warm periods, glacial meltwater laden with sediment is "washed out" and deposited in flat areas beyond the margins of a glacier. Outwash deposits consist of unconsolidated sand and gravel, and may contain boulders up to 2 m (7 ft) in diameter. Within and surrounding the park, five outwash deposits are related to till deposits that were deposited at the same time (table 3). Only three of these outwash deposits occur within the park—PEor, PEou, and PEoy. All outwash deposits are grouped and shown as unit PEo on the geologic map graphic (map 1, in pocket).

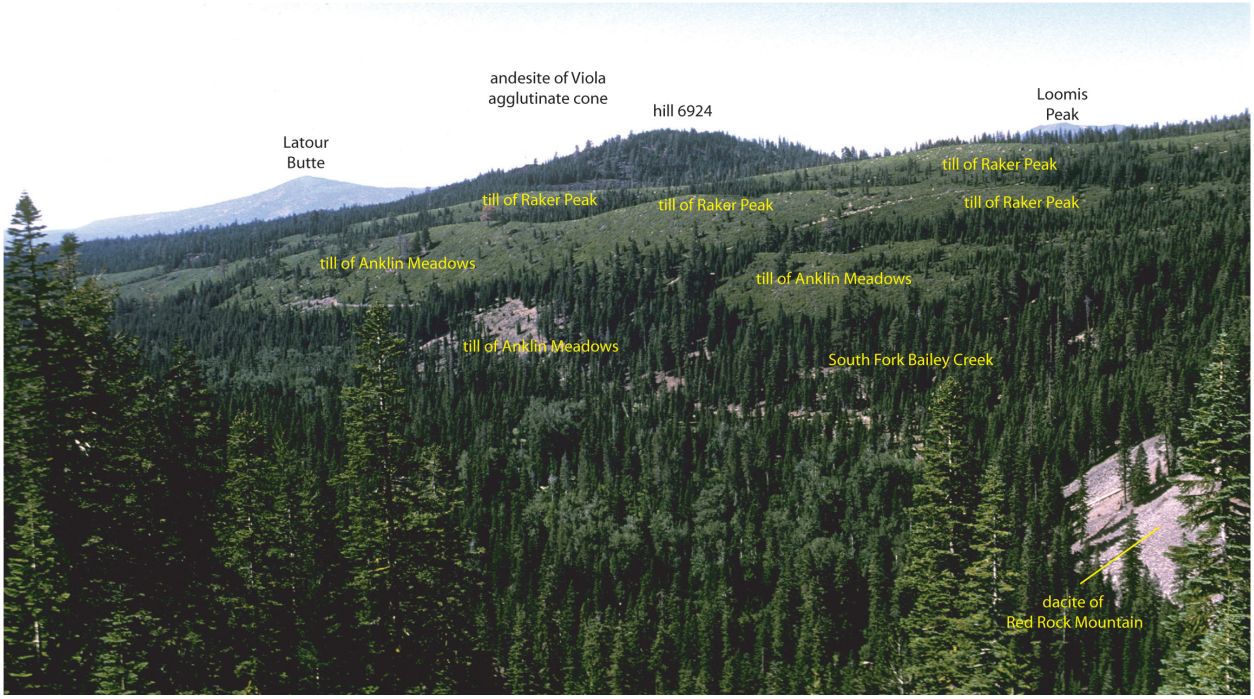

Figure 29. Till and moraines. The view shown here is looking north from Red Rock Mountain across the South Fork Bailey Creek and includes tills of Raker Peak (map unit PEtr) and Anklin Meadows (PEta). The brushy ridge extending from the upper right to the left center is a medial moraine between South Fork and North Fork Bailey Creek that consists of the late Pleistocene till of Raker Peak. Hill 6924 is an agglutinate vent of the andesite of Viola (PEav), part of the older Twin Lakes sequence of the Lassen volcanic center; its flow forms the forested slope to the left. In the right distance is Loomis Peak, composed of the rhyodacite of Loomis Peak (PErlm), part of the Bumpass sequence of the Lassen volcanic center. In the far distance on the left is Latour Butte, an andesitic volcano that is part of the Latour volcanic center. US Geological Survey photograph by Michael A. Clynne.

Table 3. Correlation of outwash and till in the Lassen area

Outwash Gravel	Till	Age, years ago
Younger (PEoy)	Younger (PEty)	35,000–8,000
Undivided (PEou)	Younger (PEty) and older (PEto)	>130,000–8,000
Anklin Meadows (PEoa)	Anklin Meadows (PEta)	25,000–17,000
Raker Peak (PEor)	Raker Peak (PEtr)	35,000–27,000
Older (PEoo)	Older (PEto)	>130,000–60,000

Source: Clynne and Muffler (2010).

Glacial Erratics

In many glaciated areas, large boulders end up stranded when glaciers recede. These out-of-place rocks, called “erratics,” lie scattered on bedrock surfaces different from their own compositions and attest to the effectiveness of glacial erosion, transport, and deposition. The boulder sitting just to the left of the parking area at Bumpass Hell is an erratic (National Park Service 1972) (fig. 27). It is a large block of dacite from Bumpass Mountain (PEdb), which was carried by a glacier and left perched at the edge of the canyon when ice melted and the glacier receded. The erratic sits on Brokeoff Volcano andesite (PEad).

Lakes

Lassen Volcanic National Park contains more than 200 lakes (National Park Service 2010). Many are small and seasonal (Kane 1982), and most have a glacial origin and occur in glacial till or scoured glacial basins. However volcanism, faulting, and slope movements also played roles in lake formation at the park.

Glacial Lakes

All glacial lakes within the park lie within the limit of Anklin Meadows till (PEta) and are, as such, 25,000–17,000 years old. An exception is Dry Lake—a closed depression in the Badger Mountain till (PEtb; 70,000–60,000 years old), specifically the terminal Badger Mountain moraine in the Panther Creek drainage (Kane 1982). However, this lake is not within the the park. Thus, all the small, till-depression lakes within the park have been on the landscape less than 25,000 years, though at least one in the area may have formed as much as 60,000 years ago.

Lakes with glacial origins also include those impounded by moraines such as Summit Lake (Kane 1980). Also, small lakes, called “tarns,” commonly occupy high-elevation basins created during the formation of a cirque (see “Glacial Features” section). In the park, Emerald Lake and Lake Helen are tarns created by glaciers that hollowed out the sides of mountains. Tarns are usually impounded by a bedrock lip covered by till or a small moraine (Kane 1982).

Lakes also form in the scoured basins of glacial valleys, including Crumbaugh, Cold Boiling, Terrace, Cliff, Shadow, Blue, and Crystal lakes in the park. Small glacial lakes may also occur in rugged terrain and on plateaus, for example, Island, Glen, East, and Indian lakes in the eastern part of the park, and Sifford and Bench lakes in the central part of the park.

Located near the southeastern corner of the park, Juniper Lake is the largest and deepest—2.1 km (1.3 mi) wide, and 72 m (235 ft) deep—in the park (Kane 1982). During the Pleistocene ice ages, the site of Juniper Lake was covered by a small ice field, which spilled south into Warner Valley and Benner Creek. The present outlet of Juniper Lake is into Warner Valley (to the west). Juniper Lake is carved into the down-dip direction of an approximately 1.4-million-year-old lava flow (PEad2) of the Dittmar volcanic center (Michael Clynne, US Geological Survey, research geologist, written communication, 10 April 2013). The lake basin also is partly bounded by 188,000-year-old lavas from Mount Harkness (PEamh). Although Kane (1982) suggested that Juniper Lake appeared to be more of a constructional depression—that is, formed by "upbuilding" (via deposition of material or volcanic eruption)—than an erosional basin, glacial carving clearly enhanced the basin (Michael Clynne, written communication, 10 April 2013).

Slope Movements and Lakes

Hat Lake is east of the Devastated Area and adjacent to the park road. Although the age of many of the lakes within the park is constrained by glacial till (see "Glacial Lakes" section), knowing the exact date of formation of a lake is unusual, but such is the case for Hat Lake. It formed on 22 May 1915 when a viscous debris flow (Hw2) slid from the upper slopes of Lassen Peak. The debris-flow deposit created the lake basin and dammed Hat Creek, creating the small lake. In addition, slope movements played a role in the development of lake basins at Forest Lake and a number of other small lakes below Brokeoff Mountain, which are closed depressions bounded by the 3,310-year-old landslide (Hsh) from Brokeoff Volcano that went down Mill Canyon. Also, Soda Lake is bounded by a landslide (Hsh), as well as alluvium (HPEf) and colluvium and talus (HPEc). The age of this landslide is unknown but could easily be younger than the 3,310-year-old slide from Brokeoff Volcano (Michael Clynne, US Geological Survey, research geologist, written communication, 10 April 2013). In the northwestern corner of the park, Manzanita Lake formed when blocky, angular rubble of the first debris avalanche of Chaos Jumbles (Hsj) dammed Manzanita Creek. Reflection and Crags lakes also formed as a result of the Chaos Jumbles debris avalanche (see "Slope Movements" section). Manzanita Lake was created in 278 ± 28 radiocarbon years before present (BP), which translates to 1672 CE. Radiocarbon ages are recorded as years before present (BP), with "present" being 1950 CE. This date was determined from trees that were drowned by Manzanita Lake (Clynne and Muffler 2010). Tree-ring data suggest that this date should be about 25 years earlier, but it is not precise (Michael A. Clynne, US Geological Survey, research geologist, written communication, 23 July 2013).

Volcanism, Faulting, and Lakes

Volcanism also played a role in the formation of lakes within the park. For instance, Snag Lake formed during the eruption of Cinder Cone in 1666 (Sheppard et al. 2009). The Painted Dunes flows (Hmp1 and Hmp2) blocked streamflow from the south into Butte Lake, which occupies a tectonically down-dropped basin, and created Snag Lake (Clynne and Muffler 2010).

Boiling Springs Lake (fig. 17), which occurs in the basalt and basaltic andesite of Sifford Mountain (PEbsm), is another interesting example of lake formation. During the middle Pleistocene Epoch (approximately 170,000 years ago), lava erupted from a vent marked by Sifford Mountain and formed this small shield volcano and associated flows. A fault runs across the Sifford Mountain lava flows directly beneath Boiling Springs Lake. The lake probably formed via a combination of down-dropping along the fault and enhanced erosion of hydrothermally altered rock. The fault serves as a pathway for thermal fluids. However, most of the water in the lake basin is meteoric (rain and snowmelt), not thermal water. Thermal activity at Boiling Springs Lake is dominated by steam and gas (Michael Clynne, US Geological Survey, research geologist, email communication, 14 August 2013).

Meadows

In general, few geologic landforms are as ephemeral as lakes, which serve as "traps" for sediment delivered by streams, organic materials provided by plants and animals, and dust from atmospheric deposition. When a lake becomes completely filled with inorganic and organic material, it has made the transition to meadow, having first gone through a wetland phase.

Not all meadows were once lakes, but at least two in the park were—upper Kings Creek Meadow and the meadow adjacent to (west of) Horseshoe Lake. Also, Dersch, Cameron, and Lower Kings Creek meadows; the meadow in Blue Lake Canyon below Soda and Blue lakes; and the meadow in the upper west fork of Manzanita Creek were probably lakes (Kane 1980).

Along with the slow encroachment of marshy edges, an important factor in the in-filling process of many lakes is the growth of a delta. Extending into the lake from the mouth of an inflowing stream, a delta is often visible as a barely submerged "fan" of sediment. This gradual replacement of a lake by delta growth occurs in the park at Crumbaugh, Manzanita, Horseshoe, and Hat lakes. In the 1980s, Hat Lake, the smallest and youngest, was well on its way to being filled in by delta growth (Kane 1980), but beavers dammed the outlet in the 1990s, raising the lake level by several feet. These beavers have since left the lake, and their dam is disintegrating (Michael Clynne, written communication, 17 July 2013).

Streams and Waterfalls

Lassen Volcanic National Park is in the Sacramento River watershed. Numerous tributaries flow within the park's boundaries such as Manzanita, North Fork Bailey, Panther, Hat, Butte, Grassy, Kings, and Hot Springs creeks. When viewed broadly, the overall drainage pattern of the park's streams appears "radial" and is controlled by basic topography. Streams radiate from a high-elevation area in the southwestern part of the park around Lassen Peak and Brokeoff Mountain. Upon closer inspection, however, the drainage pattern is not quite so simple, and geologic factors other than topographic relief control many stream locations. For example, Kings Creek, Hot Springs Creek, and the East and West forks of Sulphur Creek are probably controlled by the locations of faults. Other stream courses, such as Grassy Swale Creek and Echo-Twin Lakes drainage, follow routes that are geologic contacts (where two different ages of volcanic rocks meet, often creating natural topographic depressions). Still other streams, like upper Manzanita Creek and the headwater tributaries of Hat Creek, follow courses determined by lateral moraines (Kane 1980).

Streams in the rugged Lassen region are generally down-cutting and far from a steady state condition. Stream loads consist mostly of coarse material, with a relative paucity of silts and clays. Channel gradients are irregular, often alternating along a particular stream from steep in places where the channel is in bedrock to gentle where alluvium (HPEf) has been deposited (Kane 1980).

Despite rugged relief and ample streamflow, sizable waterfalls within the park are few (Kane 1980). Mill Creek Falls at the confluence of the eastern and western branches of the East Fork of Sulphur Creek is the highest waterfall in the area with a double-drop of about 20 m (80 ft). The stream there flows over a layer of Brokeoff Volcano lava (i.e., andesite of Mill Canyon, PEamc) that is particularly resistant to weathering. The only other major waterfall in the park is Kings Creek Falls, about 15 m (50 ft) high, which also flows over a resistant outcrop of Brokeoff Volcano lava (i.e., andesite of Rice Creek, PEar).

Geologic Issues

Geologic issues described in this section may impact park resources or visitor safety and could require attention from resource managers. Contact the Geologic Resources Division for technical or policy assistance.

During the 2004 scoping meeting and 2013 conference call, participants (see Appendix A) identified the following geologic resource management issues:

- Hydrothermal Hazards
- Volcano Hazards
- Seismic Activity
- Slope Movements
- Geothermal Development
- Abandoned Mineral Lands
- Disturbed Lands Restoration
- Manzanita Lake Dam

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

Hydrothermal Hazards

The three required elements of a hydrothermal system—abundant groundwater, permeable rock, and a heat source at depth—are present at Lassen Volcanic National Park and result in remarkable hydrothermal features at the surface. Hydrothermal features such as hot springs and fumaroles are one of the major visitor attractions at the park. However, they are also one of the main hazards (Covington 2004). The high-temperature fumaroles and mud pots pose potential burn hazards to people who stray from trails and boardwalks (Clynne et al. 2012). Thin surface crusts in hydrothermal areas are susceptible to collapse under the weight of people walking on them. Boiling mud, boiling water, and steam can cause first-, second-, and third-degree burns, which are sometimes fatal (Clynne et al. 2012).

The high-temperature, acidic, hydrothermal features at the park result in the alteration of volcanic rocks. These features also result in the alteration of anthropogenic features such as boardwalks and roads. Even boardwalks constructed on seemingly cool ground can be affected because steam vents and mud pots change in temperature and character and can migrate laterally over time. In some cases, wood posts in the ground have served as conduits or "wicks" for steam and acid. Over the years, the National Park Service has relocated the boardwalks in Bumpass Hell, Devils Kitchen, and Sulphur Works many times because acid vapors have affected both the wood and metal of these structures. At Sulphur Works, the boardwalks north of the park road were so severely compromised by thermal activity that in 2007 the National Park Service removed these structures in the interests of safety to both visitors and NPS personnel (Clynne and Muffler 2009).

Thermal activity also affects roads. Such impacts are prominent at Sulphur Works (Clynne and Muffler 2009, 2011). In recent years, fumarolic activity north of California Highway 89 (the "park road") has migrated south towards the road and become concentrated in a large, boiling mud pot adjacent to the sidewalk curb (fig. 30). Borings taken by the Federal Highway Administration in April 2009 and November 2011

Figure 30. Hydrothermal hazards at Sulphur Works. Hydrothermal activity poses a hazard where the park road (California Highway 89) crosses Sulphur Works. In recent years, fumarolic activity just north of the road has migrated south towards the road. The figure shows the view south from above the large boiling mud pot (feature 4196P) looking across California Highway 89 to the hill above a fumarole (4194C). Also shown in the photograph are a hissing, steaming pit, 2 m (7 ft) in diameter (4196E) and a large persistent fumarole on the southern side of the road (4195B). US Geological Survey photograph (with annotations) from Clynne and Muffler (2011).

recorded that boiling temperatures have risen through the substrate and compromised the integrity of the roadbed, in particular under the north lane where boiling temperatures were recorded 5–7 m (16–23 ft) below the road surface (Clynne et al. 2012). Hazard mitigation in this hydrothermal area is ongoing. Periodically, for example in May 2013 during preparation of this report, the Lassen Volcanic National Park website alerts visitors to areas such as Sulphur Works where road work and repairs are in progress and delays are expected.

Temporal and spatial variation of fumaroles has been observed in all thermal areas of the park, and has been systematically documented in recent years at Sulphur Works, Little Hot Springs Valley, and Pilot Pinnacle (Clynne et al. 2012). As hydrothermal features continue to change seasonally and annually, park staff must monitor thermal activity, particularly in areas with high visitation (Covington 2004; see "Hydrothermal Monitoring" section).

Hydrothermal Explosions

Hydrothermal explosions are produced where water contained in near-surface rock at temperatures as high as about 250°C (450°F) flashes to steam and violently disrupts the confining rock. These explosions are due to the same instability and chain reaction mechanism as geyser eruptions but are so violent that a large proportion of solid debris is expelled along with water and steam (Muffler et al. 1971).

Hydrothermal explosions present a significant hazard in many hot-spring areas (Browne and Lawless 2001; Christiansen et al. 2007). However, such hazards are more likely in thermal areas with active discharge of neutral pH, high-chloride waters, especially those hosting geysers, such as Yellowstone National Park (Muffler et al. 1971). By contrast, the hydrothermal system at Lassen Volcanic National Park is vapor dominated with acid-sulfate alteration (Christiansen et al. 2007). Thus the likelihood of a large hydrothermal explosion at the park is very low at present (Clynne et al. 2012). However, small hydrothermal explosions are possible anywhere a landslide "un-roofs" ground containing fluid above the boiling point. Such explosions have occurred in the last few decades in Bumpass Hell, Devils Kitchen, and Sulphur Works (Michael Clynne, US Geological Survey, research geologist, written communication, 17 July 2013). Moreover, intrusion of new magma into the Lassen volcanic system could alter the hydrothermal regime and make hydrothermal explosions more likely (Clynne et al. 2012).

Gas Hazards

Water vapor is the primary gas (≥90%) emitted in thermal areas. However, carbon dioxide (CO_2), hydrogen sulfide (H_2S), sulfur dioxide (SO_2), hydrogen (H), and fluorine (F) are commonly present. Normally, volcanic gases dissipate quickly into the atmosphere, and only rarely are visitors present in areas of Lassen Volcanic National Park where gas concentrations can cause harm (Clynne et al. 2012). However, thermal areas become especially hazardous when they are buried by snow after a significant storm (Clynne et al. 2012). Gases are trapped in the snow in air pockets, caves, wells, and depressions. In 1995, a skier feel into a snow cave at Sulphur Works, and although he was rescued, he died a week later in the hospital, probably of CO_2 poisoning (Michael Clynne, US Geological Survey, research geologist, written communication, 17 July 2013).

The first reported death associated with volcanically produced carbon dioxide in the United States occurred in the Horseshoe Lake area on the southern flank of Mammoth Mountain in eastern California (Hill 2000). Managers at Lassen Volcanic National Park may find the Forest Service's response at Horseshoe Lake of interest and use. High concentrations of carbon dioxide kill trees at this location, and managers mark the tree-kill zone as "keep out" during the winter months. Cross-country skiing, snowmobiling, snowshoeing, and "snow play" of any kind are considered unsafe activities due to the potential for falling into a snow well or landing face first in the snow. During the summer months, the tree-kill zone is safe for adults to walk, bike, and pass through, but activities that draw adults close to the ground such as sunbathing or picnicking are discouraged. The Forest Service does not recommend that small children or dogs enter the tree-kill area at any time (Hill 2000).

The hazard from CO_2 is amplified because CO_2 is odorless and colorless and thus not perceived readily (Wilcox 1959). By contrast, other volcanic gases such as hydrogen sulfide (H_2S) have a conspicuous "rotten egg" odor, resulting from the presence of sulfur. However, at concentrations above 0.015% (150 parts per million, ppm), the olfactory nerve is overwhelmed and the sense of smell disappears, commonly with an awareness of danger. In many cases where people have smelled "sulfurous" fumes, analysis showed that several other gases were present in equal or greater quantities. Other gases that are frequently present include hydrochloric acid, hydrofluoric acid, carbonic acid (dissolved carbon dioxide), and ammonia—all of which may be harmful if inhaled in sufficient concentration for a sufficient length of time (Wilcox 1959).

