Volcano Hazards Assessment for the Lassen Region, Northern California

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U.S. Department of the Interior
U.S. Geological Survey

FRONT COVER

The May 22, 1915, explosive eruption of Lassen Peak, California, blasted pumice and rock fragments high into the air. In this photograph, taken from Red Bluff, 65 kilometers (40 miles) west of the volcano, a huge column of volcanic ash and gas produced by the eruption rises to a height of about 9 kilometers (30,000 feet). Winds blew volcanic ash from the column eastward, raining fine ash at least as far away as Elko, Nevada, 450 kilometers (280 miles) from the volcano. The ash cloud from a similar eruption today would pose a serious hazard to aircraft flying in the western United States. (Photo by R.E. Stinson, courtesy of the National Park Service.)

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Conversion Factors

SI to Inch/Pound

Multiply	By	To obtain
	Length	
centimeter (cm)	0.3937	inch (in.)
millimeter (mm)	0.03937	inch (in.)
meter (m)	3.281	foot (ft)
kilometer (km)	0.6214	mile (mi)
meter (m)	1.094	yard (yd)
	Area	
square meter (m^2)	0.0002471	acre
square kilometer (km^2)	0.3861	square mile (mi^2)
	Volume	
cubic kilometer (km^3)	0.2399	cubic mile (mi^3)

Temperature in degrees Celsius (°C) may be converted to degrees Fahrenheit (°F) as follows: °F=(1.8x°C)+32

Temperature in degrees Fahrenheit (°F) may be converted to degrees Celsius (°C) as follows: °C=(°F-32)/1.8

Vertical coordinate information is referenced to the North American Vertical Datum of 1929 (NGVD 29)

Horizontal coordinate information is referenced to the North American Datum of 1927 (NAD 27)

Altitude, as used in this report, refers to distance above the vertical datum.

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By Michael A. Clynne, Joel E. Robinson, Manuel Nathenson, and L.J. Patrick Muffler

Executive Summary

This report evaluates the volcano-related hazards of the Lassen region, California, which is here defined as an area between the Pit River on the north and the southern limit of active Cascade volcanism, approximately 5–10 km south of the southern boundary of Lassen Volcanic National Park. Most active volcanism occurs in a zone about 40 km wide between Viola on the west and the eastern boundary of Caribou Wilderness Area, but sparser volcanism in the west extends the width of this zone to about 75 km. The report is based primarily on knowledge of hazardous phenomena observed at other, similar volcanoes and on recently published geologic mapping and geochronology (Clynne and Muffler, 2010; Christiansen and others, 2002; Clynne and others, 2008) applied to the volcano-hazards framework established by Miller (1989).

Volcanism in the Lassen Region

The Lassen region forms the southernmost segment of the Cascade arc of volcanoes (Guffanti and Weaver, 1988; Clynne and Muffler, 2010). The long-term (million-year) volcanic history of the region can be described on two spatial scales. On the regional scale, hundreds of closely spaced, small, short-lived volcanoes and a few larger lava cones and shield volcanoes make up much of the Cascade arc in the Lassen region. On the local scale, a few much larger, long-lived volcanic centers are superimposed on this regional volcanism. The volcanic center currently active is the Lassen Volcanic Center. Compared to vents of a typical Cascade composite volcano, for example Mount Shasta or Mount Rainier, the vents of the active part of the Lassen Volcanic Center are widely distributed, extending over an area 20 km north-south and 25 km east-west. Hundreds of eruptions have occurred in the Lassen Volcanic Center over its 825,000-year lifetime, including at least 14 eruptions in the past 100,000 years. These latter eruptions have included explosive events, ash fall, lahars, and emplacement of lava flows and domes. Since about 25,000 years ago, the Lassen Volcanic Center has been relatively quiet, but three eruptions during the last 1,050 years, the most recent in 1914–1917, demonstrate that it is still active. Although the probability of an eruption is very small in any given year (about 1 chance in 7,150), the potential consequences of future eruptions could be regionally significant.

In the region surrounding the Lassen Volcanic Center, there have been at least 58 eruptions of small volcanoes in the past 100,000 years, including two in the past 15,000 years. This regional volcanism is primarily mafic (basaltic) in composition, is relatively nonexplosive, and typically is concentrated in a relatively small area in any given time interval. The probability of eruption of a regional volcano, about 1 chance in 1,550 in any given year, is higher than that for the Lassen Volcanic Center. However, the consequences of a regional eruption would be less severe than those of an eruption in the Lassen Volcanic Center, because regional volcanoes typically build cinder cones and erupt small lava flows and ash fallout that affect a rather small area.

Relative to other U.S. volcanoes, the Lassen Volcanic Center has been designated a “very high threat volcano” by the U.S. Geological Survey (USGS) (Ewert and others, 2005). The basis of this designation was the center’s eruptive history, extent of the domefield, potentially explosive nature, presence of an active hydrothermal system, location in a national park with significant visitorship in the summer, and proximity to regional infrastructure.

Summary of Major Volcano-Related Hazards

The most likely volcano-related hazards in the Lassen region are summarized according to the nature and location of the volcanism. The hazards related to the small regional volcanoes in the area surrounding the Lassen Volcanic Center and to silicic to andesite volcanism in the Lassen Volcanic Center are summarized separately below. Hazards associated with the hydrothermal system, landslides, and rockfalls in Lassen Volcanic National Park are also discussed and delineated on a volcano-hazard map. A glossary at the back of this report defines selected geologic terms.

An eruption generating extremely large pyroclastic flows, for example a caldera-forming or “supervolcano” eruption producing tens to hundreds of km^3 of lava and ash is not discussed in this report because it is exceedingly unlikely. Several such large-scale events have occurred at Lassen in the past 3 million years, but none since eruption of the Rockland ash flow tuff and tephra 611,000 years ago (Lanphere and others, 2004). The magmatic system of the Lassen Volcanic Center is not presently configured for this type of eruption, and the short-term probability of such a high-consequence event is considered negligible.

Regional Mafic Lava Flows and Ash

On the basis of past activity, the most likely eruption in the Lassen region would be that of a new small mafic volcano. The eruption would probably consist of localized near-vent explosive activity that would build a cinder or spatter cone and produce modest ash fallout downwind and be accompanied by lava flowing a few kilometers from the vent. The activity would continue for a period of weeks to months. Hazards would include violent ejection of hot blocks of lava near the vent, as well as intermittent explosions that could send ash clouds several kilometers into the air and deposit more than 5 cm of ash within 10 km and lesser amounts as much as ~50 km downwind. Also possible, but less likely, are eruptions of fluid lava flows that could extend a few tens of kilometers from the vent area, cover as much as 100 km^2, and continue for as long as 5 to 10 years. The most likely locations for mafic eruptions are in a zone between the Red Cinder chain and Calif. Hwy 44 (approximately the area in and around the northeastern corner of Lassen Volcanic National Park), a zone from south of Old Station to the Pit River, a zone from the south end of Tumble Buttes chain to the vicinity of Burney Mountain, and in the area of the Red Lake cluster.

Silicic Lava Domes, Flows, and Pyroclastic Flows

The most likely type of eruption associated with silicic volcanism in the Lassen Volcanic Center would be explosive. Precursory activity could include intermittent steam explosions that eject cold rocks on ballistic trajectories near the vent, as well as send ash clouds several kilometers into the air and deposit local accumulations of ash. Precursory activity could be followed by a magmatic phase of the eruption, during which explosive silicic volcanism produces a vertical eruption column whose partial collapse could generate pyroclastic flows, build a tuff cone, and deposit ash. Hazards would include pyroclastic flows, which could travel a few tens of kilometers down valleys heading in the vent area, lateral blasts and pyroclastic surges, and ash fall deposited over considerable distances. Effusive (nonexplosive) eruptions could produce lava flows or build lava domes and might continue for a few months to a few years. Partial collapse of unstable, hot, growing lava domes could also generate pyroclastic flows affecting areas within a few kilometers of the dome. The most likely locations for this type of activity in the Lassen Volcanic Center would be in the area around Chaos Crags and in the northern part of Lassen Volcanic National Park east to Cinder Cone.

Lahars

Lassen Peak and the high-elevation areas of Lassen Volcanic National Park are covered with a deep snow pack during the winter and spring months. Consequently, there is a significant lahar hazard to drainages heading on Lassen Peak and a lesser hazard to drainages heading on the central and southwestern parts of Lassen Volcanic National Park. Rapid melting or incorporation of significant volumes of snow into turbulently flowing eruption products could cause far-traveled lahars, primarily in the valleys heading on the north flank of Lassen Peak.

Newly fallen ash is susceptible to rapid erosion, and heavy rainfall can remobilize widespread pyroclastic flows or thick ash deposits and could cause lahars in the valleys heading in Lassen Volcanic National Park and their downstream extensions. Lahars do not require a volcanic eruption to be triggered. Landslides of water-saturated, hydrothermally altered rock can transform into lahars as they move downslope. Emplacement of lahars in drainages can cause significant disruption of normal stream flow and secondary affects for decades after the initial event.

Airborne Ash

Moderate-size eruptions related to the silicic volcanism described above will produce eruption columns that rise high into the atmosphere. These will likely affect commercial and military air traffic. Significant volumes of volcanic ash may be transported and deposited over an area tens of kilometers from vents and traces of ash hundreds of kilometers farther. Airborne ash could affect the towns of Chester and Susanville and less likely Burney, Redding, and Red Bluff, for days to weeks at a time, but would likely not result in accumulation of ash sufficient to cause structural damage to buildings or infrastructure. Smaller ash eruptions accompanying the construction of cinder cones would affect much smaller areas near the vents.

Other Hazards

Landslides and rockfalls are significant hazards in the hydrothermally altered core of Brokeoff Volcano and in Mill Creek, less so in Bailey Creek. Rockfalls are also a hazard in the areas surrounding Lassen Peak and Chaos Crags and in other areas with steep cliffs. Additional hazards are associated with the hydrothermal system, including the potential of severe burns in fumaroles or mud pots and danger from toxic gases. The Lassen region is subject to considerable seismic activity, and major faults in the area are recognized as capable of moderate to large earthquakes (as large as magnitude 7), but seismic hazards are not specifically evaluated herein.

Introduction

Lassen Peak, the southernmost active Cascade volcano (fig. 1), last erupted in 1914–17 and, before the 1980–86 eruption of Mount St. Helens, was the only volcano in the conterminous United States to have erupted in the 20th century. Lassen Peak is an unusual Cascade volcano because it is not a large **composite volcano**[1] like, for example, Mount Shasta or Mount

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[1] Words in **bold type** represent the first use of terms defined in the glossary at the back of this report.

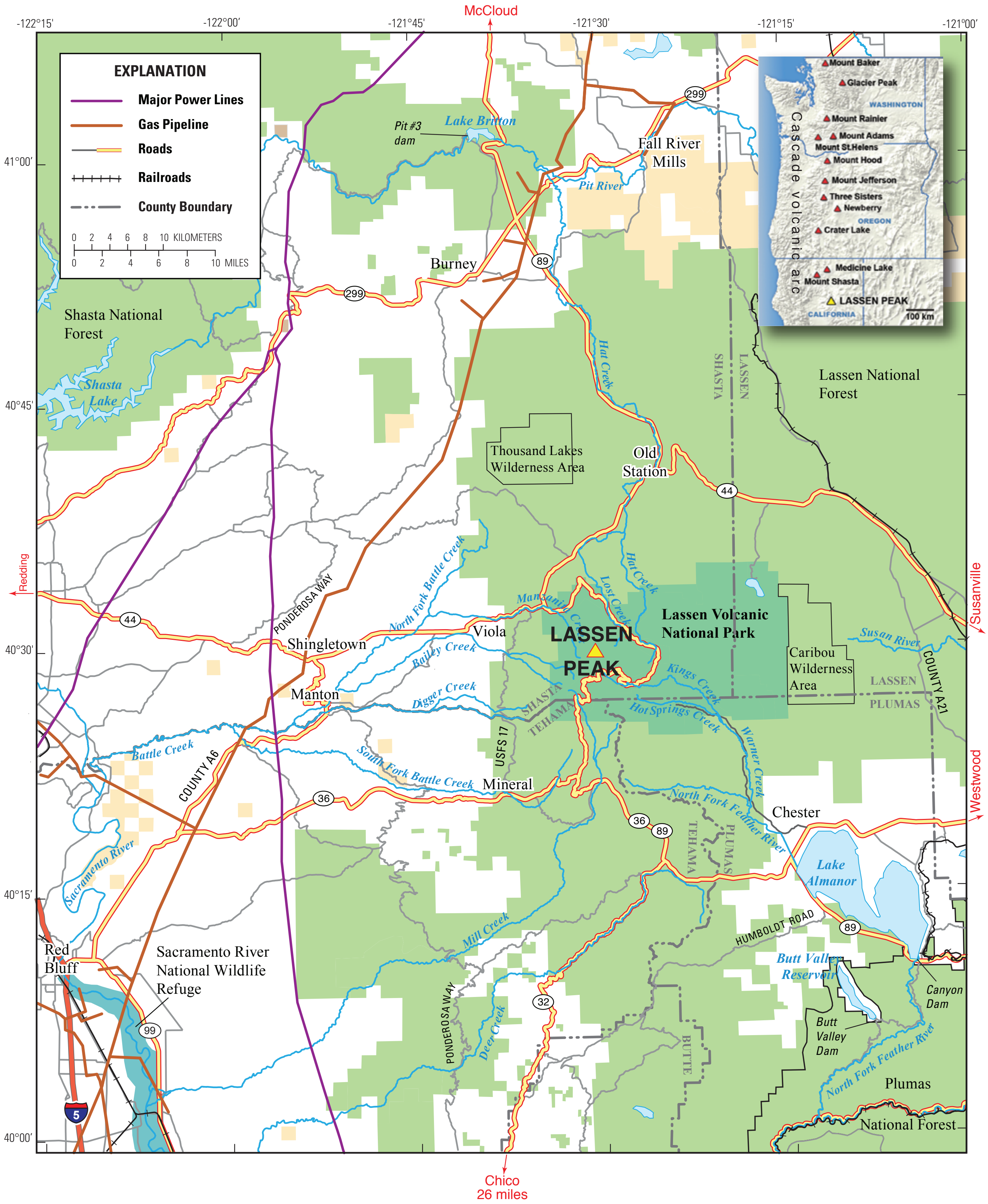

Figure 1. Map of the Lassen volcanic region and surrounding area, showing land-management boundaries and infrastructure information, including roads. Inset map shows locations of major Cascade volcanoes. Private land is white; Lassen, Shasta, and Plumas National Forests and wilderness areas are green; U.S. Bureau of Land Management land is buff. The dark-green area in the right center is Lassen Volcanic National Park. Small areas managed by other agencies, for example, the State of California, are not shown separately and are included in the white areas.

Rainier. Rather, Lassen Peak is a large volcanic **dome** within a field of domes, called the Lassen domefield. The Lassen domefield contains 30 **lava** domes that formed over the past 300,000 years at the Lassen Volcanic Center (LVC), which includes the domefield and an older related composite **andesite** volcano. The LVC is active and potentially threatens the Lassen region with a variety of volcano hazards. In the National Volcano Early Warning System (NVEWS) assessment, the Lassen Volcanic Center is described as a "very high threat volcano" (Ewert and others, 2005).

Media reports of the climactic May 1915 eruptions of Lassen Peak focused the attention of the American public on the volcanoes of the Cascade volcanic arc and their potential for eruption. Previously, Lassen Peak and Cinder Cone were recognized as noteworthy features and designated as national monuments in 1907. Following the 1915 eruption, Congress in 1916 created Lassen Volcanic National Park (LVNP). For many decades, economic growth in the immediate area was limited, and the potential for loss of life and property was relatively minor. The economy of the Lassen region today remains primarily based on forest products, ranching, recreation, and tourism. Recently, however, residential growth in the areas surrounding LVNP has increased the potential for loss of life and property in the event of a volcanic eruption. In May 1915, an eruption cloud from Lassen Peak reached an elevation of nearly 9 km (~30,000 feet), and **ash** fall was noted at least as far east as Elko, Nevada (about 450 km distant). Despite significant **lahars**, the relatively small eruption caused no deaths, and property damage was minor. But only 1,050 years ago, the Chaos Crags were formed in a sequence of major eruptions at the LVC that were 40 times bigger than those in 1915 and included **pyroclastic flows** and the construction of large lava domes. The Lassen region lies beneath major air corridors connecting southern and central California and the Pacific Northwest, and eruptions today would affect commercial and military aviation over a wide area of the western United States.

The primary purpose of this report is to describe and assess hazards from future eruptions of volcanoes in the Lassen region, which is here defined as an area between the Pit River on the north and the southern limit of active Cascade volcanism, approximately 5–10 km south of the southern boundary of LVNP. Most active volcanism occurs in a zone about 40 km wide between Viola on the west and the eastern boundary of Caribou Wilderness (fig. 1), but sparser volcanism in the west extends the width of this zone to about 75 km.

Geologic hazards at LVNP were first assessed by the USGS in 1970 and the results given to the National Park Service. A volcano-hazards assessment of California, including the Lassen region, was published by Miller (1989), and a USGS Fact Sheet based on Miller (1989) briefly summarized the hazards of the Lassen region (Clynne and others, 2000). Detailed geologic mapping in the Lassen region (Christiansen and others, 2002; Clynne and Muffler, 2010), ongoing geologic studies, hazards recognized at other active volcanoes, and geophysical monitoring of the region by the USGS provide the scientific basis for this reassessment of volcano hazards in the Lassen region.

In the pages that follow, we first define the various volcano-related hazards and present a general discussion of their effects. This discussion is modified from Miller (1989), Scott and others (1995; 2001), Waitt and others (1995), Gardner and others, 1995, Hoblitt and others (1998), and Walder and others (1999). More detailed general information on volcano hazards and the effects of eruptions can be found in Blong (1984) and Sigurdsson and others (2000).

The general discussion of volcano-related hazards is followed by discussion of the hazards specific to the Lassen region. As background, we describe the distribution, types, and magnitude of volcano-related hazardous events in the Lassen region since about 100,000 years ago. A review of the type and magnitude of activity expected in the future is presented, and the areas most likely to be affected are delineated on hazard-zonation maps. These hazard zones are modified from those of Miller (1989), primarily by applying more accurate age data for volcanism and the size of eruptions in the Lassen region. Discussions of landslides, rockfalls, and hazards associated with the Lassen **hydrothermal** system are also presented. We estimate the probability of occurrence of volcanic eruptions in the Lassen region and discuss the results in a subsequent section. Knowledge of the likelihood and hazards posed by volcanic eruptions provides planners and public officials such as the California Emergency Management Agency (CalEMA) and local governments information to mitigate the effects of future eruptions. Technical terms are defined in the glossary at the end of this report (and shown in bold font in the text at first use).

Types of Volcano Hazards and Effects of Volcanic Eruptions

Volcano hazards in volcanic arcs like the Cascades are often simply classified into two broad types of volcanoes: **mafic** and composite (for example, Scott and others, 2001). Mafic composition volcanoes (which erupt **basalt** to **basaltic andesite**)[2] are generally small, short-lived, and less violently explosive than composite volcanoes. Mafic volcanoes typically erupt only once for a brief period (weeks to a few years), but some, called **lava cones** and **shield volcanoes**, build larger edifices and are intermittently active for longer periods (centuries to a few millennia). Once a given mafic eruption has run its course, subsequent mafic eruptions typically issue from new locations. Over tens to hundreds of

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[2] Volcano hazards exist as a spectrum of possibilities related to the composition of the erupted magma. The compositional spectrum of increasing silica content of volcanic rocks—basalt, basaltic andesite, andesite, dacite, rhyodacite, and rhyolite—generally correlates with increasing explosivity. Mafic compositions (basalt and basaltic andesite) are generally less explosive, and silicic compositions (dacite, rhyodacite and rhyolite) are generally more explosive. Intermediate composition magmas (andesite) can create hazards of both mafic and silicic character. For simplicity in this report, we have placed hazards of andesite eruptions in the silicic category because they will likely occur as part of Lassen Volcanic Center eruptive activity.

thousands of years, mafic eruptions build broad platforms consisting of many extinct volcanoes.

Composite volcanoes, on the other hand, are large, long-lived features that erupt episodically for tens to hundreds of thousands of years from the same or closely-spaced **vents**, build cones thousands of meters high, and display a wide range of eruptive styles and explosivity. They are primarily **silicic** in composition (andesite, **dacite**, **rhyodacite** and **rhyolite**) and constructed from a single long-lived, **magmatic system** located in the crust beneath the volcano. The Lassen Volcanic Center is an even bigger and longer-lived silicic volcanic feature. It consists of an early **caldera** complex, a composite volcano, and a domefield of adjacent small, closely spaced, silicic lava domes and flows. These three main components of the LVC formed sequentially, from a single evolving magmatic system. The Lassen domefield is the presently active expression of the volcanic center. Below, we discuss volcano hazards under the headings of mafic for the regional volcanism and silicic for volcanism at the LVC.

A variety of hazards are associated with volcanic eruptions (fig. 2; Myers and others, 2008). Silicic eruptions can produce vertically directed **eruption columns** many thousands of meters high, lava domes and flows, and lahars (also called volcanic mudflows). Collapse of eruption columns can produce pyroclastic flows, and transport of ash from eruption clouds by the wind can result in deposition of ash as far as hundreds of kilometers downwind. The effects of mafic volcanoes are less violent and generally limited to a few tens of kilometers from the vent. They eject **tephra** (lava blocks and ash) and produce lava flows.

Definitions, more detailed descriptions, and the potential effects of general volcano and volcano-related hazards are discussed below, with an emphasis on the types of eruptions that may occur in the Lassen region. Specific volcano and volcano-related hazards in the Lassen region are discussed in the section “Volcano-Related Hazards in the Lassen Region.” Additional geologic hazards that do not require an eruption to trigger events are possible in volcanic terrains. These include earthquakes or landslides and lahars that can be triggered by earthquakes, severe rainstorms, or rain-on-snow events. At LVC, the presence of a large active hydrothermal system presents a third group of hazards.

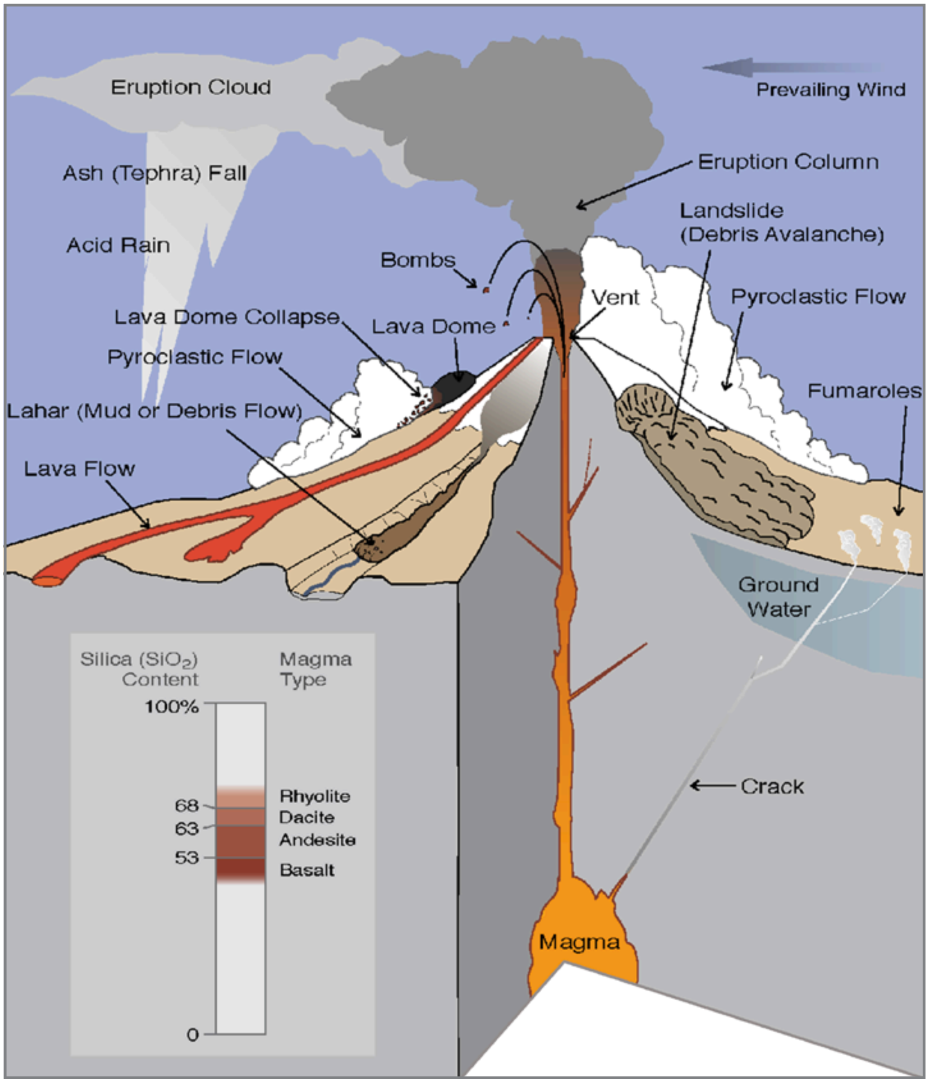


Figure 2. Volcanoes produce a wide variety of natural hazards that can kill people and destroy property. This simplified sketch shows a composite volcano typical of those found in the Cascade arc. Some hazards, such as lahars and landslides, can occur even when a volcano is not erupting (from Myers and others, 2008). Terms are defined in the glossary.

