Overview for Geologic Field-Trip Guides to Volcanoes of the Cascades Arc in Northern California

Scientific Investigations Report 2017–5022–K

U.S. Department of the Interior
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Cover: (Top) View of Medicine Lake volcano from the northeast. Photograph by Julie M. Donnelly-Nolan. (Middle) Photograph looking southwest from Emigrant Pass towards Lassen Peak (27±1 ka) in the center and Crescent Crater (236±1 ka) on the right. Photograph taken in October 1986 by M.A. Clynne. (Bottom) Aerial view from the north across the Shasta Valley sector-collapse debris-avalanche deposit, with Mount Shasta and Black Butte rising in the background. Photograph by J. Scurlock.

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By L.J. Patrick Muffler, Julie M. Donnelly-Nolan, Timothy L. Grove, Michael A. Clynne, Robert L. Christiansen, Andrew T. Calvert, and Juliet Ryan-Davis

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Preface

The North American Cordillera is home to a greater diversity of volcanic provinces than any comparably sized region in the world. The interplay between changing plate-margin interactions, tectonic complexity, intra-crustal magma differentiation, and mantle melting have resulted in a wealth of volcanic landscapes. Field trips in this series visit many of these landscapes, including (1) active subduction-related arc volcanoes in the Cascade Range; (2) flood basalts of the Columbia Plateau; (3) bimodal volcanism of the Snake River Plain-Yellowstone volcanic system; (4) some of the world's largest known ignimbrites from southern Utah, central Colorado, and northern Nevada; (5) extension-related volcanism in the Rio Grande Rift and Basin and Range Province; and (6) the spectacular eastern Sierra Nevada featuring Long Valley Caldera and the iconic Bishop Tuff. Some of the field trips focus on volcanic eruptive and emplacement processes, calling attention to the fact that the western United States provides opportunities to examine a wide range of volcanological phenomena at many scales.

The 2017 Scientific Assembly of the International Association of Volcanology and Chemistry of the Earth's Interior (IAVCEI) in Portland, Oregon, marks the first time that the U.S. volcanological community has hosted this quadrennial meeting since 1989, when it was held in Santa Fe, New Mexico. The 1989 field-trip guides are still widely used by students and professionals alike. This new set of field guides is similarly a legacy collection that summarizes decades of advances in our understanding of magmatic and tectonic processes of volcanic western North America.

The field of volcanology has flourished since the 1989 IAVCEI meeting, and it has profited from detailed field investigations coupled with emerging new analytical methods. Mapping has been enhanced by plentiful major- and trace-element whole-rock and mineral data, technical advances in radiometric dating and collection of isotopic data, GPS (Global Positioning System) advances, and the availability of lidar (light detection and ranging) imagery. Spectacularly effective microbeam instruments, geodetic and geophysical data collection and processing, paleomagnetic determinations, and modeling capabilities have combined with mapping to provide new information and insights over the past 30 years. The collective works of the international community have made it possible to prepare wholly new guides to areas across the western United States. These comprehensive field guides are available, in large part, because of enormous contributions from many experienced geologists who have devoted entire careers to their field areas. Early career scientists are carrying forward and refining their foundational work with impressive results.

Our hope is that future generations of scientists as well as the general public will use these field guides as introductions to these fascinating areas and will be enticed toward further exploration and field-based research.