Air-Quality Monitoring

Lassen Volcanic National Park is downwind of the populated Sacramento Valley and areas of agriculture and manufacturing. Air-quality studies and monitoring at the park focus on the deposition of nitrogen, sulfur, and toxic air contaminants, including mercury, from these human sources, and the effects of these compounds on natural resources, rather than on naturally emitted toxic gases from hydrothermal features. Concentrations of sulfur from volcanic emissions are considered relatively low and not known to cause acidification on sensitive resources such as high elevation lakes (National Park Service 2011). The NPS Air Resources Division supports air-quality monitoring at the park, and posts monitoring results and key references at http://nature.nps.gov/air/Permits/aris/lavo/. Park managers are encouraged to contact the Air Resources Division for technical assistance with air-quality issues.

Hydrothermal Monitoring

Hydrothermal features are dynamic. Their vigor varies both seasonally and annually, and the location of activity can change (Clynne et al. 2012). Identifying the often-changing locations of these features and monitoring their heat, water flow, and chemistry provides resource managers with data needed to make informed decisions about management options (Heasler et al. 2009). Monitoring may also help to detect changes caused by a renewed influx of magma into the Lassen volcanic center (Clynne et al. 2012).

Heasler et al. (2009)—the chapter in *Geological Monitoring* about geothermal systems and hydrothermal features—described the following methods and vital signs for understanding geothermal systems and monitoring hydrothermal features: (1) thermal feature location, (2) thermal feature extent, (3) temperature and heat flow, (4) thermal water discharge, and (5) fluid chemistry.

To potentially provide early warning of volcanic activity (see "Volcano Hazards" section), the thermal features at the park are chemically and physically monitored by the US Geological Survey and National Park Service (Sorey 1986). In addition, researchers from California State University, Chico, implemented a monitoring system at two sites within the Lassen volcanic center: (1) Sulfur Works in the central part of the volcano complex, and (2) Boiling Springs Lake southeast of the main volcano edifice (Fassett et al. 2010). Following installation of data loggers in 2007, water temperatures have been continuously measured at both sites. Sulfur Works temperatures are typically around 75°C–90°C (167°F–194°F). Water temperatures are lower during spring and early summer, following snowmelt; temperatures are generally lowest in mid-June, about 76°C (169°F). Temperatures of Boiling Springs Lake are generally between 60°C and 70°C (140°F and 158°F), with temperature decreases to 40°C or 50°C (104°F or 122°F) during the spring (Fassett et al. 2010). Researchers from California State University, Chico, hypothesized that as magmatic activity of the system changes, the temperature of the hydrothermal systems will also change, along with CO_2 concentration emitted by the magmatic system.

Volcano Hazards

Volcanic eruptions from within the Lassen volcanic center and from regional volcanoes within and near the park would impact park infrastructure, including roads, thus affecting evacuation from park areas. Hazards from regional volcanoes include effusive mafic lava flows and airborne ash. Hazards from the Lassen volcanic center include explosive silicic eruptions that create lava domes and lava flows, as well as pyroclastic flows, lahars, and airborne ash (Clynne et al. 2012) (fig. 31).

An eruption generating extremely large pyroclastic flows—for example a caldera-forming eruption that produces tens to hundreds of cubic kilometers of lava and ash—is exceedingly unlikely in the vicinity of the park because the present magmatic system is not configured for this type of eruption (Clynne et al. 2012). Although several such events have occurred in the past 3 million years, none have occurred since the eruption of the Rockland tephra (PEpr) approximately 609,000 years ago (Lanphere et al. 2004; Clynne and Muffler 2010).

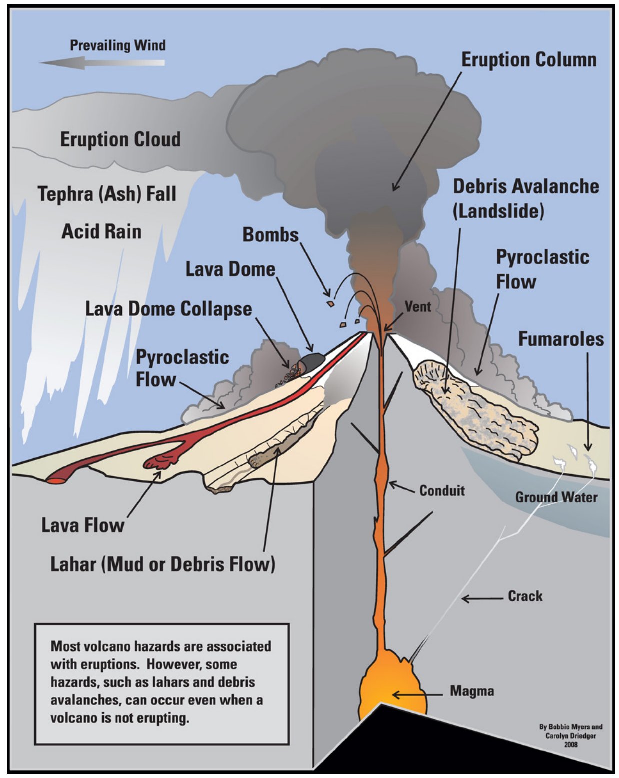

Figure 31. Volcano hazards. This graphic illustrates hazards associated with volcanic eruptions within the Lassen volcanic center and from regional volcanoes within and near Lassen Volcanic National Park. US Geological Survey graphic by Myers and Driedger (2008).

Hazards from Regional Volcanoes

The most common volcanic activity in and around the park consists of small to moderate-sized eruptions from regional volcanoes that build cinder cones as high as 300 m (1,000 ft), produce basaltic lava flows that can cover more than 2.5 km^2 (1 mi^2), and blanket many square kilometers with ash as much as several meters thick. These eruptions typically last a few months to a year, but may continue for several years. The probability of this type of eruption in the next year in the vicinity of the park is 2.3×10^{-4} (0.00023) or 0.023% (Nathenson et al. 2012). The hazard is neither higher nor lower because of the length of time since a previous eruption.

The most likely locations for eruptions of regional volcanoes around the park are in (1) a zone between the Red Cinder chain and California Highway 44 (approximately the area in and around the northeastern corner of the park), (2) a zone from south of Old Station to the Pit River, (3) a zone from the southern end of Tumble Buttes chain to the vicinity of Burney Mountain, and (4) the area of the Red Lake cluster (Clynne et al. 2012).

Hazards from Lassen Volcanic Center

Hundreds of eruptions have occurred in the Lassen volcanic center during its 825,000-year existence, including at least 14 eruptions in the past 100,000 years. Since about 25,000 years ago, the Lassen volcanic center has been relatively quiet, but three eruptive episodes during the last 1,050 years, the most recent in 1914–1917, demonstrate that the center is still active (Clynne and Muffler 2010). Eruptions have consisted of explosive events, tephra (ash falls), lahars, lava flows, and construction of lava domes (fig. 31). The probability of this type of eruption in the next year at the Lassen volcanic center is 6.5×10^{-4} (0.00065) or 0.065% (Nathenson et al. 2012). Like regional volcanism, the hazard is neither higher nor lower because of the length of time since a previous eruption.

Within the Lassen volcanic center, the most likely type of eruption would be explosive (vs. effusive eruptions from regional volcanoes). Precursory activity could include intermittent phreatic (steam) explosions that eject rocks near the vent. Erupted ash could rise several kilometers into the air and deposit local accumulations. Columns of ash that rise high into the atmosphere pose hazards to aircraft, particularly those with jet engines (Clynne et al. 2000b). Tephra from the most violent eruption of Lassen Peak on 22 May 1915 was carried by prevailing winds as far as about 500 km (310 mi) to the east where it fell on Elko, Nevada (Miller 1989).

A magmatic eruption may follow precursory activity. Silicic magma typically erupts explosively, creating a vertical eruption column and producing large volumes of tephra. Collapse of the column could generate pyroclastic flows. Objects and structures in the path of a pyroclastic flow, which tend to follow valleys, are generally destroyed or swept away. Hot debris and gasses can ignite vegetation, wood, and other combustible materials. Humans and animals may be injured or killed by a direct impact from a pyroclastic flow (e.g., burial) or inhalation of hot ash and gas around the margins of a pyroclastic flow (Miller 1989).

After an initial explosive eruption, extrusion of gas-depleted magma commonly forms lava domes. Dome formation and associated lava flows could continue for a few months to a few years. Growing lava domes are inherently unstable, and collapse of their steep sides often generates pyroclastic flows of lava blocks and ash capable of travelling several kilometers. The Chaos Crags domes (A–F) and associated deposits likely formed in this manner about 1,050 years ago. The Chaos Crags area remains the most susceptible for future dome formation and collapse at the park (Clynne et al. 2012).

Lahars

Lahars are highly mobile, fast-moving mixtures of volcanic rock fragments, sand, mud, and water that can flow many kilometers down valleys at very high speeds, as much as 100 kph (60 mph). Because of their high speeds, they are one of the deadliest volcano hazards. The major hazard to human life from a lahar is burial or impact by debris. People and animals also can be severely burned by hot debris carried by lahars. Buildings and other property in the path of a lahar can be buried, smashed, or carried away. Lahars can move or carry away vehicles and other objects as large as bridges and locomotives because of their relatively high density and viscosity (Miller 1989). Compared to “normal” storm-related flooding, the high sediment content of floods associated with lahars makes them especially dangerous and damaging (Miller 1989).

Pyroclastic flows moving over snow or an avalanche of hot rock that incorporate large amounts of snow are the most likely causes of a lahar at the park. Both these types of lahars occurred during the 1915 eruption of Lassen Peak (Clynne et al. 2012). Although lahars are often generated when hot lava or pumice rapidly melt snow or ice, they do not require a volcanic eruption to be triggered. Heavy rainfall can also generate a lahar on a steep-sided volcano. In 1963, torrential rains triggered a small lahar on the lower slopes of Lassen Peak, mobilizing recently deposited loose volcanic and sedimentary material (Clynne et al. 2012). A lahar may also form by the addition of streamflow. For example, 1,050 years ago during the Chaos Crags eruption, a pyroclastic flow moving down the Manzanita Creek drainage was transformed into a lahar by incorporating water from the creek (Clynne et al. 2012). Other lahar deposits in the geologic record at the park illustrate other means for lahar hazards. About 8,000 years ago, during the last deglaciation, lahars were initiated on Lassen Peak by mobilization of recently deposited glacial sediments (Marron and Laudon 1986; Christiansen et al. 2002). This type of lahar is very unlikely under present climatic conditions, however.

Volcano Monitoring

Although some volcanoes have erupted violently without any apparent warning, most eruptions are preceded days, weeks, months, or even years by volcanic activity on a small, relatively harmless scale (Crandell and Mullineaux 1970). The most significant precursory phenomena often include the following:

- Marked and continuing increase in the frequency and magnitude of local earthquakes
- Appearance of steam jets and clouds of water vapor, possibly accompanied by explosions and rockfalls
- Subterranean rumbling noises
- Substantial increase in the temperature and activity of hot springs and fumaroles, and the appearance of these features in new areas
- Increase in the amount of sulfur and chlorine or fluorine in fumarolic gases
- Repeated landslides on the flanks of a volcano

People living near volcanoes may detect such phenomena before an eruption. However, most pre-eruption changes are subtle, and the most effective means for detecting these changes are instrumental and include a variety of geophysical, geodetic, and geochemical techniques (Miller 1989). In the *Geological*

Monitoring chapter about volcanoes, Smith et al. (2009) described seven vital signs and methodologies for understanding and monitoring volcanoes: (1) earthquake activity, (2) ground deformation, (3) emission at ground level, (4) emission of gas plumes and ash clouds, (5) hydrologic activity, and (6) slope instability.

The USGS California Volcano Observatory (CalVO) in Menlo Park, California, coordinates monitoring of the Lassen volcanic center via periodic measurements of ground deformation and volcanic-gas emissions and continuous transmission of data from a local network of 13 seismometers (see "Seismic Activity" section). Ground deformation (swelling upward and outward of Earth's surface as magma moves into a volcanic system) is measured using the global positioning system (GPS) (US Geological Survey 2012a). Refer to the CalVO website for more information: http://volcanoes.usgs.gov/observatories/calvo/ (accessed 6 November 2013).

Although monitoring systems may be useful by indicating an increase in the probability of volcanic activity and its possible location, they typically do not indicate the kind or scale of an expected eruption, or even its certainty. Precursors to volcanic activity may continue for weeks, months, or even years before eruptive activity begins, or activity can subside at any time and not be followed by an eruption (Clynne et al. 2012).

Volcano Hazard Mitigation

The California Volcano Observatory will immediately deploy scientists and instrumentation to evaluate potential threats identified during monitoring. The National Park Service has developed an emergency operations plan (National Park Service 2012) to protect the public in the event of an impending eruption. Park managers distribute a site bulletin covering basic evacuation procedures (National Park Service 2006).

In the event of renewed volcanic activity in the park, the time of year would be an important factor. During the winter, much of the park road is covered with snow and closed, but mudflows, debris flows, or lahars could cover segments of the main park road, as well as service roads and California Highways 44 and 36, affecting both day use and overnight camping. During the summer, several thousand visitors could be in the park and almost as many more in nearby communities and resorts. Evacuation of visitors from the park, especially in the wilderness area, would be difficult without assistance from other agencies.

Seismic Activity

The Lassen area experiences tectonic, volcanic, and hydrothermal earthquakes. Tectonic earthquakes occur because the Lassen volcanic center is located along the western edge of a region of closely spaced normal faults—the Basin and Range physiographic province, which impinges on the Cascade arc (Guffanti et al. 1990). Volcanic earthquakes are generally interpreted as reflecting movement of mafic magma into the deep crust below an active volcanic area (Pitt et al. 2002). As magma moves through the Earth, it displaces and fractures rock along the way, causing earthquakes. About 25% of the seismic events in the Lassen region are associated with the Lassen hydrothermal system (Klein 1979; Walter et al. 1984). These small earthquakes are clustered beneath the hydrothermal features at shallow depth and typically occur in episodes of 10–25 events over a 1–3 day period. This seismicity is related to hydrothermal alteration and brittle failure of rock in the hydrothermal system (McLaren and Janik 1996; Janik and McLaren 2010).

Tectonic Earthquakes

The Lassen area is subject to considerable seismic activity. Three notable earthquake sequences occurred in the region in 1936, 1945–1947, and 1950 (Norris et al. 1997). These included main shocks as large as magnitude (M) = 5.5 and thousands of smaller events that were attributed to east–west extension on Basin and Range normal faults (Norris et al. 1997). Smaller bursts of seismic activity—generally with earthquakes of M = 4 to 5 and dozens of smaller shocks—occur every few years. If the earthquakes are of tectonic origin, the resulting hazard would be chiefly from landslides, rather than from volcanic phenomena (Crandell and Mullineaux 1970; see "Slope Movements" section).

Major faults in the area, including the Hat Creek fault and faults with large offsets in the Lake Almanor area, are capable of earthquakes as large as M = 7 (Wills 1990a, 1990b; Clynne et al. 2012). The Hat Creek fault offsets the 24,000-year-old Hat Creek Basalt (map unit PEbhc) by as much as 30 m (100 ft) (Muffler et al. 1994; Turrin et al. 2007). Displacement of outwash gravels (outwash of Anklin Meadows, PEoa) overlying the Hat Creek Basalt shows that vertical offset on the Hat Creek fault has averaged 1.3 mm (0.05 in) per year for the past 15,000 years (Clynne et al. 2012); this is similar to the long-term average of the fault (Muffler et al. 1994).

Work by Walker and Kattenhorn (2008) characterized the slip history and evolution of the Hat Creek fault, which reflects a complex interplay between tectonic and magmatic influences. In response to these influences, the northern portion of the fault system has migrated progressively westward, abandoning older scarps in its wake, whereas the southern portion continues to use Pleistocene slip surfaces (Walker and Kattenhorn 2008). Additionally, Blakeslee and Kattenhorn (2010) studied the evolution of the segmented Hat Creek fault, as well as the earthquake hazard associated with it. These investigators determined that the Hat Creek fault system has the potential to produce an earthquake of at least M = 6.5.

Volcanic Earthquakes

Volcanic earthquakes, which often provide the initial sign of volcanic unrest, are measured with seismometers at the park (US Geological Survey 2012c). The signals of volcanic earthquakes differ from tectonic earthquakes: they tend to be found at depths shallower than 10 km (6 mi), are small in magnitude (M < 3), occur in swarms, and are restricted to the area beneath a volcano (US Geological Survey 2012c).

Between 1982 (when the Lassen seismic network was established) and 2002, seismometers detected 29 volcanic earthquakes at depths from 13 to 23 km (8 and 14 mi), primarily in an area about 5–8 km (3–5 mi) west of Lassen Peak near the northwestern corner of the park (Pitt et al. 2002). Investigators estimated an average of about two volcanic earthquakes per year in this area. However, seismicity is clearly episodic, and as many as eight earthquakes have occurred in one year (1988) and none in others (e.g., 1991) (Pitt et al. 2002).

Since 2002, improvements in the Lassen seismic network have led to increased detection of volcanic earthquakes. Unpublished data document an average of 11 volcanic earthquakes per year between 2003 and 2011, most in small clusters (Clynne et al. 2012).

Seismic Monitoring

Currently, the US Geological Survey monitors and maintains 13 seismometers around the Lassen volcanic center. The network was installed in 1976 with several additional instruments added in each decade since (US Geological Survey 2012c). The USGS Earthquake Hazards Program posts online information about seismic activity in California, including historic information, earthquake institutions and USGS branches in California, maps, notable earthquakes, recent earthquakes, tectonic information, and information on other topics (e.g., the San Andreas fault) (http://earthquake.usgs.gov/earthquakes/states/?region=California; accessed 22 March 2013).

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

Slope Movements

In the chapter in *Geological Monitoring* about slope movements, Wieczorek and Snyder (2009) described five vital signs for understanding and monitoring slope movements: (1) types of landslide, (2) landslide causes and triggers, (3) geologic materials in landslides, (4) measurement of landslide movement, and (5) assessment of landslide hazards and risks. Also, Highland and Bobrowsky (2008) and the US Geological Survey Landslide Hazards Program (http://landslides.usgs.gov/, accessed 6 November 2013) provide detailed information regarding slope movements, monitoring, and mitigation options.

The following factors contribute to slope movement at the park: volcano edifices are typically covered with loose material; hot lava and interbedded fragmental deposits produce weak, fractured rock masses when they cool; and new lava is often deposited on steep surfaces. Furthermore, weathering and hydrothermal alteration weaken volcano edifices.

Clynne and Muffler (2010) mapped a variety of deposits related to slope movements within the park, including landslides (Hsh), debris avalanches (Hsj, PEsl, and PEs82), debris flows (Hwh and PEwb), and deposits of talus and colluvium (HPEc and PEcl). Locations of past slope movements as delineated by these map units may be prone to future activity. These units are combined and depicted as unit HPEsm on the geologic map graphic (map 1, in pocket).

Slope movement on volcano edifices can be triggered by a variety of volcanic and non-volcanic events. The onset of volcanic unrest—which includes seismic activity, steam explosions, and intrusion of magma—greatly increases the likelihood of slope movements. Non-volcanic triggers include tectonic earthquakes, rainstorms, rapid snowmelt, and day-to-day erosional processes (Clynne et al. 2012).

Chaos Jumbles

Very large debris avalanches are particularly hazardous because of their possible high speeds. The avalanche deposits of Chaos Jumbles (Hsj; fig. 32) are a noteworthy example at the park (Eppler 1984; Eppler et al. 1987). Chaos Jumbles was the result of the partial collapse of dome C (Hrcc) of Chaos Crags. Covering an area of 7 km^2 (3 mi^2), Chaos Jumbles consists of three debris-avalanche deposits that all formed during a single, short episode (Crandell and Mullineaux 1970; Clynne et al. 2002; Clynne and Muffler 2010). Trees drowned in Manzanita Lake, which formed as a result of the first debris avalanche (see “Lakes” section), yielded a radiocarbon age of 278 ± 28 radiocarbon years BP. These debris avalanches were the result of slope instability and probably not caused by a volcanic eruption (US Geological Survey 2011).

Figure 32. Chaos Crags and Chaos Jumbles. Chaos Jumbles—a huge avalanche-debris deposit (map unit Hsj)—formed as a result of partial collapse of dome C of Chaos Crags (Hrcc). The collapse was catastrophic, and three debris avalanches were emplaced in quick succession. Material from the avalanche deposits created Chaos Jumbles, which is in the foreground of the photograph. National Park Service photograph, available at http://www.flickr.com/photos/61860846@N05/ (accessed 26 March 2013).

The first and largest avalanche traveled 6 km (4 mi) downslope and ascended 120 m (400 ft) up the side of Table Mountain. The other avalanches were successively smaller and shorter, but thicker. The distance traveled—over relatively gentle slopes and up the flanks of Table Mountain—suggests that this material moved as high-speed, air-cushioned avalanches (Crandell and Mullineaux 1970; US Geological Survey 2011). Although the speed of these slides was not recorded, similar large slides elsewhere in the world attain speeds between 105 and 340 kph (65 and 210 mph). Such speeds make almost any kind of alarm system ineffective (Crandell and Mullineaux 1970). For example, an avalanche traveling 160 kph (100 mph) would move from the base of the Chaos Crags to Summertown or the Loomis Museum in about 90 seconds (Crandell and Mullineaux 1970).