Hazards Associated with Mafic Eruptions

Mafic **magma** is much less viscous and generally contains a smaller gas component than silicic magma. Mafic magma is typically less violently explosive, so that mafic eruptions generally affect smaller areas than silicic eruptions. Large fragments fall out near the vent and build a **cinder cone**, and thick accumulations of coarse tephra are generally restricted to the vicinity (within a few kilometers) of the vent. However, when mafic magma interacts with water, steam explosions can generate a large quantity of fine ash and eject it into the atmosphere. Under favorable wind conditions ash can be dispersed for significant distances: for example, the 2010 eruption of Eyjafjallajökull Volcano in Iceland caused major disruption of commercial transatlantic air traffic. Less violent interaction between mafic magma and water produces **pyroclastic surges** that build cones of ash with shallow slopes like shield volcanoes.

After the initial gas-rich part of an ascending magma body is erupted, most mafic volcanoes produce lava flows. Depending on the viscosity and rate of effusion, lava will form a thick, short lava flow or a thin widespread lava flow. Viscous flows are 10 to a few tens of meters (30–100 feet) thick and have hot but solid outer surfaces covered with blocks of lava (block flows). They move slowly downslope into valleys and may flow for a few kilometers, often stopping when the underlying slope angle decreases. Viscous flows tend to have relatively small volumes. Fluid lava flows advance in channels or lava tubes that distribute lava to the advancing front of the flow with little loss of heat. The volumes of fluid lava flows tend to be 10 to a few hundred times larger than viscous flows. They can flow for a few tens of kilometers, and they spread out and cover significant areas of valley bottoms. Individual flow lobes are thin, generally 1–3 meters (3–10 feet), but if the flow is confined by valley walls, many flow lobes can pile up to make a much thicker flow. Hazards of mafic lava flows are primarily to property and infrastructure, because the flows generally advance slowly enough for humans and animals to escape. However, lava flows destroy all structures in their path and can ignite forest fires. Lava flows can disturb drainages by diverting or damming rivers and creeks. Lava dams that impound water to form a lake are susceptible to rapid down-cutting or sudden failure that can release a large volume of water and generate a “breakout flood.”

Hazards Associated with Silicic Eruptions

The most destructive eruptions at volcanic centers (and composite volcanoes) are caused by silicic magma, which is very viscous and often gas-rich. Consequently, it can erupt explosively and can produce enormous clouds of gas and ash. As silicic magma ascends from a magma reservoir, the decrease in pressure permits gases dissolved in it to be released. The gases form bubbles that expand rapidly as the magma ascends from depth. As the magma approaches the surface, these bubbles literally explode out of the magma, fragmenting it into pieces (tephra) ranging in size from a few tens of centimeters (**pumice**) to fine dust (ash). The hot rock fragments, ash, and gases ascend vertically as a buoyant eruption column. The largest rock fragments generally fall out within a few kilometers of the vent, but small fragments, ash, and gas rise high into the air forming a billowing eruption column. Eruption columns can grow rapidly and reach heights of more than 20 km above the volcano within 30 minutes or less. Commonly, eruption columns collapse to generate pyroclastic flows. These turbulent clouds of pumice, ash, rock fragments, and gas can have temperatures of 500ºC or even higher, move downhill at speeds up to 200 kilometers per hour, travel tens of kilometers from their vent, surmount topographic barriers, and destroy everything in their path.

A **lateral blast** (also called a pyroclastic surge) is a type of pyroclastic flow that is directed laterally or subhorizontally away from the vent. This type of eruption results from the sudden release of pressure on magma intruded into a volcanic edifice. One initiation mechanism is failure of the flank of the volcano that exposes the intruded magma at the surface. The decompressed magma literally explodes out of the volcano laterally. Lateral blasts and pyroclastic surges can be more violent than pyroclastic flows generated by column collapse. Their mobility is much less inhibited by topography than typical pyroclastic flows. Lateral blasts may affect only narrow sectors or spread out from a volcano to cover a sector as broad as 180 degrees, and they can reach distances of several tens of kilometers from the volcano. Lateral blasts carrying rock debris at high speed can devastate areas of tens to hundreds of square kilometers within a few minutes and can obliterate manmade structures and forest and kill all living things by abrasion, impact, burial, and heat. The 1980 eruption of Mount St. Helens is the best-known lateral blast.

Ash ejected high into the atmosphere forms an eruption cloud. Dispersal and settling (fall out) of ash is another major hazard associated with silicic eruptions. Fine ash drifts downwind before settling and, depending on the height of the eruption cloud and direction of prevailing winds, can blanket areas tens to hundreds of kilometers away. Thick accumulations of fine ash make structures susceptible to collapse, especially if the ash gets wet. Fine silicic ash is abrasive and destructive to all types of machinery and internal combustion engines (Kenedi and others, 2002). Aircraft engines are particularly susceptible to damage from fine ash, and even small dilute ash clouds pose great hazards to aircraft that fly into them (Miller and Casadevall, 2000). Fine ash is easily remobilized by motor vehicles or helicopters, and it is expensive to remove. Thus, even thin deposits of ash can be very disruptive to human enterprises for days to weeks after deposition. Deposits of fine ash can short-circuit electric transformers and power lines, especially if the ash gets wet, which makes it adhere to surfaces and enhances electrical conductivity. Ash is not directly toxic, but like fine dust, ash suspended in the air is irritating to the eyes and lungs, and prolonged inhalation can cause chronic lung disease

(Baxter, 2000; Horwell and Baxter, 2006). Even thin accumulations of fine ash on farm or grazing land can negatively affect crops and livestock. Thick accumulations of fine ash can be remobilized into lahars by rain or snowmelt, inundate downstream valleys, and negatively affect water quality and aquatic ecosystems.

Lessons learned from the effects of the 1980 eruption of Mount St. Helens on downwind communities in Washington are now used to prepare governments, businesses, and citizens for future ash falls. These communities experienced significant disruptions in transportation, business activity, and community services as a result of **fallout** of only 5 mm to 6 cm (1/4 to 2 1/2 inches) of ash. Generally, ash fall less than about 5 mm (1/4 inch) was perceived as an inconvenience, whereas more than about 15 mm (5/8 inch) constituted a disaster. The greater the amount of ash, the longer it took for communities to recover, but in most cases communities recovered to near-normal activities within two weeks.

Eruption of gas-poor silicic magma is less explosive and affects a more limited area, generally close to the vent. **Effusive eruption** of gas-poor silicic magma builds steep-sided lava domes or thick lava flows that are fractured and often unstable and susceptible to sudden gravitational collapse as they grow larger and higher. Collapse of significant volumes of hot rock from lava domes can produce avalanches of hot rock fragments and gas called dome-collapse pyroclastic flows (also called lithic pyroclastic flows or block-and-ash flows). Although their mobility relative to pyroclastic flows generated by collapse of eruption columns is more limited, pyroclastic flows generated by collapses from large domes or domes perched high above valleys can move rapidly and travel significant distances depending on the height and size of the source dome. Some lava domes collapse repeatedly and build thick fans of rock fragments (like talus slopes) that generally extend to flat or gently sloping ground but can travel farther if they enter steep valleys. In general, bigger or higher domes will generate bigger, farther-traveled pyroclastic flows. The hazards from this type of dome-collapse event are similar to column-collapse pyroclastic flows, but they cover a more limited area. Documented eruption histories at volcanoes such as Mount St. Helens, Washington, Soufrière Hills, Montserrat, and Santiaguito, Guatemala, demonstrate that growth of lava domes and corresponding hazards can continue for years to decades.

Hazards Associated with Lahars

Snow- or ice-covered volcanoes present an additional hazard. Eruption of hot ash onto snow or pyroclastic flows traveling over snow can rapidly melt it. The rapid generation of a large volume of water on a volcano covered with loose debris can initiate a volcanic mudflow or lahar. A lahar is a water-saturated volcanic debris flow consisting of as much as 50 percent sediment (Vallance, 2000). The sediment can be recently erupted rocks and ash or older loose material on the flanks of a volcano or in a drainage. A lahar has the consistency of wet concrete and can surge down valleys and stream channels at speeds of 15–30 km per hour (Rodolfo, 2000) but can reach even higher speeds under favorable circumstances. Because they are saturated with water, large-volume lahars can flow over relatively gentle gradients and can inundate areas tens of kilometers away from their sources. Lahars generated by eruptions are responsible for significant loss of life and property damage downstream of volcanoes. They are powerful and can carry huge boulders and trees and inundate river valleys, sweep away structures, and destroy bridges. Less dramatic effects include filling buildings with debris and burying roads, farmland, and infrastructure. Lahars often transition into muddy floods as they come to rest and release a large volume of water. Lahars that flow into reservoirs can create waves that overtop dams or cause dam failure and serious floods downstream. Large lahars can block drainages, backing up water to create a lake. Eventual overtopping and failure of the lahar dam can generate a catastrophic flood unless the blockage is managed by engineers. Initiation of a lahar does not require volcanic eruption, and non-volcanic debris flows generated by severe rainstorms or rain-on-snow events can occur in volcanic or non-volcanic terrain. The long-term effects of lahars can persist for decades, as can the effects of other types of eruptions that disturb the landscape. These effects include increased rates of erosion, downstream deposition of sediment, and negative effects on water quality and navigation.

Other Volcano-Related Hazards

Steep-sided volcanic edifices are inherently unstable features that are susceptible to gravitational collapse. New lava often is deposited on steep surfaces covered with loose material, and hot lava and interbedded fragmental deposits produce weak, fractured rock masses when they cool. Weathering and hydrothermal alteration further weaken volcanic edifices. Collapse of volcanic edifices can be triggered by a variety of volcanic and nonvolcanic events. These kinds of collapses are landslides or rockfalls and are also called debris avalanches. Small debris avalanches can be triggered by **tectonic** earthquakes, rainstorms, rapid snowmelt, or normal erosional processes. On large volcanic cones (edifices), the onset of volcanic unrest with earthquakes, steam explosions, and intrusion of magma greatly increases the likelihood of debris avalanches and the possibility of catastrophic large-volume events. The largest debris avalanches are failures of the entire sides of large composite volcanoes and involve volumes as great as several cubic kilometers. These huge debris avalanches can travel for tens of kilometers down-valley and, if they contain or acquire sufficient water, can transition into lahars, further increasing their mobility.

Volcanoes emit gases during eruptions, and even when they are not erupting, gases can be released by intrusions of subsurface magma or cooling domes and lava flows. More than 90 percent of volcanic gases are water vapor or steam, most of which is heated ground water. Other common volcanic gases are carbon dioxide, sulfur gases, chlorine, and fluorine. Sulfur dioxide, hydrogen sulfide, chorine, and fluorine gases can react with water droplets in the air to create acid rain, which causes corrosion and is harmful to vegetation. Precipitation of gases onto ash particles in eruption clouds creates acid compounds that can poison livestock grazing on ash-coated grass and can contaminate water supplies. Carbon dioxide is heavier than air and in windless conditions can be trapped in low areas in concentrations that are deadly to humans and animals. Similar hazards are related to emissions of gases from hydrothermal systems.

Volcanism in the Lassen Region

The Lassen region sits astride the axis of the southernmost Cascade arc, a segment of the “Ring of Fire” of volcanoes that encircles the Pacific Ocean basin. The arc results from subduction of the oceanic Juan de Fuca Plate beneath the continental North American Plate. There are two fundamentally different scales of volcanism in the Lassen region: distributed regional volcanism and volcanic centers (fig. 3). Regional volcanism is generally nonexplosive to weakly explosive, and pyroclastic activity does not typically affect areas much beyond the immediate vicinity of the **vent**, except for minor ash fall as much as a few tens of kilometers downwind. Regional volcanoes have a wide range of forms and comprise a continuum of sizes from small cinder cones and lava flows through larger, steep-sided lava cones to broad shield volcanoes. The overall result of regional volcanism is construction of a broad platform of overlapping mafic volcanoes.

The smallest and most abundant regional volcanoes are cinder cones. Cinder cones are composed of bedded cinders or **scoria** and **bombs** piled up in a generally symmetrical cone around a vent. Typically they have an associated lava flow that erupts from the base of the cone. Cinder cones generally have a single period of activity and erupt small-volume lava flows. Cinder Cone, in eastern LVNP, is a typical cinder cone, albeit with a lava flow field that is larger than normal.

Lava cones and shield volcanoes are bigger than cinder cones and are more or less circular in plan view unless built on a slope. They are constructed by eruptions from a central vent or from flank vents high on an edifice and, depending on the viscosity of the lava, build a steep-sided lava cone or a flatter shield volcano. They are usually capped by a cinder cone but generally lack widely distributed fragmental deposits. Typically they are intermittently active for a period of decades to a few millennia and build edifices of as much as a few cubic kilometers in volume. Sugarloaf Peak is an example of a lava cone, and Prospect Peak is an example of a shield volcano in the Lassen region (plate 1).

Fluid basalt erupts from fissures and produces widespread lava flows that flood the valleys between some shield volcanoes. Erupted volumes and areas covered can be relatively large; volumes of as much as a few cubic kilometers are typical. The 24,000-year-old Hat Creek Basalt that erupted near Old Station and flowed for 20 km down the Hat Creek Valley is a typical example (fig. 4; plate 1).

Nested within the regional platform of volcanic rocks are a few long-lived foci of volcanism called “volcanic centers,” defined as voluminous (as much as a few hundred cubic kilometers), long-lived (generally a million years or longer), composite edifices (Clynne and Muffler, 2010); examples are the Lassen and Maidu Volcanic Centers (fig. 3). Volcanic centers mark the location of long-lived magmatic and volcanic systems on or along the axis of the southernmost Cascade arc. The fundamental differences between regional volcanoes and volcanic centers are the latter’s longevity, larger volume, and a wide range of composition, from andesite to rhyolite (silicic) in a single edifice or geographic locale. Five volcanic centers younger than about 3.5 million years are recognized along the present-day Cascade axis in the Lassen region (fig. 3). Late in the evolution of each volcanic center, an acidic hydrothermal system driven by heat from cooling subterranean silicic magma bodies caused alteration of the permeable rocks of the composite cone. Subsequent glacial and fluvial erosion of the altered interiors of the composite cones resulted in bowl-shaped depressions surrounded by more-resistant rims of thick, unaltered, flank lava flows. The Yana, Maidu, Dittmar, and Latour Volcanic Centers have reached this stage, and their hydrothermal systems are extinct. The Lassen Volcanic Center is the currently active volcanic center in the region and hosts continuing silicic volcanism and an active hydrothermal system.

Geologic Record of Volcanism at the Lassen Volcanic Center

Volcanism at the Lassen Volcanic Center began about 825,000 years ago and is still active. The Lassen Volcanic Center is divided into three sequences of deposits: (1) the Rockland caldera complex (825,000–610,000 years ago), an early dacite domefield and small caldera, (2) Brokeoff Volcano (590,000–385,000 years ago), an andesite composite cone, and (3) the Lassen domefield (300,000–0 years ago), a younger dacite domefield. Each sequence was formed by dozens to hundreds of eruptions. A detailed geologic map, chronology and discussion of volcanism at the LVC can be found in Clynne and Muffler (2010).

Early History of the Lassen Volcanic Center

The Rockland caldera complex was active between about 825,000 and 610,000 years ago and culminated 611,000 years ago with eruption of the Rockland tephra (Lanphere and others, 2004). The volume of the Rockland tephra was about 50 km^3, large enough to have deposited a thick layer near LVC and a thin ash layer over all of northern California as well as a large part of the western United States (Sarna-Wojcicki and others, 1985). The eruption was comparable in size to the eruption that formed Crater Lake, Oregon, the largest **Holocene** eruption in the Cascade arc. The Rockland eruption formed a small caldera, which was subsequently buried by younger volcanism at the Lassen Volcanic Center.

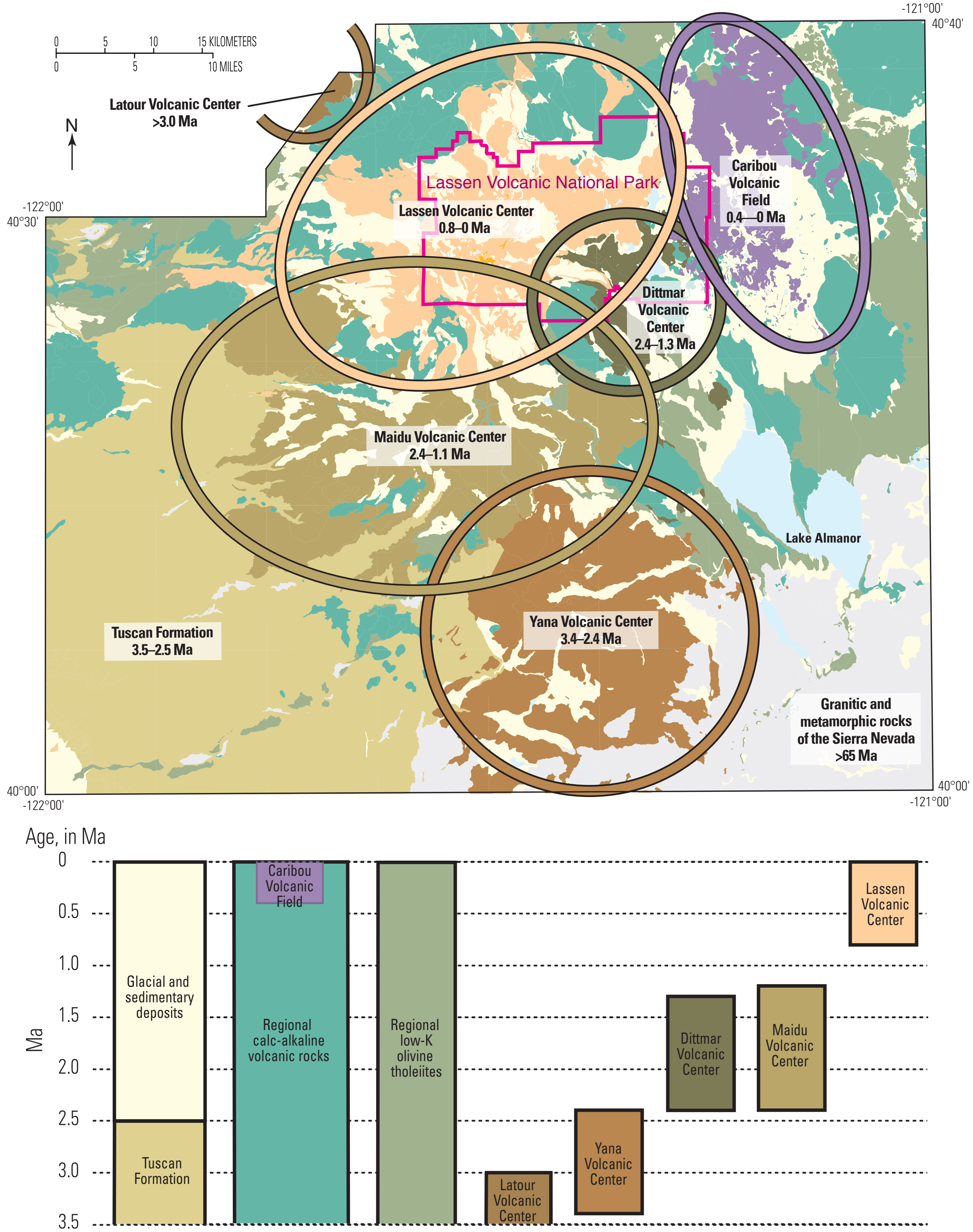


Figure 3. Simplified geologic map and stratigraphic sections of the Lassen region, modified from Clynne and Muffler (2010). Map shows ages (in millions of years, Ma) and locations of the individual volcanic centers, including the active Lassen Volcanic Center and the areas of surrounding mafic volcanism.

