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Geologic Field-Trip Guide to Medicine Lake Volcano, Northern California, Including Lava Beds National Monument

Scientific Investigations Report 2017–5022–K1

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

Cover: View of Medicine Lake volcano from the northeast. Photograph by Julie M. Donnelly-Nolan.

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By Julie M. Donnelly-Nolan and Timothy L. Grove

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RYAN K. ZINKE, Secretary

U.S. Geological Survey
William H. Werkheiser, Acting Director

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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.

Michael Dungan, University of Oregon
Judy Fierstein, U.S. Geological Survey
Cynthia Gardner, U.S. Geological Survey
Dennis Geist, National Science Foundation
Anita Grunder, Oregon State University
John Wolff, Washington State University

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.

Contributing Authors

Boise State University
Brittany D. Brand
Nicholas Pollock

Colgate University
Karen Harpp
Alison Koleszar

Durham University
Richard J. Brown

Eastern Oregon University
Mark L. Ferns

ETH Zurich
Olivier Bachmann

Georgia Institute of Technology
Josef Dufek

GNS Science, New Zealand
Natalia I. Deligne

Hamilton College
Richard M. Conrey

Massachusetts Institute of Technology
Timothy Grove

National Science Foundation
Dennis Geist (also with Colgate University and University of Idaho)

New Mexico Bureau of Geology and Mineral Resources
Paul W. Bauer
William C. McIntosh
Matthew J. Zimmerer

New Mexico State University
Emily R. Johnson

Northeastern University
Martin E. Ross

Oregon Department of Geology and Mineral Industries
William J. Burns
Lina Ma
Ian P. Madin
Jason D. McClaughry

Oregon State University
Adam J.R. Kent

Portland State University
Jonathan H. Fink (also with University of British Columbia)
Martin J. Streck
Ashley R. Streig

San Diego State University
Victor E. Camp

Smithsonian Institution
Lee Siebert

Universidad Nacional Autónoma de San Luis Potosi
Damiano Sarocchi

University of California, Davis
Kari M. Cooper

University of Liverpool
Peter B. Kokelaar

University of Northern Colorado
Steven W. Anderson

University of Oregon
Ilya N. Binderman
Michael A. Dungan
Daniele Mckay (also with Oregon State University and Oregon State University, Cascades)

University of Portland
Kristin Sweeney

University of Tasmania
Martin Jutzeler
Jocelyn McPhie

University of Utah
Jamie Farrell

U.S. Army Corps of Engineers
Keith I. Kelson

U.S. Forest Service
Gordon E. Grant (also with Oregon State University)

U.S. Geological Survey
Charles R. Bacon
Andrew T. Calvert
Christine F. Chan
Robert L. Christiansen
Michael A. Clynne
Michael A. Cosca
Julie M. Donnelly-Nolan
Benjamin J. Drenth
William C. Evans
Judy Fierstein
Cynthia A. Gardner
V.J.S. Grauch
Christopher J. Harpel
Wes Hildreth
Richard P. Hoblitt
Robert A. Jensen
Peter W. Lipman
Jacob B. Lowenstern
Jon J. Major
Seth C. Moran
Lisa A. Morgan
Leah E. Morgan
L.J. Patrick Muffler
Jim O'Connor
John S. Pallister
Thomas C. Pierson
Joel E. Robinson
Juliet Ryan-Davis
Kevin M. Scott
William E. Scott
Wayne (Pat) Shanks
David R. Sherrod
Thomas W. Sisson
Mark Evan Stelten
Weston Thelen
Ren A. Thompson
Kenzie J. Turner
James W. Vallance
Alexa R. Van Eaton
Jorge A. Vazquez
Richard B. Waitt
Heather M. Wright

U.S. Nuclear Regulatory Commission
Stephen Self (also with University of California, Berkeley)

Washington State University
Joseph R. Boro
Owen K. Neill
Stephen P. Reidel
John A. Wolff

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Contents

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Geologic Field-Trip Guide to Medicine Lake Volcano, Northern California, Including Lava Beds National Monument

By Julie M. Donnelly-Nolan[1] and Timothy L. Grove[2]