Brokeoff Volcano

The hydrothermally altered core of Brokeoff Volcano—in particular Brokeoff Mountain and Pilot Pinnacle—is susceptible to slope movements. The remaining volcano rim and core are unstable and subject to small landslides and debris flows (Hsh), dozens of which have occurred in the drainages of Sulphur Creek (Clynne and Muffler 2010). These deposits are Holocene in age, and some are subject to reactivation during spring snowmelt. In addition, several major landslides of Holocene age (Hsh) originated from the high, interior parts of the eroded volcano. The largest of these broke away from a scarp above Forest Lake about 3,310 years ago and flowed nearly 7 km (4 mi) down Mill Creek (Clynne et al. 2002). This landslide deposit contains bedrock blocks as much as 100 m (330 ft) long. Another large landslide originated from the northwestern side of Pilot Pinnacle and flowed north into Blue Lake Canyon (Clynne and Muffler 2010).

Lassen Peak

Lassen Peak is also noted for slope movements, and Clynne and Muffler (2010) mapped two significant deposits: (1) avalanche debris from Lassen Peak spread across glacial ice (PEsl), and (2) debris-flow deposits from the northeast side of Lassen Peak (Hwh). These slope deposits were emplaced during the late Pleistocene and Holocene, respectively. In addition, USGS scientists from the California Volcano Observatory noted a recent rockfall event on the northeastern flank of Lassen Peak; 10,000 m^3 (13,000 yds^3) of debris slid 610 vertical meters (2,000 vertical feet) away from the edifice in 1994. Because the park's seismic monitoring equipment did not record any seismic activity prior to this rockfall, failure most likely resulted from normal weathering that weakened the fractured volcanic rocks (US Geological Survey 2012b).

Geothermal Development

Development of geothermal resources can have significant adverse effects on hydrothermal features such as geysers, hot springs, fumaroles, mud pools, sinter terraces, and thermal ground (Barr 2001). Reduction or loss of thermal features is generally caused by declining reservoir pressure, which affects the amount of hydrothermal fluids reaching the surface. Activities such as geothermal drilling and withdrawal may result in reservoir pressure decline. If allowed to continue, the hydrothermal features may die and hydrothermal flow may reverse with cold groundwater flowing down into the reservoir (Barr 2001).

The Geothermal Steam Act of 1970 as amended in 1988 provides the basis for managing and protecting hydrothermal features within the National Park System (Barr 2001; see also Appendix B). Mitigating impacts of geothermal development on park resources involves not only the National Park Service, but also the US Geological Survey, which does research in parks; the Bureau of Land Management (US Department of the Interior), the leasing agency (regardless of federal land ownership); and the Forest Service (US Department of Agriculture), the principal surface management agency adjacent to many parks. The Department of Energy, which deals with energy issues, may also become involved (Barr 2001).

In the history of Lassen Volcanic National Park, two instances of geothermal exploration have had the potential to impact hydrothermal features. First, in 1962, the Shasta Forest No. 1 well was drilled on an inholding in the park (Patrick Muffler, US Geological Survey, scientist emeritus, written communication, 19 July 2013). The inholding included Terminal Geyser, which is one in a series of fumaroles that encompasses Devils Kitchen, Drakesbad, and Boiling Springs Lake. This exploratory well was drilled to a depth of 392 m (1,285 ft). At the time of drilling, no geothermal resource was evident, so drilling was stopped and the well was capped in a manner to allow future exploration at the site (Herbst 1979). Renewed development activity and deepening of the well, now referred to as the Walker O well (fig. 33), in 1978 by the Phillips Petroleum Company raised public and NPS concern over potential damage to nearby park thermal features (see Clynne et al. 1982). Concern prompted condemnation proceedings of the private land and mineral rights in the early 1980s. Ultimately, Lassen Volcanic National Park acquired the land and mineral rights at fair market value (Barr 2001). The National Park Service also acquired the liability for plugging the well and reclaiming the site.

The Walker O well, abandoned in 1979, remained unplugged and un-maintained until the late 1990s. Over the intervening years, the access road to the site began to erode and the drill pad began to slump. Park staff became increasingly concerned about the stability of the well and the potential for a blowout or emission of hazardous gas (Nagle 1985). The well was finally plugged in October 1997 (Mark Ziegenbein, Geologic Resources Division, geologist, email communications, March 2005). Staff from Yosemite and Lassen Volcanic national parks reclaimed the access road and well site in July 1999 (Louise Johnson, Lassen Volcanic National Park, chief of Resource Management, email communications, March 2005).

Figure 33. Walker O geothermal well. In 1962, an exploratory well was drilled on an inholding near Terminal Geyser (in the background; see also fig. 18). The threat of geothermal development at this site lasted until 1979 when the well was abandoned and the National Park Service obtained the land and mineral rights. The well was finally plugged in 1997. National Park Service photograph by John M. Mahoney, copied from Krahe and Catton (2010).

The second instance of potential impacts to hydrothermal features at the park occurred when the Forest Service proposed leasing of approximately 405,000 ha (1 million ac) for energy development south of the park. This geothermal area became known as the Lassen Known Geothermal Resource Area (KGRA).

A study conducted by the US Geological Survey found a hydrologic connection between the KGRA and the hydrothermal areas within the park (Muffler et al. 1982). These findings and the Geothermal Steam Act Amendments of 1988, which require determination of the impacts to geothermal features listed in the act before any leasing actions occur, resulted in the Forest Service putting a hold on potential leases (National Park Service 1994). Ultimately, the Bureau of Land Management established a buffer zone south of the park where no leasing of land for geothermal development occurs (Barr 2001; Clynne et al. 2003). Areas east and west of the park are not known to have a connection to the Lassen hydrothermal system, and these areas have not been closed to leasing for hydrothermal energy development (Barr 2001). However, the Bureau of Land Management, National Park Service, US Geological Survey, and the Forest Service have an interagency agreement in place that ensures that the National Park Service is consulted prior to any leasing, drilling, or other development in an area that may impact the park's hydrothermal features (Covington 2004).

Abandoned Mineral Lands

The National Park Service is in the process of conducting an inventory and assessment of its abandoned mineral lands (AML). The inventory is completed except for National Park System units in California, where approximately 80% of the documented AML features are located (Burghardt et al. 2013). The AML database lists eight surface mines within Lassen Volcanic National Park. However, with the inventory of California parks still underway, much is unknown about these sites, and no assessment has occurred since 1999 (see Ziegenbein and Wagner 2000).

In 1999 the NPS Geologic Resources and Water Resources divisions responded to a technical assistance request to assess disturbed lands in the park. As part of this inventory, Ziegenbein and Wagner (2000) assessed and summarized the status of 22 disturbed sites, including eight gravel/borrow pits, two volcanic rock (dacite) quarries, and a pumice pit (a total of 11 sites with mining activity). At the time of this assessment, four of these 11 sites were "active," primarily for storing sand and gravel, and disposing of concrete, asphalt, tree stumps, and slash. Ziegenbein and Wagner (2000) did not indicate that extraction of mineral resources was occurring at these sites. Three of the sites were noted as possibly containing hazardous or contaminated materials: Butte Lake pit, Crags pit, and Summertown pumice pit (Ziegenbein and Wagner 2000).

During the review process of this report, Patrick Muffler (US Geological Survey, scientist emeritus) noted that Sulphur Works apparently had been mined for sulfur at some point in the historic past (written communication, 30 June 2013). Indeed, Krahe and Catton (2010)—an administrative history of Lassen Volcanic National Park—reported that Dr. Mathias B. Supan of Red Bluff held a mining claim in Sulphur Works from which he extracted sulfur each summer for about 20 years, ca. 1865. Supan hauled the material by pack train to a furnace and retort on Paynes Creek. According to Krahe and Catton (2010, p. 12), Supan "used his knowledge of chemistry and medicine to experiment with various products that he dispensed in his drug store in Red Bluff. Cooking the sulphur in kilns, he made bricks and various kinds of earthenware products. Using the ferrous salts that formed a crust at the edge of the hot springs, he produced dyes and printers' ink, which he sold in San Francisco." In addition, Bumpass Hell also attracted prospectors. In the early 1880s, a surveyor of the General Land Office labeled "Bumpber's [sic.] Hell, Boiling Sulphur Spring" on a map and recorded a mining shaft 20 feet deep (abandoned)" (Krahe and Catton 2010, p. 12).

The Geologic Resources Division, which is administering the AML inventory, may be consulted for assistance and guidance regarding AML sites within the park, as well as about updates on the status of the inventory.

Disturbed Lands Restoration

Activities such as logging, ranching, and recreation created disturbed lands prior to park establishment in 1916. After establishment of the park, the National Park Service built roads and other infrastructure to facilitate administration and management. Many of these activities disturbed surface hydrology (Zeigenbein and Wagner 2000).

Dream Lake

An assessment of disturbed lands in Lassen Volcanic National Park by Ziegenbein and Wagner (2000), and the 2004 Geologic Resources Evaluation (now Geologic Resources Inventory) scoping summary, identified Dream Lake for restoration. An earthen dam—about 80 m (260 ft) long, 4 m (11 ft) high, and 1.2 m wide (4 ft) at its top—created Dream Lake—a small, 0.7-ha (1.7-ac) reservoir on the southern side of Drakesbad Meadow (fig. 34). The dam, constructed in 1932, impounded approximately 1.2 surface ha (3 surface ac) of water for recreational purposes at the Drakesbad Guest Ranch.

Figure 34. Dream Lake. Constructed in 1932, an earthen dam created Dream Lake for recreational purposes, primarily at Drakesbad Guest Ranch. The National Park Service removed the dam and lake in 2011–2012. National Park Service photograph, available at http://flic.kr/p/dCn6L4 (accessed 12 November 2013).

Ziegenbein and Wagner (2000) documented evidence of erosion and piping on the downstream side of the dam. These signs of deterioration showed that water had briefly flowed over the top of the dam at some point in the past. Erosion and piping in an earthen dam are precursors to dam failure, which could occur the next time stream inflow exceeded the spillway channel capacity (Ziegenbein and Wagner 2000). The dam had survived many seasons, but Ziegenbein and Wagner (2000) warned that failure could occur at any time within the next few years or up to 20 years, and a flood resulting from dam failure would have been hazardous to park visitors and employees, as well as infrastructure in the area. Sudden release at maximum reservoir volume and high discharge would have been relatively violent and could have released tons of sediment to the system, as well as scoured the abandoned streambed and relict riparian areas below the dam. Scouring and vegetative damage would have likely created bank instability and increased erosion for years thereafter (Ziegenbein and Wagner 2000).

In July 2011, park staff began to restore the area with guidance from the Warner Valley comprehensive site plan and final environmental impact statement (National Park Service 2010). The process of removing the dam and lake began with extraction of trees that had grown on the dam, followed by breaching the dam by hand (fig. 35). Resource staff monitored water quality for turbidity

Figure 35. Breaching of the dam at Dream Lake. The earthen dam at Dream Lake was breached by hand in July 2011. Water flow was monitored to manage sediment discharging into Hot Springs Creek. National Park Service photograph, available at http://flic.kr/p/dCsxzb (accessed 13 November 2013).

Figure 36. Spring-fed channel at the former Dream Lake. As Dream Lake drained away, spring-fed streams carved meandering channels into the exposed lake bottom. National Park Service photograph, available at http://flic.kr/p/dCsxLY (accessed 13 November 2013).

Figure 37. Dream lake/meadow. Following dam removal, meadow plants immediately flourished on the lake bottom in the springtime. National Park Service photograph, available at http://flic.kr/p/dCsySh (accessed 13 November 2013).

throughout the drainage and earth moving processes. Complete drainage of the lake took five weeks (Janet Coles, Guadalupe Mountains National Park, chief of Resource Management, formerly with Lassen Volcanic National Park, written communication, 9 April 2013).

After draining, spring-fed streams established channels in the former lake bed (fig. 36). Natural revegetation started almost immediately once organic material within the lake bed was exposed to the sun (Carpenter 2012; Janet Coles, written communication, 9 April 2013; fig. 37). Placement of plugs of native grasses and sedges in disturbed areas augmented natural revegetation (Carpenter 2012).

In mid-October 2011, park personnel removed the remainder of the dam with a small excavator and used the excavated material to help reestablish the original grade of the basin. Additional material was removed from the dam site in 2012 in order to match the new level of the water table (Janet Coles, written communication, 9 April 2013).

Drakesbad Meadow

In the early part of the 20th century, ranchers dug thousands of meters of ditches to drain a 33-ha (82-ac) wet meadow–fen complex in the Warner Valley in order to provide better pasture for domestic livestock (fig. 38). The process created Drakesbad Meadow and dewatered (and degraded) an uncommon montane fen ecosystem (Havens 2012). Agricultural uses of the meadow ceased in the 1950s, but later modifications include a service road that blocked sheet flow (overland flow) from hillside springs to the upper meadow (fig. 39). Additionally, an elevated causeway was built to facilitate horseback and hiker access from the Drakesbad Guest Ranch to surrounding trails. The causeway, which bisects the meadow from north to south, prevents surface water flow from west to east (Schook and Potter 2012).

Figure 38. Ditch through Drakesbad Meadow. Ranchers in Warner Valley created ditches to divert spring–fed water flow through the meadow and into adjacent Hot Springs Creek in order to make the meadow more favorable for livestock grazing. National Park Service photograph, available at http://flic.kr/p/dCtG6S (accessed 13 November 2013).

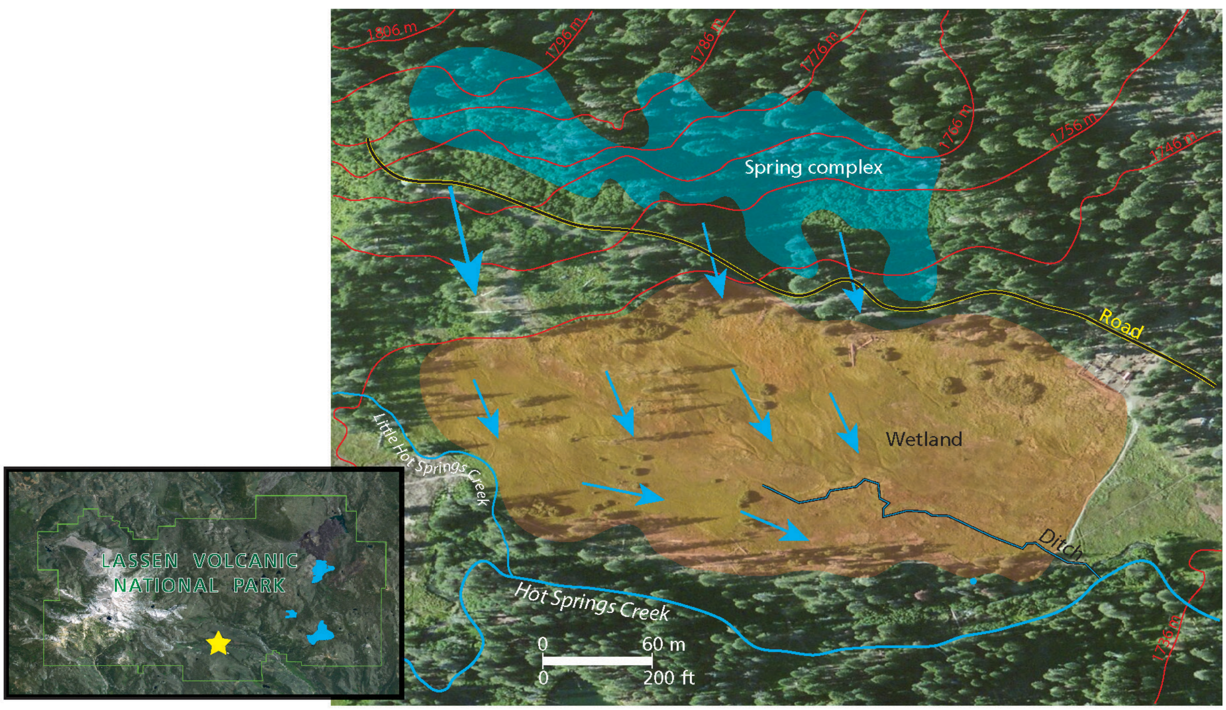

Figure 39. Map of Drakesbad Meadow. Historically, Drakesbad Meadow (location within the park indicated by a yellow star on inset map) was a montane fen, which had been degraded and dewatered with drainage ditches (fig. 38) and by a road that impacted surface and groundwater flow of springs north of the meadow. Snag Lake, Horseshoe Lake, and Juniper Lake are highlighted in blue on the inset map, north to south respectively. The site map (right) shows topography (red lines), wetland/groundwater discharge areas, and major groundwater flow paths (blue arrows). Aerial imagery from ESRI ArcGIS Imagery base map, annotation by Trista Thornberry-Ehrlich (Colorado State University) with information from Patterson and Cooper (2007).

Figure 40. The return of Drakesbad fen. Only about a month after the artificial drainage ditches were filled, the water level in the meadow had risen substantially, making former locations of the ditches difficult to distinguish. National Park Service photograph, available at http://flic.kr/p/dCoBt6 (accessed 13 November 2013).

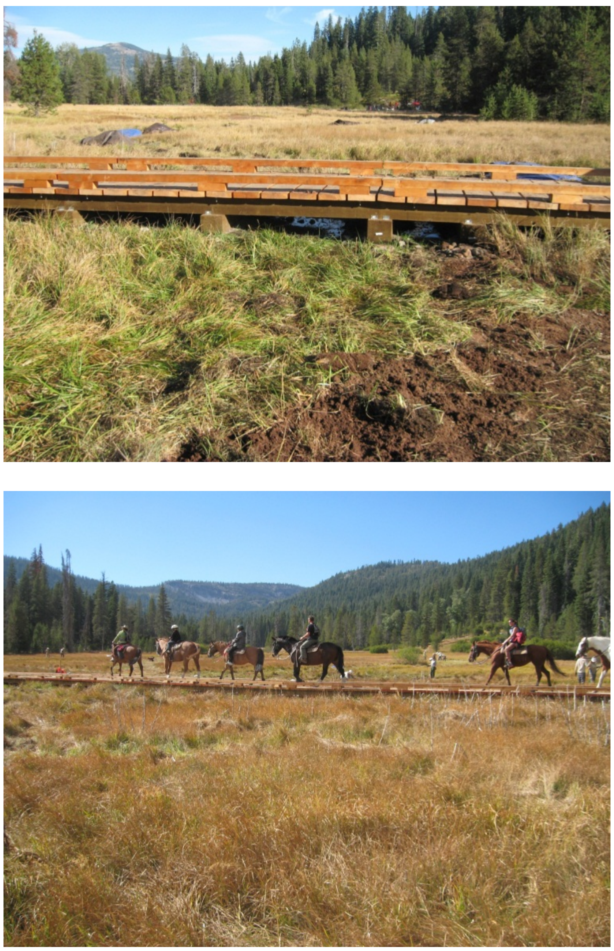

Figure 41. Boardwalk across Drakesbad Meadow. The causeway that impacted west–east sheet flow across the meadow was replaced by a "floating" boardwalk that permits flow across the area while providing for "dry" passage of hikers and horseback riders. National Park Service photographs, available at http://flic.kr/p/dCtHf3 (left) and http://flic.kr/p/dCohbc (right) (accessed 13 November 2013).

The alteration of water flow as a result of trenches, road, and causeway impacts hydrology and plant communities. Fens in the Lassen region will not persist under the drought-like conditions created by these water diversions (Patterson and Cooper 2007). However, well-designed restoration projects can be used to restore modified hydrologic regimes and peat-forming vegetation necessary for the persistence of fen wetlands. Patterson and Cooper (2007) implemented a pilot restoration project by installing a series of culverts placed under the road to allow water to flow toward Drakesbad Meadow. This effort provided partial restoration of the meadow's hydrologic regime, but could be improved with the construction of a permeable road base (Cooper et al. 2012).

In fall 2012, park staff began formal restoration of Drakesbad Meadow (fig. 40; see Cooper et al. 2012). The deepest ditches were filled with a soil mixture specially prepared for the project and then revegetated in order to slow and spread surface water. Within just a few days after completion of the fill project, the water table began to rise (Havens 2012). Groundwater levels will continue to be monitored (Janet Coles, written communication, 9 April 2013). In addition, a "floating" boardwalk replaced the causeway and now permits flow of water across the area while still providing access for horseback riders and hikers (fig. 41).

Manzanita Lake Dam

In 1911 the Northern California Power Company constructed Manzanita Lake Dam to enlarge a natural lake and increase water supply to a downstream power plant. Manzanita Lake presently contains about 640,000 m^3 (520 acre-feet) of water. The dam is believed to be homogeneous fill, consisting of silty sand and gravel (Danley 2004).

In 1931, ownership of the dam and reservoir was transferred to the federal government and incorporated into Lassen Volcanic National Park. The dam is not historically significant, but the lake is a popular visitor attraction, and the dam maintains lake levels (fig. 42). Also, the dam (and higher water levels) creates wetland habitat for native trout and bald eagles (National Park Service 1994).