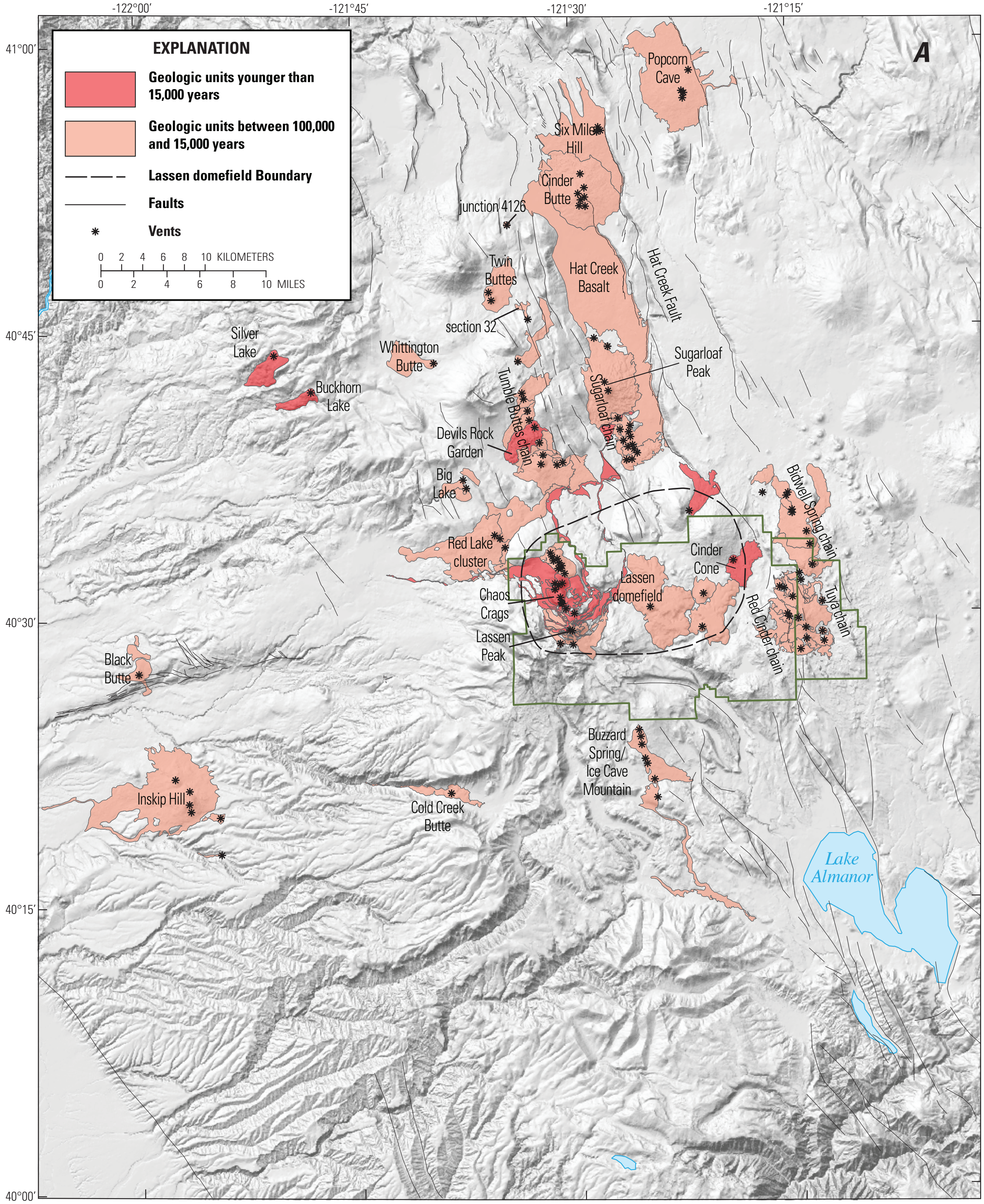
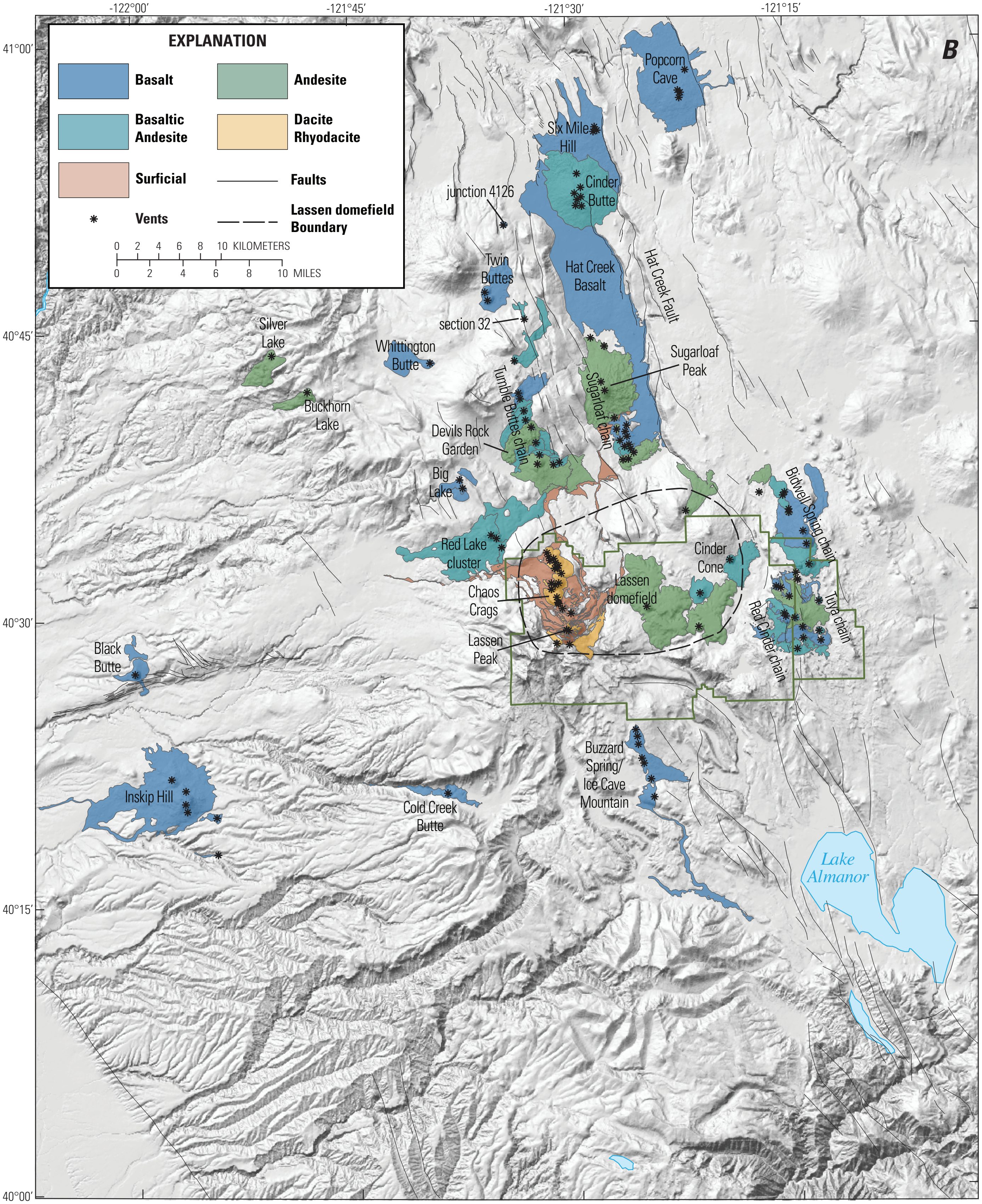


Figure 4. Maps showing the location and area covered by volcanic deposits less than 100,000 years old in the Lassen region differentiated by age (*A*) and composition (*B*). *C*, Enlarged depiction of the Lassen domefield. See explanation in *B* for compositions. Dashed black oval encloses the approximate area of units younger than 100,000 years old in the Lassen Volcanic Center, except for those that extend down Lost, Hat, and Manzanita Creeks. Units in dark red are younger than 15,000 years; units in light red are 15,000 to 100,000 years old. Thin black lines are faults of Quaternary age. Green outline is the combined boundary of Lassen Volcanic National Park and adjacent Caribou Wilderness Area. (digital elevation model base from Gesch, 2007)



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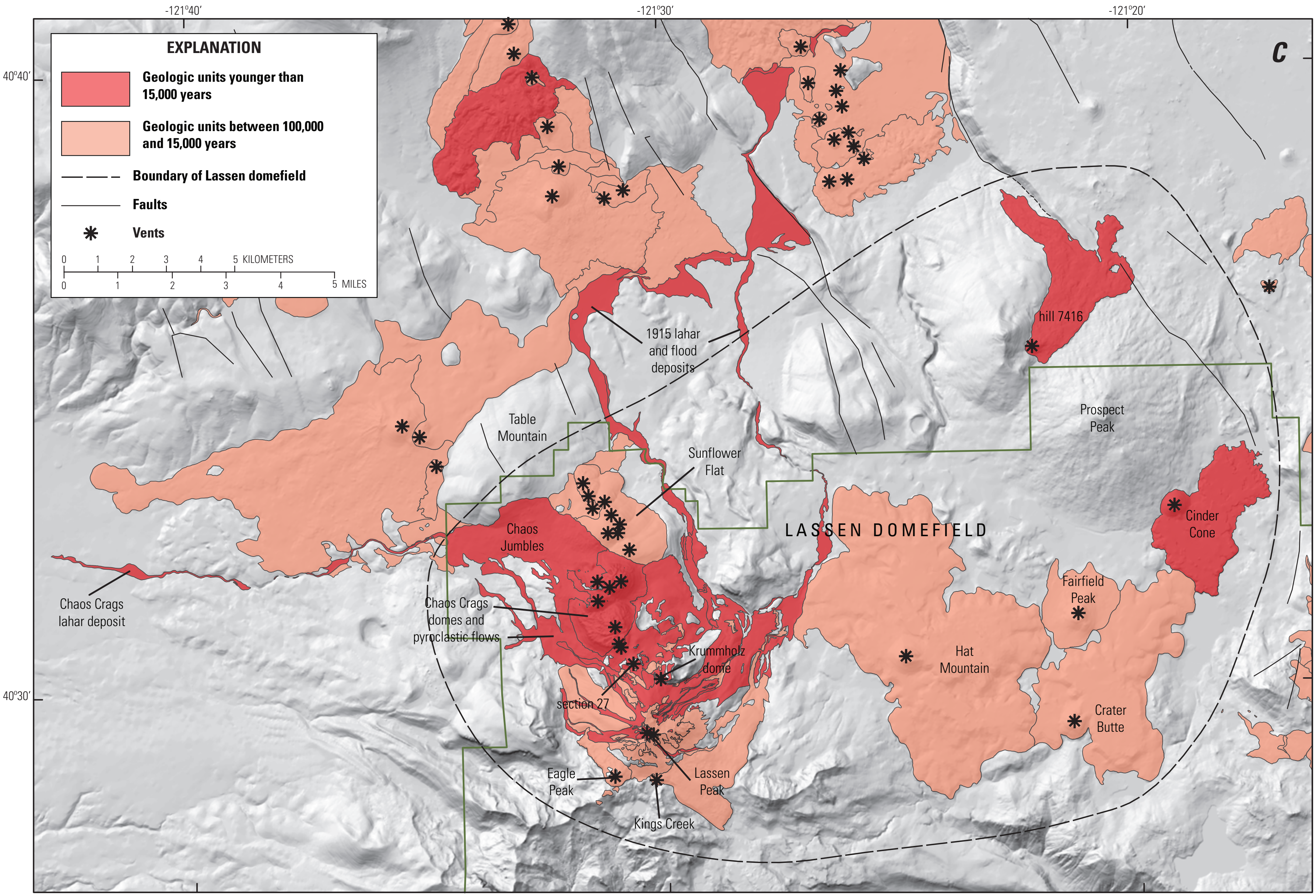


Figure 4.—Continued.

Table 1. Chronology of eruptions less than 100,000 years old in the Lassen Volcanic Center (Clynne and Muffler, 2010).

[Recent eruptions are from the historical record. Ages with uncertainties were measured using ^{40}Ar/^{39}Ar, K-Ar, or radiocarbon. Others are estimates constrained by stratigraphy and geomorphology. Cinder Cone age is from tree-ring chronology (Sheppard and others, 2009). Radiocarbon age is for weighted mean with standard error and is converted to calibrated age by choosing oldest peak based on paleomagnetic data (Nathenson and others, 2007). Age of andesite of Eagle Peak is chosen to be slightly younger than rhyodacite of Eagle Peak because it was the waning stage of that eruption. Areas are based on mapped areas of lava flows and domes, and volumes include additions for any associated pyroclastic deposits. For parts of lava flows buried by surficial deposits, areas and thicknesses have been estimated, and they are added to the area and volume exposed. Estimates of areas and volumes of fragmental deposits are provided in the notes column. Volumes of the fragmental deposits have been added to the volume column. The location of all places named herein can be found in Clynne and Muffler, 2010.]

Eruption	Age	Best age	Area (km^2)	Volume (km^3)	Notes
Deposits of 1914–1917 eruption of Lassen Peak	1914–1917 C.E.	1914 C.E.	0.107	0.007	Volume is proximal juvenile component; additional volume of nonjuvenile material in debris flows not included. Lahars and pyroclastic flows cover an additional ~8 km^2. Distal tephra volume ~0.02 km^3
Basaltic andesites of Cinder Cone	1666 C.E.	1666 C.E.	8.4	0.37	Tephra covers a minimum of an additional 96 km^2.
Rhyodacite of Chaos Crags	1,103±13 years	1,050 cal. yrs BP	4.54	1.19	Pyroclastic flows and air-fall cover a minimum of an additional 9.4 km^2.
Andesite of hill 7416	~12–15 ka	13 ka	8.0	0.21	
Dacite of Lassen Peak	27±1 ka	27 ka	9.4	2.07	Estimate of pre-glacial area; total includes 0.15 km^3 of pyroclastic-flow deposits
Rhyodacite of Kings Creek	35±1 ka	35 ka	6.4	0.53	Includes 0.75 km^2 of buried lava; volume includes 0.08 km^3 of pyroclastic-flow deposits spread over at least 8 km^2
Andesite of Hat Mountain	~40 ka	40 ka	39.6	4.72	Includes 1.9 km^2 of buried lava flow
Rhyodacite of Sunflower Flat	41±1 ka	41 ka	5.5	0.76	Includes 0.76 km^2 of buried lava; and 0.024 km^3 of pyroclastic-flow deposits spread over at least 2.4 km^2
Rhyodacite of Krummholz	43±2 ka	43 ka	1.00	0.06	Includes 0.78 km^2 of buried lava flow
Rhyodacite of Section 27	~50 ka	50 ka	0.75	0.045	Includes 0.72 km^2 of buried lava flow
Andesite of Eagle Peak	~66 ka	65.9 ka	0.0201	0.0006	Area and volume are for pyroclastic-flow deposit
Rhyodacite of Eagle Peak	66±4 ka	66 ka	1.14	0.09	Includes 0.12 km^2 of buried lava flow; and 0.015 km^3 of pyroclastic-flow deposits spread over at least 5 km^2
Basaltic andesite of Fairfield Peak	82±14 ka	82 ka	8.2	0.22	Includes 4.0 km^2 of buried lava flow
Andesite of Crater Butte	93±13 ka	93 ka	17.3	1.73	Includes 1.0 km^2 of buried lava flow

The Brokeoff Volcano was a typical andesite composite cone similar in volume to Mount Hood, Oregon, but smaller than the largest volcanoes in the Cascade arc, such as Mount Shasta or Mount Rainier. Brokeoff Volcano was centered in the southwestern portion of LVNP and was about 3,500 m high with a volume of about 80 km^3. It was active from about 590,000 to 385,000 years ago and probably erupted hundreds of times. During its lifetime it produced a variety of lava flows and fragmental deposits, including lahars, near-vent explosion deposits, and a small debris avalanche.

Subsequent to extinction of the Brokeoff Volcano, volcanism in the Lassen Volcanic Center shifted location and character to the Lassen domefield. The domefield (fig. 4) consists of about 30 volcanoes that produced fragmental deposits from **explosive eruptions** and domes and lava flows from effusive eruptions in two episodes at 300,000–190,000 and 90,000–0 years ago. The earlier episode consisted of at least 15 lava-dome eruptions and 3 lava flows, mostly in the area adjacent to the north flank of Brokeoff Volcano. Pyroclastic deposits associated with the early domefield sequence are poorly preserved, but were probably not extensive. The later episode consists of seven explosive and lava-dome eruptions and seven lava-flow eruptions, recognized mostly in the area north and northeast of Lassen Peak, and is discussed in more detail in the next section.

Eruptive Activity from 100,000 to 15,000 Years Ago at the Lassen Volcanic Center

Three andesite volcanoes in the area east of Lassen Peak in the central part of LVNP and a fourth on the southwest flank of Lassen Peak, erupted between 100,000 and ~40,000 years ago. These eruptions were not strongly explosive and produced **agglutinated** cinder cones and lava flows (table 1, fig. 4*C*). Their products are Crater Butte (93,000 years old), Fairfield Peak (82,000 years old), andesite of Eagle Peak (~65,900 years old), and Hat Mountain (~40,000 years old).

Six silicic lava domes or dome complexes and lava flows formed between 100,000 and 27,000 years ago at the LVC. The vents are all located in the area between Lassen Peak and

Sunflower Flat in the northwest corner of LVNP and built the young part of the Lassen domefield (fig 4C; plate 1). The domes and flows are Eagle Peak (66,000 years old), rhyodacite lava flows of section 27 (~50,000 years old), Krummholz dome (43,000 years old), Sunflower Flat domes (41,000 years old), Kings Creek lava flow (35,000 years old), and Lassen Peak dome (27,000 years old) (Turrin and others, 1998). All of these are glacially eroded, and pyroclastic deposits are not well preserved. Some have poorly preserved pyroclastic flow deposits, but all likely had an explosive phase.

Eruptive Activity Since 15,000 Years Ago at the Lassen Volcanic Center

The youngest volcanic eruptions in the Lassen region are less than about 15,000 years old. This threshold marks the end of the last large glacial advance in the Lassen region. Deposits older than about 15,000 years, especially deposits of explosive eruptions, are poorly preserved. Likely future eruptions are well illustrated by some of the more recent eruptions in LVNP.

Four eruptions have occurred in the Lassen Volcanic Center in the past 15,000 years: two andesite eruptions, one andesite to dacite eruption, and one dacite to rhyodacite eruption (table 1). Andesite of hill 7416 is estimated to be 12,000–15,000 years old. Its vent, located just northwest of Prospect Peak, built a cinder cone and erupted a large andesite lava flow that traveled nearly 7 km to the north. The flow covers an area of 8.0 km^2 and has a volume of at least 0.21 km^3. Cinder Cone, in the northeastern corner of LVNP, built two cinder cones and erupted five basaltic andesite to andesite lava flows in 1666 C.E. (fig. 5; Sheppard and others, 2009). This eruption produced an oval-shaped tephra deposit covering about 100 km^2 and ranging from 2.5 to 0.05 meters thick (Heiken, 1978). An additional area of 90 km^2 has 1–5 centimeters of tephra. The five lava flows cover about 8.4 km^2. The total volume of the Cinder Cone eruption is about 0.37 km^3.

The approximately 1,050-year-old eruptions of Chaos Crags and the 1914–1917 eruption of Lassen Peak serve as models for the types and magnitude of explosive silicic volcanic activity that can be expected in the LVC in the future. The dacite to rhyodacite eruption of Chaos Crags began with explosive activity that emplaced two pyroclastic flows extending as much as to 5 km from the vent and built a small tuff cone (fig. 6). Effusion of a small lava dome then plugged the vent. Subsequently, a much larger explosive event violently destroyed the small lava dome, built a second tuff cone, and produced a pyroclastic flow that followed the drainages of Manzanita, Lost, and Hat Creeks for as much as 20 km. An accompanying ash fall can be traced for about 40 km to the northeast, but fine ash must have fallen at much greater distances. Continued effusive activity then built five more lava domes. Hot collapse events from two of the growing domes emplaced pyroclastic flows a few kilometers long. Total volume of the Chaos Crags eruptive sequence is about 1.19 km^3, not including distal tephra that is not preserved.

The andesite to dacite 1914–1917 C.E. eruption of Lassen Peak comprised a year-long precursory period of intermittent steam (**phreatic**) explosions followed by a week-long period of intense eruptive activity in May 1915 (Clynne and others, 1998). Two years of waning activity, characterized by small steam explosions, completed the eruptive sequence. The most significant events occurred on May 19 and 22, 1915, when the eruptions devastated the northeast flank of Lassen Peak (fig. 7). On May 19 an avalanche of hot rock and snow roared 6 km down the drainage of Lost Creek

Figure 5. Aerial view looking northwest at Cinder Cone. All tephra and lava flows were erupted in 1666. High-relief gray areas with red to tan patches in the foreground and middle ground are early ash-covered lava flows from Cinder Cone. Dark areas in the middle ground and at the lower right are slightly later ash-free lava flows from Cinder Cone. Cinder Cone is 215 meters high.

when a large explosion disrupted a growing lava dome. The avalanche swiftly melted snow to generate a lahar that swept 16 km down Lost Creek to near the vicinity of its join with Hat Creek (plate 1). Water escaping from the lahar material immediately after deposition caused flooding farther downstream in the Hat Creek Valley. On May 22, Lassen Peak explosively erupted a vertically directed column of pumice, ash, and hot gas that rose to an elevation of about 9 km (30,000 feet). Collapse of this eruption column generated a pyroclastic flow that swept across still snow-covered parts of the northeast flank of Lassen Peak. Melting of this snow transformed the pyroclastic flow into a lahar that followed the path of the May 19 lahar. The May 22 lahar also came to rest in the vicinity of the confluence of Lost and Hat Creeks, dewatered, and caused a second flood in lower Hat Creek. Six additional small lahars descended the east, north, and west flanks of Lassen Peak but did not get beyond the base of the mountain. Pumice blocks and smaller fragments from the eruption column fell in a narrow northeast-directed lobe for a distance of about 25 km from Lassen Peak, and fine ash fell as far away as Elko, Nevada (about 450 km distant). Despite the significant effects of the 1915 eruption, the total erupted volume was small, about 0.03 km^3 (table 1).

Geologic Record of Regional Volcanism

Regional volcanism in the area surrounding the Lassen Volcanic Center has been continuous during the lifetime of the Cascade arc in northern California. Dozens of cinder cones, lava cones, and shield volcanoes dot the landscape. A detailed geologic map, chronology, and discussion of regional volcanism at Lassen can be found in Clynne and Muffler (2010).

Regional Volcanism from 100,000 to 15,000 Years Ago

Approximately 56 small regional volcanoes in the Lassen region erupted between 100,000 and ~20,000 years ago (table 2). In general, these volcanoes were not strongly explosive, and their products consist of cinder cones, lava flows, and ash deposits of restricted areal extent. Although located all around the periphery of the LVC, most of them are concentrated in four relatively restricted areas. They are arranged as chains of vents parallel to the regional fault pattern: Tumble Buttes chain, Red Cinder chain, Bidwell Spring chain, and Sugarloaf chain (fig. 4*A*, *B*, plate 1). A fifth group includes a few small clusters of vents

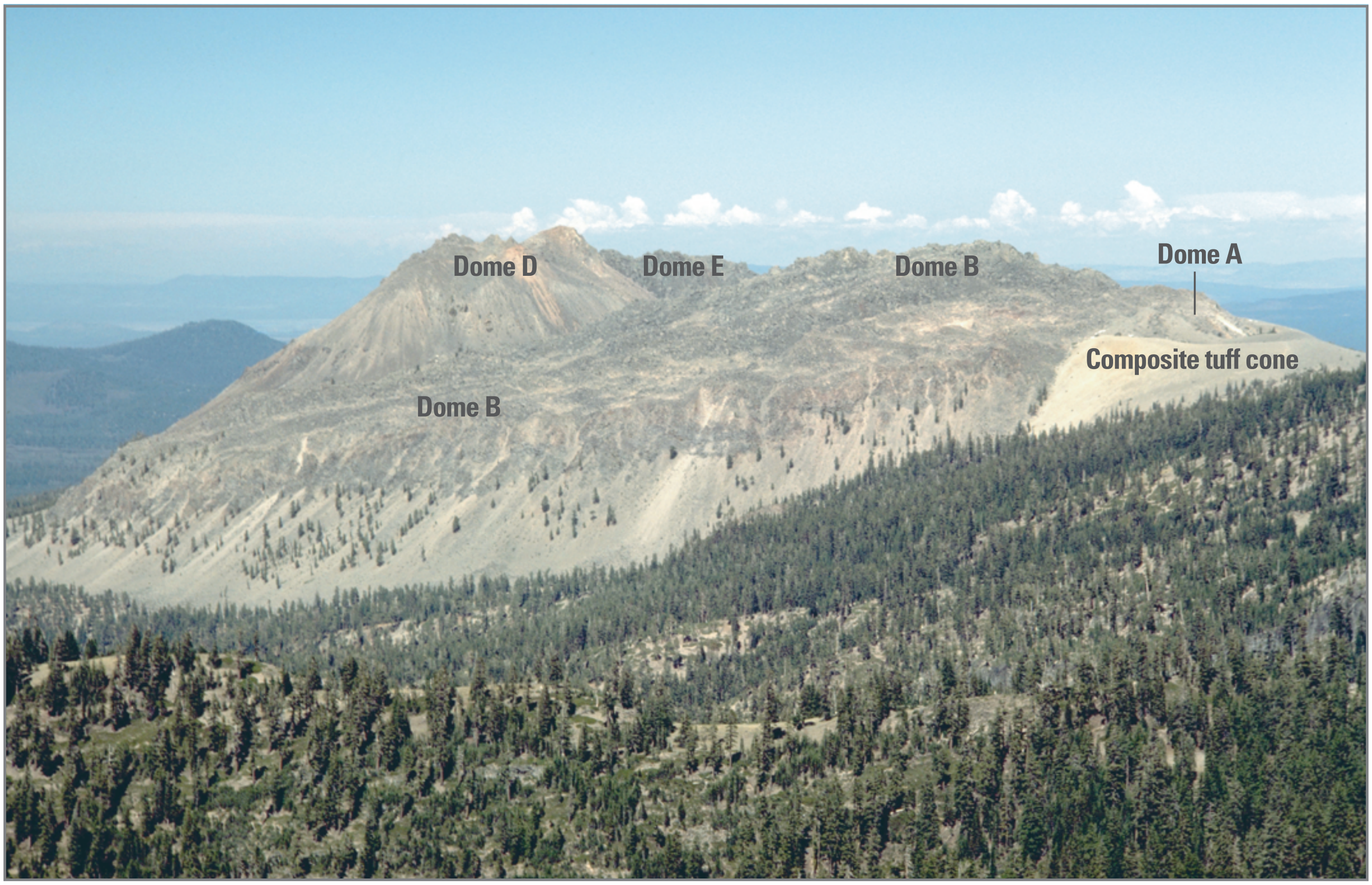


Figure 6. View of the 1,050-year-old Chaos Crags domes from southwest. Composite tuff cone formed by initial pyroclastic eruptions of Chaos Crags at right. Most of the area immediately surrounding the Chaos Crags domes is covered with as much as 1 m of air-fall pumice from the initial pyroclastic eruptions. Adjacent areas and drainages are filled with as much as 5 m of pyroclastic-flow deposits. Hot, partial dome-collapse pyroclastic deposits from domes D and E are present at the bases of those domes (not visible in the picture). Dome A is visible in the crater of the tuff cone. Large coulee sloping from the upper right to lower left is dome B. High craggy dome in center 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.