Introduction

Medicine Lake volcano is among the very best places in the United States to see and walk on a variety of well-exposed young lava flows that range in composition from basalt to rhyolite. This field-trip guide to the volcano and to Lava Beds National Monument, which occupies part of the north flank, directs visitors to a wide range of lava flow compositions and volcanic phenomena, many of them well exposed and Holocene in age. The writing of the guide was prompted by a field trip to the California Cascades Arc (hereafter the Cascades) organized in conjunction with the International Association of Volcanology and Chemistry of the Earth's Interior (IAVCEI) quadrennial meeting in Portland, Oregon, in August of 2017. This report is one of a group of three guides describing the three major volcanic centers of the southern Cascades Volcanic Arc. The guides describing the Mount Shasta (Christiansen and others, 2017) and Lassen Volcanic Center (Clynne and Muffler, 2017) parts of the trip share an introduction (Muffler and others, 2017) written as an overview to the IAVCEI field trip. However, this guide to Medicine Lake volcano has descriptions of many more stops than are included in the 2017 field trip. The 23 stops described here feature a range of compositions and volcanic phenomena. Many other stops are possible and some have been previously described (Donnelly-Nolan and others, 1981; Donnelly-Nolan, 1987; Muffler and others, 1989), but these 23 have been selected to highlight the variety of volcanic phenomena at this rear-arc center, the range of compositions, and for the practical reason that they are readily accessible. Open ground cracks, various vent features, tuffs, lava-tube caves, evidence for glaciation, and lava flows that contain inclusions and show visible evidence of compositional zonation are described and visited along the route. For sites described in earlier guides, we have updated the descriptions to incorporate the nearly three decades of work since the original publications.

Geologic and Tectonic Setting

Medicine Lake volcano and its surrounding lavas cover about 2,200 square kilometers (km^2) in northern California ~55 km east-northeast of Mount Shasta (fig. 1). Its volume is estimated at ~600 km^3, the largest in the Cascades Arc with the possible exception of the rear-arc Newberry Volcano in central Oregon. Eruptions at this large rear-arc, shield-shaped (fig. 2) composite volcano have taken place over a span of half a million years, most recently about 950 years ago at Glass Mountain. The volcano is located east of the Cascades Arc axis at the west edge of the extensional Basin and Range Province (Donnelly-Nolan and others, 2008). Vent alignments and open ground cracks are visible evidence of tectonic control in this extensional environment. Evidence of glaciation is present in the form of polish and striations. Additional details of the tectonic setting and eruptive history are described in an overview paper by Donnelly-Nolan and others (2008) and in the pamphlet accompanying the geologic map (Donnelly-Nolan, 2010). Published data include argon ages (Donnelly-Nolan and Lanphere, 2005) and chemical analyses of pre-Holocene lavas (Donnelly-Nolan, 2008).

Lava compositions range from basalt (both tholeiitic and calc-alkaline) to rhyolite, and include compositionally zoned lavas of both mafic and silicic composition, including the late Holocene compositionally zoned rhyolite and dacite of Glass Mountain. A single ash-flow tuff eruption occurred ~180,000 years ago and produced the ~10-km^3 dacitic tuff of Antelope Well. Eruption of the tuff contributed to caldera formation, but much of the physical expression of the caldera is related to a

[1]U.S. Geological Survey.

[2]Massachusetts Institute of Technology.