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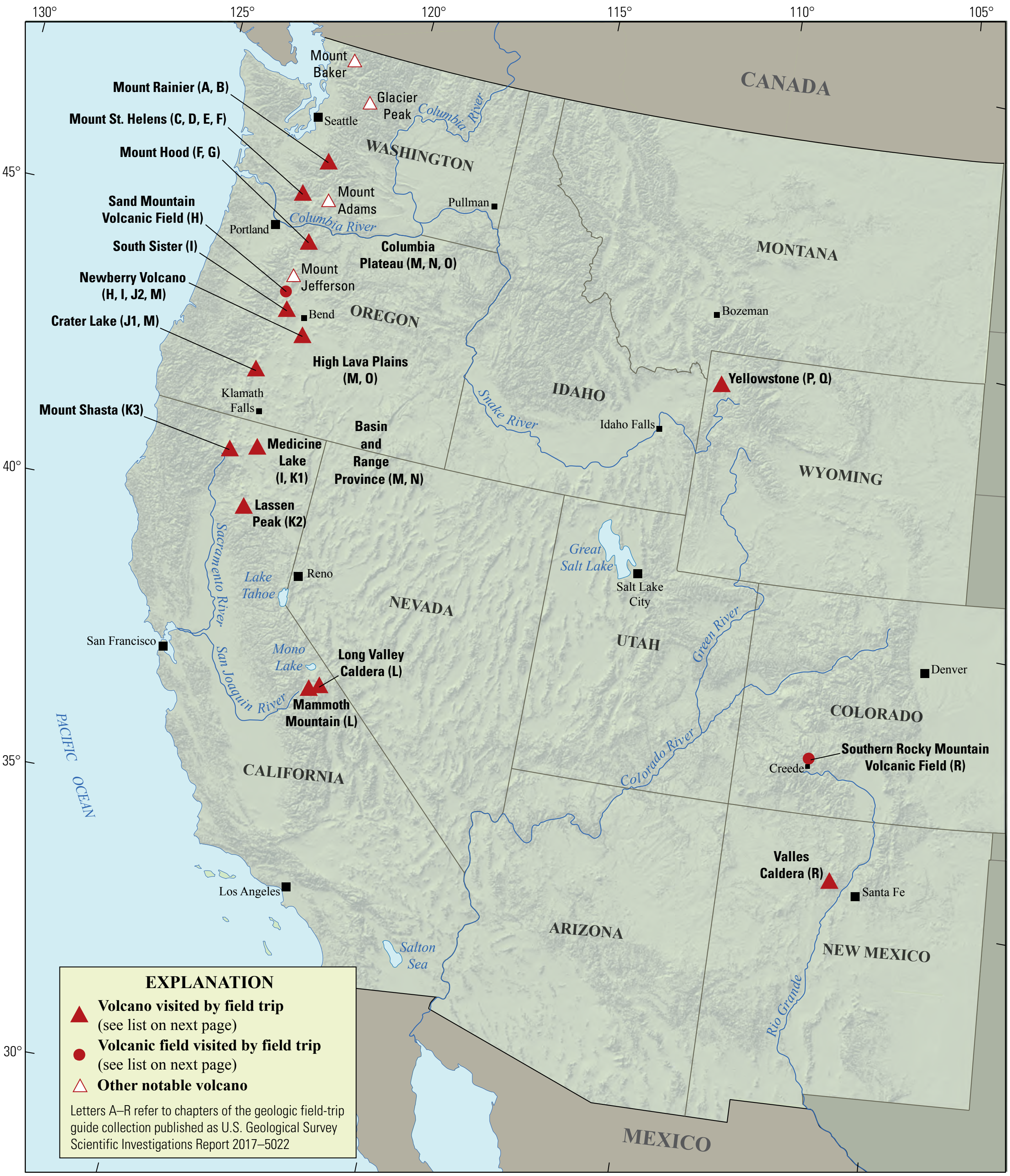
Field-trip committee, IAVCEI 2017



Map of the western United States showing volcanoes and volcanic fields visited by geologic field trips scheduled in conjunction with the 2017 meeting of the International Association of Volcanology and Chemistry of the Earth's Interior (IAVCEI) in Portland, Oregon, and available as chapters in U.S. Geological Survey Scientific Investigations Report 2017–5022. Shaded-relief base from U.S. Geological Survey National Elevation Dataset 30-meter digital elevation model data.

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Contents

Figures

Overview for Geologic Field-Trip Guides to Volcanoes of the Cascades Arc in Northern California

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The 2017 IAVCEI Field Trip

This guidebook to volcanoes of the Cascades Volcanic Arc in Northern California (hereafter abbreviated as the California Cascades) was prepared for one of the field trips accompanying the quadrennial Scientific Assembly of the International Association of Volcanology and Chemistry of the Earth's Interior (IAVCEI) held in Portland, Oregon, in August 2017. The California Cascades field trip is a loop beginning and ending in Portland (fig. 1). The route of day 1 goes eastward across the Cascades just south of Mount Hood, travels south along the east side of the Cascades for an overview of the central Oregon volcanoes (including Three Sisters and Newberry Volcano), and ends at Klamath Falls, Oregon. Day 2 and much of day 3 focus on Medicine Lake Volcano. The latter part of day 3 consists of a drive south across the Pit River into the Hat Creek Valley and then clockwise around Lassen Volcanic Center to the town of Chester, California. Day 4 goes from south to north across Lassen Volcanic Center, ending at Burney, California. Day 5 and the first part of day 6 follow a clockwise route around Mount Shasta. The trip returns to Portland on the latter part of day 6, west of the Cascades through the Klamath Mountains and the Willamette Valley.