Table 2. Chronology of eruptions less than 100,000 years old for the mafic vents in the Lassen segment of the Cascade Range.

[Unit names in italics are from the geologic map of Lassen Volcanic National Park and vicinity (Clynne and Muffler, 2010) and unpublished mapping of the Lake Almanor and Burney quadrangles. Names in roman font are from unpublished reconnaissance mapping in the surrounding area. Ages with uncertainties were measured using $^{40}Ar/^{39}Ar$ or K-Ar. Others are estimates constrained by stratigraphy and geomorphology. Areas are based on mapped areas of lava flows, and volumes include additions for any associated tephra. For parts of lava flows buried by surficial deposits, areas and thicknesses have been estimated, and they are added to the area and volume. ka = thousands of years]

Eruption	Sequence or cluster	Age (ka)	Area (km^2)	Volume (km^3)	Notes
Tholeiitic basalts of Big Lake	Red Lake cluster	50–75	5.4	0.148	
Basaltic andesite and andesite of Red Lake Mountain[1]	Red Lake cluster	~75	29.2	0.86	
Basaltic andesite of Red Mountain	Red Lake cluster	75–100	12.0	0.259	
Andesite of Devils Rock Garden	Tumble Buttes chain	10–15	7.5	0.57	
Andesite of Bear Wallow Butte	Tumble Buttes chain	35.1±3.1	12.5	0.453	
Hall Butte	Tumble Buttes chain	35–50	5.4	0.144	
Hill 6795	Tumble Buttes chain	35–50	1.17	0.0224	
Basaltic andesite of hill 6770	Tumble Buttes chain	35–50	2.96	0.085	
Basaltic andesite of Tumble Buttes	Tumble Buttes chain	35–50	2.21	0.074	
Basaltic andesite of hill 5410	Tumble Buttes chain	35–50	1.14	0.0135	Includes 0.20 km^2 of buried lava flow
Basaltic andesite of Bear Wallow Butte	Tumble Buttes chain	35–50	1.27	0.0211	Includes 0.32 km^2 of buried lava flow
Eiler Butte	Tumble Buttes chain	35–50	7.0	0.150	
Basaltic andesite of hill 6138	Tumble Buttes chain	~50	1.30	0.0258	
Basaltic andesite of Section 5	Tumble Buttes chain	~50	1.94	0.051	
Andesite of Tumble Buttes	Tumble Buttes chain	50–75	5.9	0.059	
Basaltic andesite of Mud Lake	Tumble Buttes chain	75–100	2.27	0.0227	
Andesite of Sugarloaf Peak	Sugarloaf chain	46±7	32.4	2.64	
Basaltic andesite of Little Potato Butte	Sugarloaf chain	67±4	1.05	0.077	
Andesite of Potato Butte	Sugarloaf chain	77±11	5.7	0.280	
Basaltic andesite of hill 4709	Sugarloaf chain	~80	0.94	0.0163	
Andesites of Old Station	Sugarloaf chain	75–100	0.418	0.0167	
Hill 4041	Sugarloaf chain	80–100	0.305	0.0061	
Hill 4899	Sugarloaf chain	80–100	0.55	0.0201	
Highway 89	Sugarloaf chain	80–100	0.100	0.00100	
Popcorn Cave	Cinder Butte cluster	30–50	52	1.75	
Cinder Butte	Cinder Butte cluster	38±7	38.8	2.59	
Six Mile Hill	Cinder Butte cluster	40–50	30.8	0.50	
Andesite of Bidwell Spring	Bidwell Spring chain	25–45	3.75	0.114	Includes 1.2 km^2 of buried lava flow
Basaltic andesite of Pole Spring Road	Bidwell Spring chain	25–45	2.69	0.072	Includes 0.30 km^2 of buried lava flow
Basaltic andesite of section 36	Bidwell Spring chain	25–45	1.20	0.0332	

Table 2. Chronology of eruptions less than 100,000 years old for the mafic vents in the Lassen segment of the Cascade Range.—Continued.

Eruption	Sequence or cluster	Age (ka)	Area (km^2)	Volume (km^3)	Notes
Basalt of Twin Buttes	Bidwell Spring chain	46±3	19.8	0.80	
Basaltic andesites of Black Butte	Bidwell Spring chain	~50	10.7	0.334	Includes 2.30 km^2 of buried lava flow
Basaltic andesite of Red Cinder Cone	Red Cinder chain	20–25	1.64	0.054	
Basalt of Red Cinder Cone	Red Cinder chain	20–25	1.65	0.120	Includes 0.57 km^2 of buried lava flow
Basaltic andesite of Red Cinder	Red Cinder chain	25–40	8.3	0.201	Includes 3.5 km^2 of buried lava flow
Basalt of hill 8030	Red Cinder chain	25–40	7.3	0.178	Includes 2.0 km^2 of buried lava flow
Basalt of Cameron Meadow	Red Cinder chain	25–40	3.92	0.078	Includes 3.0 km^2 of buried lava flow
Basalt of Ash Butte	Red Cinder chain	40–70	1.10	0.062	
Basalt of hill 2283	Red Cinder chain	40–70	0.88	0.0292	Includes 0.16 km^2 of buried lava flow
Basalt of section 25	Red Cinder chain	40–70	1.08	0.0185	
Andesite of Red Cinder	Red Cinder chain	69±20	18.1	1.81	Includes 6.9 km^2 of buried lava flow and shield under Red Cinder edifice
Basalt east of Ash Butte	Red Cinder chain	70–100	1.19	0.0178	Includes 1.0 km^2 of buried lava flow
Basalt of Widow Lake	Red Cinder chain	~100	0.80	0.0295	Includes 0.6 km^2 of buried lava flow
Basaltic andesites of Long Lake	Red Cinder chain	~100	9.3	0.249	Includes 3.6 km^2 of buried lava flow
Basaltic andesite of Caribou Wilderness	Red Cinder chain	~100	1.20	0.0240	Includes 1.0 km^2 of buried lava flow
Basalts of Triangle Lake	Red Cinder chain	~100	2.70	0.050	Includes 0.75 km^2 of buried lava flow
Miscellaneous group					
Silver Lake[2]	north of Miller Mtn.	10–15	8.3	0.249	Does not include area of scoria
Twin Buttes	SE of Burney Mtn.	15–25	10.1	0.296	
Basaltic andesite of Turnaround Lake	Tuya chain	17–35	0.88	0.079	
Hat Creek Basalt (tholeiitic)	near Old Station	24±6	99	2.47	
Basaltic andesite of section 32	SE of Twin Buttes	35-50	1.04	0.0228	
Basalt of junction 4126	NE of Twin Buttes	35-50	0.300	0.0110	
Basalt of Inskip Hill[3]	Inskip Hill	~50	62	2.51	
Tholeiitic basalts of Buzzard Springs	near Sifford Mtn.	65±45	11.1	0.137	Includes 0.30 km^2 of buried lava flow
Tholeiitic basalt of Ice Cave Mountain	near Sifford Mtn.	~65	13.5	0.162	Includes 2.6 km^2 of buried lava flow
Basalt of Black Butte	west of Shingletown	~70	6.5	0.137	Includes 3.8 km^2 of ash
Basalts of Cold Creek Butte	west of Mineral	75–100	7.1	0.275	Includes 1.2 km^2 of buried lava flow
Whittington Place	west of Magee Peak	75–100	7.9	0.079	

[1] Includes basaltic andesite of Eskimo Hill.

[2] Includes flow at Buckhorn Lake.

[3] Includes Little Inskip Hill, vents at Paynes Creek and vents in Oak Creek.

and additional widely dispersed vents. At least 40 more vents erupted between 120,000 and 100,000 years ago.

The Tumble Buttes chain consists of a 13-km-long, north-northwest-oriented linear array of 13 cinder cones and lava flows just north of LVNP. The vents range in age from nearly 100,000 to 35,000 years (one vent is inferred to be younger and is discussed below). The Red Cinder chain consists of a north-northwest-oriented elongate area about 10 km long with 12 vents that range in age from ~100,000 to ~20,000–25,000 years. Just north of the Red Cinder chain, the Bidwell Spring chain includes 5 vents aligned in a 10-km-long chain. The Sugarloaf chain includes 8 vents, arranged in a north-northwest oriented array about 12 km long, that range in age from ~80,000–100,000 to 46,000 years (Turrin and others, 2007). The fifth group includes clusters of vents around Cinder Butte, the Red Lake cluster, Buzzard Spring-Ice Cave Mountain and eight other widely dispersed vents ranging in age from ~75,000–100,000 to ~20,000 years.

Regional Volcanism in the Past 15,000 Years

Of the approximately 58 small mafic volcanoes in the Lassen region that erupted within the last 100,000 years (table 2), only a few are younger than 15,000 years old (table 2). One, the Devils Rock Garden flow, is the youngest vent in the Tumble Buttes chain (figure 4*A*). The others are vents located near Silver and Buckhorn Lakes. In general, these were not strongly explosive and consist of cinder cones, lava flows, and ash deposits of restricted areal extent. All are probably between 15,000 and 10,000 years old (fig. 4*A*).

Magma Beneath the Lassen Volcanic Center

The presence of magma stored in the shallow crust beneath a volcano is generally accepted as a precondition for future volcanic activity. At the LVC, the existence of a vigorous hydrothermal system and young silicic volcanism implies that an active magma reservoir lies beneath. Several unsuccessful attempts have been made to locate and delineate this reservoir (Iyer, 1984; Berge and Monfort, 1986; Berge and Stauber, 1987; Amato and Berge, 1988). These geophysical surveys found low-velocity zones that suggest the presence of magma in the crust beneath the Lassen Volcanic Center but

Figure 7. Aerial view of the area devastated by the 1915 eruption of Lassen Peak looking southwest. Area with sparse trees marks the path of the avalanche and lahars of May 19–20, 1915, and the pyroclastic flow and lahars of May 22. Small dark crags just to the right of the summit of Lassen Peak are a remnant of the May 19–20 lava flow. The composite dacite dome of Lassen Peak (27,000 years, or 27 ka, old) dominates the upper part of the view. Lithic pyroclastic flow deposits from hot partial collapses of Lassen Peak during eruption of Lassen Peak 27,000 years ago, are exposed in the headwaters of Lost Creek. Area left of the large snow patch on the east flank of Lassen Peak is the dacite lava flow of Kings Creek (35,000 years old). Pyroclastic flows related to this eruption are exposed in the West Fork of Hat Creek (just off the photograph to the east). The area devastated by the 1915 eruption continues to the north off the bottom of the picture.

failed to detect a discrete magma reservoir. The smallest bodies that these surveys could detect was about 5 km in diameter, and Clynne (1985) interpreted these studies to indicate that the Lassen magmatic system contains one or more small dispersed bodies of silicic magma in a larger but mostly solidified zone of silicic magma beneath the volcanic center. More recent petrologic studies support this model (Feeley and others, 2008; Underwood and others, 2012; Clynne and Muffler, 2010). The mineralogy of the young silicic rocks suggests that the magma bodies that produced the Lassen Peak and Chaos Crags eruptions reside at a depth of at least 8 km, but data required to evaluate quantitatively the depth and amount of magma beneath the LVC are not available.

Geologic models of the Lassen region indicate that regional mafic volcanism is derived from dispersed flux of mafic magma (basalt) that rapidly traverses the Earth's crust to the surface. A higher and more focused flux of mafic magma and heat beneath the LVC leads to melting of crustal rocks (Guffanti and others, 1990), which produces silicic magma that accumulates beneath the volcanic center. Intrusions of mafic magma into an existing or mostly solidified silicic magma body can add sufficient heat and volatiles to regenerate the body and maintain it at least partially molten for thousands of years. If sufficiently large, these mafic magma intrusion events can trigger eruptions of the silicic magma. The presence of quenched mafic inclusions in most silicic lavas at LVC indicates that mafic magma was intruded into a silicic magma reservoir shortly before an eruption, thus documenting the presence of mafic magma that otherwise did not reach the surface (Clynne 1999; Underwood and others, 2012). Petrologic and chemical studies document that each intrusive event involves a different batch of mafic magma. More importantly, each batch of mafic magma has a significant effect on the composition of the silicic magma that it intrudes. Thus, the mostly liquid parts of the silicic magma body beneath LVC are probably relatively small, in agreement with the geophysical evidence discussed above. The mostly solid parts of the silicic magma are too viscous to be eruptible, but they are ductile enough that intrusions of mafic magma cannot pass through them. Instead such intrusions rejuvenate the silicic magma and provoke the type of silicic eruptions that have occurred at LVC in the past 100,000 years. The most significant implication of this interpretation of no large silicic magma chamber is that a large, caldera-forming eruption is not likely at the Lassen Volcanic Center in the foreseeable future.

Lassen Hydrothermal System

The Lassen Volcanic Center hosts far and away the most extensive hydrothermal system in the Cascade arc. The presence of the hydrothermal system indicates that hot rock or magma lies in the shallow subsurface beneath the LVC and indicates the potential for volcanic eruptions. The surface manifestations of the hydrothermal system include steam vents and hot springs, and alteration of the surface rocks by acidic water and gases creates unstable hazardous ground.

Steam vents and hot springs are the surface expressions of hydrothermal systems in which cold surface water percolates deep into the ground where it is heated by thermal energy from a heat source. The LVC is the host to such a system because it has the three required elements: abundant groundwater, permeable rock, and a heat source at depth.

The Lassen hydrothermal system consists of a shallow vapor-dominated reservoir underlain by a reservoir of hot water at a temperature of 240˚C (Muffler and others, 1982; Ingebritsen and Sorey, 1985, 1987; Clynne and others, 2003). Recharge of the system by meteoric water occurs primarily in the high-topography area of the Lassen domefield, especially in the vicinity of Lassen Peak. The cold water percolates to great depth, where it encounters and is heated by hot rock associated with the Lassen magmatic system. The heated water and dissolved volcanic gases emitted by the hot rock rise to a depth of about 1 km below the surface, where they accumulate in fractures beneath the area of thermal features. All thermal features in LVNP are driven by boiling and steam separation in this reservoir; the hottest and most vigorous features are at Bumpass Hell and Boiling Springs Lake, which mark the principal areas of upflow and steam discharge from the Lassen hydrothermal system (Janik and McLaren, 2010). Steam-dominated features occur at five additional areas in LVNP: Sulphur Works, Pilot Pinnacle, Little Hot Springs Valley, Devils Kitchen, and Terminal Geyser (fig. 8). Springs depositing travertine ($CaCO_3$) occur on the periphery of some of the steam-dominated thermal areas in Little Hot Springs Valley (fig. 8). Morgan and Growler Hot Springs at lower elevations south of LVNP in Mill Creek mark the lateral discharge of near-neutral-pH, chloride-bearing hot water from the deep hot-water reservoirs under Bumpass Hell. Morgan and Growler Hot Springs deposit siliceous sinter, in contrast to the **acid-sulfate alteration** at Bumpass Hell, Sulphur Works, and Devils Kitchen. Hot water that deposits travertine at Drakesbad (fig. 8) is from a separate hydrothermal upflow centered in the Devils Kitchen or Boiling Springs Lake area (Janik and McLaren, 2010).

Boiling of the 240˚C hot water in the deep reservoir provides the steam that feeds the surface hydrothermal features of LVNP. This steam contains hydrogen sulfide (H_2S), which oxidizes in the near-surface environment to produce sulfuric acid that in turn reacts with the near-surface volcanic rocks, altering them to soft, light-gray to white slopes (fig. 9) composed primarily of opal (SiO_2) and kaolinite (a clay mineral). The major thermal areas within the LVNP display numerous thermal vents, ranging from superheated **fumaroles** with temperatures as high as 161°C at Bumpass Hell and 147°C at Little Hot Springs Valley (Janik and Bergfeld, 2010), steam vents at the boiling point for this altitude (~92°C), **mud pots** ranging in temperature from boiling to near ambient, and warm to hot ground commonly covered with orange and yellow sulfates. Native sulfur (S) is common on the walls of steam vents, and gray to black pyrite (FeS_2) is common as linings of the vents and discharge channels, as scum floating on the surface of pools, and as dispersions in mud pots.

The vigor of the surface hydrothermal features varies both seasonally and from year to year. To potentially provide early warning of impending volcanic activity, the thermal features in LVNP are chemically and physically monitored by the USGS and the National Park Service (Sorey, 1986) to detect changes that may be caused by renewed influx of magma into the LVC.

Seismicity and Ground Deformation

Other expressions of the active nature of the Lassen region include frequent earthquakes and slow deformation of the ground surface in response to changes at depth. Increased seismicity and ground deformation are often the first indication of a potential eruption in volcanically active areas. However, many volcanic areas located in tectonically active regions, like the Lassen region, experience earthquakes and deformation related to both tectonic and volcanic seismicity.

The Lassen region experiences both tectonic earthquakes and earthquakes of volcanic origin (long-period quakes). Tectonic earthquakes occur because Lassen is located along the western edge of a region of closely spaced NNW-trending normal faults that characterize the Basin and Range Province (Guffanti and others, 1990). The majority of earthquakes in the region occur in a broad NNW-trending seismic zone that extends from the Sierra Nevada through the Lassen region to about 20 km northeast of Lassen Peak (fig. 3). These earthquakes are tectonic in origin and are associated with the impingement of Basin and Range tectonism on the Cascade arc. The Lassen Volcanic Center is also within a developing zone of strike-slip faulting called the Walker Lane that is associated with interaction between the North American and Pacific tectonic plates (Faulds and Henry, 2008).

Tectonic Earthquakes

Tectonic earthquakes associated with plate movements are common in the Lassen region. Three vigorous earthquake sequences occurred in the region in 1936, 1945–1947, and 1950 (Norris and others, 1997). These included main shocks as large as magnitude 5.5 and thousands of smaller events and were attributed to approximately east-west extension in the Lassen region localized on Basin and Range normal faults (Norris and others, 1997). Smaller bursts of seismic activity, generally with earthquakes as large as about magnitude 4–5 and including dozens of smaller shocks, occur every few years in the Lassen region. Basin and Range

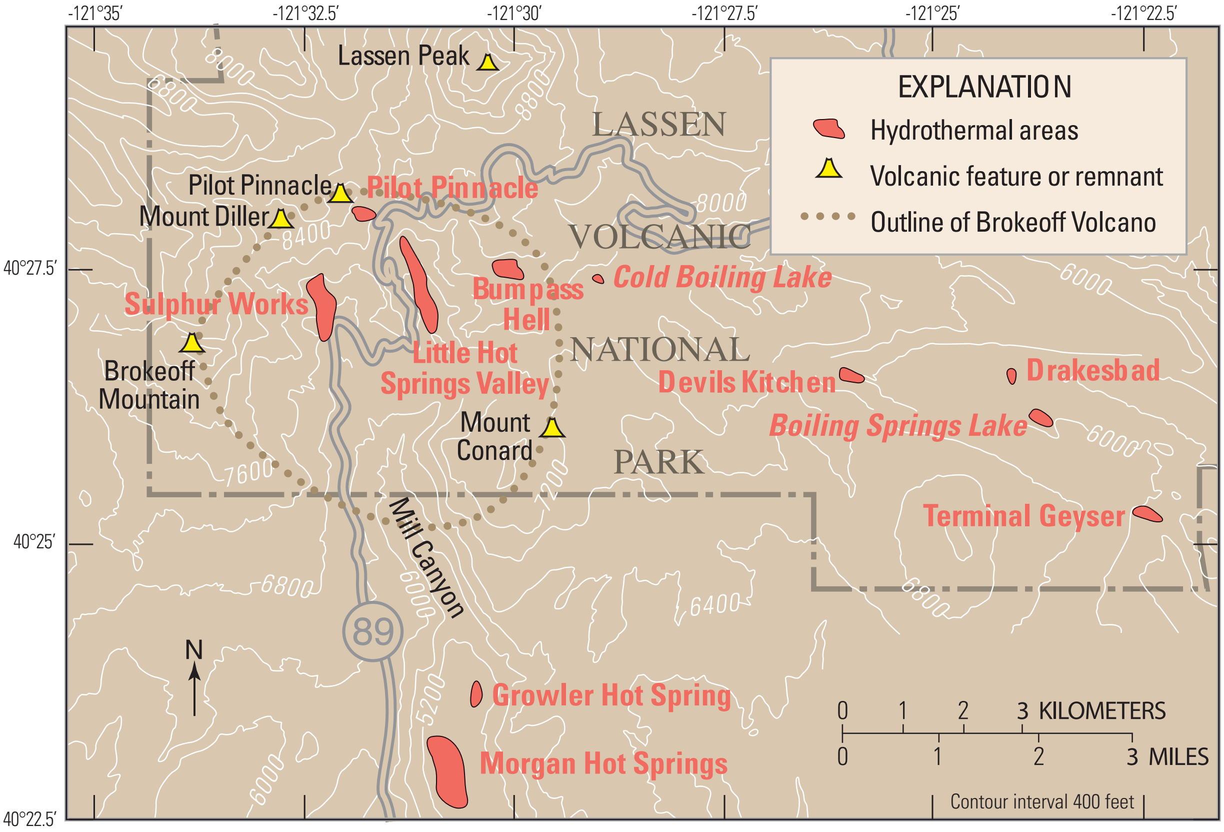


Figure 8. Map showing the location of the major thermal areas in Lassen Volcanic National Park and vicinity.

faults in the Lassen region, including the Hat Creek Fault and faults with large offsets in the Lake Almanor area, are considered active and capable of earthquakes as large as magnitude 7 (Wills, 1990a, b). The Hat Creek Fault offsets the 24,000-year-old Hat Creek Basalt by as much as 30 m (Muffler and others, 1994; Turrin and others, 2007). Despite the lack of historical seismicity, displacement of outwash gravels overlying the Hat Creek Basalt shows that vertical offset on the Hat Creek Fault has averaged ~1.3 mm per year for the past 15,000 years, a figure similar to the longer-term average (Muffler and others, 1994).

About 25 percent of the seismic events in the Lassen region are associated with the Lassen hydrothermal system (Klein, 1979; Walter and others, 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. McLaren and Janik (1996) and Janik and McLaren (2010) interpret this seismicity to be related to hydrothermal alteration and brittle failure of rock in the hydrothermal system.

Long-Period Earthquakes

Pitt and others (2002) described long-period (LP) seismicity in the Lassen region. Between 1982 (when the Lassen seismic net was established) and 2002, 29 LP earthquakes at depths from 13 to 23 km were detected, primarily in the area about 5–8 km west of Lassen Peak near the northwest corner of LVNP. Accounting for some periods in which the seismic net was not operational, the average was about two LP earthquakes per year. The seismicity, however, is clearly episodic, as many as eight earthquakes in one year (1988) and no earthquakes in others (for example, 1991). Since 2002, improvements in the seismic net have led to increased detection of LP earthquakes. An average of 11 LP earthquakes per year were detected between 2003 and 2011, most in small clusters (A.M. Pitt, unpublished data).

These LP earthquakes are generally interpreted to reflect movement of mafic magma in the deep crust below active volcanic areas (Pitt and others, 2002). However, even high levels of long-period activity often do not result in immediate

Figure 9. View looking east-southeast from trail at the west end of Bumpass Hell (see fig. 8). Bumpass Hell is the surface expression of a major upflow from the vapor-dominated reservoir of the Lassen hydrothermal system (Muffler and others, 1982; Ingebritsen and Sorey, 1985, 1987; Janik and McLaren, 2010) and contains many fumaroles, mud pots, and acid hot springs (Muffler and others, 1983). Big Boiler is a superheated fumarole with temperatures as high as 161°C (Janik and Bergfeld, 2010).

volcanic activity (for example, at Long Valley, Calif.; Pitt and Hill, 1994). The growing evidence that recharge of silicic magma bodies by injections of hot mafic magma (Clynne, 1999, Pallister and others, 1996) plays a role in triggering volcanic eruptions makes it important to monitor LP seismicity. An increase in the level of LP seismicity may provide the earliest indication that a volcanic system is being recharged. A subsequent sudden increase in small, similar-magnitude, high-frequency earthquakes and **harmonic tremor** indicates unrest in the volcanic system that might evolve toward an eruption.

Ground Deformation

Measuring deformation of the ground surface plays an important role in detecting movements related to both tectonic and volcanic activity. Measurements on a regional scale permit interpretation of plate-tectonic movements and large-scale interactions. Measurements on a more local scale may detect the rise of fresh magma into the shallow magma system beneath a volcano and thereby indicate the potential for an eruption. Few ground deformation surveys have been undertaken at Lassen.