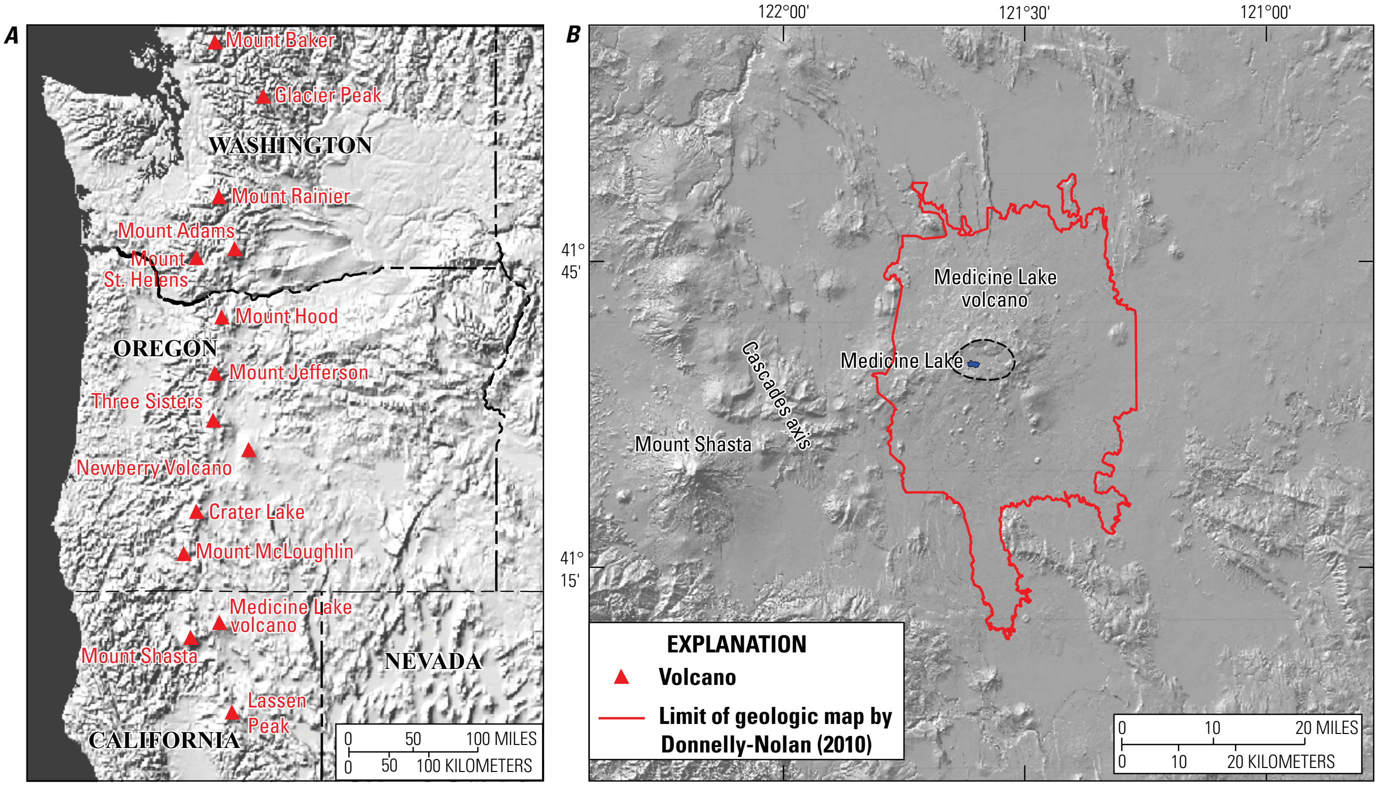


Figure 1. Location map showing (*A*) where Medicine Lake volcano is located within the Cascades Volcanic Arc, and (*B*) its location east of the arc axis (red outline is limit of geologic map by Donnelly-Nolan, 2010). The center of the volcano is located 57 kilometers east-northeast of Mount Shasta.

combination of andesitic rim eruptions and central subsidence. Mafic lavas including basalt and basaltic andesite dominate the eruptive history and include some widespread basaltic units (fig. 3); only about 5 percent of the surface area of the volcano is mapped as dacite and rhyolite. However, the erupted volume of these silicic components is considerably greater based on drill hole data from the many geothermal wells. Hot gases emerge at the Hot Spot west of Glass Mountain and the volcano has, for many years, been a site of exploration for geothermal energy. Some drill holes encountered granitic rocks at depth (Donnelly-Nolan, 2006) and granitic inclusions were also found in a number of lava flows. Dating of some of the inclusions and a drill hole sample (Lutz and others, 2000) gives ages ranging from ~300 ka to Holocene (Lowenstern and others, 2000, 2003), indicating that the granitic material represents subjacent, slowly cooled bodies of silicic magma.

The volcano has one of the best-documented records (Nathenson and others, 2007) of postglacial volcanism in the Cascades. Seventeen eruptions have taken place since ~13 ka, ranging in composition from basalt to rhyolite. Included here is a map (fig. 4) showing the distribution of young lavas and their compositions, which was originally published as part of a hazards assessment (Donnelly-Nolan and others, 2007). Also included in this guide are selected figures (figs. 5, 6) from Donnelly-Nolan and others (2016) showing the compositional range of the postglacial materials and their distribution in time. Eruptive activity at the volcano was strongly episodic in postglacial time, based on radiocarbon dating (Nathenson and others, 2007) and paleomagnetic sampling (Donnelly-Nolan and others, 2016).

The first geologic publications that describe the volcano were published in the late 1920s and early 1930s (Stearns, 1928; Peacock, 1931; Powers, 1932; Anderson, 1933). The classic reference that describes the geology of the volcano and includes a geologic map is Anderson (1941). Prior to our work, several authors documented evidence of compositional zonation and mixing of lavas (Anderson, 1933; Eichelberger, 1974, 1975; Condie and Hayslip, 1975; Anderson, 1976). Mertzman published several papers about the volcano that are primarily focused on petrology, among them Mertzman (1977a,b) and Mertzman and Williams (1981), the latter describes inclusions in Little Glass Mountain. A comprehensive list of references is available in the pamphlet that accompanies the geologic map of Donnelly-Nolan (2010).

A

B

Figure 2. (*A*) Photograph looking south across the Tule Lake basin toward the broad shield-shaped edifice of Medicine Lake volcano. On the right is the upfaulted ridge of Gillem Fault that projects directly south into Lava Beds National Monument. (*B*) View west-southwest of the broad Medicine Lake volcano edifice from the back-arc volcanic terrane of the Hackamore center (Donnelly-Nolan and others, 1996).