As currently configured, the dam's spillway cannot handle more than a 5- to 10- year flood without overtopping. In addition to the potentially inadequate spillway, large-diameter conifer and deciduous trees are growing on the dam. Seeping and piping around rotting tree root cavities, as well as rodent burrows or unconsolidated dam fill, may create unstable conditions. During an annual inspection of the dam, NPS staff members monitor tree health and look for evidence of piping and seepage (Harry 2008).

Following a 1996 environmental assessment that identified alternatives and addressed public comments, park managers decided to maintain the dam and develop an appropriate emergency action plan in the event of imminent dam failure. The plan calls for inspecting the dam whenever rainfall exceeds 5 cm (2 in) in a 24-hour period and after significant storms.

Due to the age and unknown construction and materials of the dam, the National Park Service considers any earthquake greater than magnitude (M) = 5.4 occurring in the vicinity of the Manzanita Lake as a threat to the dam, and will initiate an emergency inspection if such an event occurs (Harry 2008). Notably, seismic activity may coincide with a volcanic eruption, and due to the proximity of vents to Manzanita Lake, ash fall, debris flows, and lava flows could hinder access to the dam for inspection.

Should the dam fail, the flood would significantly impact California Highway 44, which is 6.8 km (4.2 mi) downstream of the dam (Trieste 1995). In addition, dam failure would likely wash out Forest Service Road 17, which is 1.6 km (1 mi) below the dam. If failure appears imminent, the emergency plan will be put into action and local emergency management and transportation personnel will be notified immediately.

Figure 42. Manzanita Lake. In 1911 the Northern California Power Company constructed a dam to enlarge Manzanita Lake, a popular visitor attraction. The dam maintains lake levels and creates wetland habitat. National Park Service photograph, available at http://flic.kr/p/eY87Ea (accessed 13 November 2013).

Geologic History

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

Volcanism in the Lassen area is an outcome of the Cascadia subduction zone offshore of northern California (fig. 2). For the past 12 million years, the axis of the Lassen segment of volcanism has migrated westward from the California-Nevada border to its present position, while the width of the volcanic arc has narrowed (Guffanti et al. 1990) (fig. 43). Twelve million years ago, the southern limit of active volcanism was approximately at the latitude of Lake Tahoe, 180 km (110 mi) southeast of the park. By 3 million years ago, the southern limit of active volcanism had moved to around the Yana volcanic center, 30 km (20 mi) south of Lassen Peak near Lake Almanor. Today, active volcanism corresponds to the southern boundary of the park (Clynne and Muffler 2010).

Regional Volcanism

Regional volcanoes, including cinder cones and shield volcanoes within and surrounding the park, have built a broad platform of volcanic rocks that are part of the Cascade arc. Volcanic centers, such as the Lassen volcanic center, punctuate this volcanic platform. Clynne and Muffler (2010) mapped regional volcanic rocks north and west (shown as unit PE-Rnw on map 1, in pocket) and south and east (PE-Rse) of the Lassen volcanic center, as well as in the Caribou volcanic field (PE-Rc), which is centered 20–30 km (12–19 mi) east of the Lassen volcanic center. Older volcanic rocks (PEPL-Ro), deposited more than 650,000 years ago, surround the Caribou volcanic field to the north, east, and south, and form a base on which the volcanic field was built.

Regional Volcanic Rocks North and West of the Lassen Volcanic Center, *1.8 million to 11,700 years ago*

Clynne and Muffler (2010) separated the regional volcanic rocks north and west of the Lassen volcanic center by age; these rocks are middle Pleistocene and older (1.8 million–125,000 years ago) and late Pleistocene (125,000–11,700 years ago). None of these late Pleistocene volcanic rocks occur within the park. The 24,000-year-old Hat Creek basalt (PEbhc) is the closest and youngest of these rocks. The southernmost edge of the flow is north of the park (fig. 10).

Cinders of basaltic andesite of Little Bunchgrass Meadow (PEmbgci) are part of the "middle Pleistocene and older" grouping and were emplaced 143,000 ± 6,000 years ago. This unit is the youngest of these regional volcanic rocks within the park. Andesite of section 22 (PEa22) is the oldest unit of these regional volcanic rocks within the park, and was emplaced during the early Pleistocene Epoch, approximately 1 million–900,000 years ago (Clynne and Muffler 2010). The shield volcanoes of Prospect Peak, which is composed of andesite and basaltic andesite of Prospect Peak (PEap), and Table Mountain, which is composed of andesite of Table Mountain (PEat), are part of this grouping of regional volcanic rocks.

Regional Volcanic Rocks South and East of the Lassen Volcanic Center, *1.7 million to 65,000 years ago*

Regional volcanic rocks south and east of the Lassen volcanic center are bracketed in age by the basaltic andesites of South Fork Battle Creek (PEmbc; approximately 1.7 million years ago) and tholeiitic basalts of Buzzard Springs (PEbbz; approximately 65,000 years ago). Sifford Mountain (PEbsm, PEbsmci), Mount Harkness (PEamh, PEamhci), and Huckleberry Lake (PEmhi, PEmhici) are features of this grouping of rocks within the park. Sifford Mountain is the youngest dated regional volcano from this grouping of regional volcanic rocks. This 170,000-year-old peak is the southernmost volcano in the park. The oldest unit within the park from this grouping of rocks is the middle-Pleistocene basaltic andesite of Huckleberry Lake (PEmhl, PEmhlci).

Regional Volcanic Rocks of the Caribou Volcanic Field, *450,000 years ago to the present*

Volcanic activity in the Caribou volcanic field began about 450,000 years ago and is still active, and thus contemporaneous with the Lassen volcanic center. Regional volcanic rocks of the Caribou volcanic field include the Red Cinder chain in the eastern part of the park and Caribou Wilderness. This chain of vents takes its name from Red Cinder—a cinder cone composed of basaltic andesite (PEmrr). The summit of Red Cinder—2,552 m (8,374 ft) in elevation—is just east of the park; the western flank of Red Cinder and much of the lava flow associated with the cone is within the park boundary. Red Cinder is the dominant volcano in this chain. Nearby Red Cinder Cone, within the park, is composed of two vents that issued basaltic andesite (PEmrc) from the more northern vent and basalt (PEbrc) from the southern vent. The southern vent area of Red Cinder Cone—2,441 m (8,008 ft) in elevation—is the highest point in the eastern part of the park.

Volcanic Centers

Five volcanic centers occur in the park and vicinity: Latour, Yana, Dittmar, Maidu, and Lassen (table 4). Typically, a single volcanic center is active and becomes extinct before, or as, the next center begins. However, activity within the Maidu and Dittmar volcanic centers coincided (table 4).

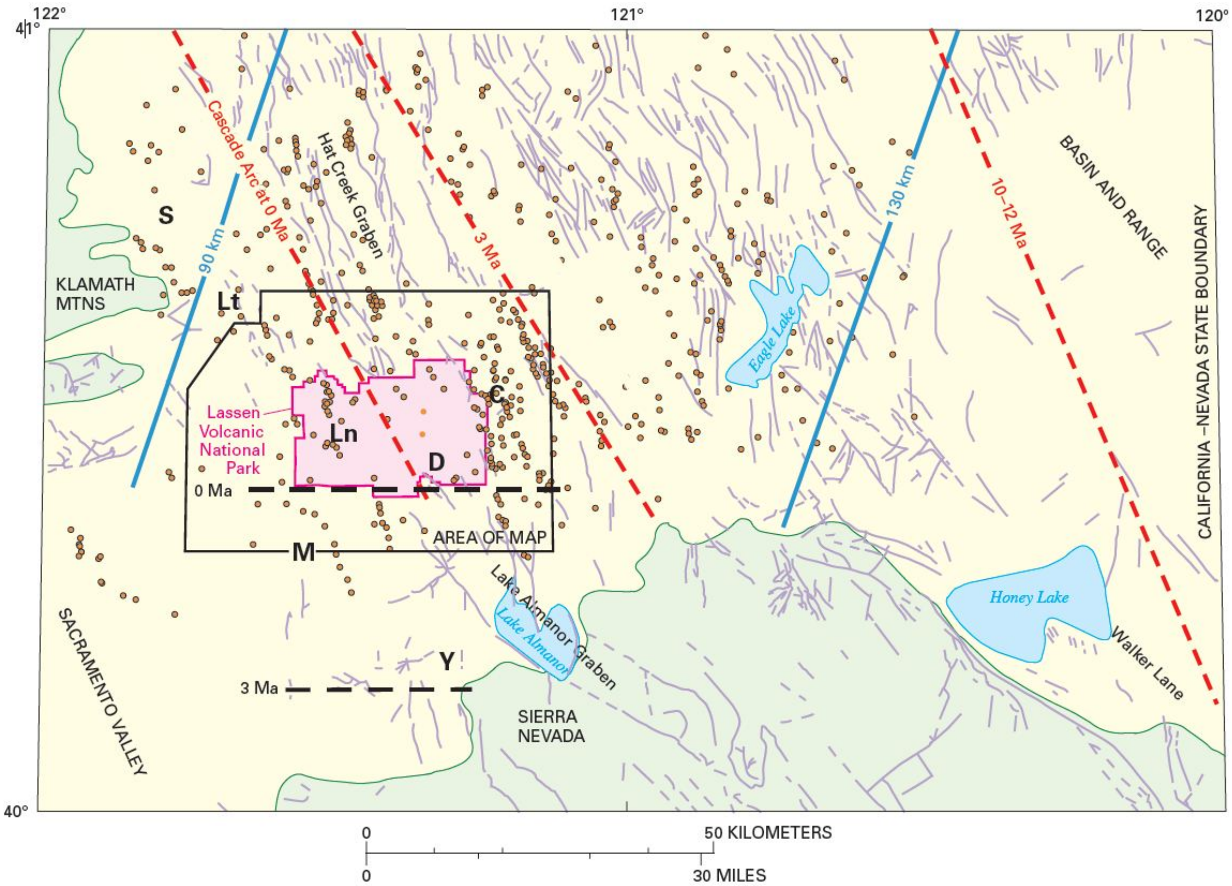

Figure 43. Map of regional geologic setting of Lassen Volcanic National Park. The Lassen volcanic center (Ln) is the currently active volcanic center in the Lassen area. Bold purple letters indicate the positions of the volcanic centers in the Lassen area: Y = Yana, M = Maidu, D = Dittmar, Ln = Lassen, and Lt = Latour. C = Caribou volcanic field. The Snow Mountain volcanic center (S) is north of the map area and is not discussed in this report. Though not labeled specifically, regional volcanoes are part of the light-yellow background area, which covers volcanic rocks of late Pliocene to Holocene age. Green background indicates Paleozoic to Mesozoic metamorphic-plutonic basement of the Sierra Nevada and Klamath provinces. Short, dashed red lines show the position of the axis of the Cascade volcanic arc at the times indicated; Ma = millions of years ago. Thick, dashed black lines indicate the southern terminus of arc volcanism at the times indicated. Thin violet lines show the location of faults. Orange dots indicate the locations of volcanic vents younger than about 7 million years; older vents are not shown. The black outline indicates the area covered by the GRI digital geologic data. The red outline indicates the boundary of Lassen Volcanic National Park and the area covered by the geologic map graphic (map 1, in pocket). Graphic from Clynne and Muffler (2010).

Table 4. Volcanic centers

Volcanic Center	Age (years ago)
Lassen	825,000–0
Maidu	2.4–1.2 million
Dittmar	2.4–1.4 million
Yana	3.4–2.4 million
Latour	>3 million

Source: Clynne and Muffler (2010).

Latour, *active more than 3 million years ago*

The Latour volcanic center is northwest of the park (fig. 43). It consisted of an andesite volcano and flanking silicic rocks similar to the other volcanic centers in the Lassen area. Latour Butte is a remnant of the larger volcanic center. Scientists know very little about the history of this particular volcanic center (Clynne and Muffler 2010).

Yana, *active from 3.4 to 2.4 million years ago*

The Yana volcanic center is south of the park, approximately 20 km (12 mi) southwest of Chester, California (figs. 43 and 44). Rocks of the Yana volcanic center dominate the area southwest of Lake Almanor (fig. 43). Butt Mountain, Ruffa Ridge, and Humboldt Peak are the major remnants of a deeply eroded andesitic composite volcano that was 15–20 km (24–32 mi) in diameter (fig. 44).

Dittmar, *active from 2.4 to 1.4 million years ago*

The Dittmar volcanic center (shown as unit PEPL-D on map 1, in pocket) is in the southeastern part of the park and centered in the upper Warner Creek valley just north of Kelly Mountain (fig. 43). The center has a diameter of about 20 km (12 mi). Saddle Mountain, Pilot Mountain, Kelly Mountain, and Mount Hoffman are the largest remnants of a deeply eroded andesitic composite volcano that once dominated this volcanic center.

Maidu, *active from 2.4 to 1.2 million years ago*

The Maidu volcanic center is southwest of the park in the area around Battle Creek Meadows near the town of

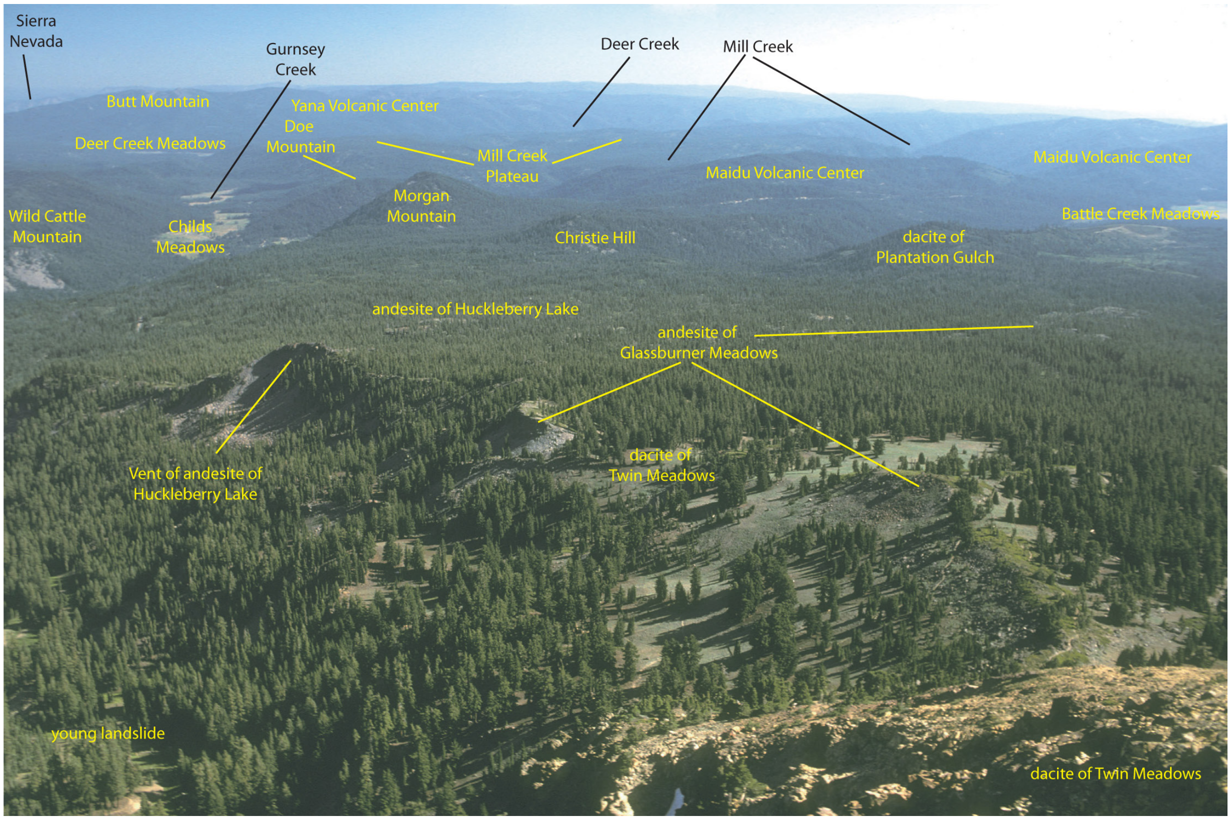

Figure 44. Volcanic centers. The southern flank of Brokeoff Mountain is covered mostly by lava flows of the regional basaltic andesite of Huckleberry Lake (map unit PEmhl). Volcanic rocks of the Maidu and Yana volcanic centers are in the distance. The forested area at the left bottom of the photograph is floored by the 3,310 ± 55 year BP landslide (Qsh) that originated at the large scarp below Brokeoff Mountain and flowed for at least 7 km (4 mi) down Mill Canyon. The dacites of Morgan Mountain, Christie Hill, and Plantation Gulch, prominent in the upper center of the photograph, are partially buried by lavas from Brokeoff Volcano. These three domes are part of the Rockland caldera complex and at an estimated 825,000–800,000 years old are probably the oldest preserved units of the Lassen volcanic center. The dissected area between Childs Meadows and Battle Creek Meadows forms the eastern flank of the Maidu volcanic center and is mostly beyond the area mapped by Clynne and Muffler (2010). The Mill Creek Plateau is one of several large and thick rhyolite lava flows that flank the Maidu volcanic center. The andesites of Doe Mountain and Wild Cattle Mountain are part of the Dittmar volcanic center. The Yana volcanic center and Butt Mountain form most of the skyline well beyond the map area. Deer Creek is between the Maidu and Yana volcanic centers. The northern Sierra Nevada mountain range is partially visible beyond the Yana volcanic center. US Geological Survey photograph by Michael A. Clynne.

Mineral, California (figs. 43 and 44). Lava flows (PLam) from the Maidu volcanic center underlie the park headquarters. The center was at least 25 km (15 mi) across. Hampton Butte and Turner Mountain are the largest remnants of the hydrothermally altered and deeply eroded andesitic composite volcano. Outcrops of the remnant volcano are well exposed in the canyon walls of Mill Creek. Early work by scientists suggested that the central depression (Battle Creek Meadows) was a caldera, but no evidence has been found to support this hypothesis (Wood and Kienle 1990).

Lassen, *active from 825,000 years ago to the present*

The Lassen volcanic center is the presently active volcanic center in the Lassen area (fig. 43). Clynne and Muffler (2010) designated the major stratigraphic divisions / eruptive stages of the Lassen volcanic center as the Rockland caldera complex, Brokeoff Volcano, and the Lassen domefield. Each stage is distinctive from the others, but all are linked by a common magmatic system (Clynne and Muffler 2010). Together they represent a continuum of volcanic activity over the past 825,000 years.

Rockland Caldera Complex, 825,000 to 609,000 years ago

The life of the Rockland caldera complex (shown as unit PE-Lr on map 1, in pocket) ended with the eruption of Rockland tephra (PEpr), approximately 609,000 years ago, which slightly predates the Brokeoff Volcano. Wind widely distributed this ash-fall deposit, but no Rockland tephra occurs within the park. Tephra was deposited in northern and central California, off the northern California coast, and northeast into Idaho (Sarna-Wojcicki et al. 1985; Clynne and Muffler 2010).

The estimated volume of the Rockland tephra is 50 km^3 (12 mi^3) dense rock equivalent (Sarna-Wojcicki et al. 1985), which is similar to the amount produced during the climactic eruption of Mount Mazama at Crater Lake National Park (Bacon 1983; see the GRI report by KellerLynn 2013 for a summary). Although not readily apparent on the landscape today, an eruption of this magnitude must have formed a collapse caldera, which volcanic materials of Brokeoff and younger volcanoes likely filled (Clynne and Muffler 2010). The Rockland caldera complex consists of a group of mostly dacite and rhyolite domes and their associated flows, including the dacites of Panther Creek (PEdp), Flatiron Ridge (PEdfr), and Bench Lake (PEdbl); and the rhyolite of Raker Peak

(PErr). The rhyolite may represent a pre-caldera leak of the Rockland magma chamber (Clynne and Muffler 2010). Volcanic activity of these domes and flows culminated in the explosive eruption of the Rockland tephra.

Brokeoff Volcano, 590,000 to 385,000 years ago

Soon after eruption of the Rockland tephra, the Rockland caldera began to fill as renewed activity formed Brokeoff Volcano—a large composite volcano with a volume of 80 km^3 (19 mi^3) (Clynne and Muffler 2010). Before hydrothermal alteration weakened and glacial advances eroded the volcano edifice, this mountain dominated what is now the southwestern part of Lassen Volcanic National Park. The summit rose to an elevation of 3,300 m (11,000 ft) (Kane 1980).

Clynne and Muffler (2010) divided the stratigraphy of Brokeoff Volcano into two sequences: Mill Canyon (shown as unit PE-Lvm on map 1, in pocket) and Diller (unit PE-Lvd). The Mill Canyon sequence consists of the andesite of Mill Canyon (PEamc) and the dacite of Twin Meadows (PEdt). These lava flows erupted from a central vent between about 590,000 and 470,000 years ago; the vents, however, are not preserved (Clynne and Muffler 2010).

The Diller sequence consists primarily of six voluminous, andesitic lava flows that erupted from vents on the flanks of Brokeoff Volcano between 470,000 and 385,000 years ago. These units include the andesites of Rice Creek (PEar), Bluff Falls quarry (PEabf), Glassburner Meadows (PEag), Manzanita Creek (PEamz), Digger Creek (PEadc), and Mount Diller (PEamd).