Field-measurement campaigns around Lassen Peak in 1981, 1982, and 1984 detected no significant deformation (Poland and others, 2004). Leveling surveys designed to provide a baseline for detection of large-scale deformation in the Lassen region were conducted in 1991 by the USGS (Dzurisin, 1999). Leveling lines were run between Viola and Old Station and between Mineral and Chester, and comparison with surveys made in 1932 by the U.S. Coast and Geodetic Survey revealed no changes larger than the uncertainties in the measurements. Thus the area was apparently stable within the precision of the measurements between 1932 and 1991.

Interferometric synthetic aperture radar (InSAR) images spanning the 1996–2000 time interval indicate as much as about 1 centimeter/year subsidence over an area ~40 km in diameter and centered about 5 km southeast of Lassen Peak (Poland and others, 2004). More sensitive measurements conducted using the Global Positioning System in 2004 confirm that subsidence has been taking place since at least 1981. The large area of deformation and the presumed lack of a large magma chamber at Lassen led Poland and others (2004) to interpret the deformation as tectonic and resulting from Basin and Range extension.

Volcano-Related Hazards in the Lassen Region

This section discusses the character, hazards, and the most likely locations of future volcanic eruptions in the Lassen region. Mafic eruptions occur in the area surrounding the Lassen Volcanic Center, but generally not within it. This is because ascending mafic magma is intercepted by the partially molten silicic magmatic system under the Lassen Volcanic Center and mixes with it to produce andesite magma. Conversely, silicic eruptions occur only within the area of the surface expression of the LVC because generation of silicic magma is confined to beneath that area.

Hazardous areas are described as volcano hazard zones and are shown on figure 10 and plate 1. These hazard zones are defined on the basis of the location and character of volcanism in the past 100,000 years, with emphasis on the past 50,000 years. Most of these hazard zones are similar to those shown in Miller (1989), but they have been modified to take into account geologic data acquired since his report. One difference between hazard zones depicted herein and in Miller (1989) is his Pyroclastic Flow Hazard Zone. To define that zone, Miller used a hypothetical eruption similar to that of Mount Mazama (volume ~50 km^3) as an analogue for the largest possible eruption at Lassen. However, an eruption of that size is unprecedented at Lassen in the past 100,000 years, and there is no indication that the magmatic system is evolving toward such a large eruption. The largest **postglacial** (<15,000 years) eruption at Lassen was the Chaos Crags eruption, which produced a total volume of ~1.19 km^3 (table 1), most of which erupted as lava. We estimate that the largest credible explosive eruption at Lassen would be no larger than the 1980 eruption at Mount St. Helens (total volume ~1.4 km^3, ash volume ~1.1 km^3; Brantley and Myers, 2000), and we use this volume to designate silicic eruption hazard zones (Combined Flowage Hazard Zone and Silicic Ash Hazard Zone).

The most likely volcanic event in the Lassen region is a short-lived mafic eruption, possibly lasting as long as a year, and producing a cinder cone, local tephra fall, and lava flows. The Mafic Vent and Lava Flow Hazard Zone is based on a few-kilometer buffer zone around the vents and adjacent valley bottoms of all mafic eruptions in the past 100,000 years. The Mafic Ash Hazard Zone is based on the thickness of tephra produced by the 1666 C.E. eruption of Cinder Cone, a well-preserved eruption, and is extrapolated to the entire area of potential mafic volcanism.

The most likely silicic volcanic event would be an eruption of duration and magnitude similar to the 1915 eruption of Lassen Peak or the 1,050-year-old Chaos Crags eruptive sequence. These two eruptions were of significantly different size and duration, and their effects were also very different, but in combination they are likely analogues for the range of volcanic eruptions expected at LVC. Such an event might include an extended period of precursory phreatic activity, explosive activity resulting in pyroclastic flows and (or) lahars, proximal and distal ash fall, and emplacement of silicic lava flows or domes. The most likely location of a silicic event is in the vicinity of Lassen Peak and Chaos Crags. An additional likely location for lava flows is the eastern part of the Lassen domefield in the vicinity of Hat Mountain and Cinder Cone. In the following sections, more detailed discussions of the volcanic and other hazards in the LVC and surrounding area are presented.

An eruption generating extremely large pyroclastic flows, for example a caldera-forming or “supervolcano” eruption on a scale of 10s to 100s of cubic kilometers, is not considered likely at LVC. Several such large-scale events have occurred in the Lassen region in the past 3 million years, although none since the eruption of the Rockland ash-flow tuff and tephra about 611,000 years ago (Lanphere and others, 2004). However, the magmatic system of the LVC is not presently configured for this type of eruption, and the probability of such a high-consequence event is considered negligible in the foreseeable future (Nathenson and others, 2012).

Hazards Associated with Mafic Volcanism in the Lassen Region

This section discusses the likely locations and effects of explosive and effusive mafic eruptions in the Lassen region– primarily lava flows and ash fall. The effects of these types of eruptions were covered under the section titled “Hazards Associated with Mafic Eruptions.” Hazard zones for these types of eruptions are shown on figure 10 and plate 1.

Mafic Lava Flows

Mafic lava flows and associated cinder cones are the most common volcanic features in the Lassen region (figs. 2, 3, 4, and 10). Two types of mafic lava flows associated with regional volcanism in the Lassen region are discussed together—cinder cones with small lava flows and larger volume, more fluid lava flows.

Eruptions producing cinder cones and small lava flows could occur anywhere in the region surrounding the Lassen Volcanic Center. Mafic lava flows are generally small, typically being limited to a few kilometers in length and covering a few square kilometers (fig. 11). Fifty-four eruptions that built cinder cones and (or) emitted lava flows and are known or estimated to be less than 100,000 years old are listed in table 2. The outlines of individual mafic lava flows or groups of such flows are shown in blue on figure 10 and plate 1, and the locations of their vents are shown as asterisks. The distribution of these vents and lava flows defines a Mafic Vent and Lava Flow Hazard Zone (the solid blue line on fig. 10 and plate 1). This hazard zone indicates the area where new mafic vents are most likely to be located and adjoining areas downhill that new lava flows might be expected to cover.

The alignments of vents shown on figure 10 and plate 1 demonstrate that their location is controlled by fractures (faults) in the crust and that, although new mafic volcanism could occur anywhere in this zone, it is more likely in a few areas where the youngest mafic lava flows are concentrated. These are NNE-aligned chains or clusters of vents identified in table 2, for example the Red Cinder chain, the Bidwell Spring chain, vents in the area of the Hat Creek Valley, the Tumble Buttes chain and the Red Lake cluster. Together these and other alignments define several larger zones of likely locations for mafic volcanism: (1) a zone from the Red Cinder chain to Calif. Hwy 44, (2) a zone from south of Old Station to near the Pit River, (3) a zone from the south end of Tumble Buttes chain (approximately Calif. Hwy 44) to Burney Mountain, and (4) the Red Lake cluster (fig 4A, B, plate 1). Mafic volcanism in the other parts of the hazard zone shown in plate 1, for example west of LVC in the vicinity of Inskip Hill, Black Butte, or Silver Lake or south of the LVC around Mineral, is possible but less likely than the areas discussed above.

The largest mafic lava flows in the Lassen region are fluid basalt flows associated with Basin and Range volcanism (designated as tholeiitic in table 2). These erupt from fissures with little associated ash, and the lava is generally distributed through lava tubes. In the Lassen region, they most commonly erupt slightly east of the main Cascade arc axis. These fluid lava-flow eruptions occur much less frequently than the smaller cinder-cone and lava-flow eruptions (only 4 of the total of 58 eruptions listed in table 2 are fluid mafic lava flows). But these lava flows erupt much larger volumes (1–3 km^3) than the small mafic lava flows and cover much greater areas, often as much as 100 km^2, and voluminous eruptions could extend beyond the designated lava flow hazard zone (plate 1) in some valleys. The youngest large basalt lava flow in the Lassen region is the 24,000-year-old Hat Creek Basalt, which erupted from a fissure vent just south of Old Station (Muffler and others, 1994; Turrin and others, 2007). As much as ~2.5 km^3 of lava from this vent was distributed for 20 km north in lava tubes and covered nearly 100 km^2 of the Hat Creek Valley. Much smaller, young fluid lava flows include the vents near Big Lake north of LVNP and the Buzzard Spring and Ice Cave Mountain vents in the meadows along the North Fork Feather River (table 2).

Lava flows are not likely to advance rapidly enough to overtake fleeing people but would damage or destroy everything in their path, including forests and structures. During dry weather the advancing front of a lava flow in the forest would ignite fires. An eruption at the south end of the Tumble Buttes chain or the Red Lake cluster could easily block Calif. Hwys 44 and 89. An eruption in the Hat Creek Valley could block or disrupt traffic on Calif. Hwys 44 and 89. Wooden-pole power and telephone lines would be destroyed, and steel-pole power lines and other critical infrastructure could be destroyed, buried, or cut off by mafic lava flows.

Mafic Ash

The presence of mafic cinder cones in the area surrounding the Lassen Volcanic Center indicates explosive activity at those vents. Eruption columns associated with formation of cinder cones can rise several kilometers into the atmosphere (for example Luhr and Simkin, 1993; Hill and others, 1998). Close to vents, mafic ash (tephra)

Figure 10. Map of volcano hazard zones in the Lassen region (see also plate 1). The Mafic Vent and Lava Flow Hazard Zone is shown by the solid blue line, which encloses the area of regional mafic vents (black asterisks) and lava flows (blue) less than 100,000 years old. Mafic lava flows will likely cover similar areas depending on the topography in the immediate area of the vent and the volume of lava erupted. Although mafic volcanism is possible anywhere in the area, it is more likely in a few named areas (a zone from the Red Cinder and Bidwell Spring chains through the Hat Creek Valley, the area of the Tumble Buttes chain, and the area of the Red Lake cluster). The area covered by eruption of new flows will depend on the topography in the immediate area of the vent and the volume of lava erupted. Blue dotted line defines the Mafic Ash Hazard Zone and encloses area where more than 5 cm of mafic ash is possible. The boundary is drawn ~10 km from the potential vent areas and is based on the 5-cm isopach associated with the 1666 eruption of Cinder Cone (Heiken, 1978; Clynne and Muffler, 2010). The prevailing wind direction makes it most likely that ash deposits will extend east to northeast of new vents (see fig. 13). Red solid line denotes the Silicic Vent, Lava Dome and Flow Hazard Zone, which encompasses the area of silicic vents (black asterisks) for eruptions in the Lassen domefield less than 100,000 years old. The area covered by silicic lava domes and flows less than 100,000 years old is shown in red. The area covered by a new eruption will depend on the topography in the immediate area of the vent and the volume of lava erupted. The Andesite Vent and Lava Flow Hazard Zone is shown by the solid magenta line. It denotes the area of andesite and more mafic lava flows and vents (black asterisks) less than 100,000 years old in the Lassen Volcanic Center. Vents of renewed andesite volcanism associated with the Lassen domefield will most likely be confined to this area. The magenta areas show the extent of andesite lava flows less than 100,000 years old. New andesite lava flows will likely cover similar areas depending on the topography in the immediate area of the vent and the volume of lava erupted. Ash fall thicker than 5 cm associated with these eruptions will most likely be contained within the Mafic Ash Hazard Zone (blue dotted line). The red dashed line encloses a Combined Flowage Hazard Zone that includes pyroclastic flows, blasts and surges generated by silicic eruptions, and the area that could be affected by more than 15 cm of silicic ash fall. Beyond areas within a few km of vents, pyroclastic flows and lahars will be confined mostly to valleys of the major drainages. Volcanic blasts and pyroclastic surges are less affected by topography and may extent out to the vicinity of the dashed red line. The Silicic Ash Hazard Zone shown by the red dotted line indicates the area that could be affected by more than 5 cm of silicic ash. The prevailing wind direction makes it most likely that ash deposits will extend east to northeast of new vents (see fig. 13). Yellow indicates areas potentially subject to inundation by lahars generated by pyroclastic flows or other volcanic events originating in the Silicic Vent, Lava Dome and Flow Hazard Zone (Robinson and Clynne, 2012). Green indicates areas downstream of lahar deposition that are potentially subject to floods generated by dewatering of lahars. These areas are modified from Miller (1989). See text for further explanation of all hazard zones. (digital elevation model from Gesch, 2007)

EXPLANATION

VOLCANO HAZARD ZONES

[See text for additional explanation]

LASSEN REGION

🟦 **Mafic Lava Flows**
Areas covered by mafic lava flows younger than 100,000 years

— **Mafic Vent and Lava Flow Hazard Zone**
Area most likely for eruption of mafic vents and lava flows

······· **Mafic Ash Hazard Zone**
Area surrounding Mafic Vent and Lava Flow Hazard Zone and subject to more than 5 cm of mafic ash

LASSEN VOLCANIC CENTER

🟪 **Andesite Lava Flows**
Areas covered by andesitic lava flows younger than 100,000 years

— **Andesite Vent and Lava Flow Hazard Zone**
Area most likely for eruption of andesite vents and lava flows in Lassen Volcanic Center. Also subject to thick accumulations of ash

🟥 **Silicic Lava Flows**
Areas covered by silicic domes and lava flows younger than 100,000 years

— **Silicic Vent, Lava Dome, and Flow Hazard Zone**
Area most likely for eruptions of silicic vents, lava domes, and flows. Subject to thick accumulations of silicic ash. Also the area of initiation of pyroclastic flows, blasts, surges, and lahars

— — **Combined Flowage Hazard Zone**
Area adjacent to explosive volcanoes or vents and subject to pyroclastic flow, blast, or surge eruptions. Also subject to deposition of more than 15 cm of silicic ash

······· **Silicic Ash Hazard Zone**
Area surrounding the Combined Flowage Hazards Zone and subject to more than 5 cm of silicic ash

🟨 **Lahar Hazard Zones**
Areas beyond the lava flows shown in the Silicic Vent, Lava Dome, and Flow Hazard Zone and subject to inundation by lahars

— **Flood Hazard Zones**
Areas beyond the Lahar Hazard Zones subject to floods

* **Vents**

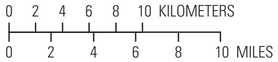
INFRASTRUCTURE

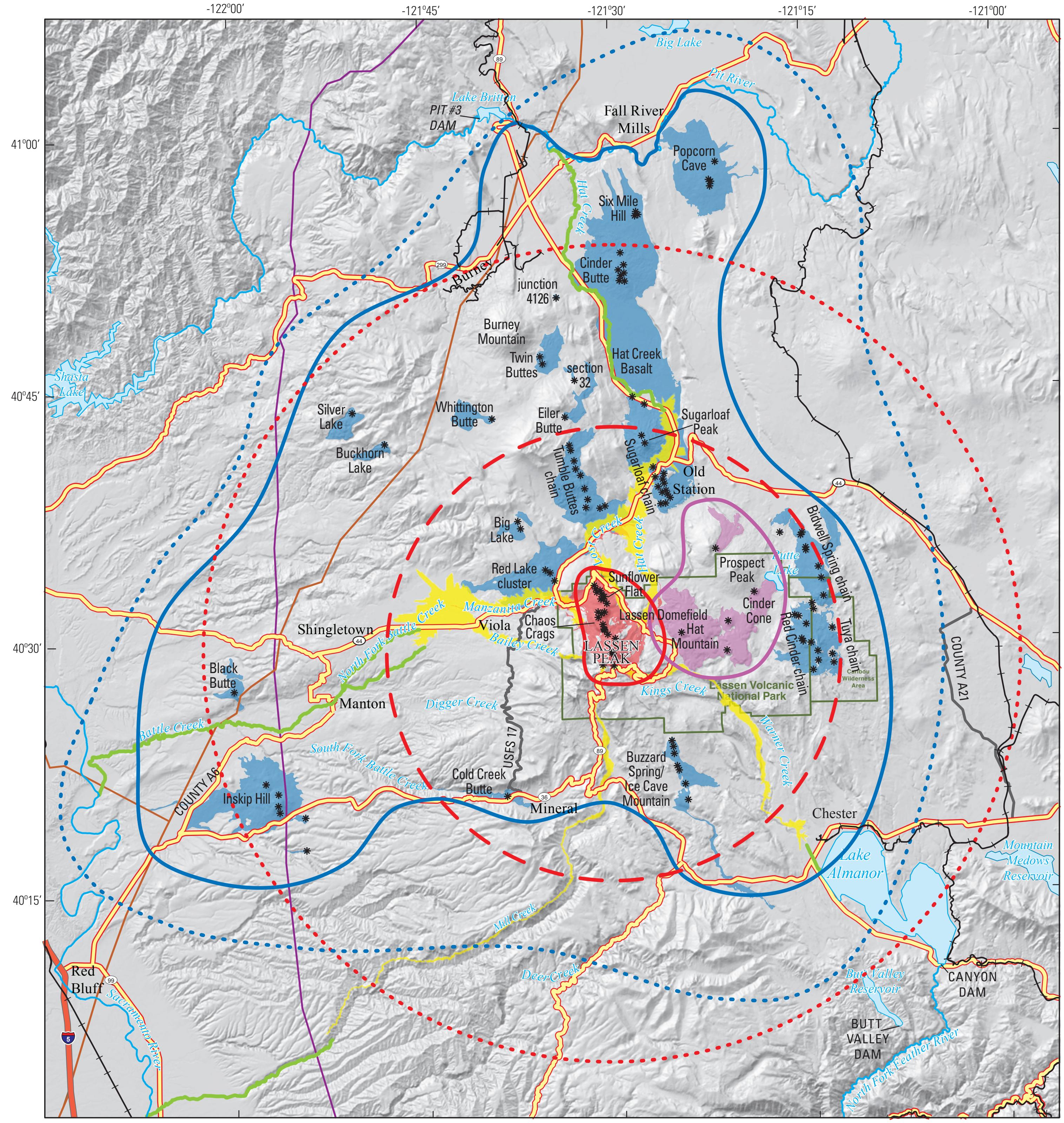
— **Major Power Lines**

— **Gas Pipeline**

▬ **Roads**

┼┼┼ **Railroads**

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Fall River Mills
Popcorn Cave
Hat Creek
Six Mile Hill
Cinder Butte
299
Burney
junction 4126
Burney Mountain
Twin Buttes
section 32
Hat Creek Basalt
Shasta Lake
Silver Lake
Whittington Butte
Eiler Butte
Sugarloaf Peak
Buckhorn Lake
Tumble Buttes chain
Sugarloaf chain
Old Station
44
Bidwell Spring chain
Big Lake
Lost Creek
Hat Creek
Butte Lake
Prospect Peak
Red Lake cluster
Sunflower Flat
Cinder Cone
Manzanita Creek
Lassen Domefield
Chaos Crags
Hat Mountain
Shingletown
North Fork Battle Creek
Viola
Bailey Creek
LASSEN PEAK
Red Cinder chain
Tuya chain
Caribou Wilderness Area
COUNTY A21
Black Butte
Kings Creek
Lassen Volcanic National Park
Manton
Digger Creek
Battle Creek
USFS 17
Warner Creek
South Fork Battle Creek
89
Buzzard Spring/ Ice Cave Mountain
COUNTY A6
Cold Creek Butte
Inskip Hill
36
Mineral
Chester
Lake Almanor
Mountain Medows Reservoir
Mill Creek
Red Bluff
99
Deer Creek
Butt Valley Reservoir
CANYON DAM
Sacramento River
5
BUTT VALLEY DAM
North Fork Feather River

deposits could be several meters thick, but such deposits typically thin abruptly away from their vents (fig. 12). The hazard zone for accumulation of mafic ash 5 or more centimeters thick is based on the 1666 C.E. eruption of Cinder Cone in LVNP. The total volume of Cinder Cone ash is calculated to be about 0.034 km^3 using the method of Fierstein and Nathenson (1992). At Cinder Cone, the 5-cm contour describes an oval-shaped area covering about 250 km^2 and extending 10 km from the vent. The Mafic Ash Hazard Zone extends approximately 10 km (dotted blue line on figure 10 and plate 1) beyond the area of potential new vents shown in the Mafic Vent and Lava Flow Hazard Zone. Thinner accumulations of ash could extend at least another 10 km from vents, depending on the explosivity of individual eruptions and wind conditions. The most likely locations for new vents were discussed in the previous section. Eruptions producing mafic ash generally last from weeks to months or a year, but on rare occasions they can last as long as 10 years.

Eruption of mafic magma through bodies of water or interaction with groundwater can also produce explosive eruptions. The affected areas and thicknesses of ash accumulations are generally similar to those of cinder cone eruptions. However, if large plumes of steam are generated, ash can be carried much higher into the air and transported much farther (as much as hundreds of kilometers) than typical. Although this type of **phreatomagmatic eruption** has occurred in the Lassen region in the past, it is not common, and none has occurred in the past 100,000 years. Explosions that occur when lava flows into a body of water, for example, a lake, generally affect only the immediate area of the interaction. Thus, separate hazard zones for phreatomagmatic activity and lava flowing into water are not drawn on figure 10 and plate 1.

Hazards Associated with Silicic Volcanism at the Lassen Volcanic Center

This section discusses the likely locations of silicic explosive and effusive eruptions at the Lassen Volcanic Center including lava domes and flows, pyroclastic flows, lateral blasts, airborne ash and ash fall, and lahars. Table 1 lists the eruptions that have occurred at the LVC in the past 100,000 years. Five hazard zones for these types of events are shown in figure 10 and plate 1. They are: (1) Silicic Vent, Lava Dome and Flow Hazard Zone, (2) Andesite Vent and Lava Flow Hazard Zone, (3) Combined Flowage Hazard Zone, (4) Silicic Ash Hazard Zone, and (5) Lahar Hazard Zone. Downwind silicic ash hazards are also discussed, but a specific hazard zone is not designated. Hazards from floods resulting from lahars are also discussed. The effects of these types of eruptions were discussed in previous sections under the heading Hazards Associated with Silicic Eruptions.

Lava Domes and Flows

Silicic to andesitic lava domes and flows are common eruptive features of volcanism at the Lassen Volcanic Center and are discussed in this section. Lava domes occur primarily in the western part of the Lassen domefield in the northwest corner of LVNP. Thick andesite lava-flow complexes form the eastern part of the Lassen domefield.

Silicic lava flows and domes are most likely to occur in the immediate vicinity of Chaos Crags and Lassen Peak and are unlikely to occur outside the area of the western part of the Lassen domefield. The hazard zone for silicic lava domes and flows is shown on figure 10 and plate 1 as the solid red line (Silicic Vent, Lava Dome and Flow Hazard Zone). Lava domes and short, thick

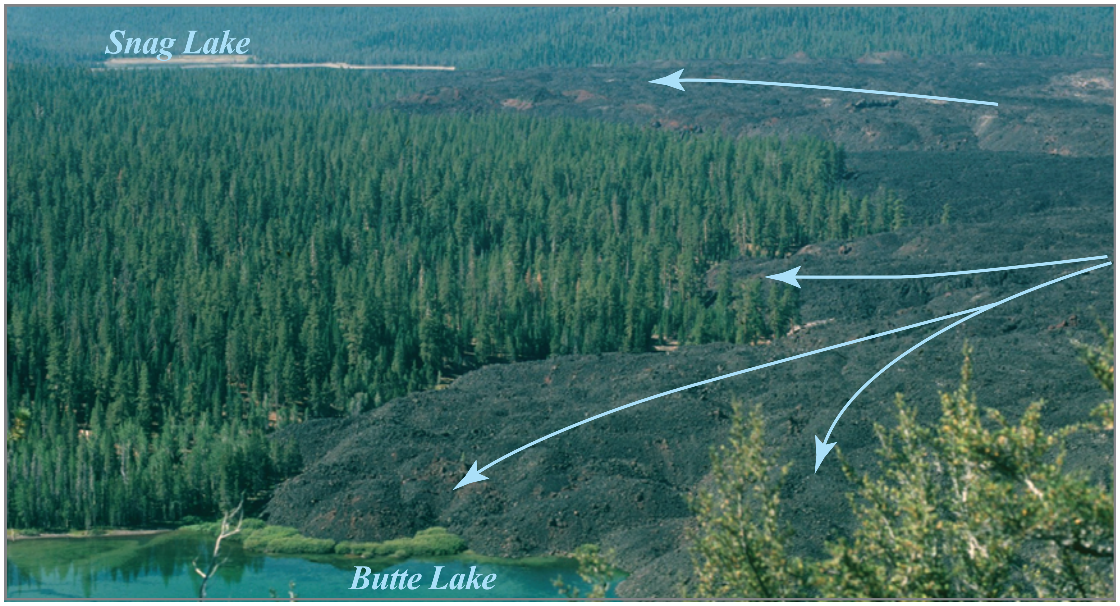


Figure 11. Steep front of block lava flows from the 1666 eruption of Cinder Cone (telephoto view looking southwest from Sunrise Peak). The lava flow fronts at Cinder Cone range in height from 10 to 50 m and typically are 20 to 30 m high. Blue arrows indicate the direction of advance of the lava flows. Snag Lake (barely visible at top left) was created by damming of drainage by the lava flows. Future lavas flows in the Lassen region can potentially also dam drainages.