Each of the following three sections of this guidebook addresses one of the major volcanic regions: Lassen Volcanic Center (a volcanic field that spans the volcanic arc), Mount Shasta (a fore-arc stratocone), and Medicine Lake Volcano (a rear-arc, shield-shaped edifice). Each section of the guide provides (1) an overview of the extensive field and laboratory studies, (2) an introduction to the literature, and (3) directions to the most important and accessible field localities. The field-trip sections contain far more stops than can possibly be visited in the actual 6-day 2017 IAVCEI excursion from Portland. We have included extra stops in order to provide a field-trip guide that will have lasting utility for those who may have more time or may want to emphasize one particular volcanic area. Specific stops on the 2017 IAVCEI excursion will reflect the necessary logistic and time constraints.

Geological Overview

The Cascades Volcanic Arc in California consists of three major Quaternary volcanic centers: Medicine Lake Volcano, Lassen Volcanic Center, and Mount Shasta, as well as surrounding volcanic terrain. In the nearly three decades since the previous IAVCEI field trip to the region (Muffler and others, 1989), each of the Quaternary volcanic centers has been the subject of intensive interdisciplinary field studies, including geology, geochemistry, petrology, geochronology, paleomagnetism, and geophysics. Detailed eruptive histories have been established and characterized by detailed geologic mapping (Clynne and Muffler, 2010; Donnelly-Nolan, 2010; Calvert and Christiansen, 2011) and comprehensive chemical analyses (fig. 2). Experimental- and field-petrology studies have established the nature of mantle source regions for both the arc and the back-arc lavas and have elucidated the crystallization processes (under both wet and dry conditions) that have given rise to the compositional diversity observed in the lavas (for example, Bartels and others, 1991; Bullen and Clynne, 1990; Clynne, 1990; Grove and others, 1982; Grove and others, 1997; Grove and others, 2005). Wet (calc-alkaline) basalts are produced by interaction of fluids from the subducting slab with the mantle (Baker and others, 1994), whereas dry (tholeiitic) magmas are produced by near-anhydrous melting (Till and others, 2013) in the uppermost mantle wedge above the subducting slab. It is notable that both tholeiitic and calc-alkaline rocks erupt in close temporal and spatial proximity throughout the California Cascades.

Mount Shasta is a stratovolcano dominated by andesite and dacite produced by interaction of mantle-derived mafic magmas and a shallow crustal magma system. At an elevation of 14,179 ft (4,322 m), Mount Shasta rises over 10,000 ft (3,000 m) above the underlying terrain and dominates the skyline throughout much of northernmost California. Its eruptive volume over the past 600–700 k.y. is >400 km^3, making it the largest stratovolcano in the Cascades; its eruption rate is 0.6 km^3 per thousand years.