Lassen Domefield, 300,000 years ago to the present

The Lassen volcanic center was "quiet" from about 385,000 to 315,000 years ago. Then, the character and locus of volcanism changed dramatically—from the andesitic composite cone of Brokeoff Volcano to the Lassen domefield, which consists of a core of dacite domes surrounded by an arc of andesite and basaltic andesite flows. The domefield, which is focused in the northwestern corner of the park, became active about 300,000 years ago.

Dacite domes of the Lassen domefield erupted along the northern flank of Brokeoff Volcano and are divided on the basis of age into two sequences—the Bumpass (shown as unit HPE-Lb on map 1, in pocket; approximately 300,000–190,000 years ago) and Eagle Peak (unit HPE-Le; approximately the last 70,000 years). A notable feature of the Bumpass sequence is the dacite that makes up Bumpass Mountain (PEdb). The 27,000-year-old dacite of Lassen Peak (PEdl) and the 1,050-year-old rhyodacites of Chaos Crags (Hrca–Hrcf) are part of the Eagle Peak sequence.

The andesite and basaltic andesite flows that form an arc around the dacite domes erupted in two groups—the older Twin Lakes sequence and the younger Twin Lakes sequence. The older Twin Lakes sequence (unit HPE-Lto on map 1, in pocket; 310,000–240,000 years ago) is contemporaneous with the Bumpass sequence (of dacite domes). The andesite of Raker Peak (PEarp) is part of the older Twin Lakes sequence. These andesite lava flows are much younger than the underlying rhyolite of Raker Peak (see "Rockland Caldera Complex" section). The andesite formed a lava cone with agglutinate scoria at the vent.

The younger Twin Lakes sequence (unit HPE-Lty; approximately the past 90,000 years) is contemporaneous with the Eagle Peak sequence (of dacite domes). Cinder Cone and the summit eruptions of Lassen Peak are part of the younger Twin Lakes sequence (see "Recent Volcanic Activity" section).

The Lassen domefield was apparently "quiet" for 100,000 years between 190,000 and 90,000 years ago (Clynne and Muffler 2010).

Glaciations

More than 130,000 to 8,000 years ago

Glaciers covered the park's landscape while Lassen Peak was forming 27,000 years ago. Glacial deposits in the Lost, Hat, and Manzanita Creek drainages, which are intercalated with volcanic rocks of the Eagle Peak sequence, are evidence of glacier-volcano interactions. The Eagle Peak sequence includes the most prominent young volcanic features in the park, such as Lassen Peak and Chaos Crags. Most of the rock units of the Eagle Peak sequence are glaciated, for example, the rhyodacites of Eagle Peak (map units PEpe and PEre), section 27 (PEr27), Krummholz (PErkr), Sunflower Flat (PEpsf and PErsf), and Kings Creek (Pepk and PErk).

Five episodes of Pleistocene glaciations and one Holocene glacial advance are recognized in the Lassen area. These advances are represented by the tills of Badger Mountain (PEtb), Raker Peak (PEtr), and Anklin Meadows (PEta); the post-maximum till of Raker Peak (PEtrl); and late till of Anklin Meadows (HPEtal). In addition, an early Holocene advance—represented by till or protalus-rampart debris (Hth)—occurred at the base of Lassen Peak. Outside the Hat, Lost, and Manzanita Creek drainages, Clynne and Muffler (2010) grouped glacial deposits into two units—till, older glaciation (PEto) and till, younger glaciations (PEty). Units PEtr, PEtrl, PEta, PEtal, and Hth, mapped in the Lost, Hat, and Manzanita Creek drainages, are equivalent in age to the younger till unit (PEty). The younger part of PEto is equivalent in age to till of Badger Mountain (PEtb) (table 5).

The estimated age of the older till unit (PEto) ranges between about 130,000 and 60,000 years ago (Clynne and Muffler 2010). Till from the younger glaciations (PEty) is between 35,000 and 8,000 years old. The boundary between these two units corresponds to the boundary between middle and early Wisconsinan glacial stages as defined by Colman and Pierce (1992), or approximately the Tioga and Tahoe glacial advances as used by Kane (1982) (table 5).

Outwash gravel is associated with these till deposits. Clynne and Muffler (2010) mapped five units/ages of outwash deposits. From youngest to oldest these are (1) outwash gravel of older glaciations (PEoo), which corresponds to older tills (PEto); (2) Raker Peak outwash (PEor), which corresponds to Raker Peak till (PEtr); (3)

Table 5. Glacial/volcanic chronology of the Lassen area

Estimated Age (years ago)	Map Units from Clynne and Muffler (2010)	Map Units from Christiansen et al. (2002)	Correlation to Sierra Nevada Glacial Chronology Units
12,000–8,000	Till, younger glaciations (PEty)	Till or protalus-rampart deposit (Hth)	Late Tioga till
12,000		Late till of Anklin Meadows (HPEtal)	
25,000–17,000		Till of Anklin Meadows (PEta)	Late Tioga till Middle Tioga till
27,000	Dacite of Lassen Peak (PEdl, PEpfl)		
~27,000	Till, younger glaciations (PEty)	Post-maximum till of Raker Peak, consisting of avalanche debris (PEtrl)	Early Tioga till
35,000–27,000		Till of Raker Peak (PEtr)	
35,000	Rhyodacite of Kings Creek (PEpk, PErk)		
41,000	Rhyodacite of Sunflower Flat (PEpsf, PErsf)		
43,000	Rhyodacite of Krummholz (PErkr)		
60,000–50,000	Rhyodacite of section 27 (PEr27)		
Boundary between middle and early Wisconsinan glacial stages			
70,000–60,000	Till, older glaciations (PEto)	Till of Badger Mountain (PEtb)	Tahoe till
65,000	Rhyodacite of Eagle Peak (PEpe, PEre)		
70,000–60,000	Till, older glaciations (PEto)	Till of Badger Mountain (PEtb)	Tahoe till
>130,000			Pre-Tahoe till

Sources: Crandell (1972), Kane (1982), Christiansen et al. (2002), and Clynne and Muffler (2010).

Anklin Meadows outwash (PEoa), which corresponds to Anklin Meadows till (PEta); (4) an undivided outwash deposit (PEou), which corresponds to older and younger tills (PEto and PEty) in the Manzanita Creek and Battle Creek meadows; and (5) outwash gravel of younger glaciations (PEoy), which corresponds to till of younger glaciations (PEty). Most outwash gravels were deposited by glacial meltwater outside the park, though a few deposits of PEoy, PEou, and PEor occur within the park.

Recent Volcanic Activity

The Lassen volcanic center is still active, and three eruptions have occurred during the Holocene Epoch (fig. 3). These are Chaos Crags, Cinder Cone, and the Lassen Peak.

Chaos Crags, *erupted 1,050 years ago*

Located northwest of Lassen Peak, Chaos Crags is the youngest unit of the Eagle Peak sequence and consists of six rhyodacitic lava domes and associated pyroclastic deposits (Christiansen et al. 2002). These deposits illustrate a typical silicic eruption in the Lassen volcanic center. Initial activity included formation of a tephra cone, emplacement of two pyroclastic flows, and growth of a dome that plugged the vent. After a brief hiatus in activity, a violent eruption destroyed the first dome (dome A, Hrca) and emplaced a pyroclastic flow and tephra. This violent eruption was followed by the growth of five domes—domes B, C, D, E, and F (Hrcb–Hrcf; fig. 45). Hot, dome-collapse debris avalanches affected domes D and E (US Geological Survey 2011). Later (278 ± 28 years BP), dome C (Hrcc) partially collapsed as a series of three debris avalanches, which emplaced Chaos Jumbles (Hsj) (Eppler 1984; Eppler et al. 1987; Clynne and Muffler 2010).

Cinder Cone, erupted in 1666

Cinder Cone is the youngest cinder cone in Lassen Volcanic National Park and the second youngest eruption in the Twin Lakes sequence. The story of Cinder Cone highlights many types of volcanic features in the park. It also incorporates the creation of one lake and the partial infilling of another. The story includes the formation of two cinder cones, five lava flows, and a blanket of tephra, all during a single eruptive sequence in 1666 (Sheppard et al. 2009). Total volume of erupted material was approximately 0.4 km^3 (0.1 mi^3), with 88% as lava and 12% as tephra (Clynne and Bleick 2011).

Three of the five flows—Old Bench lava flow (Hmo) and Painted Dunes flows 1 and 2 (Hmp1 and Hmp2)—erupted from a cone that is now located on the southern side of the volcano known as "Cinder Cone." This other cone shares the same composition as the flows erupted from it (i.e., units Hmo, Hmp1, and Hmp2). Eruption of the Painted Dunes lava flows destroyed most of this cone, and much of what remained of the cone was buried during the construction of Cinder Cone and eruption of Fantastic Lava Beds flows (Hmf1 and Hmf2). Blocks of red cemented scoria within the Painted Dunes lava flows are pieces of this other cone that were transported by flowing lava (Clynne et al. 2000a). Several meters of weakly oxidized ash from later eruptions almost completely cover the cone. Remnants of the cone are recognized by their irregular shape and Painted Dunes composition (Clynne and Muffler 2010). During the eruption of this cinder cone, the Painted Dunes flows blocked drainage from the central part of the park and created Snag Lake (fig. 46).

Construction of Cinder Cone (Hmfci) and eruption of the Fantastic Lava Beds flows 1 and 2 (Hmf1 and Hmf2) followed destruction of the previous cone (Hmpci)

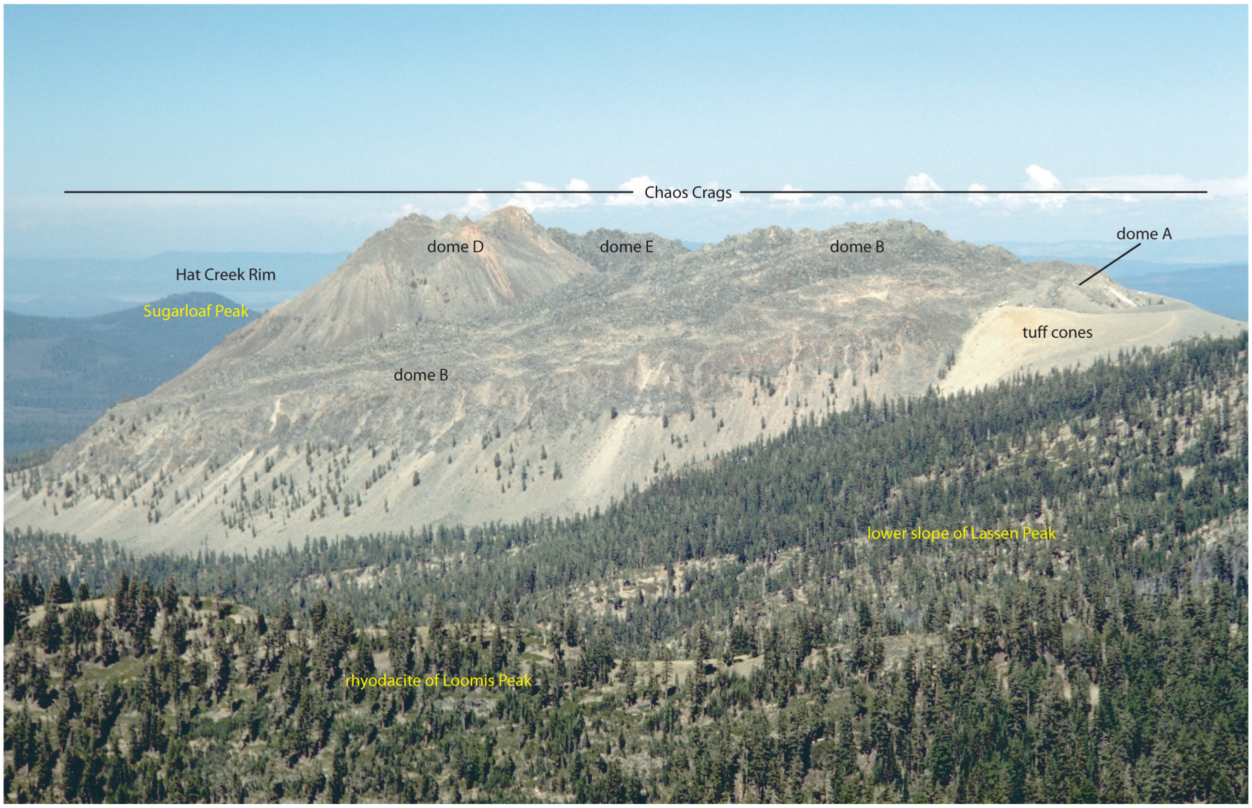

Figure 45. Chaos Crags. Chaos Crags consists of six rhyodacite lava domes and associated pyroclastic deposits. Dome A is visible in the crater of the tuff cone (light-colored area at the right of the photograph). The large sloping landform from upper right to lower left is dome B. The high craggy dome in the center of the photograph is dome D, and dome E is visible on the skyline behind it. Domes C and F are hidden behind domes D and E, respectively. US Geological Survey photograph by Michael A. Clynne.

Figure 46. Snag and Butte lakes. During the eruption sequence of Cinder Cone, Snag Lake (at upper left of photograph) formed as the Painted Dunes lava flows (map units Hmp1 and Hmp2) dammed drainages coming from the center of Lassen Volcanic National Park. Butte Lake (bottom left, foreground) was partially filled by the Fantastic Lava Beds flows (Hmf1 and Hmf2). US Geological Survey photograph from Clynne et al. (2012).

(Clynne and Bleick 2011). Cinder Cone is composed of scoria bombs, lapilli, and ash of Fantastic Lava Beds composition. Cinder Cone has a double rim, but the inner and outer rims have no discernable difference in lithology or composition. Deposits of diatomite (Hd) around the base of the Fantastic Lava Beds flows indicate that Butte Lake was considerably larger before the eruption of Cinder Cone and was partially filled by the Fantastic Lava Beds flows.

During the sequence of the Cinder Cone eruption, the silica composition of magma changed (Clynne and Muffler 2010), starting as basaltic andesite (53.5%–54.1% SiO_2) in the Old Bench flow, becoming more andesitic (57.1%–59.7% SiO_2) as Painted Dunes flow 2 was deposited, then turning more basaltic (56.4%–57.3% SiO_2) again as Fantastic Lava Beds flow 1 was deposited. Finally, the youngest flow—Fantastic Lava Beds flow 2—is basaltic andesite (55.1%–56.2% SiO_2).

Though chemically distinct, the lava flows and cinders at Cinder Cone are similar in appearance. They are dark, fine-grained rocks, containing a few visible crystals of the minerals olivine, plagioclase, and quartz. Both the Painted Dunes and Fantastic Lava Beds flows have rough, block-covered surfaces with considerable relief (fig. 47).

The informally named “Painted Dunes ash deposit” makes up the tephra component of the Cinder Cone eruption sequence. The colorfully oxidized ash covers the Old Bench and Painted Dunes 1 flows (figs. 12 and 13).

Figure 47. Fantastic Lava Beds flow 2. The rough, minimally weathered surface of the Fantastic Lava Beds flow misled early scientists and visitors into believing that the eruption had occurred relatively recently. It was reputed to have been witnessed in 1851 (Clynne et al. 2000a). However, the eruption is now known to have occurred in 1666 as a single, continuous event that probably spanned no more than a few months. Fantastic Lava Beds flow 2 was the last flow erupted at Cinder Cone. US Geological Survey photograph from Clynne et al. (2000a), available at http://pubs.usgs.gov/fs/2000/fs023-00/fs023-00.pdf (accessed 3 April 2013).

Lassen Peak, *erupted in 1914–1917*

The 1914–1917 eruptions of Lassen Peak comprise the most recent volcanic activity in the Twin Lakes sequence (fig. 48). Magmatic activity affected primarily the northeastern flank and slope of Lassen Peak, now called the “Devastated Area,” and the valleys of Lost Creek and Hat Creek as far as about 50 km (30 mi) downstream (fig. 11).

Lassen Peak began erupting on 30 May 1914, with a phreatic (steam) explosion at the summit. By mid-May 1915, more than 180 steam explosions had blasted out and created a 300-m- (1,000-ft-) wide crater.

In the week before 19 May 1915, a small dacite lava dome (Hd4) began to fill the crater. Late in the evening of 19 May 1915, the growing dacite dome was disrupted by a large explosion. Hot blocks of lava (Hp9) were thrown onto the snow-covered upper flanks and summit of Lassen Peak, which initiated an avalanche of snow and rock that swept down the steep northeastern face, over the low ridge northeast of Emigrant Pass, and into Hat Creek (Hsw9). A debris flow (also Hsw9), consisting of melted snow and underlying loose rock, came soon after. The debris flow followed the same path as the avalanche until it encountered the low ridge northeast of Emigrant Pass, which deflected it west into Lost Creek. The debris flow continued down Lost Creek for another 7 km (4 mi) before coming to rest in a large, flat area 3 km (2 mi) west of Twin Bridges.

During the early morning hours of 20 May 1915, the debris-flow and avalanche deposits (Hsw9) released large volumes of water that caused a flood along Hat Creek north of Old Station. These flood deposits (Hf9) occur beyond the boundaries of the park. Also in the late evening and early morning of 19–20 May 1915, dacite lava (Hd9), which was more fluid than that erupted during the previous week, welled up into and filled the newly excavated crater. This lava flowed over two low areas on the rim and emplaced two short flows on the steep western and northeastern flanks of Lassen Peak.

Two days later (22 May 1915), the eruptive sequence culminated with a vertically directed column of pumice and gas, which blasted through the 19–20 May lava flow (Hd9), created a new crater, and rose to 9,100 m (30,000 ft) into the air. Partial collapse of the column initiated a pyroclastic flow (Hpw2) on the northeastern slope of Lassen Peak, which rapidly melted snow in its path. By the time this pyroclastic flow reached the lower Devastated Area, it had transformed into a fluid debris flow (also Hpw2) that traveled down Lost Creek to beyond Twin Bridges, where it released water and caused a second flood along Hat Creek north of Old Station. Continued fallout from the eruption cloud emplaced a pumice deposit (Hp2) on the upper slopes of Lassen Peak. Pumice that fell on high-elevation, snow-covered areas generated six viscous debris flows (Hw2) that were emplaced on the western, northern, and eastern flanks of Lassen Peak. One of these debris flows (Hw2) dammed streamflow and created Hat Lake. The 19 May lava flow (Hp9) on the northeastern flank of Lassen Peak was removed during this eruption and incorporated into the 22 May 1915 deposits (Hpw2, Hp2, and Hw2). The still-hot lava at the summit partially slumped back into the 22 May 1915 crater.

For several subsequent years, spring snowmelt percolating into Lassen Peak encountered hot rock that triggered steam explosions. Particularly vigorous phreatic explosions in May 1917 blasted out the western of the two craters at the summit of Lassen Peak and emplaced phreatic deposits (Hp17).

Present-Day (Non-Volcanic) Geologic Activity

At present, hydrothermal features such as those at Bumpass Hell and Devils Kitchen attest to an active geothermal heat source underlying the Lassen volcanic center, as well as to the potential for future volcanic activity. The focus of hydrothermal activity shifts with time as underground plumbing changes and pathways of fluid are sealed by mineral deposition or fractured by earthquakes (Clynne et al. 2003). Hydrothermal alteration of volcanic rocks makes them susceptible to erosion and slope movements. The ongoing hydrothermal activity at the park brings the geologic story to the present day, as park managers address infrastructure and public-safety challenges caused by these dynamic, shifting conditions.