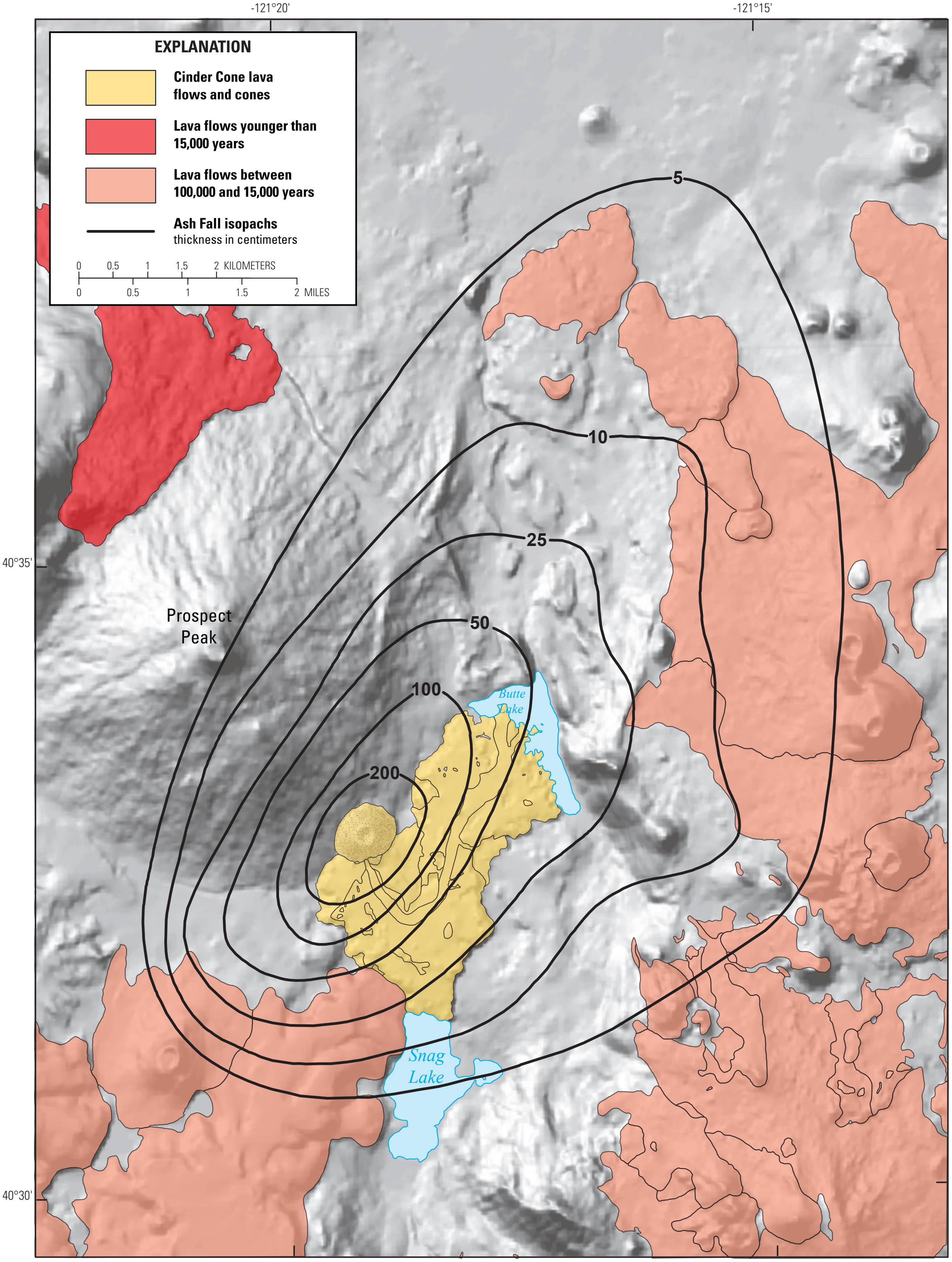


Figure 12. Map showing thickness (isopachs in centimeters) of the ash deposits from the 1666 eruption of Cinder Cone (adapted from Heiken, 1978). Vent cinder cones are indicated with stipple pattern and the area covered by lava flows in buff (black lines indicate internal flow contacts in Cinder Cone and the older lava flows). (digital elevation model from Gesch, 2007)

lava flows associated with silicic volcanism in the LVC typically cover only a few square kilometers but can be as much as 1–2 km^3 in volume (figs. 5 and 6). Lava domes tend to occur in small groups or clusters that result from local shifting of the vent during dome growth. The viscous nature of silicic lava flows and the slow documented eruption rates at volcanoes such as Mount St. Helens indicate that such an eruption could extend over years to decades. Growth of lava domes is generally non-explosive, but periods of heightened activity resulting in explosions and pyroclastic flows (see section on “Combined Flowage Hazard Zone”) can occur if gas-rich magma reaches the vent.

Lava domes at Lassen are typically <1 km^3 in volume but occasionally larger and are very steep, often unstable, and subject to collapse events. Collapse of growing lava domes can generate pyroclastic flows of hot dome rock called lithic pyroclastic flows or block and ash flows. Most lava domes grow by adding lava to the interior of the dome. The outer surface expands to accommodate the new lava being pushed up into the growing dome. The relatively cool and solid exterior of the dome cracks and portions of it can fail as small collapse events. Breaking of the solid but still hot rock during collapse events allows escape of contained gases that gives lithic pyroclastic flows considerable mobility. Both Lassen Peak and the Chaos Crags have generated lithic pyroclastic flows that traveled as far as 5 km from their sources. The hazard zone for dome collapse events is confined to an area of about 5 km from any growing dome. This zone is not shown separately on figure 10 and plate 1, but it would be contained within the Combined Flowage Hazard Zone shown as the dashed red line.

At the LVC, andesite lava flows are most likely in the eastern part of the Lassen domefield in LVNP in the vicinity of Hat Mountain and Cinder Cone. The Andesite Vent and Lava Flow Hazard Zone is shown as the solid magenta line on figure 10 and plate 1. Andesite lava flows associated with the LVC are thicker and tend to have larger volumes than typical mafic lava flows in the surrounding area. Andesite lava flows in the eastern part of the Lassen domefield are as much as several cubic kilometers in volume and can cover several tens of square kilometers with lava. Four andesite lava-flow complexes have been emplaced on the Lassen domefield in the past 100,000 years (table 1). The largest of these, Hat Mountain, covers nearly 100 km^2 and has a volume of about 4.7 km^3. The others are smaller, but still substantial and cover a combined area of ~40 km^2. The length of time required to emplace these flows is unknown, but it is probably comparable to that for lava domes. Mild explosions that build cinder cones are associated with the vent areas of andesite lava flows. The effects of these eruptions are similar to those described for mafic ash.

Pyroclastic Flows and Lateral Blasts

Explosive silicic volcanism in the Lassen Volcanic Center is likely to generate pyroclastic flows. These will most likely occur in the early stages of silicic eruptions, but after precursory activity. Pyroclastic flows generated by eruption column-collapse events will flow off the high ground around the vent and be channeled by topography down valleys. Pyroclastic flows from the Chaos Crags eruption flowed down valleys for as much as about 20 km. The vents for explosive silicic eruptions will most likely be located in the area of youngest volcanism in the LVC, the area of the Silicic Vent, Lava Dome and Flow Hazard Zone. The valleys most likely to be effected are Manzanita Creek, Lost Creek and Hat Creek. The Combined Flowage Hazard Zone (dashed red line on figure 10 and plate 1) is for explosive silicic eruptions, including pyroclastic flows, similar to the magnitude of the Chaos Crags eruption, which is the largest known in the past 100,000 years. An eruption generating larger pyroclastic flows is much less likely and would be unprecedented in the Lassen region in the past 100,000 years.

Some types of more energetic explosive eruptions, for example lateral blasts and pyroclastic surges, are not as effected by topography as pyroclastic flows generated by collapse of eruption columns. These are pyroclastic blasts and surges that are directed away from vents at high speeds (for example, the blast at Mount St. Helens on May 18, 1980). They are less likely at Lassen than column-collapse pyroclastic flows, but a small pyroclastic surge occurred at Lassen in 1915. Lateral blasts and pyroclastic surges are expected to be confined to the Combined Flowage Hazard Zone.

Airborne Ash and Tephra Fallout

Tephra fallout accompanying a silicic eruption could be regionally widespread if the eruption column reaches at least several kilometers into the atmosphere, as would be likely. Winds in the Lassen region blow dominantly toward the east and northeast (fig. 13). Depending on plume height, wind direction, and duration and volume of the eruption, fallout could cause short-term disruption of activities in Redding, Chico, Red Bluff, the Chester-Lake Almanor area, Susanville, Alturas, and Reno, Nevada and perhaps as far away as rural northern Nevada and southern Oregon. Local communities, Lassen Volcanic National Park, adjacent Lassen National Forest, roads and highways, and utility corridors could be affected for days or weeks, depending on the duration of the eruption.

Past tephra eruptions are poorly represented in the geologic record at Lassen, probably because of removal of deposits by glacial erosion. The two postglacial explosive silicic eruptions, that of Chaos Crags and the 1915 eruption of Lassen Peak, have mappable tephra deposits, and it is likely that most of the 30 or more pre-glacial silicic eruptions also emitted ash. Tephra plumes produced in the Chaos Crags and 1915 eruptions (fig. 14) were directed to the northeast by the most common prevailing wind direction to the northeast. Although a traceable deposit of the 1915 eruption is preserved for only about 25 km from Lassen Peak, ash fell as far away as Elko, Nevada, nearly 450 km from Lassen. Tephra fallout volume for this eruption is estimated to be at least 25,000,000 m^3 (0.025 km^3). The Chaos Crags eruption was much larger, but is traceable for only about 40 km because it is older and thus has been subjected to more erosion.

Near-vent accumulations of tephra from explosive silicic eruptions could be many meters thick, but no permanent habitations lie close to likely vent locations at Lassen. The hazard zone for 15 cm or more of silicic ash is confined to the area of the Combined Flowage Hazard Zone shown on figure

10 and plate 1. The hazard zone for 5 cm or more of silicic ash is shown as a dotted red circle on figure 10 and plate 1 (Silicic Ash Hazard Zone). Figure 15 shows the estimated annual probability of 1 cm or more of tephra accumulation from eruptions of the major Cascade volcanoes including the LVC (Hoblitt and Scott, 2011; Richard Hoblitt, written commun., 2012). In the area east of the LVC, the chance of 1 cm of tephra falling in any given year is between 0.0002 and 0.001 (1 in 5,000 to 1 in 1,000). Although 1 cm of ash may seem a very small amount, experience with Mount St. Helens eruptions indicates that as little as a few millimeters of ash is sufficient to slow vehicle traffic to a crawl, potentially disrupt electrical distribution, and to close businesses for as long as a week (Schuster, 1981, and references therein).

Numerous examples of engine failure, loss of visibility, and loss of navigational and operational instruments have occurred in aircraft encounters with airborne volcanic ash. The Lassen Volcanic Center sits directly below the primary air corridor between the southwestern and northwestern United States, and any eruption generating tephra is likely

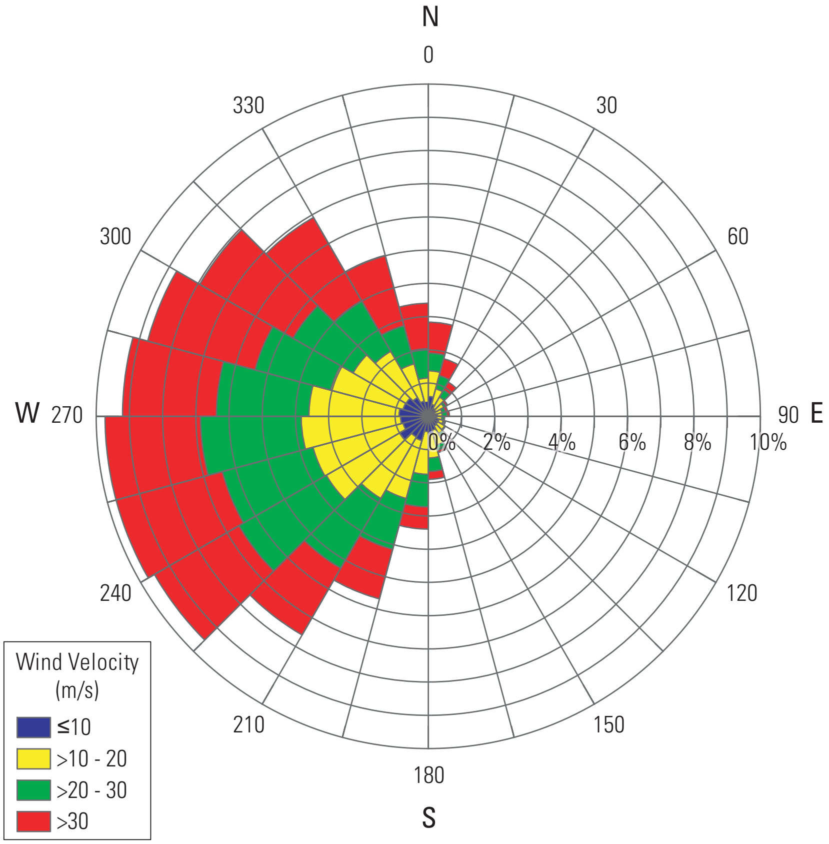


Figure 13. Rose diagram showing directions from which winds blow in the vicinity of Lassen Peak (Donnelly-Nolan and others, 2007). Diagram also shows relative frequencies of wind speeds (in percent of time) at an elevation of 9,360 m. Data from 1997–2006, comprising 14,608 data points from NOAA-ARL final archive (http://www.arl.noaa.gov/ready-bin/fnl.pl, last accessed August 15, 2007).

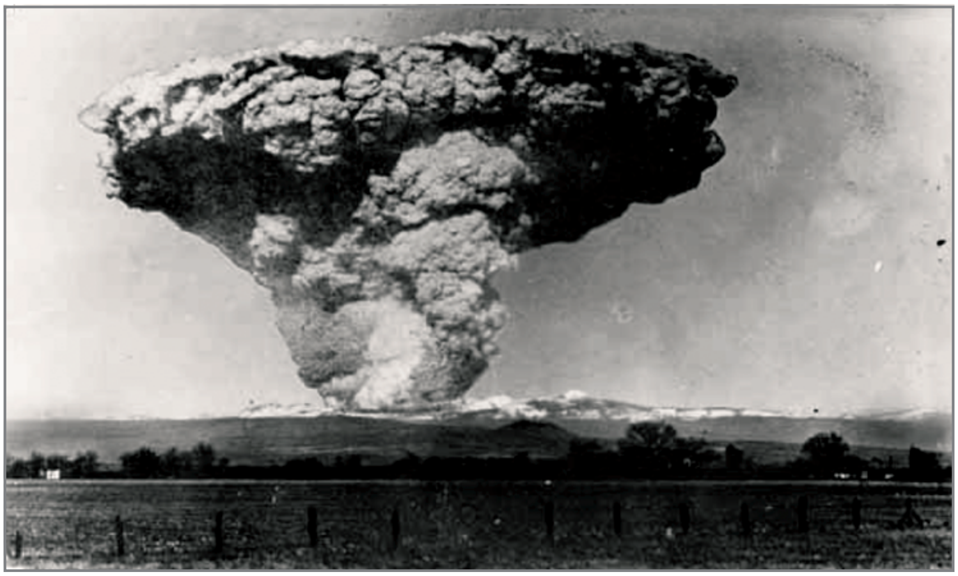


Figure 14. Plume generated by the Lassen Peak eruption of May 22, 1915. This plume reached a height of about 9 km, and ash from the it fell in a lobe directed to the northeast and as far as Elko, Nevada, about 450 km distant. Historic photograph taken by R.I. Meyers from Anderson in the Sacramento Valley about 65 km west of Lassen Peak. Eruption cloud photographically pasted onto a more photogenic foreground by Benjamin Franklin Loomis in 1915, courtesy of the National Park Service.

to cause temporary re-routing of commercial air traffic. Depending on the factors discussed above, operations at local airports, for example in Chester and Susanville, might be disrupted. Redding and Chico could also be affected if the winds were blowing to the west or south. Airports at greater distances, for example Reno, Sacramento, or the San Francisco Bay Area, might be affected under favorable circumstances or in larger eruptions. Eruption columns affecting commercial aircraft are not likely to persist in the atmosphere for more than a few days at a time.

Lahars and Lahar-Generated Floods

Any volcano with a significant cover of snow or ice is subject to lahars induced by sudden melting of snow and ice. Lahars are sparse in the geologic record at LVC, but events prior to 15,000 years ago have been obscured by the effects of glaciation. At Lassen, the most likely events to cause lahars are pyroclastic flows moving over snow or avalanches of hot rock that incorporate large amounts of snow. Both these types of lahars occurred during the 1915 eruption of Lassen Peak (fig. 16). A pyroclastic flow that went down Manzanita Creek during the Chaos Crags eruption was transformed into a lahar by incorporating water from the creek. Torrential rains onto recently deposited loose volcanic or sedimentary material may also trigger a lahar, and in 1963 a small lahar of this type occurred on the lower slopes of Lassen Peak. Lahars may also be triggered by landslides of hydrothermally altered rock. Although the altered core of the Brokeoff Volcano has been the site of many landslides, some of which traveled considerable distances, there is no evidence that any transformed into significant lahars. Lahars were also initiated at Lassen by mobilization of recently deposited glacial sediments during the last deglaciation event about 8,000 years ago (Marron and Laudon, 1986; Christiansen and others, 2002), but this type of lahar is very unlikely under the present climatic conditions.

At LVC, lahars are not expected to be as large as those described at many Cascade composite volcanoes. Lassen Peak, the LVC's largest edifice, is not large compared to most Cascade composite volcanoes, does not have any glaciers, and has only 1 small permanent snowfield. The winter of 1914–1915 was an exceptional year for snowfall on Lassen Peak (Day and Allen, 1925) and probably approximates the largest volume of snow that could be available to generate lahars. Robinson and Clynne (2012) calculated the inundation areas for the lahars generated on May 19 and 22, 1915, with LAHARZ (Iverson and others, 1998), a computer

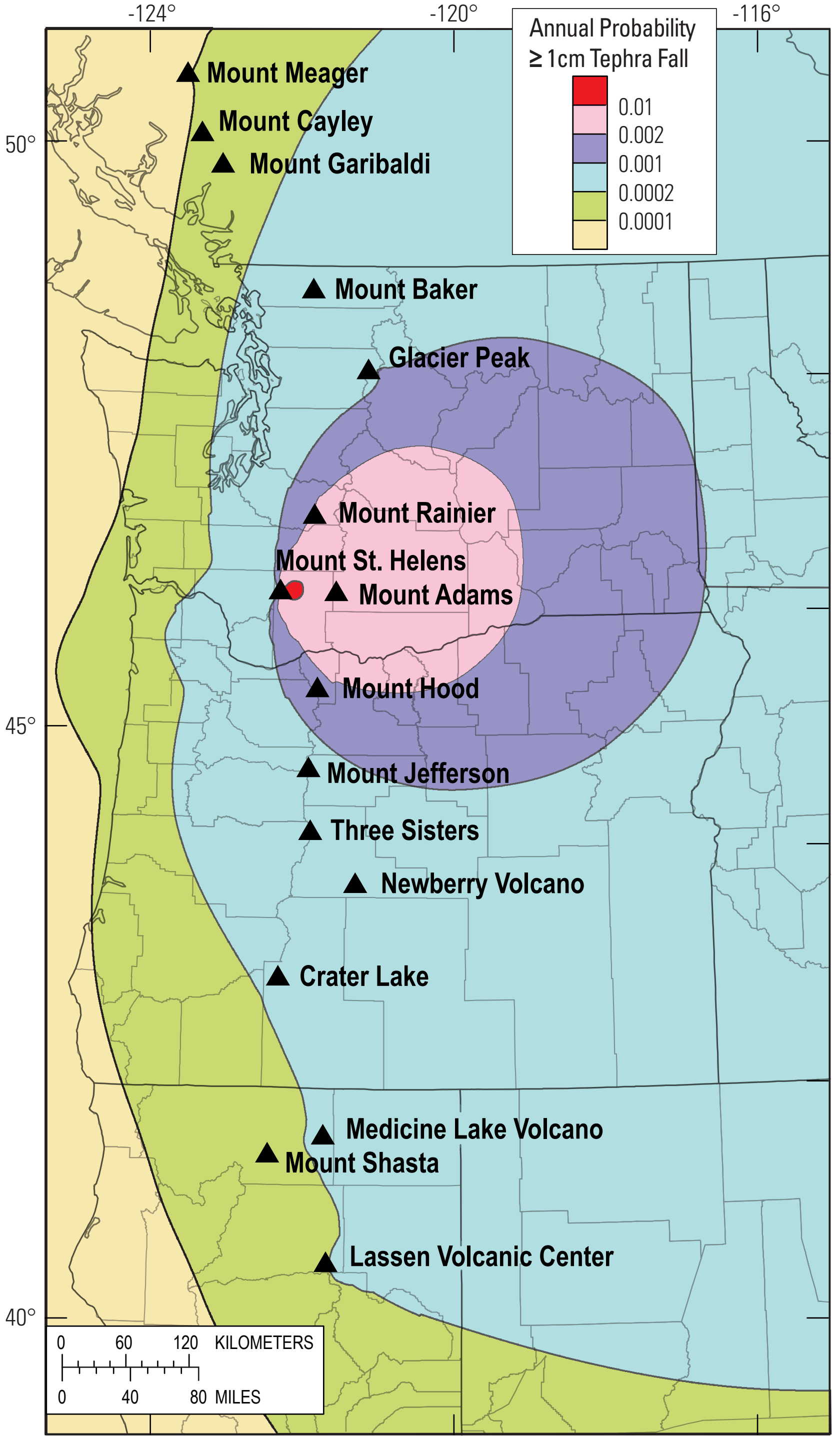


Figure 15. Map showing annual probability of 1 centimeter or more of tephra accumulation from any major Cascade volcano (black triangles) (Hoblitt and Scott, 2011; Richard Hoblitt, written commun., 2012) using the method of Hoblitt and others (1987). The Lassen region has a probability of 0.0001 (0.01 percent) to 0.001 (0.1 percent)– 1 in 5,000 to 1 in 1,000– each year of receiving 1 centimeter or more of tephra. The area around Mount St. Helens dominates the probablity because it is the most active explosive volcano in the Cascade Range. Black lines are state and county boundaries.

program that uses a digital elevation model to estimate the extent of inundation by lahars of a given volume. They found that the inundation areas calculated using estimated volumes for the May 19 and 22 lahars corresponded closely with the mapped deposits.

At LVC, lahars can originate in any of the drainages heading in the high-elevation terrain around Lassen Peak, including Mill Creek, Bailey Creek, Manzanita Creek, Lost Creek, Hat Creek, and Warner Creek. However, they are most likely in Lost, Hat, and Manzanita Creeks. Robinson and Clynne (2012) used LAHARZ to calculate inundation zones for lahars originating in drainages heading on Lassen Peak, plus Bailey Creek. Model input parameters included water volumes available as snow in the various drainage basins. Lahar volumes modeled were 1, 3, 10, 30, 60, and 90 million m^3, values corresponding to small (1, 3), medium (10, 30) and large (60, 90) lahars. Maximum volumes were scaled to be appropriate for the maximum water content of snow in each drainage basin (Robinson and Clynne, 2012). Smaller volume lahars will be much more frequent than the larger volume lahars. The largest volume modeled lahars are the maximum size events that can be expected to be generated from Lassen Peak and require that the maximum water content of snow be available in a given drainage basin and that it all be melted in a single event. Medium-size lahars like those generated in 1915 (~15 million m^3) are much more likely.