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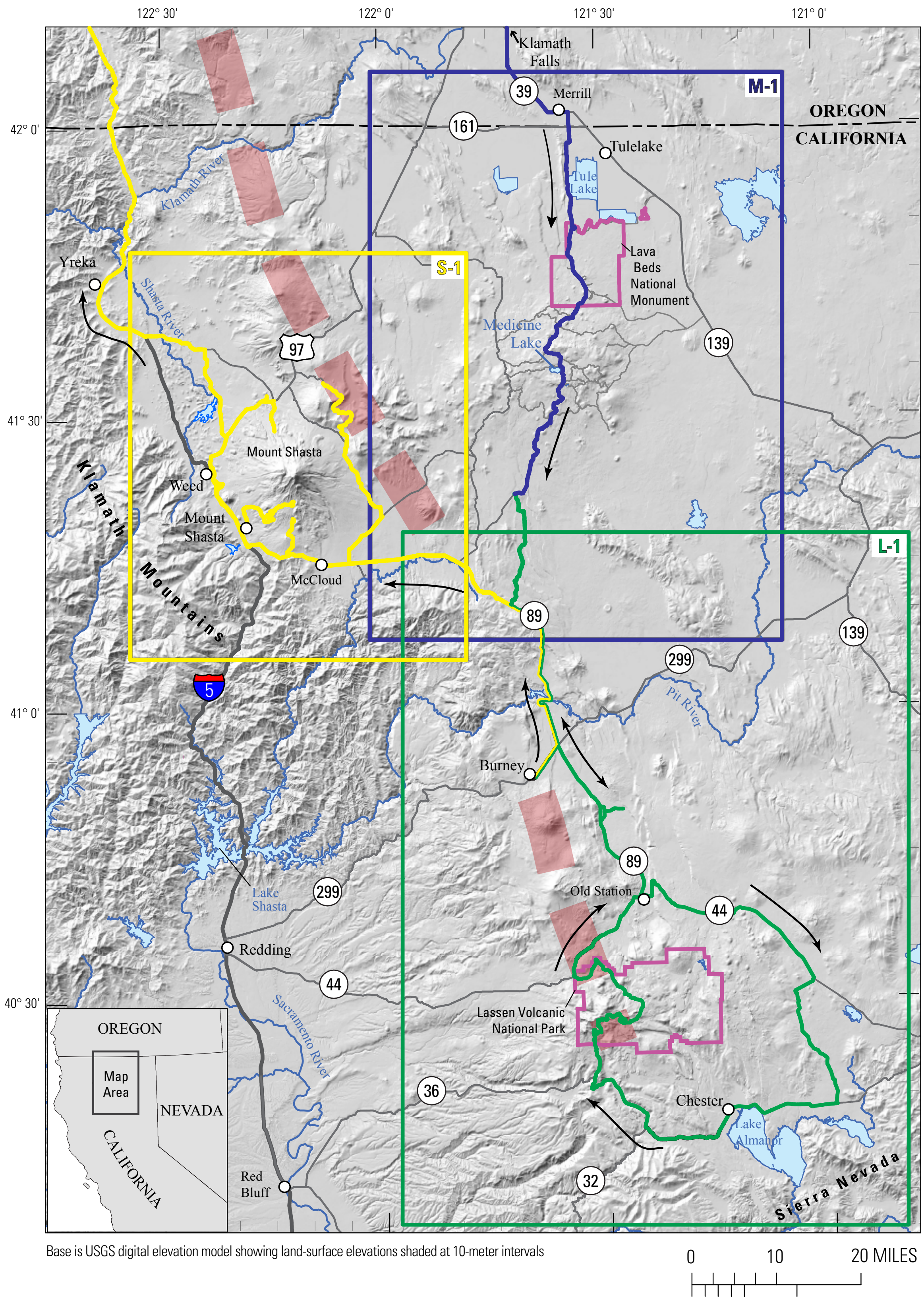

Figure 1. Index map for the field trip to the California Cascades. Generalized field-trip route shown as heavy colored lines. Axis of the Cascades Volcanic Arc shown by thick dashed red line. The colored rectangles designated M-1, S-1, and L-1 refer to the first figures in each of the Medicine Lake Volcano, Lassen Volcanic Center, and Mount Shasta chapters. These figures are more detailed maps of the field-trip route for those chapters.