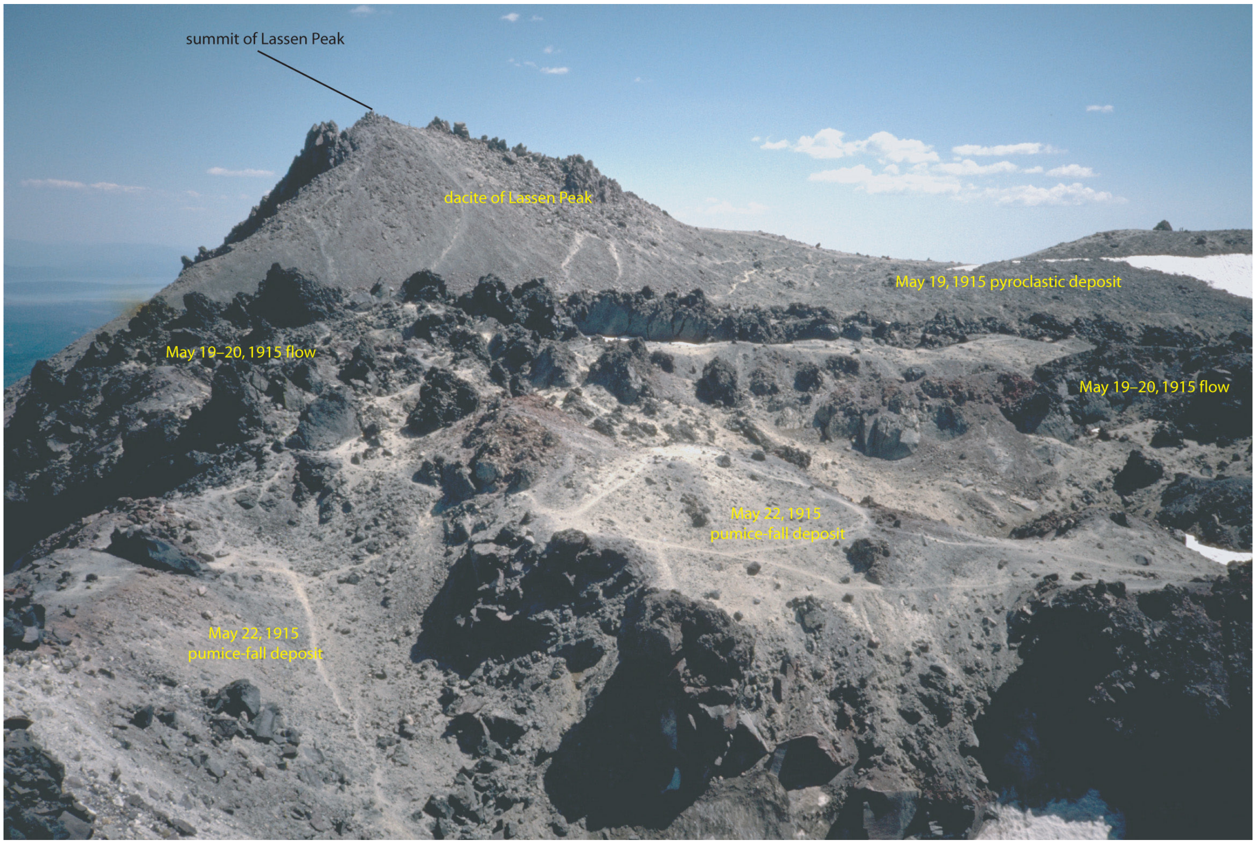

Figure 48. 1915 crater at summit of Lassen Peak. The summit of Lassen Peak consists of the 27,000-year-old dacite of Lassen Peak (map unit PEdl). Deposits of the 19–20 May 1915 eruption partly fill the crater formed at the summit between 30 May 1914 and 14 May 1915. The 19 May 1915 pyroclastic deposit was formed by an explosion that reopened the summit crater through the dacite dome of 14–19 May 1915. The dacite lava flow of 19–20 May 1915 (unit Hd9) fills this crater and is mantled by the pumice-fall deposit of 22 May 1915 (Hp2). US Geological Survey photograph by Patrick Muffler.

Geologic Map Data

This section summarizes the geologic map data for Lassen Volcanic National Park. The geologic map graphic (map 1, 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, these maps show the location, extent, and age of rocks and unconsolidated deposits. Geologic maps can be divided into two primary types: surficial and bedrock. Surficial geologic maps typically encompass deposits that are unconsolidated and formed during the past 2.6 million years (the Quaternary Period). Surficial map units are differentiated by geologic process or depositional environment. Bedrock geologic maps encompass older, typically more consolidated sedimentary, metamorphic, and/or igneous rocks. Bedrock map units are differentiated based on age and/or rock type. Both bedrock and surficial geologic map data are provided in the GRI data set for Lassen Volcanic National Park.

Geologic maps also commonly depict geomorphic features, structural interpretations (such as faults and 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 localities, may be indicated on geologic maps.

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 maps such as a correlation chart of map units, unit descriptions, map legend, map notes, references, and figures. The GRI team used the following sources to produce the digital geologic data for the Lassen Volcanic National Park GRI data set:

Clynne, M. A., and L. J. P. Muffler. 2010. Geologic map of Lassen Volcanic National Park and vicinity, California (scale 1:50,000). Scientific investigations map 2899. US Geological Survey, Washington, DC, USA. http://pubs.usgs.gov/sim/2899/ (accessed 13 March 2013).

Muffler, L. J. P., J. E. Robinson, T. J. Felgar, D. R. Dutton, and M. A. Clynne. 2010. Database for the geologic map of Lassen Volcanic National Park and vicinity, California (scale 1:24,000). *Data to accompany* M. A. Clynne and L. J. Muffler, authors. Geologic map of Lassen Volcanic National Park and vicinity, California (scale 1:50,000). Scientific investigations map 2899. US Geological Survey, Washington, DC, USA. http://pubs.usgs.gov/sim/2899/database.html (accessed 9 August 2013).

Clynne and Muffler (2010; scale 1:50,000) provided information for the "Geologic Features and Processes," "Geologic Issues," and "Geologic History" sections of this report. Muffler et al. (2010; scale 1:24,000) includes the six quadrangles (i.e., Lassen Peak, Mount Harkness, Manzanita Lake, Prospect Peak, Reading Peak, and West Prospect Peak) that cover the area of the park (fig. 49). These data accompany Clynne and Muffler (2010) and are provided on the attached CD. These data are also available at http://pubs.usgs.gov/sim/2899/database.html (accessed 9 August 2013).

Geologic GIS Data

The GRI team implements a GIS data model that standardizes map deliverables. The data model is included on the enclosed CD and is also available 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 Lassen Volcanic National Park using data model version 2.1.

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

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

- Data in ESRI geodatabase and shapefile GIS formats
- Layer files with feature symbology (see table 6)
- Federal Geographic Data Committee (FGDC)–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

Table 6. Geology data layers in the Lassen Volcanic National Park GIS data

Data Layer	Data Layer Code	On Geologic Map Graphic?
Geologic sample locations	lavogsl	No
Volcanic point features	lavovpf	Yes
Glacial line features	lavogfl	No
Ash from cinder cones, isopachs	lavocn1	Yes
Volcanic line features	lavovlf	Yes
Map symbology	lavosym	Yes
Faults	lavoflt	Yes
Geologic contacts	lavoglga	No
Geologic units	lavoglg	Yes, simplified

Map Unit Properties Table

The Map Unit Properties Table (in pocket) lists the geologic time division (age), GRI map symbol, and a simplified description for each of the geologic map units within Lassen Volcanic National Park. Following the structure of the report, the Map Unit Properties Table summarizes the geologic features and processes, issues, and history associated with each map unit. Symbols used on the geologic map graphic (map 1, in pocket) are also listed.

The source map by Clynne and Muffler (2010) delineated 327 map units. Thus to make the accompanying Map Unit Properties Table of a reasonable size, only the map units that occur within the boundaries of the park are included. These units are from the 1:50,000-scale map (i.e., Clynne and Muffler 2010). For a list and description of all units in the GRI GIS data, refer to lavo_geology.pdf on the attached CD.

Geologic Map Graphic

The geologic map graphic (map 1, in pocket) displays the GRI digital geologic data draped over a shaded relief image of the park and surrounding area. The geologic map is simplified and clipped to the park boundary. It consists of 18 units that delineate alluvium, slope-movement deposits, hydrothermal deposits, glacial deposits (till and outwash), diatomite, the seven sequences of the Lassen volcanic center, rocks of the Dittmar volcanic center, regional volcanic rocks (north and west, south and east, and within the Caribou volcanic field), and older rocks of the Caribou area. For graphic clarity, not all GIS feature classes are visible on the geologic map graphic, as indicated in table 6. Geographic information and selected park features have been added to the graphic. Digital elevation data and added geographic information are not included with the GRI GIS data but are available from a variety of online sources.

Use Constraints

Based on the scales of the source maps (1:24,000 and 1:50,000) and US National Map Accuracy Standards, geologic features represented in the geologic map data are horizontally within 12 m (40 ft) on 1:24,000-scale maps and 25 m (82 ft) on 1:50,000-scale map of their true locations. Minor inaccuracies may exist regarding the locations of geologic features relative to other geologic or geographic features on the geologic map graphic (map 1, in pocket).

Graphic and written information provided in this report is not a substitute for site-specific investigations. Ground-disturbing activities should neither be permitted nor denied based upon the information provided here. Please contact the NPS Geologic Resources Division with any questions.

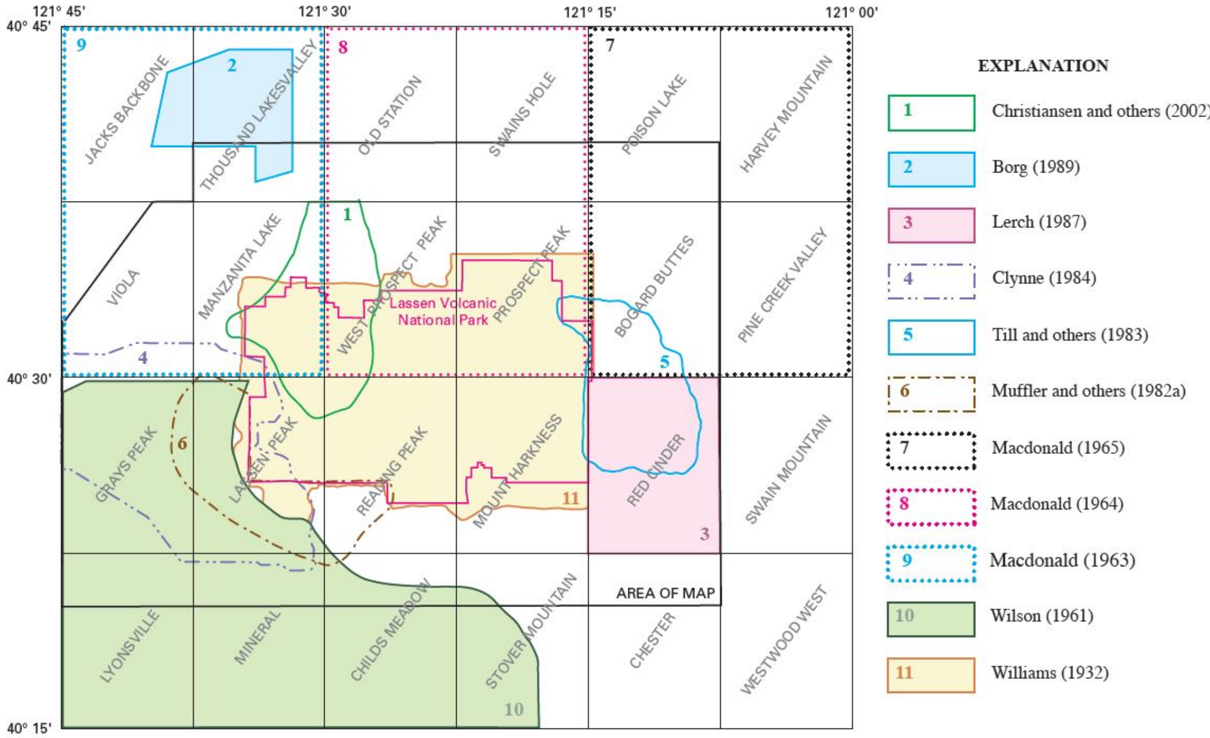

Figure 49. GRI source maps. This figure shows areas of published geologic mapping for Lassen Volcanic National Park and vicinity. The "area of map" outlined in black delineates the extent of mapping by Clynne and Muffler (2010; scale 1:50,000). At a scale of 1:24,000, Muffler et al. (2010) provided data for six quadrangles (i.e., Lassen Peak, Mount Harkness, Manzanita Lake, Prospect Peak, Reading Peak, and West Prospect Peak), which cover the area of the park. These data accompany Clynne and Muffler (2010) and are part of the GRI data set (see attached CD). Graphic from Clynne and Muffler (2010).

Glossary

This glossary 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.*

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

agglutinate. A welded pyroclastic deposit. The term is commonly used for deposits of bombs fused while hot and viscous. Agglutinate typically occurs in spatter cones.

alluvium. Stream-deposited sediment.

andesite. Volcanic rock (or lava) characteristically medium dark in color and containing 57%–63% silica and moderate amounts of iron and magnesium.

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

arête. A sharp-edged rocky ridge or spur, commonly present above the snowline in rugged mountains sculpted by glaciers. An arête results from the continued backward growth of the walls of adjoining cirques.

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

basalt. Volcanic rock (or lava) that characteristically is dark in color (gray to black), contains 45%–53% silica, and is rich in iron and magnesium. Basaltic lavas are more fluid than andesites or dacites, which contain more silica.

basaltic andesite. Volcanic rock, commonly dark gray to black, with about 53%–57% silica.

basement. The undifferentiated rocks, commonly igneous and metamorphic, that underlie rocks exposed at the surface.

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

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

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

brittle. Describes a rock that fractures (breaks) before sustaining deformation.

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

carapace. As used by Clynne and Muffler (2010), carapace is the outer "shell" or covering of a lava flow.

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

cinder cone. A conical hill, often steep, formed by accumulation of solidified fragments of lava that fall around the vent of a single basaltic or andesitic eruption. The rock fragments, often called cinders or scoria, are glassy and contain numerous gas bubbles "frozen" into place as magma exploded into the air and then cooled quickly. Cinder cones range in size from tens to hundreds of meters tall.

cirque. A deep, steep-walled, half-bowl–like recess or hollow located high on the side of a mountain and commonly at the head of a glacial valley. Produced by the erosive activity of a mountain glacier.

chalcedony. A cryptocrystalline variety of quartz. It is commonly microscopically fibrous, may be translucent or semitransparent, and has a nearly waxlike luster, a uniform tint, and a white, pale-blue, gray, brown, or black color. Chalcedony is the material of much chert, and often occurs as an aqueous deposit filling or lining cavities in rocks.

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

clast. An individual grain or rock fragment in a sedimentary rock, produced by the physical disintegration of a larger rock mass. Also, the term is often used in lieu of "pyroclast" for igneous (pyroclastic or debris flow) deposits.

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

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

coignimbrite. Refers to fallout tephra deposited from a pyroclastic flow. Near-vent breccias composed of large lithic clasts that dropped from pyroclastic flows and fine-grained ash elutriated from the top of a pyroclastic flow by the turbulent rise of hot gases.

colluvium. A general term for any loose, heterogeneous, and incoherent mass of soil material and/or rock fragments deposited through the action of surface runoff (rainwash, sheetwash) or slow continuous downslope creep. Usually collects at the base of a slope or hillside, but includes loose material covering hillsides.

columnar joints. Parallel, prismatic columns, polygonal in cross section, in basaltic flows and sometimes in other extrusive and intrusive rocks; they form as a result of contraction during cooling.

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

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

"Continental" is also used in reference to a plate. See "plate tectonics."

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

dacite. Volcanic rock (or lava) that characteristically is light in color and contains 62%–69% silica and moderate amounts of sodium and potassium. Dacite lavas are viscous and tend to form thick blocky lava flows or steep-sided piles of lava called lava domes. Dacitic magmas tend to erupt explosively, thus also ejecting abundant ash and pumice.

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

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

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

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

diatom. A microscopic, single-celled alga that secretes walls of silica, called frustules. Diatoms live in freshwater or marine environment.

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

drift (glacial). A general term applied to all rock material (clay, silt, sand, gravel, and boulders) transported by a glacier and deposited directly by or from the ice, or by running water emanating from a glacier.

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

edifice. The constructional mass of a volcano.

effusive eruption. An eruption that produces mainly lava flows and domes (as opposed to an explosive eruption).

erratic. A rock fragment carried by glacial ice deposited at some distance from the outcrop from which it was derived, and generally, though not necessarily, resting on bedrock of different lithology. Size ranges from a pebble to a house-size block.

explosive eruption. An energetic eruption that produces mainly ash, pumice, and fragmental ballistic debris (as opposed to an effusive eruption).

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

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

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

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

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

geomorphology. The study of the general configuration of surface landforms and their relationships to underlying structures, and of the history of geologic changes as recorded by these surface features.

graben. A down-dropped structural block bounded by steeply dipping, normal faults.

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

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

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

kipuka. An area surrounded by a lava flow.

lahar. A mixture of water and volcanic debris that moves rapidly downstream. Consistency can range from that of muddy dishwater to that of wet cement, depending on the ratio of water to debris. Also called a volcanic mudflow or debris flow. A key characteristic of a lahar is that it has a substantial component (generally >50 %) of fine-grained material, clay- and sand-sized that acts as a matrix to give the deposit the strength it needs to carry the bigger clasts.

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

lapilli. Pyroclastic materials that may be essential, accessory, or accidental in origin, of a size range that has been variously defined within the limits of 2 and 64 mm (0.08 and 2.5 in). The fragments may be either solidified or still viscous when they land (though some classifications restrict the term to the former); thus there is no characteristic shape. An individual fragment is called a lapillus.

last glacial maximum. Time period when continental ice sheets and glaciers reached their maximum extent during the most recent ice age (about 20,000 years ago).

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

lava dome. A steep-sided mass of viscous and often 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 tube. Natural conduits through which lava travels beneath the surface of a lava flow. Forms by the crusting over of lava channels and pahoehoe flows. Also, a cavernous segment of the conduit remaining after flow ceases.

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.

magmatic arc. Zone of plutons or volcanic rocks formed at a convergent boundary. The arc is generally 100–200 km (60–120 mi) or more behind the surface expression of the convergent boundary, that is the oceanic trench.

meteoric water. Water of recent atmospheric origin.

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 by glacial ice movement.

normal fault. A dip-slip fault in which the hanging wall moves down relative to the footwall. Compare with "reverse fault" and "thrust fault."

oceanic crust. Earth's crust, formed at spreading ridges, that underlies ocean basins; 6 to 7 km (3 to 4 mi) thick and generally of basaltic composition. "Oceanic" is also used in reference to a plate. See "plate tectonics."

opal. A mineral or mineral gel: $SiO_2 \bullet nH_2O$. It consists of packed spheres of silica, and has a varying proportion of water (as much as 20% but usually 3%–9%). It occurs in nearly all colors, is transparent to nearly opaque, and typically exhibits a marked iridescent play of color.

outwash. Glacial sediment transported and deposited by meltwater streams.

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

phenocryst. A large, ordinarily conspicuous crystal in a porphyritic igneous rock.

phreatic eruption. An eruption that primarily involves steam explosions. Usually groundwater flashed (became suddenly converted) into steam by the heat of subsurface magma.

piping. Erosion or solution by percolating water in a layer of subsoil, resulting in caving and in the formation of narrow conduits, tunnels, or "pipes" through which soluble or granular soil material is removed, especially the movement of material, from the permeable foundation of a dam or levee, by the flow or seepage of water along underground passages.

plate tectonics. The concept that the lithosphere is broken up into a series of rigid plates that move over Earth's surface above a less viscous asthenosphere.

porphyritic. Describes an igneous rock of any composition that contains conspicuous phenocrysts in fine-grained groundmass.

pumice. Solidified "frothy" lava; highly vesicular and very low density.

pyroclast. An individual particle ejected during a volcanic eruption.

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

pyroclastic flow. A hot—typically >800°C (1,470°F)—chaotic mixture of rock fragments, gas, and ash that travels rapidly (tens of meters per second) away from a volcanic vent or collapsing flow front.

quartz. Crystalline silica, an important rock-forming mineral: SiO_2.

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

recharge. Infiltration process that replenishes groundwater.

rhyodacite. Volcanic rock (or lava) that is intermediate in composition between rhyolite and dacite. It contains 68%–72% silica.

rhyolite. Volcanic rock (or lava) that characteristically is light in color, contains 69% or more of silica, and is rich in potassium and sodium. Low-silica rhyolite contains 69%–74% silica. High-silica rhyolite contains 75%–80% silica. Rhyolitic lavas are viscous and tend to form thick blocky lava flows or steep-sided piles of lava called lava domes. Rhyolite magmas tend to erupt explosively, commonly also producing abundant ash and pumice.

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

rift valley. A depression formed by grabens along the crest of an oceanic spreading ridge or in a continental rift zone.

roche moutonnée. An elongate, eroded ridge or knob of bedrock carved by a glacier parallel to the direction of motion, with gentle upstream and steep downstream surfaces.

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

rockfall. The most rapid mass-wasting process, in which rocks are dislodged and move downslope rapidly.

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 cinders and other pyroclasts, normally of basaltic or andesitic composition.

sheet flow. An overland flow or downslope movement of water, in the form of a thin, continuous film, over relatively smooth soil or rock surfaces and not concentrated into channels larger than rills.

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

silica. Silicon dioxide, SiO_2. It occurs as crystalline quartz, crytocrystalline chalcedony, and amorphous opal; dominantly in sand, diatomite, and chert; and combined in silicates as an essential constituent of many minerals.

silicate. A compound whose crystal structure contains the SiO_4 tetrahedra.

siliceous. Said of a rock or other substance containing abundant silica.

silicic. Said of a silica-rich igneous rock or magma. Although there is no firm agreement among petrologists, the amount of silica is usually said to constitute at least 65% or two-thirds of the rock. In addition to the combined silica in feldspars, silicic rocks generally contain free silica in the form of quartz. Granite and rhyolite are typical silicic rocks.

sinter. The lightweight, porous, opaline variety of silica that is white or nearly white and deposited as an incrustation by precipitation from the waters of geysers and hot springs. Also known as "siliceous sinter."

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

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

soil. The unconsolidated mineral or organic matter on the surface of the earth that has been affected by climate (water and temperature) and organisms (macro and micro), conditioned by relief, acting on parent material over a period of time. Soil differs from the material from which it is derived in many ways.

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

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

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

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

striations (glacial). One of a series of long, delicate, finely cut, commonly straight and parallel furrows or lines inscribed on a bedrock surface by the rasping and rubbing of rock fragments embedded at the base of a moving glacier, and usually oriented in the direction of ice movement; also formed on the rock fragments transported by the ice.