The results reported by Robinson and Clynne (2012) are used to delineate Lahar Hazard Zones for lahars in each of the valleys originating in the area of Lassen Peak. These are shown on figure 10 and plate 1. Lahars of the largest modeled volume will be confined to the area of the Combined Flowage Hazard Zone for Manzanita and Bailey Creeks (fig. 10 and plate 1). Only the largest volume lahars (unprecedented for Lassen) could extend as far as about 5 km beyond the Combined Flowage Hazard Zone in Hat Creek. Most modeled lahars in the Warner Creek drainage would be confined to the Combined Flowage Hazard Zone, but the largest (unprecedented at Lassen) would approach Chester. Only small-volume lahars in the Mill Creek drainage would be contained within the Combined Flowage Hazard Zone, and larger volume lahars could extend considerably beyond it. However, large-volume lahars in Warner and Mill Creeks are less likely than in the drainages heading on the north side of Lassen Peak, because vent locations are more likely to be on the north side of the volcano. Lahars starting at a lower elevation than the upper flanks of Lassen Peak would have a smaller potential water volume and a smaller drop in elevation to traverse and are expected to be smaller and less mobile than those generated in 1915. They will most likely be confined to the Combined Flowage Hazard Zone shown on figure 10 and plate 1.

Lahars can initiate flooding farther downstream than they travel. When the mass of water-saturated sediment comes to rest, water is released and continues downstream. Depending on the amount and grain size of sediment carried, these are hyperconcentrated stream flows or muddy floods. Both of the mudflows in Lost and Hat Creeks generated by the May 19 and May 22, 1915, eruptions of Lassen Peak stopped in the vicinity of the confluence of Lost and Hat Creeks. The effects described in the historical literature farther down Hat Creek were muddy floods. In 1915, fish kills from muddy water were noted along the entire length of Hat Creek (Merrill, 1916; Bryant, 1918; Shehley, 1922), as far as 50 km from Lassen Peak. Flood Hazard Zones that extend beyond the Lahar Hazard Zones for the valleys of Hat Creek, North Fork Battle Creek, Mill Creek, and the North Fork of the Feather River are shown on figure 10 and plate 1.

Figure 16. Historic photographs taken in 1915 by Benjamin Franklin Loomis of the effects of lahars from Lassen Peak. Photographs courtesy of the National Park Service. *A*, View of logjam in Lost Creek after lahar of May 19, 1915. *B*, View of lower Lost Creek after lahars of May 1915.

Other Hazards in the Lassen Region

The Lassen region is mountainous and thus includes a variety of other geologic hazards associated with mountainous areas, especially landslides and rockfalls. In addition there are hazards associated with the hydrothermal system at the Lassen Volcanic Center.

Landslides and Rockfalls

In this section, we discuss landslides and rockfalls that are not directly related to volcanic eruptions but are the result of secondary processes related to volcanism at the LVC. Landslides and rockfalls are common hazards in any mountainous terrain, particularly those with volcanic or glacial landscapes. Many rockfalls occur without warning or are triggered by earthquakes. Volcanic landforms such as lava domes, edifices composed of fragmental deposits, or interbedded lava flows and volcanic breccias can be inherently unstable. Normal freeze-thaw processes attack weak and heavily jointed volcanic rocks, enhancing this instability. Thus, rockfalls of a variety of sizes are constant hazards in areas of exposed rock. The 10,000-m^3 rockfall that occurred on the northeast flank of Lassen Peak in August 1993 (Norris and others, 1993) is typical of this type of rockfall. Talus cones, especially around the bases of Lassen Peak and Brokeoff Mountain, and in valleys below cliffs exposed in Mill Creek and Bailey Creek, attest to the rockfall hazards in LVNP. The hazard associated with typical small rockfall events normally does not extend beyond the base of talus cones. Large, precariously perched boulders near the summit of Diamond Peak also pose a hazard to vehicles driving on the Park road below, should they be dislodged by an earthquake or by normal erosion.

Hydrothermal alteration and oversteepening of valley walls and cirques by glacial erosion further contribute to instability of volcanic rocks. Human activity, for example road building in unstable hydrothermally altered deposits, also contributes to landslide hazards. Such landslide hazards are distributed throughout LVNP, but are particularly prevalent in the high, steep country of Brokeoff Volcano. In this area, small landslides have to be dealt with nearly every year, particularly where steep slopes are disrupted by road cuts and associated fill. The Park road (Calif. Hwy 89) that leads from Sulphur Works around Diamond Peak to the Bumpass Hell parking lot is particularly susceptible to continuing rock fall onto the road and to slumping of the road east and south into Little Hot Springs Valley. This rockfall and landslide hazard potential, however, is unlikely to affect vehicles or persons using the road, particularly because the road is closed over the winter.

In addition to these widespread, small landslide and rockfall hazards, LVNP is susceptible to hazards from larger landslides related to two specific geological environments: Chaos Crags and the core of Brokeoff Volcano.

Chaos Jumbles

The Chaos Crags are a complex of 6 volcanic domes that together form the youngest large volcanic landform in LVNP, having erupted about 1,050 years ago (Clynne and others, 2008). Approximately 340 years ago, dome C of Chaos Crags was the source of Chaos Jumbles (fig. 17), a complex of major rock avalanche deposits (Crandell and others, 1974; Eppler and others, 1987; Christiansen and others, 2002). The hazards of and potential for similar events in the future were evaluated by Eppler and others (1987).

Chaos Jumbles is made up of the deposits of three separate rockfall avalanches that in combination cover 6.8 km^2. The deposits consist of a monolithologic breccia of dacite blocks in a matrix of pulverized dacite. The first rockfall avalanche was the largest and traveled 4.5 km with a 650-m vertical drop from the top of the

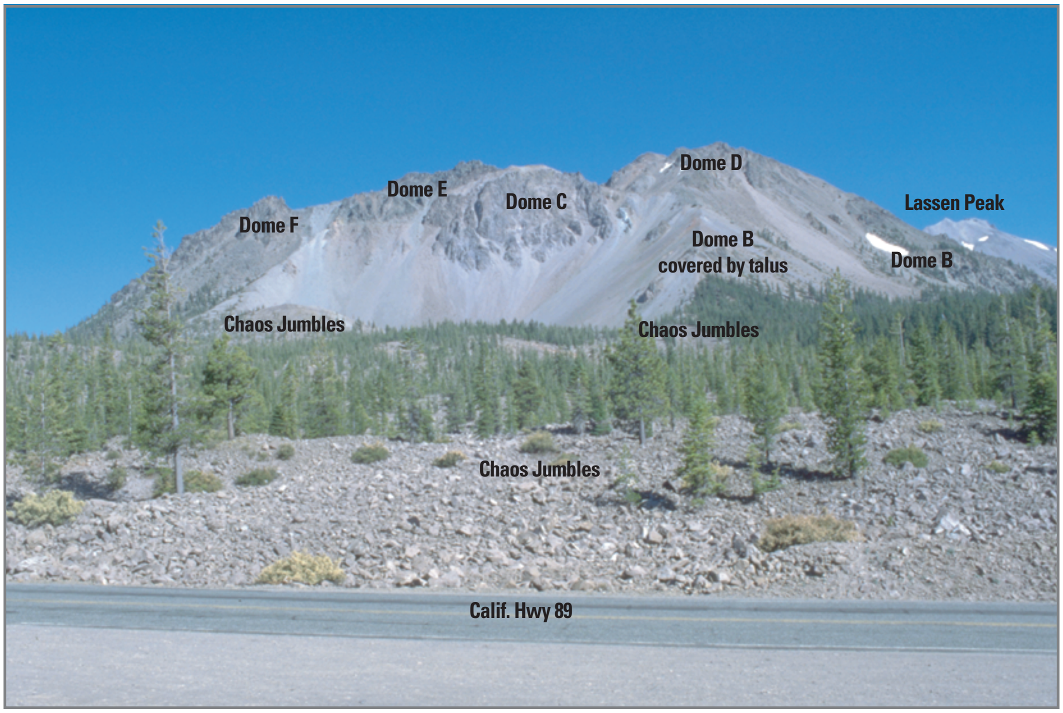


Figure 17. View of Chaos Crags looking southeast from Calif. Hwy 89 where it crosses Chaos Jumbles. Hummocky surface of the rock-avalanche deposits of Chaos Jumbles (formed about 340 years ago) dominates the foreground and middle ground. The oval-shaped massive rock cliff (dome C) in the center of the view is the source of the Chaos Jumbles rock avalanches. The highest peak is dome D, and the high ground above and to the left of dome C is dome E. Small peak on the far left is dome F. The sparsely tree-covered area (below the large snow patch) on the far right is the margin of dome B. Lassen Peak (formed 27,000 years ago) is visible on the far right skyline.

breakaway scar on dome C of Chaos Crags. The second and third avalanches were successively smaller and shorter, but thicker. The initial direction of each avalanche was west-northwest toward Table Mountain (fig. 4*C*), and the first avalanche deposit rode up nearly 125 m onto Table Mountain before being deflected to the west.

Steep-sided volcanic domes such as Chaos Crags are clearly unstable and prone to collapse, but the trigger for the Chaos Jumbles avalanches is unknown. A number of mechanisms have been proposed, including an explosion at the base of dome C (Williams, 1932) and renewed volcanic activity on dome D, which was reported to be steaming in 1857 by the Brewer Survey (Brewer, 1930). However, there is no evidence to support either of these ideas, and the most likely explanation is triggering by a large earthquake. Approximately 90 percent of dome C collapsed in the 3 rockfall avalanches, leaving only about 10 percent of the dome still intact. Thus, Eppler and others (1987) suggested that an avalanche resulting from a further collapse of dome C would barely reach the Park road and thus would pose little danger to Park visitors. However, collapse of other domes at Chaos Crags is still a potential hazard. Large-volume avalanches from older domes in LVNP are less likely because those domes are less steep, glaciated, and eroded.

Brokeoff Volcano

Brokeoff Volcano is composed of two sequences of deposits (Clynne and Muffler, 2010). The younger sequence consists primarily of six thick, large-volume, lithologically similar, lava flows that erupted from flank vents. These flows generally lack interbedded pyroclastic deposits, are resistant to erosion, and are not prone to major landslides. The underlying older sequence, on the other hand, consists of dozens of small-volume lava flows and interbedded fragmental deposits erupted from a central vent. These thin lava flows and breccias in the central core of Brokeoff Volcano are very prone to landslides, primarily in areas where the rocks are hydrothermally altered (fig. 18).

The older deposits of Brokeoff Volcano have been subjected to intense and protracted alteration related to hydrothermal systems (Crowley and others, 2004; John and others, 2006, 2009). Centers of acidic hydrothermal alteration occur in the area between Diamond Peak, Brokeoff Mountain, Mount Diller, and Pilot Pinnacle, and a large area of alteration occurs in the area in and above the east side of Little Hot Springs Valley (fig. 19). The weak, altered rocks are prone to erosion by fluvial and landslide processes (Clynne and Muffler, 2010). Much of the core area of Brokeoff Volcano is covered today by landslide deposits (fig. 19).

Hydrothermal alteration in the core of Brokeoff Volcano is ongoing in the headwaters of Mill Creek, particularly in Little Hot Springs Valley and in the Sulphur Works and Pilot Pinnacle areas (figs. 8, 19). This ongoing hydrothermal activity promotes and exacerbates landslide activity in a positive feedback loop. Steam and acid gases rising from the underlying vapor-dominated reservoir (Muffler and others, 1982; Janik and McLaren, 2010) alter the bedrock and existing landslide material to an unstable mixture of opal and clay.

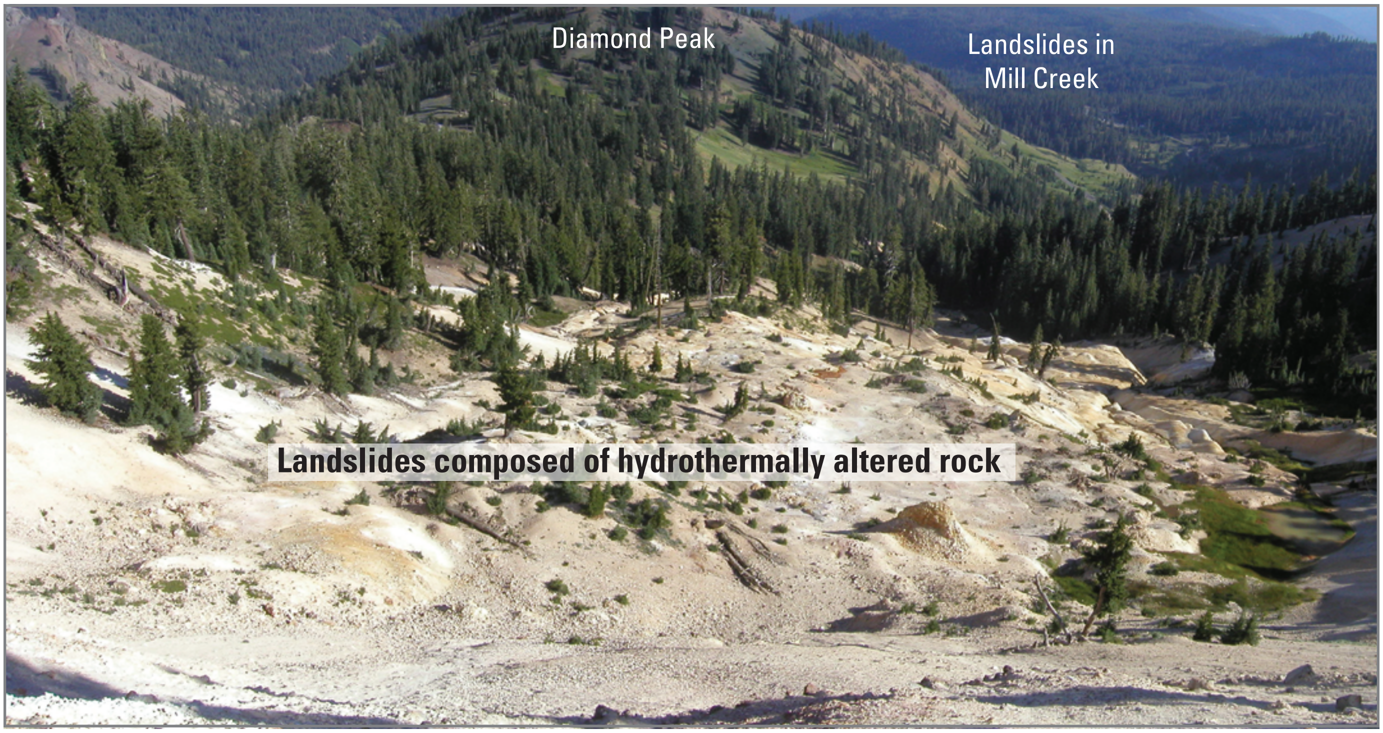


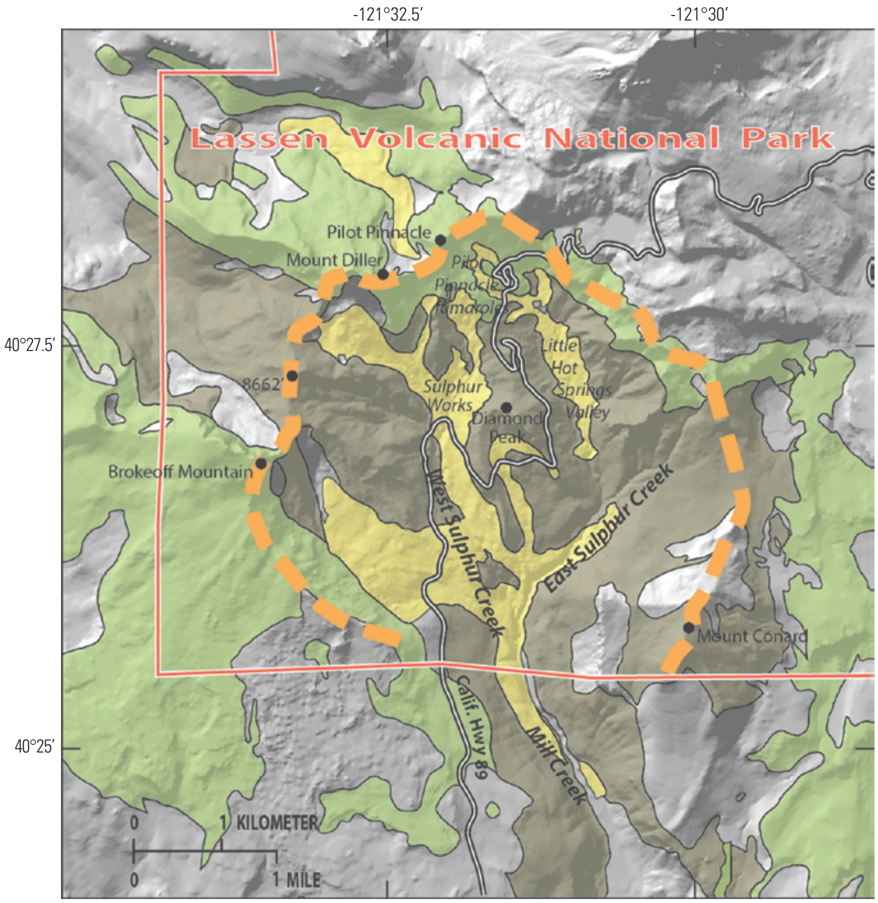
Figure 18. View looking south of active landslides in the area south of Pilot Pinnacle (off the photograph to the left) and west of Diamond Peak. Most of the central area of Brokeoff Volcano is covered by these young landslides. Landslides form in clay-rich hydrothermally altered lava flows and fragmental deposits and are most active during the annual spring snowmelt.

Landslides remove overburden from the hydrothermal conduits, thus making it easier for steam and gas to reach the surface and further alter the rock and landslide material. This feedback loop proceeds continuously, accelerating near-surface hydrothermal alteration and greatly enhancing removal of hydrothermally altered flows and breccias that form the core of Brokeoff Volcano. Weak, hydrothermally altered rocks and clay-rich deposits become saturated with water and move downslope under their own weight, particularly in the spring during periods of rapid snowmelt. Reactivation of older landslide deposits by this mechanism is common. The result is a complex of small, young landslides throughout the areas of active hydrothermal alteration.

Significant landslides can also occur in the areas of older hydrothermal alteration away from modern hydrothermal vents. Retreat of glaciers left areas of steep and slide-prone terrain in cirque headwalls and valley walls. Indeed, the south entrance station and the nearby visitor center of LVNP are located on a large landslide that moved 7 km down Mill Creek from the cliff at the base of Brokeoff Mountain 3,310±55 years ago (Clynne and others, 2008). Reactivation of a small part of this landslide in January 1997 temporarily blocked the Park road just south of the entrance station. Such landslides can be significant events, especially in steep canyons, such as the canyon of Mill Creek. Lake deposits preserved on the canyon walls at the confluence of East and West Sulphur Creeks demonstrate that at one time a landslide temporarily blocked the drainage of East Sulphur Creek. Eventual failure of this blockage undoubtedly created a flood downstream in Mill Creek.

Hydrothermal Hazards

In addition to the landslide hazards discussed in the preceding section, the hydrothermal system at Lassen presents a variety of hazards to the infrastructure of LVNP, NPS personnel, and Park visitors. These are discussed in this section. An overview of the Lassen geothermal system was presented in a previous section.



EXPLANATION

▬ ▬ Rim of erosional amphitheater in Brokeoff Volcano

🟨 Landslide deposits within and around Brokeoff Volcano. Within the erosional amphitheater, many of these deposits have a matrix of soft, clay-rich, hydrothermally altered, volcanic rock.

🟩 Upper and outer part of Brokeoff Volcano, composed of seven large-volume and thick lava flows not hydrothermally altered and thus resistant to erosion.

▨ Core of Brokeoff Volcano, composed of small-volume, thin lava flows interbedded with fragmental deposits, many of which are hydrothermally altered clay-rich material easily eroded by glaciers and streams and prone to landsliding.

Figure 19. Map showing the distribution of landslides in the eroded core of Brokeoff Volcano, adapted from sheet 1 of Clynne and Muffler (2010). The hollowed-out core of Brokeoff Volcano is the product of enhanced glacial and fluvial erosion of weak, hydrothermally altered rock, and much of the core area is now covered by material emplaced by landslides. The largest remnants of the Brokeoff Volcano—Mount Diller and Brokeoff Mountain—were protected from erosion by thick, unaltered lava flows on their outer flanks. (digital elevation model from Gesch, 2007)

Hazards to People

The high-temperature fumaroles and mud pots in LVNP present potential burn hazards to persons straying from trails and boardwalks in hydrothermal areas. Thin crusts in the hydrothermal areas are susceptible to collapse under the weight of persons walking on them. First-, second-, third-degree and sometimes fatal burns from boiling mud or water and steam have affected persons in similar thermal areas throughout the United States (particularly in Yellowstone National Park) and the world (probably best documented in New Zealand).

The gases hydrogen sulfide (H_2S) and carbon dioxide (CO_2) accompany steam in thermal areas throughout the world; their hazards are discussed extensively in Christiansen and others (2007, p. 34–36), from which much of the following is adapted.

Although CO_2 is ubiquitous in the atmosphere at a concentration of 0.038 percent, both CO_2 and H_2S can be lethal in higher concentrations; 0.5 percent is the threshold limit value for continuous 8-hour exposure to CO_2. Signs of intoxication, however, appear in a 30-minute exposure at 5 percent (Aero Medical Association, 1953), and a few minutes of exposure at 7–10 percent produces unconsciousness (Flury and Zernik, 1931; Hunter, 1975). H_2S at 0.005–0.01 percent causes mild conjunctivitis and respiratory irritation after 1 hour, and 0.07–0.1 percent results in rapid unconsciousness, cessation of respiration, and death (Yant, 1930).

Typically, the gas released from fumaroles contains 95–99 percent CO_2 and 1–5 percent H_2S. Normally, these gases dissipate safely in the surrounding air; concentrations at waist level are rarely above 0.1 percent and 0.0002 percent respectively, even adjacent to fumaroles (Christiansen and others, 2007, p. 34, based on unpublished data of Jacob Lowenstern and Henry Heasler). Both gases, however, are heavier than air and, under calm conditions, can collect in low-lying areas sheltered from the wind. In particular, these gases can collect in pits or caves that can form in deep snow around areas of gas venting. The hazard from CO_2 is exacerbated because CO_2 is odorless and colorless and thus cannot be perceived readily. H_2S has a conspicuous "rotten egg" smell at low concentrations, but at concentrations above 0.015 percent (150 parts per million) the olfactory nerve is overwhelmed and the sense of smell disappears, often together with awareness of danger (Mandavia, 2009).

Toxic gases from fumaroles thus pose a potential hazard to Park visitors and staff, and thermal areas are especially hazardous when buried by snow after a significant storm. Normally, the gases dissipate quickly into the atmosphere, and only rarely are visitors present where gas concentrations can cause harm. Nevertheless, fatal incidents such as those at Mammoth Mountain in eastern California (Hill, 2000; Becerra, 2006) and at Lassen in 1995 (Arthur and Packer, 1995) are possible. Also, unless safety measures are utilized, incidents similar to the one that caused a worker's death at Tower Junction in Yellowstone National Park (Whittlesey, 1995, p. 67) could occur.

Hazards to Structures

The high-temperature, acidic, hydrothermal features of LVNP not only alter the volcanic rocks, but also affect man-made features, primarily roads and boardwalks. Boardwalks in Bumpass Hell, Devils Kitchen, and Sulphur Works have been re-located many times over the years as the acid vapors affected both wood and metal. In some cases, wood posts in the ground have served as conduits or "wicks" for steam and acid. Even boardwalks constructed on seemingly cool ground can be affected, because the steam vents and mud pots change in temperature and character and can migrate laterally with time. Roads can be affected and undermined by thermal activity, most prominently at Sulphur Works.