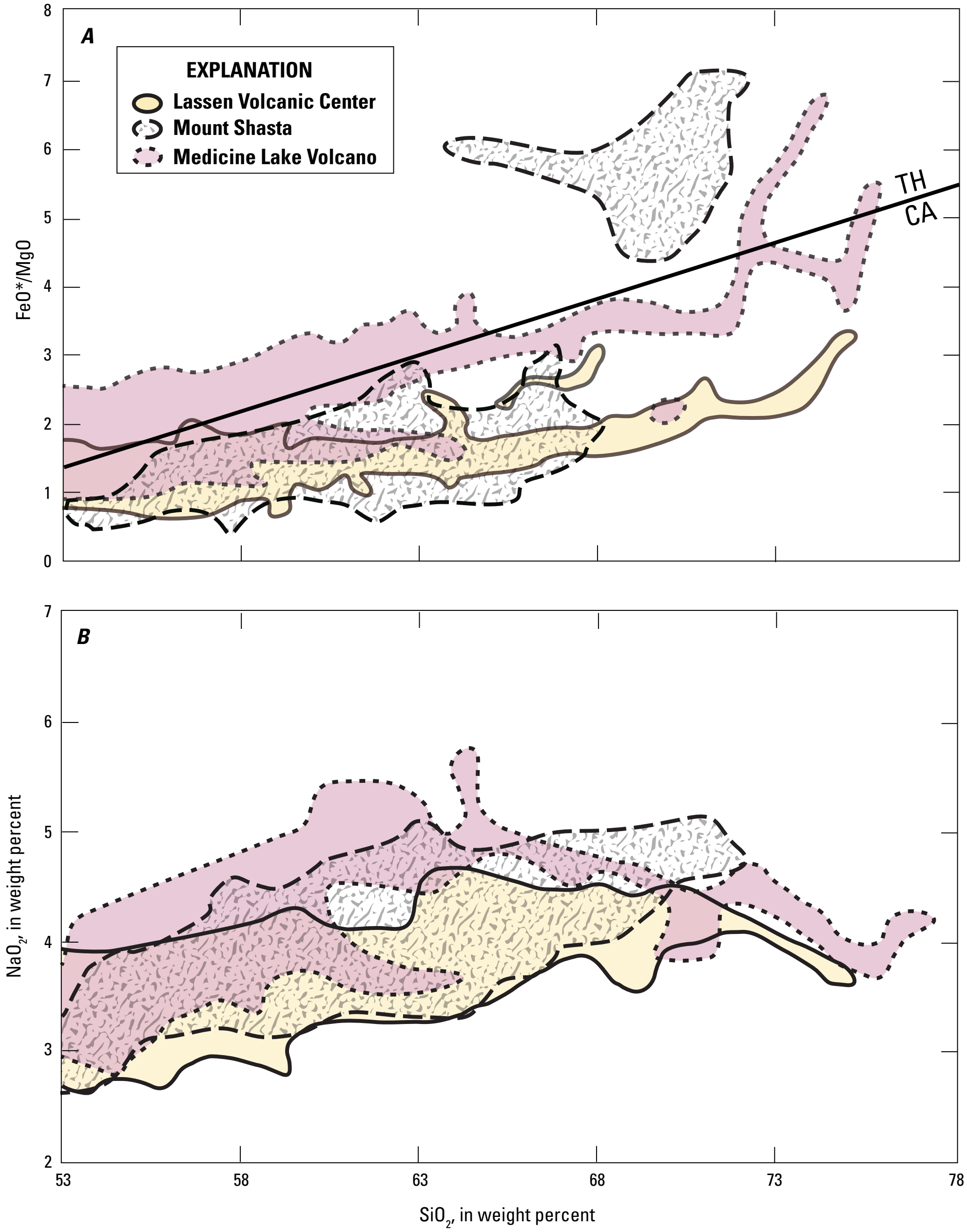

Figure 2. Variation of FeO*/MgO versus SiO_2 (*A*) and Na_2O versus SiO_2 (*B*) in lavas of the California Cascades. Lassen Volcanic Center and Mount Shasta both exhibit very low FeO*/MgO, some of lowest values found in arcs globally. Some lavas from Medicine Lake exhibit elevated Na_2O contents as a consequence of crystallization under "moist" conditions (Mandler and others, 2014). Data sources: Lassen, 439 analyses from Clynne and others (2008); Medicine Lake, 268 analyses from Donnelly-Nolan (2008); Shasta, 75 analyses from Baker and others (1994), Grove and others (2002), and Grove and others (2005), plus 790 analyses from Christiansen (2017). The line dividing tholeiitic (TH) from calc-alkaline (CA) lavas is from Miyashiro (1974). Modified from figure 10 of Mandler and others (2014).

In contrast to Mount Shasta, Medicine Lake Volcano is a broad, shield-shaped edifice that has erupted the full range of compositions, from primitive basalt to high-silica rhyolite. Most of its surface is mapped as mafic lavas (basalt to andesite), but geothermal drilling has identified a silicic core (Donnelly-Nolan and others, 2008; Donnelly-Nolan, 2010). Medicine Lake lavas record both dry and wet mantle melting, dry and wet crustal-level fractional crystallization, and open-system magma-chamber processes. At 7,913 ft (2,412 m) elevation, Medicine Lake Volcano rises only ~4,300 ft (~1,300 m) above the adjacent Modoc Plateau, but its lavas cover an area of ~2,000 km^2. Over the past ~500 k.y., Medicine Lake Volcano erupted a volume of ~600 km^3 (significantly more than the volume of Mount Shasta) with an eruption rate of 1.2 km^3 per thousand years.