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

sulfate. A mineral compound characterized by the sulfate radical SO_4^-. Anhydrous sulfates, such as barite, $BaSO_4$, have divalent cations linked to the sulfate radical; hydrous and basic sulfates, such as gypsum, $CaSO_4 \cdot 2H_2O$, contain water molecules.

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

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 during an explosive volcanic eruption.

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.

tuff. Generally fine-grained, igneous rock formed of consolidated volcanic ash.

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

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

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

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

volcanic arc. A commonly curved, linear zone of volcanoes above a subduction zone. On the scale of hundreds of kilometers.

water table. The upper surface of the saturated zone; the zone of rock in an aquifer saturated with water.

Wisconsinan. Pertaining to the classical fourth glacial stage of the Pleistocene Epoch in North America, following the Sangamonian interglacial stage and preceding the Holocene.

Literature Cited

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

Bacon, C. R. 1983. Eruptive history of Mount Mazama and Crater Lake caldera, Cascade Range, USA. Journal of Volcanology and Geothermal Research 18:57–115.

Barr, D. L. 2001. The Geothermal Steam Act and the National Park Service. Department of Energy, Yucca Mountain Project, executive potential program development assignment, 20 August 2001 to 19 October 2001, National Park Service, Geological Resources Division, Lakewood, Colorado, USA.

Blakeslee, M. W., and S. A. Kattenhorn. 2010. Earthquake hazard and segmented fault evolution, Hat Creek fault, northern California. Eos, Transactions of the America Geophysical Union, fall meeting supplement 91, abstract T31B-2164. http://www.webpages.uidaho.edu/~simkat/abstracts/agu10b.html (accessed 13 August 2013).

Braile, L.W. 2009. Seismic monitoring. Pages 229–244 *in* R. Young, R. and L. Norby, editors. Geological monitoring. Geological Society of America, Boulder, Colorado, USA. http://nature.nps.gov/geology/monitoring/seismic.cfm (accessed 1 February 2013).

Browne, P. R. L., and J. V. Lawless. 2001. Characteristics of hydrothermal eruptions, with examples from New Zealand and elsewhere. Earth-Science Reviews 52:299–331.

Burghardt, J. E., E. S. Norby, and H. S. Pranger II. 2013. Interim inventory and assessment of abandoned mineral lands in the National Park System. Natural resource technical report NPS/NRSS/GRD/NRTR-2013/659. National Park Service, Fort Collins, Colorado, USA. http://www.nature.nps.gov/geology/aml/inventory/NPS_AML-IandA_508_Compliant-2013-0308-FINAL.pdf (accessed 22 May 2013).

Carpenter, J. 2012. Park removes dam, restores stream valley. Online article (InsideNPS). Lassen Volcanic National Park, Mineral, California, USA. http://inside.nps.gov/index.cfm?handler=viewprintheadline&type=Announcements&id=11713 (accessed 27 March 2013; accessible from NPS computers only).

Christiansen, R. L., M. A. Clynne, and L. J. P. Muffler. 2002. Geologic map of Lassen Peak, Chaos Crags, and upper Hat Creek area, California (scales 1:24,000 and 1:2,500). Geologic investigations series I-2723. US Geological Survey, Washington, DC, USA. http://pubs.usgs.gov/imap/i2723/ (accessed 11 March 2013).

Christiansen, R. L., J. B. Lowenstern, R. B. Smith, H. Heasler, L. A. Morgan, M. Nathenson, L. G. Mastin, L. J. P. Muffler, and J. E. Robinson. 2007. Preliminary assessment of volcanic and hydrothermal hazards in Yellowstone National Park and vicinity. Open-file report 2007-1071. US Geological Survey, Reston, Virginia, USA. http://pubs.usgs.gov/of/2007/1071/of2007-1071.pdf (accessed 5 June 2013).

Clynne, M. A. 1990, Stratigraphic, lithologic, and major element geochemical constraints on magmatic evolution at Lassen volcanic center, California. Journal of Geophysical Research 95(B12):19,651–19,669.

Clynne, M. A., and H. Bleick. 2011. Stratigraphy and compositional evolution of Cinder Cone, a composite monogenetic cone in Lassen Volcanic National Park, California. Poster V13C-2621. American Geophysical Union, Annual Meeting, 5–9 December 2011, San Francisco, California, USA.

Clynne, M. A., C. A. Brook, and L. J. P. Muffler. 1982. The geothermal resource in Section 36, Lassen Volcanic National Park: data, models, and options for evaluation. Administrative report (May 1982). Prepared for the National Park Service by US Geological Survey, Menlo Park, California, USA.

Clynne, M. A., D. E. Champion, D. A. Trimble, J. W. Hendley II, and P. H. Stauffer. 2000a. How old is "Cinder Cone"?—solving a mystery in Lassen Volcanic National Park, California. Fact sheet 023-00. US Geological Survey, Vancouver, Washington, USA. http://pubs.er.usgs.gov/publication/fs02300 (accessed 11 March 2013).

Clynne, M. A., R. L. Christiansen, D. A. Trimble, and J. P. McGeehin. 2002. Radiocarbon dates from volcanic deposits of the Chaos Crags and Cinder Cone eruptive sequences and other deposits, Lassen Volcanic National Park and vicinity, California. Open-file report 02-290. US Geological Survey, Washington, DC, USA. http://pubs.usgs.gov/of/2002/of02-290/ (accessed 21 March 2013).

Clynne, M. A., R. L. Christiansen, T. J. Felger, P. H. Stauffer, and J. W. Hendley II. 1999. Eruptions of Lassen Peak, California, 1914–1917. Fact sheet 173-98. US Geological Survey, Vancouver, Washington, USA. http://pubs.er.usgs.gov/publication/fs17398 (accessed 11 March 2013).

Clynne, M. A., R. L. Christiansen, C. D. Miller, P. H. Stauffer, and J. W. Hendley II. 2000b. Volcano hazards of the Lassen Volcanic National Park area, California. Fact sheet 022-00. US Geological Survey, Vancouver, Washington, USA. http://pubs.er.usgs.gov/publication/fs02200 (accessed 11 March 2013).

Clynne, M. A., C. J. Janik, and L. J. P. Muffler. 2003. "Hot water" in Lassen Volcanic National Park—fumaroles, steaming ground, and boiling mudpots. Fact sheet 101-02. US Geological Survey, Menlo Park, California, USA. http://pubs.usgs.gov/fs/2002/fs101-02/ (accessed 12 April 2013).

Clynne, M. A., and L. J. P. Muffler. 2009. Changing fumarolic activity at Sulphur Works: impact on the park road (Calif. Hwy 89). Report to the National Park Service. US Geological Survey, Menlo Park, California, USA.

Clynne, M. A., and L. J. P. Muffler. 2010. Geologic map of Lassen Volcanic National Park and vicinity, California (scale 1:50,000). Scientific investigations map 2899. US Geological Survey, Menlo Park, California, USA. http://pubs.er.usgs.gov/publication/sim2899 (accessed 10 April 2013).

Clynne, M. A., and L. J. P. Muffler. 2011. Narrative and evaluation of boring at Sulphur Works, Lassen Volcanic National Park, California, 01, 02, and 11 November 2011. Report to the National Park Service. US Geological Survey, Volcano Science Center, Menlo Park, California, USA.

Clynne, M. A., J. E. Robinson, M. Nathenson, and L. J. P. Muffler. 2012. Volcano hazards assessment for the Lassen region, northern California. Scientific investigations report 2012-5176-A. US Geological Survey, Menlo Park, California, USA. http://pubs.usgs.gov/sir/2012/5176/a/ (accessed 10 April 2013).

Colman, S. M., and K. L. Pierce. 1992. Varied records of early Wisconsin alpine glaciation in the western United States derived from weathering-rind thicknesses. Pages 269–278 *in* P. U. Clark and P. D. Lea, editors. The last interglacial-glacial transition in North America. Special paper 270. Geological Society of America, Boulder, Colorado, USA.

Cooper, D. J., D. Schook, and E. Wolf. 2012. Restoration prioritization and procedures for Drakesbad Meadow, Lassen Volcanic National Park, California (February 2012). Colorado State University, Department of Forest and Rangeland Stewardship, Fort Collins, Colorado, USA.

Covington, S. 2004. Lassen Volcanic National Park geologic resources management issues scoping summary (27 May 2004). National Park Service, Geologic Resources Division, Lakewood, Colorado, USA. http://www.nature.nps.gov/geology/inventory/gre_publications.cfm (accessed 20 November 2013).

Crandell, D. R. 1972. Glaciations near Lassen Peak, northern California. Pages C-179–C-188 *in* Geological Survey research 1972. Professional Paper 800-C. US Geological Survey, Washington, DC, USA. http://pubs.usgs.gov/pp/0800c/report.pdf (accessed 17 April 2013).

Crandell, D. R., and D. R. Mullineaux. 1970. Potential geologic hazards in Lassen Volcanic National Park, California. Report to the National Park Service. US Geological Survey, Menlo Park, California, USA.

Crowley, J. K., J. C. Mars, D. A. John, L. J. P. Muffler, and M. A. Clynne. 2004. Hydrothermal mineral zoning within an eroded stratocone: remote sensing spectral analysis of Brokeoff Volcano, California. Pages 215–226 *in* P. L. King, M. S. Ramsey, and G. A. Swayze, editors. Infrared spectroscopy in geochemistry, exploration geochemistry, and remote sensing. Short Course 33. Mineralogical Association of Canada, London, Ontario, Canada.

Danley, C. S. 2004. Intermediate examination report (July 2004), Safety Evaluation of Existing Dams (SEED) Program, National Park Service, Manzanita Lake Dam, Lassen Volcanic National Park, California. Prepared by Bureau of Reclamation, Denver, Colorado, USA.

Eppler, D. B. 1984. Characteristics of volcanic blasts, mudflows, and rock-fall avalanches in Lassen Volcanic National Park, California. Dissertation. Arizona State University, Tempe, Arizona, USA.

Eppler, D. B., J. Fink, and R. Fletcher. 1987. Rheologic properties and kinematics of emplacement of the Chaos Jumbles rockfall avalanche, Lassen Volcanic National Park, California. Journal of Geophysical Research 92(B5):3623–3633.

Fassett, L., K. Boyle, S. Holt, R. Teasdale, and D. Brown. 2010. Monitoring the hydrothermal system at Lassen volcanic center, California. Geological Society of America Abstracts with Programs 42(4):61. https://gsa.confex.com/gsa/2010CD/finalprogram/abstract_173643.htm (accessed 15 March 2013).

Finch, R. H., and C. A. Anderson. 1930. The quartz basalt eruptions of Cinder Cone, Lassen Volcanic National Park, California. University of California Publications in Geological Sciences 19(10):245–273.

Guffanti, M., M. A. Clynne, J. G. Smith, L. J. P. Muffler, and T. D. Bullen. 1990. Late Cenozoic volcanism, subduction, and extension in the Lassen region of California, southern Cascade Range. Journal of Geophysical Research 95(B12):19,453–19,464.

Harry, D. 2008. Emergency action plan, Manzanita Lake Dam, annual revision. National Park Service, Lassen Volcanic National Park, Shasta County, California, USA.

Havens, M. 2012. Large-scale ecological restoration completed in Warner Valley. Online article (InsideNPS). Lassen Volcanic National Park, Mineral, California, USA. http://inside.nps.gov/index.cfm?handler=viewprintheadline&type=Announcements&id=13165 (accessed 27 March 2013; accessible from NPS computers only).

Heasler, H. P., C. Jaworowski, and D. Foley. 2009. Geothermal systems and monitoring hydrothermal features. Pages 105–140 *in* R. Young and L. Norby, editors. Geological monitoring. Geological Society of America, Boulder, Colorado, USA. http://www.nature.nps.gov/geology/monitoring/files/geomon-05.pdf (accessed 15 March 2013).

Heiken, G. 1978. Characteristics of tephra from Cinder Cone, Lassen Volcanic National Park, California. Bulletin of Volcanology 41(2):119–130.

Herbst, R. L. 1979. Letter to Honorable Phillip Burton, chairman, Subcommittee on National Parks and Insular Affairs, Committee on Interior and Insular Affairs, House of Representatives, Washington, DC, USA. Reference L1425(640), ES-57309. From US Department of the Interior, Office of the Secretary, Washington, DC, USA (11 November 1979).

Highland, L. M. and P. Bobrowsky. 2008. The landslide handbook—a guide to understanding landslides. Circular 1325. US Geological Survey, Reston, Virginia, USA. http://pubs.usgs.gov/circ/1325/ (accessed 2 May 2013).

Hill, P. M. 2000. Possible asphyxiation from carbon dioxide of a cross-country skier in eastern California—a deadly volcanic hazard. Wilderness and Environmental Medicine 11:192–195.

Ingebritsen, S. E., and M. L. Sorey, M.L. 1985. A quantitative analysis of the Lassen hydrothermal system, north-central California. Water Resources Research 21:853–868.

Janik, C. J., and D. Bergfeld. 2010. Analyses of gas, steam and water samples collected in and around Lassen Volcanic National Park, California, 1975–2002. Open-file report 2010-1036. US Geological Survey, Menlo Park, California, USA. http://pubs.er.usgs.gov/publication/ofr20101036 (accessed 16 April 2013).

Janik, C. J., and M. K. McLaren. 2010. Seismicity and fluid geochemistry at Lassen Volcanic National Park, California: evidence for two circulation cells in the hydrothermal system. Journal of Volcanology and Geothermal Research 189:257–277.

John, D. A., G. N. Breit, R. G. Lee, J. H. Dilles, L. J. P. Muffler, and M. A. Clynne. 2006. Fossil magmatic-hydrothermal systems in Pleistocene Brokeoff Volcano, Lassen Volcanic National Park. Eos, Transactions of the American Geophysical Union, fall meeting supplement 87(52), abstract V53A-1745.

John, D. A., G. N. Breit, R. G. Lee, J. H. Dilles, A. T. Calvert, L. J. P. Muffler, M. A. Clynne, and R. O. Rye. 2009. Pleistocene magmatic-hydrothermal systems in the Lassen Peak area, northeastern California. Geological Society of America Abstracts with Programs 41(7):525.

Kane, P. S. 1980. Through Vulcan's eye—the geology and geomorphology of Lassen Volcanic National Park. Lassen Loomis Museum Association, Mineral, California, USA.

Kane, P. 1982. Pleistocene glaciation, Lassen Volcanic National Park. California Geology 35(5):95–105.

KellerLynn, K. 2013. Crater Lake National Park: geologic resources inventory report. Natural resource report NPS/NRSS/GRD/NRR—2013/719. National Park Service, Fort Collins, Colorado, USA. http://www.nature.nps.gov/geology/inventory/gre_publications.cfm (accessed 3 January 2014).

KellerLynn, K. 2014. Lava Beds National Monument geologic resources inventory report. Natural resource report. National Park Service, Fort Collins, Colorado, USA, *in review*.

Kiver, E. P., and D. V. Harris. 1999. Geology of US parklands. 5th edition. John Wiley & Sons, Inc., New York, New York, USA.

Klein, F. W. 1979. Earthquakes in Lassen Volcanic National Park, California. Bulletin of the Seismological Society of America 69:867–875.

Krahe, D. L., and T. Catton. 2010. Little gem of the Cascades: an administrative history of Lassen Volcanic National Park (September 2010). University of Montana, Missoula, Montana, USA. http://www.nps.gov/lavo/historyculture/upload/Lassen-Volcanic-National-Park-Administrative-History.pdf (accessed 26 March 2013).

Lanphere, M. A, D. E. Champion, M. A. Clynne, J. B. Lowenstern, A. M. Sarna-Wojcicki, and J. L. Wooden. 2004. Age of the Rockland tephra, western USA. Quaternary Research 62:94–104.

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

Marron, D. C., and J. A. Laudon. 1986. Susceptibility to mudflows in the vicinity of Lassen Peak, California. Pages 97–106 *in* S. Subitzky, editor. Selected papers in the hydrologic sciences 1986. Water-supply paper 2310. US Geological Survey, Denver, Colorado, USA. http://pubs.usgs.gov/wsp/2310/report.pdf (accessed 19 June 2013).

McLaren, M. K., and C. J. Janik. 1996. Microearthquake clusters and the Lassen hydrothermal system, northern California. Abstract. Eos, Transactions of the American Geophysical Union, fall meeting supplement 77(46):513.

Miller, D. C. 1989. Potential hazards from future volcanic eruptions in California. Bulletin 1847. US Geological Survey, Washington, DC, USA.

Muffler, L .J. P., M. A. Clynne, A. T. Calvert, and D. E. Champion. 2011. Diverse, mantle-derived batches of basalt erupted along a short normal fault zone: the Poison Lake chain, southernmost Cascades. Geological Society of America Bulletin 123(10/12):2177–2200.

Muffler, L. J. P., M. A. Clynne, and D. E. Champion. 1994. Late Quaternary normal faulting of the Hat Creek Basalt, northern California. Geological Society of America Bulletin 106:195–200.

Muffler, L. J. P., N. L. Nehring, A. H. Truesdell, C. J. Janik, M. A. Clynne, and J. M. Thompson. 1982. The Lassen geothermal system. Pages 349–356 *in* Proceedings of the Pacific Geothermal Conference, 8–12 November 1982, Auckland, New Zealand.

Muffler, L. J. P., J. E. Robinson, T. J. Felgar, D. R. Dutton, and M. A. Clynne. 2010. Database for the geologic map of Lassen Volcanic National Park and vicinity, California (scale 1:24,000). *Data to accompany* M. A. Clynne and L. J. Muffler, authors. Geologic map of Lassen Volcanic National Park and vicinity, California (scale 1:50,000). Scientific investigations map 2899. US Geological Survey, Washington, DC, USA. http://pubs.usgs.gov/sim/2899/ (accessed 13 March 2013).

Muffler, L. J. P, D. E. White, and A. H. Truesdell. 1971. Hydrothermal explosion craters in Yellowstone National Park. Geological Society of America Bulletin 82(3):723–740.

Myers, B., and C. Driedger. 2008. Geologic hazards at volcanoes. General information product 64. US Geological Survey, Washington, DC, USA. http://pubs.usgs.gov/gip/64/gip64.pdf (accessed 13 November 2013).

Nagle, W. F. 1985. Abandoned (active) geothermal well within Lassen Volcanic National Park. Memorandum to chief, Mineral Resources Branch, Energy, Mining and Mineral Division, Denver (31 October 1985). From geologist, Mineral Resources Branch, Energy, Mining and Mineral Division, Denver, Colorado, USA.

Nathenson, M., M. A. Clynne, and L. J. P. Muffler. 2012. Probabilities for the Lassen volcanic center and regional volcanism, northern California, and probabilities for large explosive eruptions in the Cascade Range. Scientific investigations report 2012–5176-B. US Geological Survey, Reston, Virginia, USA. http://pubs.usgs.gov/sir/2012/5176/b/ (accessed 10 June 2013).

National Park Service. 1972. Bumpass Hell nature trail: Lassen Volcanic National Park. Loomis Museum Association, Mineral, California, USA.

National Park Service. 1994. Statement for management, Lassen Volcanic National Park (April 1994). National Park Service, Lassen Volcanic National Park, Mineral, California, USA.

National Park Service. 2006. Basic evacuation procedures for Lassen Volcanic residents. Site bulletin. Lassen Volcanic National Park, Mineral, California, USA.

National Park Service. 2010. Warner Valley comprehensive site plan final environmental impact statement (September 2010). Lassen Volcanic National Park, Mineral, California, USA. http://www.nps.gov/lavo/parkmgmt/upload/Warner_Valley_Final_EIS_Sept-2010.pdf (accessed 27 March 2013).

National Park Service. 2011. Air pollution impacts: Lassen Volcanic National Park. Online information. National Park Service, Air Resources Division, Lakewood, Colorado, USA. http://nature.nps.gov/air/Permits/aris/lavo/impacts.cfm?tab=0#TabbedPanels1 (accessed 21 May 2013).

National Park Service. 2012. Guidance document: emergency operations plan for Lassen Volcanic NP. United States Department of the Interior, National Park Service, Lassen Volcanic National Park, Mineral, California, USA.

Neuendorf, K. K. E., J. P. Mehl, Jr., and J. A. Jackson. 2005. Glossary of geology. 5th edition. American Geological Institute, Alexandria, Virginia, USA.

Norris, R. D., K. L. Meagher, and C. S. Weaver. 1997. The 1936, 1945–1947, and 1950 earthquake sequences near Lassen Peak, California. Journal of Geophysical Research 102:449–457.

Patterson, L., and D. J. Cooper. 2007. The use of hydrologic and ecological indicators for the restoration of drainage ditches and water diversions in a mountain fen, Cascade Range, California. Wetlands 27(2):290–304.

Pitt, A. M., D. P. Hill, S. W. Walter, and M. J. S. Johnson. 2002. Midcrustal, long-period earthquakes beneath northern California volcanic areas. Seismological Research Letters 73:144–152.

Sarna-Wojcicki, A. M., C. E. Meyer, H. R. Bowman, N. T. Hall, P. C. Russell, M. J. Woodward, and J. L. Slate. 1985. Correlation of the Rockland ash bed, a 400,000-year-old stratigraphic marker in northern California and western Nevada, and implications for Middle Pleistocene paleogeography of central California. Quaternary Geology 23:236–257.