The temporal and spatial variation of fumaroles has been observed in all thermal areas of LVNP, but it has been most systematically documented in recent years at Sulphur Works, Little Hot Springs Valley, and Pilot Pinnacle. The boardwalks north of the LVNP road at Sulphur Works were so severely compromised by thermal activity that in 2007 they were removed in the interests of safety to both visitors and NPS personnel. In recent years, fumarolic activity just north of Calif. Hwy 89 at Sulphur Works has migrated south towards the road and has become concentrated in a large, boiling mud pot adjacent to the sidewalk curb (fig. 20). In addition, borings by the Federal Highway Administration in April 2009 and in November 2011 demonstrated that boiling temperatures have risen to a depth of 5–7 m under the north lane of the Park road and compromised the integrity of the roadbed.

Hydrothermal Explosions

Hydrothermal explosions present a significant hazard in many hot-spring areas (Browne and Lawless, 2001). Such hazards are more likely in thermal areas with active discharge of neutral, high-chloride waters, especially those hosting geysers, as in Yellowstone National Park, than in vapor-dominated areas with acid-sulfate alteration (Christiansen and others, 2007). In LVNP the near-surface hydrothermal systems are all of the vapor-dominated type. Although small explosions as vents or mud pots change in character or migrate have occurred and are likely in the future, there is no evidence of large craters in the Lassen thermal areas. Consequently, the likelihood of large hydrothermal explosions such as have occurred in Yellowstone is very low. However, intrusion of new magma into the volcanic system could alter the groundwater/hydrothermal regime and make hydrothermal explosions more likely.

Volcanic Event Frequency, Probability and Magnitude

Long-term probabilities of volcanic eruptions at the Lassen Volcanic Center and in the wider Lassen region have been estimated based on mathematical modeling of the eruption chronology and are presented in Nathenson and others (2012), along with the methodology and relative uncertainties for deriving those probabilities. The data contained in that analysis are also used to estimate the cumulative probability of the volume of eruptions and the size of area covered by lava flows (fig. 21).

For the LVC, the annual probability of a volcanic eruption is 0.00014 (0.014 percent), which translates to an average recurrence interval of 7,150 years. The largest eruption in the LVC covered an area of 39.6 km^2 and had a volume of 4.72 km^3. If an eruption occurs, the probability of it being larger than 2 km^3 is about 0.1 (10 percent), whereas the probability of an eruptive volume greater than about 0.35 km^3 is about 0.5 (50 percent). Similarly, the probability that the area covered by a lava flow will be greater than about 17 km^2 is about 0.1 (10 percent), and the probability that the area covered will be greater than about 7 km^2 is 0.5 (50 percent).

For regional mafic volcanism in the Lassen region, the annual probability of a volcanic eruption is 0.00065 (0.065 percent), which translates to an average recurrence interval of 1,550 years. The largest regional mafic eruption covered an area of 99 km^2 and had a volume of 2.6 km^3. If an eruption occurs, the probability of it being larger than about 1.3 km^3 is about 0.1 (10 percent), whereas the probability of an eruptive volume greater than about 0.1 km^3 is about 0.5 (50 percent). The probability that the area covered by a lava flow will be greater than about 30 km^2 is about 0.1 (10 percent), and the probability that the area covered will be greater than about 4 km^2 is 0.5 (50 percent). Thus, the potential volumes of eruptions and areas covered by lava flows could be significant, but most eruptions will be small.

Figure 20. Dynamic nature of hydrothermal features at Sulphur Works shown by changes from 2004 to 2008. Photograph looking northwest across Calif. Hwy 89 was taken August 16, 2004. Dotted lines denote vents that either enlarged (C) or were new (L and M) as of October 12, 2005. Solid line represents the boundary of the large mud pot resulting from the collapse of the area between vent M and vent C, sometime between October 16, 2005 and June 20, 2008, probably in the winter of 2007–2008. Vents A, B, D, and E are essentially unchanged from August 2004 to June 2008.

It should be noted that the rate of volcanism at Lassen is not controlled by some simple predictable process. The values given here are long-term averages based on the known past eruptions in the surrounding region or at the LVC—an eruption cannot be considered "due" every 1,550 or 7,150 years, and the hazard is not higher or lower because of the length of time since the previous eruption. Volcanism at Lassen is episodic in the long term, and events tend to occur in clusters or episodes on a variety of time scales (Clynne and Muffler, 2010). Volcanic eruptions are a complex function of evolution of the magma bodies in the shallow subsurface and recharge from greater depth and are not predictable in advance of premonitory activity. Thus, the average values stated are only a general guide to the expected frequency and magnitude of volcanic eruptions in the Lassen region.

The probabilities of eruptions stated above do not account for periods of unrest at volcanoes that do not culminate in an eruption. This is because the geologic record preserves no evidence of intrusive events that did not result in an eruption. The global experience of volcanologists is that unrest experienced at volcanic systems often does not lead to an eruption on the human time scale, but nevertheless can cause great anxiety and disruption locally. Any unrest at a volcano requires a significant effort by scientists to perform short- to long-term monitoring, data collection, and interpretation so that local managers can respond appropriately.

Volcano Monitoring and Response

Volcanic eruptions are typically preceded over periods of days to years by precursory phenomena related to the rise of magma toward the surface. Monitoring of changes in seismic activity, ground deformation, gas emissions, and changes in hydrothermal systems provide the opportunity to make forecasts of probable eruptions. However, it is not uncommon for volcanoes to have multiple discrete phases of unrest related to intrusions of new magma at depth that do not reach the surface as eruptions. Eruption forecasts are typically provided within the context of the known eruptive history at a volcano, although unprecedented events are always possible and need to be considered by scientists within the context of the changes occurring at the volcano. Detailed discussion of volcano monitoring and risk assessment and hazard mitigation can be found in Scarpa and Tilling (1996).

A network of eight seismic stations, including one short-period 3-component instrument and one broad-band instrument, are installed in the Lassen region. Data from these instruments are transmitted to USGS offices in Menlo Park, California. A report on seismic monitoring at Cascade volcanoes (Moran, 2004) assesses Lassen as one of the better-monitored volcanoes in the Cascades but recommends some improvements to increase capability and reliability. Given the large area in which potential volcanic activity might occur in the Lassen region, it is important to locate seismic events with high precision in order to forecast potential vent sites.

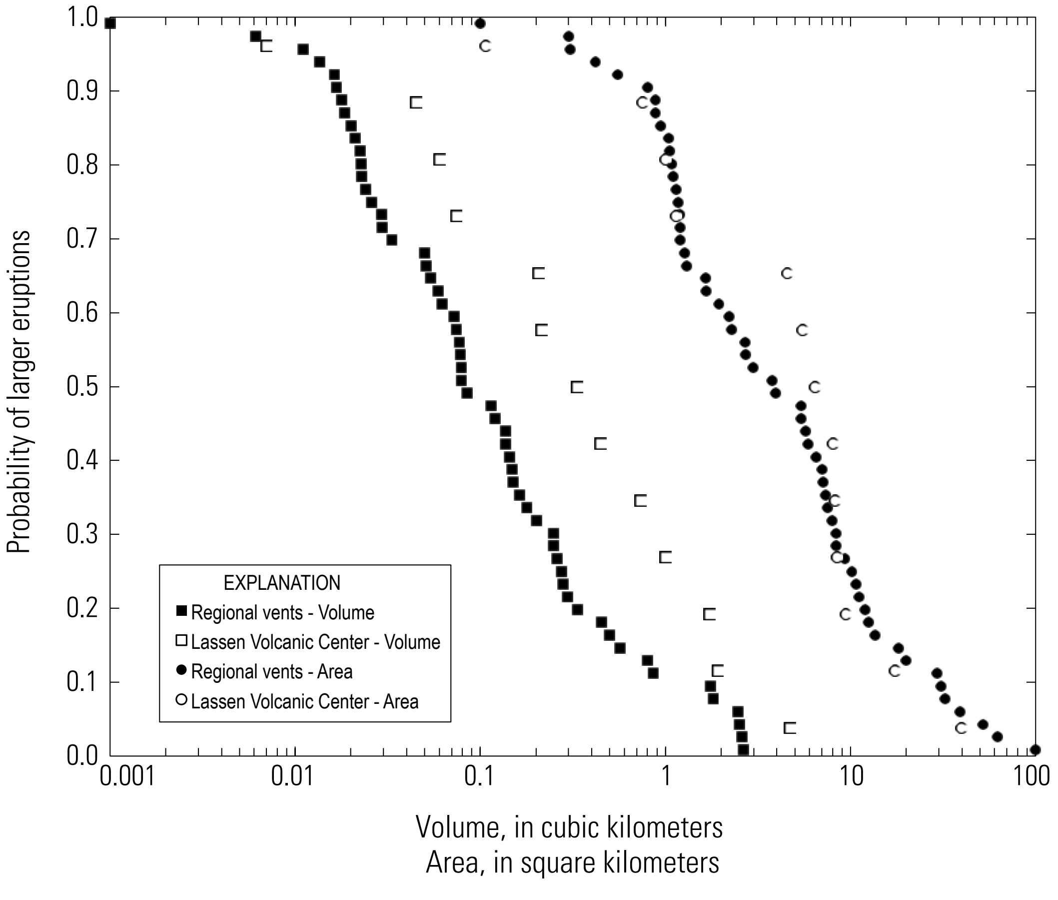


Figure 21. Graph showing estimated cumulative probabilities of the volume and area of eruptions for the Lassen Volcanic Center and for regional mafic vents for the past 100,000 years. For data and methodology, see Nathenson and others (2012).

Table 3. Volcano Alert Levels and Aviation Color Code used by USGS volcano observatories

Volcano Alert Levels Used by USGS Volcano Observatories

Alert Levels are intended to inform people on the ground about a volcano's status and are issued in conjunction with the Aviation Color Code. Notifications are issued for both increasing and decreasing volcanic activity and are accompanied by text with details (as known) about the nature of the unrest or eruption and about potential or current hazards and likely outcomes.

Term	Description
NORMAL	Volcano is in typical background, noneruptive state or, *after a change from a higher level,* volcanic activity has ceased and volcano has returned to noneruptive background state.
ADVISORY	Volcano is exhibiting signs of elevated unrest above known background level or, *after a change from a higher level,* volcanic activity has decreased significantly but continues to be closely monitored for possible renewed increase.
WATCH	Volcano is exhibiting heightened or escalating unrest with increased potential of eruption, timeframe uncertain, **OR** eruption is underway but poses limited hazards.
WARNING	Hazardous eruption is imminent, underway, or suspected.

Aviation Color Code Used by USGS Volcano Observatories

Color codes, which are in accordance with recommended International Civil Aviation Organization (ICAO) procedures, are intended to inform the aviation sector about a volcano's status and are issued in conjunction with an Alert Level. Notifications are issued for both increasing and decreasing volcanic activity and are accompanied by text with details (as known) about the nature of the unrest or eruption, especially in regard to ash-plume information and likely outcomes.

Color	Description
GREEN	Volcano is in typical background, noneruptive state or, *after a change from a higher level,* volcanic activity has ceased and volcano has returned to noneruptive background state.
YELLOW	Volcano is exhibiting signs of elevated unrest above known background level or, *after a change from a higher level,* volcanic activity has decreased significantly but continues to be closely monitored for possible renewed increase.
ORANGE	Volcano is exhibiting heightened or escalating unrest with increased potential of eruption, timeframe uncertain, **OR** eruption is underway with no or minor volcanic-ash emissions [ash-plume height specified, if possible].
RED	Eruption is imminent with significant emission of volcanic ash into the atmosphere likely **OR** eruption is underway or suspected with significant emission of volcanic ash into the atmosphere [ash-plume height specified, if possible].

Monitoring of ground deformation at volcanoes has changed dramatically in recent decades. Ground movement has in the past been measured by precise leveling surveys (Dzurisin and others, 1982; Dzurisin, 1999; Poland and others, 2004), but such studies are labor-intensive, performed on an intermittent basis, and can be done only in the summer when the area is free of snow. Recently, eight Plate Boundary Observatory (PBO) permanent GPS sites funded by the National Science Foundation were installed in LVNP or the immediate area (UNAVCO, 2009). At this writing, three more such sites are approved but not yet installed. Two more sites are nearby in northern California. These sites may be sufficient to detect initial stages of ground deformation associated with either volcanic or tectonic processes in the Lassen region on a real-time basis, and additional sites could be installed relatively quickly, snow conditions and weather permitting, should the existing network indicate deformation interpreted to be associated with potential volcanic activity.

According to the report of the proposed National Volcano Early Warning System (NVEWS) (Ewert and others, 2005), in order to be well monitored in real time, the Lassen Volcanic Center would potentially need installation of 4 to 12 additional seismic stations and some additional continuous GPS stations, in addition to airborne gas surveys and applications of remote sensing techniques. The information generated by these techniques would be evaluated by USGS scientists for any changes, such as an increase in seismicity, ground deformation, or changes in gas composition or flux. Monitoring would involve personnel at the USGS California Volcano Observatory (CalVO), based in Menlo Park, California. CalVO publishes a monthly status report for California volcanoes on the Internet (http://volcanoes.usgs.gov/observatories/calvo/). The USGS National Volcano alert-notification system (Gardner and Guffanti, 2006), included here as table 3, is the system used to notify the public of significant changes in the activity status of U.S. volcanoes.

Additional related information can be obtained online at the Web site for the USGS Volcano Hazards Program (http://volcanoes.usgs.gov) and the USGS California Volcano Observatory Web site (http://volcanoes.usgs.gov/observatories/calvo). Information about volcanic ash is available at http://volcanoes.usgs.gov/ash/ and at http://www.ivhhn.org/, where two pamphlets ("The Health Hazards of Volcanic Ash; a Guide for the Public," and "Guidelines for Preparedness Before, During, and After an Airfall") are available. Information about volcano monitoring can be obtained at http://volcanoes.usgs.gov/About/Monitoring/monitor.html. Fact sheets describing volcano hazards (Myers and others, 2008) and the USGS Volcano National Early Warning System (Ewert and others, 2006) are available on line at http://pubs.usgs.gov/fs/fs002-097/ and http://pubs.usgs.gov/2006/fs2006/3142/, respectively.

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Glossary

This glossary provides definitions for a variety of technical terms commonly used in writing on volcanoes and volcanic geology. Some terms are not used directly in this report but are provided as synonyms or additional information that can be cross-referenced with other publications. Terms shown in **bold type** within definitions are themselves separately defined in this glossary.

A

Acid-sulfate alteration Alteration of volcanic rock produced near the ground surface by sulfuric acid, which results from oxidation of hydrogen sulfide (H_2S) that accompanies steam rising to the surface in fumarolic areas. The material produced by acid-sulfate alteration is composed primarily of amorphous **silica** (SiO_2) and kaolinite (a clay mineral).

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

Andesite Volcanic rock, typically gray to black, or shades of red when oxidized, with 57–63 percent **silica**. Andesite **lavas** are moderately viscous and tend to form thick blocky lava flows.

Ash Fine fragments (less than 2 mm across) of volcanic rock formed and ejected in an **explosive eruption.**

Ash-flow tuff Deposit of a hot, chaotic mixture of **pumice**, **ash**, and gas (**pyroclastic flow**) that travels rapidly (as fast as tens of meters per second) away from a volcanic **vent** during an **explosive eruption**. Ash-flow tuffs are often called ignimbrites in the literature.

B

Basalt Volcanic rock with about 47–53 percent **silica**, typically gray to black, or shades of red when oxidized. Basalt **lavas** are fluid and tend to form thin, widespread **lava** flows.

Basaltic andesite Volcanic rock, typically gray to black, or shades of red when oxidized, with 53–57 percent silica. Basaltic andesite lavas are fluid to moderately viscous and tend to form thin to thick **lava** flows.

Base surge A ring-shaped cloud of gas and suspended solid rock fragments that moves radially outward at high velocity from the base of a vertical **eruption column**. Can accompany **phreatomagmatic eruptions**.

Bomb (volcanic) Fragments bigger than 3 inches across ejected explosively from a volcanic **vent** on an arcuate, ballistic trajectory. Typically found in, or peripheral to, cinder **cones** formed over **mafic** vents.

C

Caldera A large, basin-shaped volcanic depression, more or less circular in form; typically more than 2 km across. Commonly formed by collapse during withdrawal or ejection of a large volume of **magma** leaving the roof of a **magma** reservoir unsupported.

Cinder cone A conical hill formed by accumulation of solidified bubble-rich fragments (ash), clots (**scoria**), and blobs (**bombs**) of **lava** that fall around the vent of a single **basaltic** or **andesitic** eruption.

Cirque A steep-walled hollow formed by glacial erosion at the head of a glacial valley.

Composite volcano A large, long-lived volcano that erupts episodically for tens to hundreds of thousands of years from the same or closely-spaced **vents**, and displays a wide range of eruptive styles and explosivity. Generally andesitic to silicic in composition.

Coulee A short, thick **lava** flow with steep, block-covered sides, usually of **silicic** composition.

D

Dacite Generally light-colored volcanic rock with 63–68 percent **silica**. Dacite **lavas** are viscous and tend to form very thick, blocky **lava** flows or steep-sided piles of **lava** called **lava domes**. Dacite **magmas** also tend to erupt explosively, thus ejecting abundant **pumice** and **ash**.

Dike A tabular, commonly vertically oriented, **igneous** intrusion, typically much longer than it is wide.

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. Typically **silicic** (**dacite**, **rhyodacite**, or **rhyolite**) in composition.

E

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

Ejecta Material explosively ejected from a volcano (more or less synonymous with **tephra**).

Eruption column The ascending, vertical part of a mass of erupting debris and volcanic gases that rises directly above a volcanic **vent**. Higher in the atmosphere, columns usually spread laterally into plumes or umbrella-shaped eruption clouds. Synonym for eruption plume.

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

F

Fallout A general term for all the **ash** and debris that falls to Earth (also known as ash fall or tephra fall) from an eruption cloud.

Fumarole A **hydrothermal** feature that emits primarily steam.

H

Harmonic tremor Continuous long-period volcanic ground vibration that indicates movement of magma or gas. It often, but not necessarily, precedes an eruption.

Holocene The youngest geologic time period, considered to include the past 11,700 years.

Hydrothermal Of or relating to hot water.

Hydrothermal explosion Explosion that can occur when hot water within a volcano's **hydrothermal** system flashes to steam, breaking rocks and throwing them into the air

I

Igneous Refers to rocks formed by solidification of **magma**.

L

Lahar A mixture of water and volcanic debris that moves rapidly down stream channels. Consistency can range from that of muddy water to that of wet cement, depending on the ratio of water to debris. Also called a volcanic mudflow or debris flow.

Lateral Blast A **pyroclastic surge** that is laterally or subhorizontally directed away from the volcano. A type of **pyroclastic flow**.

Lava Molten rock (**magma**) that reaches the Earth's surface and maintains its integrity as a fluid or viscous mass, rather than exploding into fragments.

M

Mafic Describes **magma** that contains lower amounts of **silica** (<57 percent) and is generally less viscous and less gas-rich than **silicic** magma. Tends to erupt **effusively**, as **lava** flows. Includes **basalt** and **basaltic andesite**. **Andesite**, an intermediate composition magma, can create hazards associated with both mafic and silicic compositions.

Magma Molten rock beneath the Earth's surface.

Magmatic system The generation, accumulation, evolution and storage of magma in the Earth's crust beneath a volcano is its magmatic system.

Mud pot A **hydrothermal** feature that consists of a bubbling pool of hot, often boiling, mud.

P

Paleomagnetic studies Investigations of the orientation and (or) intensity of the Earth's magnetic field in the past, as recorded in geologic materials. The magnetic poles wander about the Earth's axis of rotation, and the paleomagnetic pole position at the time of cooling of a volcanic rock is "frozen in" by magnetic minerals. An empirical calibration of this secular variation over time allows eruption ages to be constrained and isolated outcrops to be correlated with one another.

Petrology The study of rocks, including their occurrence, composition, origin, and evolution.

Phreatic eruption An eruption that primarily involves steam explosions, usually ground-water flashed to steam by the heat of subsurface **magma**.

Phreatomagmatic eruption An eruption that involves both **magma** and water, which typically interact explosively, leading to concurrent ejection of steam and **pyroclastic** fragments.

Pleistocene The geologic time period preceding the **Holocene**. Extends from 2.6 million years ago to 11,700 years ago. Older works used 1.81 million years as the beginning of the Pleistocene.

Postglacial Refers to the time since the end of the last major ice age (about 15,000 years ago in the Lassen region).

Pumice Highly vesicular (rich in gas bubbles) volcanic **ejecta**, typically **silicic** in composition. Pumice is essentially **magma** that has been frothed up by escaping gases and then cooled and solidified during eruption. If sufficiently bubble-rich, pumice will float on water. Near a **vent**, pumice can accumulate to form a pumice cone.

Pyroclastic General term applied to volcanic products or processes that involve explosive ejection and fragmentation of erupting material. Literally means “fire-broken.”

Pyroclastic flow A hot, chaotic, turbulently flowing mixture of rock fragments, **ash**, and gas resulting from **explosive** eruptions of composite volcanoes. There are two types of pyroclastic flows, which can be described as pumiceous and lithic (sometimes called block and ash flows). Pumiceous pyroclastic flows are pyroclastic flows generated by gravitational collapse of vertically directly **eruption columns** of hot gas, **pumice** fragments, and **ash**. They are hot (hundreds of degrees Celsius), move rapidly (as fast as tens of meters per second), and are highly mobile (depending on topography, they can travel tens of kilometers from the **vent**). When laterally or subhorizontally directed, are also called **lateral blasts**. Lithic pyroclastic flows are pyroclastic flows generated by gravitational collapse of growing lava **domes**. They consist of dense rock fragments, **ash**, and hot gas. They are also hot (as much as hundreds of degrees Celsius) and move rapidly (as fast as tens of meters per second), but they are not as mobile as pumiceous pyroclastic flows.

Pyroclastic surge A fluidized mass of turbulent gas and rock fragments that is ejected during some volcanic eruptions. It is a type of **pyroclastic flow** that has a lower density or contains a much higher proportion of gas to rock, which makes it more turbulent and allows it to rise over ridges and hills rather than always travel downhill as most **pyroclastic flows** do. When laterally or subhorizontally directed is also called a **lateral blast**.

R

Rhyodacite Volcanic rock with 68–72 percent **silica**. Rhyodacite lavas are very viscous and tend to form very thick blocky lava flows or steep-sided piles of **lava** called **lava domes**. Rhyodacite magmas also tend to erupt explosively, ejecting abundant **pumice** and **ash**.

Rhyolite Volcanic rock with 72–76 percent **silica**. Rhyolite lavas are very viscous and tend to form very thick blocky lava flows or steep-sided piles of **lava** called **lava domes**. Rhyolite magmas also tend to erupt explosively, ejecting abundant **pumice** and **ash**.

S

Scoria Vesicular volcanic **ejecta**, essentially **magma** that has been frothed by escaping gases. Scoria is typically more coarsely vesicular and more dense than pumice and usually forms from magma of **andesite** to **basalt** compositions.

Silica Silicon dioxide (SiO_2), the most abundant component of volcanic rocks and **magmas**. In **magma**, silica polymerizes to form loose frameworks of molecules that are the dominant control on the viscosity. **Basaltic** magma has low SiO_2 and is fairly fluid. With increasing SiO_2 content, **basaltic**

andesite, **andesite**, **dacite**, **rhyodacite**, and **rhyolite** magmas become progressively more viscous, thus retarding movement of the magma. Because it is more difficult for dissolved gas to escape from more viscous magma, higher silica magmas tend to erupt more explosively.

Siliceous sinter Amorphous SiO_2 deposited on the ground surface by precipitation from hot water flowing from a near-neutral, chloride-bearing hot spring.

Silicic Describes an **igneous** rock or **magma** that contains more than ~63 percent silica and is generally viscous, gas-rich and tends to erupt explosively. Includes **dacite**, **rhyodacite**, and **rhyolite**. **Andesite**, an intermediate composition magma, can create hazards associated with both mafic and silicic compositions.

Spatter cone A steep-sided cone constructed of **agglutinate** at a **mafic vent**. Most spatter cones are small (typically a few tens of meters or less in height) and commonly form in linear groups along a fissure.

T

Tectonic Relating to deformation of the Earth's crust by regional forces such as those generated by plate tectonics.

Tephra Any type and size of rock fragment that is forcibly ejected from a volcano and travels an airborne path during an eruption, including **ash**, **bombs**, **scoria**, and **pumice** (more or less synonymous with tephra).

V

Vent Any opening at the Earth's surface through which **magma** erupts or volcanic gases are emitted. Also used for hydrothermal features (that is, hot-spring vents) that emit dominantly hot water or steam.

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