The Lassen region, in contrast to both Mount Shasta and Medicine Lake Volcano, is not a single prominent edifice, but instead is a laterally extensive, long-lived volcanic field (the Lassen Volcanic Center) with many dozens of vents (Clynne and Muffler, 2010). The dacite dome of Lassen Peak, at an elevation of 10,462 ft (3,189 m), rises nearly 6,000 ft (~1,800 m) above the underlying, older volcanic centers (Muffler and Clynne, 2015). From 825 ka to 600 ka, the Lassen Volcanic Center was a dacitic caldera complex, from 590 ka to 390 ka a true andesitic stratocone, and from 325 ka to the present a silicic domefield. Repeated interaction of mantle-derived mafic magmas with a shallow body of rhyodacite crystal mush has produced a suite of mixed magmas (Clynne, 1999). Total volume of the eruptive products of the Lassen Volcanic Center is only ~200 km^3 over its lifetime of 825 k.y., giving an eruption rate of only 0.24 km^3 per thousand years.

All three volcanic centers have erupted in the Holocene, with the most recent magmatic eruptions being ~3.1 ka at Mount Shasta, ~950 years ago at Medicine Lake Volcano, and 102 years ago at Lassen Peak in the Lassen Volcanic Center.

Cascades volcanism is directly related to the subducting Juan de Fuca Plate (Bacon and others, 1997; Hildreth, 2007). Modern seismic investigations in the southern Cascades clearly show that the Juan de Fuca Plate is subducting under the North American Plate at a shallow angle (see figure 6a of McCrory and others, 2012). The Juan de Fuca slab surface is 90 km below the Lassen Volcanic Center, 70 km below Mount Shasta, and 85 km below Medicine Lake Volcano (figure 4c of McCrory and others, 2012).

Within the North American Plate, the Cascades Volcanic Arc in California is bounded by three major tectonic regimes: (1) the counterclockwise-rotating fore-arc blocks of southern Oregon and northwestern California (Wells and McCaffrey, 2013); (2) the Sierra Nevada block to the south; and (3) the Basin and Range Province to the east. Geodetic data show that all of these blocks are moving to the northwest at 5–11 mm per year relative to stable North America (Thatcher and others, 2014), but the exact boundaries between and among them are subject to conflicting interpretations. Impingement of the Basin and Range Province on the Lassen area and Medicine Lake Volcano is expressed both by normal faults and by vent alignments controlled by these faults (for example, Muffler and others, 2011).

The right-lateral Walker Lane separates the Sierra Nevada block from the Basin and Range Province to the east (Faulds and Henry, 2008). This broad, linear zone of distributed dextral strike-slip faulting, parallel to and inboard of the San Andreas Fault System, accommodates about 20 percent of the relative motion between the North American and Pacific Plates (Unruh, 1995). The California Cascades can be considered a transitional zone, where horizontal stress is transferred from northwest-southeast dextral shear of the Walker Lane to dominantly east-west extension of the Cascade Range in Oregon (Blakely and others, 1997).

The Lassen Volcanic Center overlies several older (~2.4–1.1 Ma) volcanic centers, with a few windows into Paleozoic and Mesozoic igneous and metamorphic rocks and Cretaceous sedimentary rocks. Mount Shasta, being west of the Cascade axis, lies directly on Paleozoic sedimentary and metamorphic rocks, although numerous mafic centers ranging in age from 6 to 1.2 Ma define an east-northeast-trending highland between Medicine Lake and Mount Shasta. No basement rocks are exposed near Medicine Lake Volcano, nor were older rocks penetrated by geothermal drilling. The terrain of Tertiary volcanoes and shallow plutons termed the “Western Cascades” in Oregon extends south only to the northern part of the Mount Shasta region.

Admonitions

Collecting rock samples in Lassen Volcanic National Park and in Lava Beds National Monument is prohibited without a special permit from the National Park Service. Please abide by this restriction.

Several of the field-trip stops are along busy, dangerous highways. Be aware of fast-moving traffic, particularly large trucks. Look both ways before attempting to cross a highway. **Be alert and be careful!**

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We acknowledge technical reviews by Marianne Guffanti and Thomas Giachetti for all four sections of this field-trip guide, as well as the careful editing by Katherine Jacques, Claire Landowski, and Jan Zigler.

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