Schook, D., and C. Potter. 2012. Causeway removal, Drakesbad Meadow, LAVA [sic.], 29–30 May 2012. Report to the National Park Service. Colorado State University, Fort Collins, Colorado, USA.

Schulz, P. E. 1952. Geology of Lassen's landscape. Lassen Volcanic National Park and Loomis Museum Association, Mineral, California, USA.

Sheppard, P. R., M. H. Ort, K. C. Anderson, M. A. Clynne, and E. M. May. 2009. Multiple dendrochronological responses to the eruption of Cinder Cone, Lassen Volcanic National Park, California. Dendrochronologia 27:13–221.

Siering, P. L., J. M. Clarke, and M. S. Wilson. 2006. Geochemical and biological diversity of acidic, hot springs in Lassen Volcanic National Park. Geomicrobiology Journal 23:129–141.

Simkin, T., R. I. Tilling, P. R. Vogt, S. H. Kirby, P. Kimberly, and D. B. Stewart. 2006. This dynamic planet: world map of volcanoes, earthquakes, impact craters and plate tectonics. Geologic investigations map I-2800. US Geological Survey, Washington, DC, USA. http://pubs.usgs.gov/imap/2800/ (accessed 15 August 2013).

Smith, J. G., J. Dehn, R. P. Hoblitt, R. G. LaHusen, J. B. Lowenstern, S. C. Moran, L. McClelland, K. A. McGee, M. Nathenson, P. G. Okubo, J. S. Pallister, M. P. Poland, J. A. Power, D. J. Schneider, and T. W. Sisson. 2009. Volcano monitoring. Pages 273–305 *in* R. Young and L. Norby, editors. Geological monitoring. Geological Society of America, Boulder, Colorado, USA. http://nature.nps.gov/geology/monitoring/volcanic.cfm (accessed 30 January 2013).

Sorey, M. L. 1986. Hot spring monitoring at Lassen Volcanic National Park, California, 1983–1985. Pages 141–147 *in* Proceedings, Eleventh Workshop on Geothermal Reservoir Engineering, Stanford University, 21–23 January 1986, Stanford, California, USA.

Sorey, M. L., and E. M. Colvard. 1994. Measurement of heat and mass flow from thermal areas in Lassen Volcanic National Park, California, 1984–93. Water resources investigations report 94-4180-A. US Geological Survey, Washington, DC, USA. http://pubs.er.usgs.gov/publication/wri944180A (accessed 20 November 2013).

Thornberry-Ehrlich, T. 2009. Hawai'i Volcanoes National Park geologic resources inventory report. Natural resource report NPS/NRPC/GRD/NRR—2009/163. National Park Service, Denver, Colorado. http://www.nature.nps.gov/geology/inventory/gre_publications.cfm (accessed 14 March 2013).

Thornberry-Ehrlich, T. 2011. Haleakalā National Park: geologic resources inventory report. Natural resource report NPS/ NRSS/GRD/NRR—2011/453. National Park Service, Fort Collins, Colorado, USA. http://www.nature.nps.gov/geology/inventory/gre_publications.cfm (accessed 14 March 2013).

Trieste, D. J. 1995. Downstream hazard classification reevaluation, National Park Service, Lassen Volcanic National Park, California. US Department of the Interior, Bureau of Reclamation, Denver, Colorado, USA.

Truesdell, A. H., E. Mazor, and N. L. Nehring. 1983. The origin of thermal fluids at Lassen Volcanic National Park: evidence from noble and reactive gas abundances. Pages 343–348 *in* Transactions 7. Geothermal resources: energy on tap! Geothermal Resources Council, 1983 Annual Meeting, Portland, Oregon, USA.

Turrin, B. D., R. L. Christiansen, M. A. Clynne, D. E. Champion, W. J. Gerstel, L. J. P. Muffler, D. A. Trimble. 1998. Age of Lassen Peak, California, and implications for the ages of late Pleistocene glaciations in the southern Cascade Range. Geological Society of America Bulletin 110(7):931–945.

Turrin, B. D., L. J. P. Muffler, M. A. Clynne, M.A., and D. E. Champion. 2007. Robust 24 ± 6 ka $^{40}Ar/^{39}Ar$ age of a low-potassium tholeiitic basalt in the Lassen region of NE California. Quaternary Research 68:96–110.

US Geological Survey. 2003. America's volcanic past, Lassen Volcanic National Park, California. Online information. US Geological Survey, Cascades Volcano Observatory, Vancouver, Washington, USA. http://vulcan.wr.usgs.gov/LivingWith/VolcanicPast/Places/volcanic_past_lassen.html (accessed 28 March 2013).

US Geological Survey. 2011. Chaos Crags and Chaos Jumbles, Lassen volcanic center. Online information. US Geological Survey, Volcano Hazards Program, California Volcano Observatory, Menlo Park, California, USA. http://volcanoes.usgs.gov/volcanoes/lassen_volcanic_center/lassen_volcanic_center_geo_hist_22.html (accessed 5April 2013).

US Geological Survey. 2012a. Deformation monitoring at Lassen volcanic center. Online information. US Geological Survey, Volcano Hazards Program, California Volcano Observatory, Menlo Park, California, USA. http://volcanoes.usgs.gov/volcanoes/lassen_volcanic_center/lassen_volcanic_center_monitoring_62.html (accessed 20 March 2013).

US Geological Survey. 2012b. Landslides and rockfalls at Lassen volcanic center. Online information. US Geological Survey, Volcano Hazards Program, California Volcano Observatory, Menlo Park, California, USA. http://volcanoes.usgs.gov/volcanoes/lassen_volcanic_center/lassen_volcanic_center_hazard_28.html (accessed 21 March 2013).

US Geological Survey. 2012c. Seismic monitoring at Lassen volcanic center. Online information. US Geological Survey, Volcano Hazards Program, California Volcano Observatory, Menlo Park, California, USA. http://volcanoes.usgs.gov/volcanoes/lassen_volcanic_center/lassen_volcanic_center_monitoring_63.html (accessed 21 March 2013).

Walker, E. L., and S. A. Kattenhorn. 2008. Slip history and evolution of the Hat Creek fault, northern California. Eos, Transactions of the American Geophysical Union, fall meeting supplement 89(52), abstract T21B-1976. http://www.webpages.uidaho.edu/~simkat/abstracts/agu08d.html (accessed 13 August 2013).

Walter, S. R., V. Rojas, and A. Kollman. 1984. Seismicity of the Lassen Peak area, California. Geothermal Resources Council Transactions 8:523–527.

White, D. E., L. J. P. Muffler, and A. H. Truesdell. 1971. Vapor-dominated hydrothermal systems compared with hot-water systems. Economic Geology 66(1):75–97.

Wieczorek, G. F., and J. B. Snyder. 2009. Monitoring slope movements. Pages 245–271 *in* R. Young and L. Norby, editors. Geological monitoring. Geological Society of America, Boulder, Colorado, USA. http://nature.nps.gov/geology/monitoring/slopes.cfm (accessed 6 February 2013).

Wilcox, R. E. 1959. Some effects of recent volcanic ash falls with especial reference to Alaska. Pages 409–476 *in* Bulletin 1028-N. US Geological Survey, Washington, DC, USA. http://pubs.usgs.gov/bul/1028n/report.pdf (accessed 17 April 2013).

Williams, H. 1932. Geology of Lassen Volcanic National Park, California. University of California, Berkeley, Department of Geological Sciences Bulletin 21(8):195–385.

Wills, C. J. 1990a. Hat Creek, McArthur and related faults, Shasta, Lassen, Modoc, and Siskiyou counties, California. Fault evaluation report 209. California Department of Conservation, Division of Mines and Geology, Sacramento, California, USA.

Wills, C. J. 1990b. Faults in the Lake Almanor area, Plumas and Lassen counties, California. Fault evaluation report 212. California Department of Conservation, Division of Mines and Geology, Sacramento, California, USA.

Wood, C. A., and J. Kienle, editors. 1990. Volcanoes of North America, United States and Canada. Cambridge University Press, New York, New York, USA.

Young, R., and L. Norby, editors. 2009. Geological monitoring. Geological Society of America, Boulder, Colorado, USA. http://nature.nps.gov/geology/monitoring/index.cfm (accessed 15 February 2013).

Ziegenbein, M. S., and J. Wagner. 2000. Lassen Volcanic National Park disturbed lands inventory and recommendations. Technical Information Center (TIC) document number 111/D-84. National Park Service, Natural Resource Program Center, Denver, Colorado, USA.

Additional References

This section lists additional references, resources, and websites that may be of use to resource managers. Web addresses are current as of November 2013. 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

Harris, A. G., E. Tuttle, and S. D. Tuttle. 2004. Geology of national parks. Sixth edition. Kendall/Hunt Publishing Company., Dubuque, Iowa, USA.

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

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

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#_Toc157232681

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

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

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

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

Geological Surveys and Societies

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

USGS California Volcano Observatory: http://volcanoes.usgs.gov/observatories/calvo/

US Geological Survey: http://www.usgs.gov/

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

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

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

US Geological Survey Reference Tools

US Geological Survey national geologic map database (NGMDB): http://ngmdb.usgs.gov/

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

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

US Geological Survey geoPDFs (download searchable PDFs of any topographic map in the United States): http://store.usgs.gov (click on "Map Locator & Downloader")

US Geological Survey publications warehouse (many publications available online): http://pubs.er.usgs.gov

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

US Geological Survey, Volcano Hazards Program online glossary: http://volcanoes.usgs.gov/vsc/glossary.html#glnk-56

Appendix A: GRI Participants

The following people attended the GRI scoping meeting for Lassen Volcanic National Park, held on 1 March 2004, or the follow-up report writing conference call, held on 8 April 2013. Discussions during these meetings supplied a foundation for this GRI report. The scoping summary document is available on the GRI publications website: http://go.nps.gov/gripubs.

2004 scoping meeting participants

Name	Affiliation	Position
Tim Connors	NPS Geologic Resources Division	Geologist
Sid Covington	NPS Geologic Resources Division	Geologist
Anne Poole	NPS Geologic Resources Division	Geologist
Pete Biggam	NPS Natural Resources Information Division	Soil Scientist
Chris Currens	US Geological Survey, Biological Resources Division	Aquatic Biologist
Marsha Davis	NPS Columbia Cascades Support Office	Geologist
Louise Johnson	Lassen Volcanic National Park	Chief, Natural Resources
Daniel Sarr	NPS Klamath Network	Network Coordinator
Bob Truitt	NPS Klamath Network	Data Manager
Hanna Waterstat	NPS Klamath Network	Data Miner
Gary Rosenlieb	NPS Water Resources Division	Water Quality Program Lead

2013 conference call participants

Name	Affiliation	Position
Michael Clynne	US Geological Survey	Geologist
Marsha Davis	NPS Columbia Cascades Support Office	Geologist
Katie KellerLynn	Colorado State University	Geologist, GRI Research Associate
Jason Kenworthy	NPS Geologic Resources Division	Geologist, GRI Reports Coordinator
Patrick Muffler	US Geological Survey	Scientist Emeritus
Rebecca Port	NPS Geologic Resources Division	Geologist, GRI Report Writer/Editor
Dave Worthington	Lassen Volcanic National Park	Chief of Resource Management

Appendix B: Geologic Resource Laws, Regulations, and Policies

The 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 GRD for detailed guidance.

Resource	Resource-specific Laws	Resource-specific Regulations	2006 Management Policies
Rocks and Minerals	**NPS Organic Act**, **16 USC. § 1 *et seq.*** directs the NPS to conserve all resources in parks (which includes rock and mineral resources) unless otherwise authorized by law. **Exception: 16 USC. § 445c (c) – Pipestone National Monument enabling statute** authorizes Native American collection of catlinite (red pipestone).	**36 C.F.R. § 2.1** prohibits possessing, destroying, disturbing mineral resources…in park units. **Exception: 36 C.F.R. § 7.91** allows limited gold panning in Whiskeytown. **Exception: 36 C.F.R. § 13.35** allows some surface collection of rocks and minerals in some Alaska parks (not Klondike Gold Rush, Sitka, Denali, Glacier Bay, and Katmai) by non-disturbing methods (e.g., no pickaxes), which can be stopped by superintendent if collection causes significant adverse effects on park resources and visitor enjoyment.	**Section 4.8.2** requires NPS to protect geologic features from adverse effects of human activity.
Geothermal	**Geothermal Steam Act of 1970, 30 USC. § 1001 *et seq.*** as amended in 1988, states -No geothermal leasing is allowed in parks. -"Significant" thermal features exist in 16 park units (the features listed by the NPS at 52 Fed. Reg. 28793-28800 (August 3, 1987), plus the thermal features in Crater Lake, Big Bend, and Lake Mead). -NPS is required to monitor those features. -Based on scientific evidence, Secretary of Interior must protect significant NPS thermal features from leasing effects. **Geothermal Steam Act Amendments of 1988, Public Law 100- 443** prohibits geothermal leasing in the Island Park known geothermal resource area near Yellowstone and outside 16 designated NPS units if subsequent geothermal development would significantly adversely affect identified thermal features.	None Applicable.	**Section 4.8.2.3** requires NPS to -Preserve/maintain integrity of all thermal resources in parks. -Work closely with outside agencies. -Monitor significant thermal features.

Resource	Resource-specific Laws	Resource-specific Regulations	2006 Management Policies
Mining Claims	**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 & economic validity requirements for "unpatented" claims (the right to extract Federally-owned locatable minerals). Imposes additional requirements for the processing of "patenting" claims (claimant owns surface and subsurface). Use of patented mining claims may be limited in Wild and Scenic Rivers and OLYM, GLBA, CORO, ORPI, DEVA. **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.

Resource	Resource-specific Laws	Resource-specific Regulations	2006 Management Policies
Federal Mineral Leasing (Oil & Gas, Salable Minerals, and Non-locatable Minerals)	**The Mineral Leasing Act, 30 USC. § 181 *et seq.***, and the **Mineral Leasing Act for Acquired Lands, 30 USC. § 351 *et seq.*** do not authorize the BLM to lease federally owned minerals in NPS units. **Exceptions**: Glen Canyon NRA (16 USC. § 460dd et seq.), Lake Mead NRA (16 USC. § 460n et seq.), and Whiskeytown-Shasta-Trinity NRA (16 USC. § 460q et seq.) authorizes the BLM to issue federal mineral leases in these units provided that the BLM obtains NPS consent. Such consent must be predicated on an NPS finding of no significant adverse effect on park resources and/or administration. **Exceptions**: Native American Lands Within NPS Boundaries Under the Indian Allottee Leasing Act of 1909, (25 USC. § 396), and the Indian Leasing Act of 1938 (25 USC. §§ 396a, 398 and 399) and Indian Mineral Development Act of 1982 (25 USC.S. §§ 2101-2108), all minerals are subject to lease and apply to Native American trust lands within NPS units. **Federal Coal Leasing Amendments Act of 1975, 30 USC. § 201** does not authorize the BLM to issue leases for coal mining on any area of the national park system.	**36 C.F.R. § 5.14** states prospecting, mining, and…leasing under the mineral leasing laws [is] prohibited in park areas except as authorized by law. **BLM regulations at 43 C.F.R. Parts 3100, 3400, and 3500** govern Federal mineral leasing. **Regulations re: Native American Lands within NPS Units:** 25 C.F.R. pt. 211 governs leasing of tribal lands for mineral development. 25 C.F.R. pt. 212 governs leasing of allotted lands for mineral development. 25 C.F.R. pt. 216 governs surface exploration, mining, and reclamation of lands during mineral development. 25 C.F.R. pt. 224 governs tribal energy resource agreements. 25 C.F.R. pt. 225 governs mineral agreements for the development of Indian-owned minerals entered into pursuant to the Indian Mineral Development Act of 1982, Pub. L. No. 97-382, 96 Stat. 1938 (codified at 25 USC.S. §§ 2101-2108). 30 C.F.R. §§ 1202.100-1202.101 governs royalties on oil produced from Indian leases. 30 C.F.R. §§ 1202.550-1202.558 governs royalties on gas production from Indian leases. 30 C.F.R. §§ 1206.50-1206.62 & §§ 1206.170-1206.176 governs product valuation for mineral resources produced from Indian oil and gas leases. 30 C.F.R. § 1206.450 governs the valuation coal from Indian Tribal and Allotted leases. 43 C.F.R. pt. 3160 governs onshore oil and gas operations, which are overseen by the Bureau of Land Management	**Section 8.7.2** states that all NPS units are closed to new federal mineral leasing except Glen Canyon, Lake Mead and Whiskeytown-Shasta-Trinity NRAs.

Resource	Resource-specific Laws	Resource-specific Regulations	2006 Management Policies
Nonfederal minerals other than oil and gas	**NPS Organic Act, 16 USC. §§ 1 and 3** **Surface Mining Control and Reclamation Act of 1977, 30 USC § 1201 *et. seq.*** prohibits surface coal mining operations on any lands within the boundaries of a NPS unit, subject to valid existing rights.	**NPS regulations at 36 C.F.R. Parts 1, 5, and 6** require the owners/operators of other types of mineral rights to obtain a special use permit from the NPS as a § 5.3 business operation, and § 5.7 – Construction of buildings or other facilities, and to comply with the solid waste regulations at Part 6. **SMCRA Regulations at 30 C.F.R. Chapter VII** govern surface mining operations on Federal lands and Indian lands by requiring permits, bonding, insurance, reclamation , and employee protection. Part 7 of the regulations states that National Park System lands are unsuitable for surface mining.	**Section 8.7.3** states that operators exercising rights in a park unit must comply with 36 CFR Parts 1 and 5.
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 National Recreation Area, 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 NEPA & other federal, state, and local laws, and a finding of non-impairment. - After finding the use is park's most reasonable alternative based on environment and economics. - Parks should use existing pits and create new pits only in accordance with park-wide borrow management plan. - Spoil areas must comply with Part 6 standards - NPS must evaluate use of external quarries. Any deviations from this policy require written waiver from the Secretary, Assistant Secretary, or Director.

Resource	Resource-specific Laws	Resource-specific Regulations	2006 Management Policies
Upland and Fluvial Processes	**Rivers and Harbors Appropriation Act of 1899, 33 USC. § 403** prohibits the construction of any obstruction, on the waters of the united states, not authorized by congress or approved by the USACE. **Clean Water Act 33USC. § 1342** requires a permit from the USACE prior to any discharge of dredged or fill material into navigable waters (waters of the US (including streams)). **Executive Order 11988** requires federal agencies to avoid adverse impacts to floodplains. (see also D.O. 77-2) **Executive Order 11990** requires plans for potentially affected wetlands (including riparian wetlands). (see also D.O. 77-1)	None Applicable.	**Section 4.1** requires NPS to manage natural resources to preserve fundamental physical and biological processes, as well as individual species, features, and plant and animal communities; maintain all components and processes of naturally evolving park ecosystems. **Section 4.1.5** directs the NPS to re-establish natural functions and processes in human-disturbed components of natural systems in parks unless directed otherwise by Congress. **Section 4.4.2.4** directs the NPS to allow natural recovery of landscapes disturbed by natural phenomena, unless manipulation of the landscape is necessary to protect park development or human safety. **Section 4.6.4** directs the NPS to (1) manage for the preservation of floodplain values; [and] (2) minimize potentially hazardous conditions associated with flooding **Section 4.6.6** directs the NPS to manage watersheds as complete hydrologic systems and minimize human- caused disturbance to the natural upland processes that deliver water, sediment, and woody debris to streams **Section 4.8.1** directs the NPS to allow natural geologic processes to proceed unimpeded. Geologic processes…include…erosion and sedimentation…processes. **Section 4.8.2** directs the NPS to protect geologic features from the unacceptable impacts of human activity while allowing natural processes to continue.

Resource	Resource-specific Laws	Resource-specific Regulations	2006 Management Policies
Soils	**Soil and Water Resources Conservation Act, 16 USC. §§ 2011 – 2009** provides for the collection and analysis of soil and related resource data and the appraisal of the status, condition, and trends for these resources. **Farmland Protection Policy Act, 7 USC. § 4201 *et. seq.*** requires NPS to identify and take into account the adverse effects of Federal programs on the preservation of farmland; consider alternative actions, and assure that such Federal programs are compatible with State, unit of local government, and private programs and policies to protect farmland. NPS actions are subject to the FPPA if they may irreversibly convert farmland (directly or indirectly) to nonagricultural use and are completed by a Federal agency or with assistance from a Federal agency. Applicable projects require coordination with the Department of Agriculture's Natural Resources Conservation Service (NRCS).	**7 C.F.R. Parts 610 and 611**are the US Department of Agriculture regulations for the Natural Resources Conservation Service. Part 610 governs the NRCS technical assistance program, soil erosion predictions, and the conservation of private grazing land. Part 611 governs soil surveys and cartographic operations. The NRCS works with the NPS through cooperative arrangements.	**Section 4.8.2.4** requires NPS to: - Prevent unnatural erosion, removal, and contamination. - Conduct soil surveys. - Minimize unavoidable excavation. - Develop/follow written prescriptions (instructions).

NPS 111/123450, January 2014

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