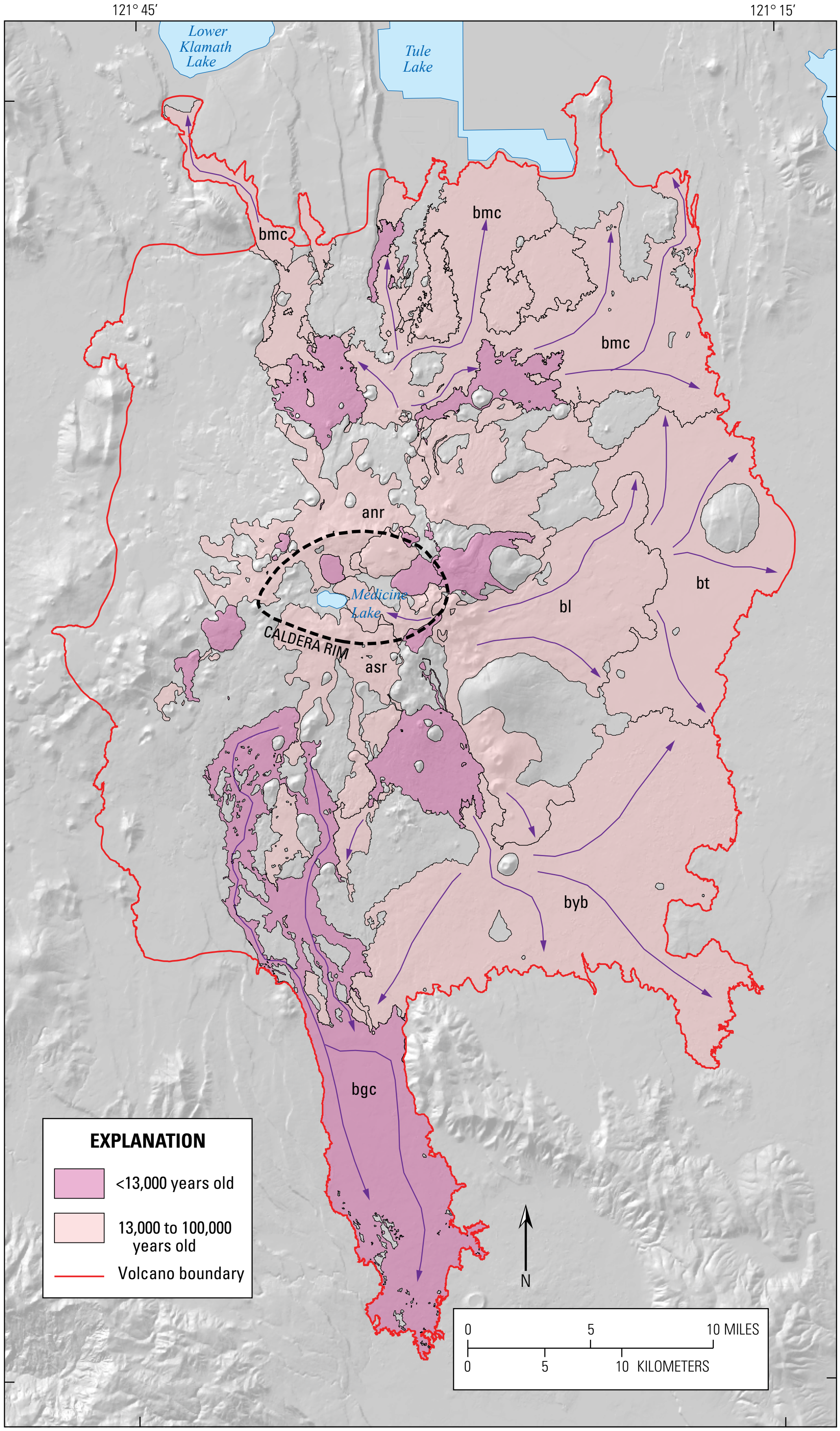


Figure 3. Map adapted from Donnelly-Nolan and others (2007, their fig. 2) shows Medicine Lake volcano lava flows from 100,000 to 13,000 years old in shades of pink. Postglacial lavas <13,000 years old are shown in darker pink. Major lava flows are labeled, including anr (andesite of north rim) and asr (andesite of south rim). Five very large basalt lava flows are also labeled: bgc, basalt of Giant Crater; bmc, basalt of Mammoth Crater; byb, basalt of Yellowjacket Butte; bl, Lake basalt of Anderson (1941); bt, basalt of Tionesta.Flow directions are indicated by arrows on the five large basalt flows.

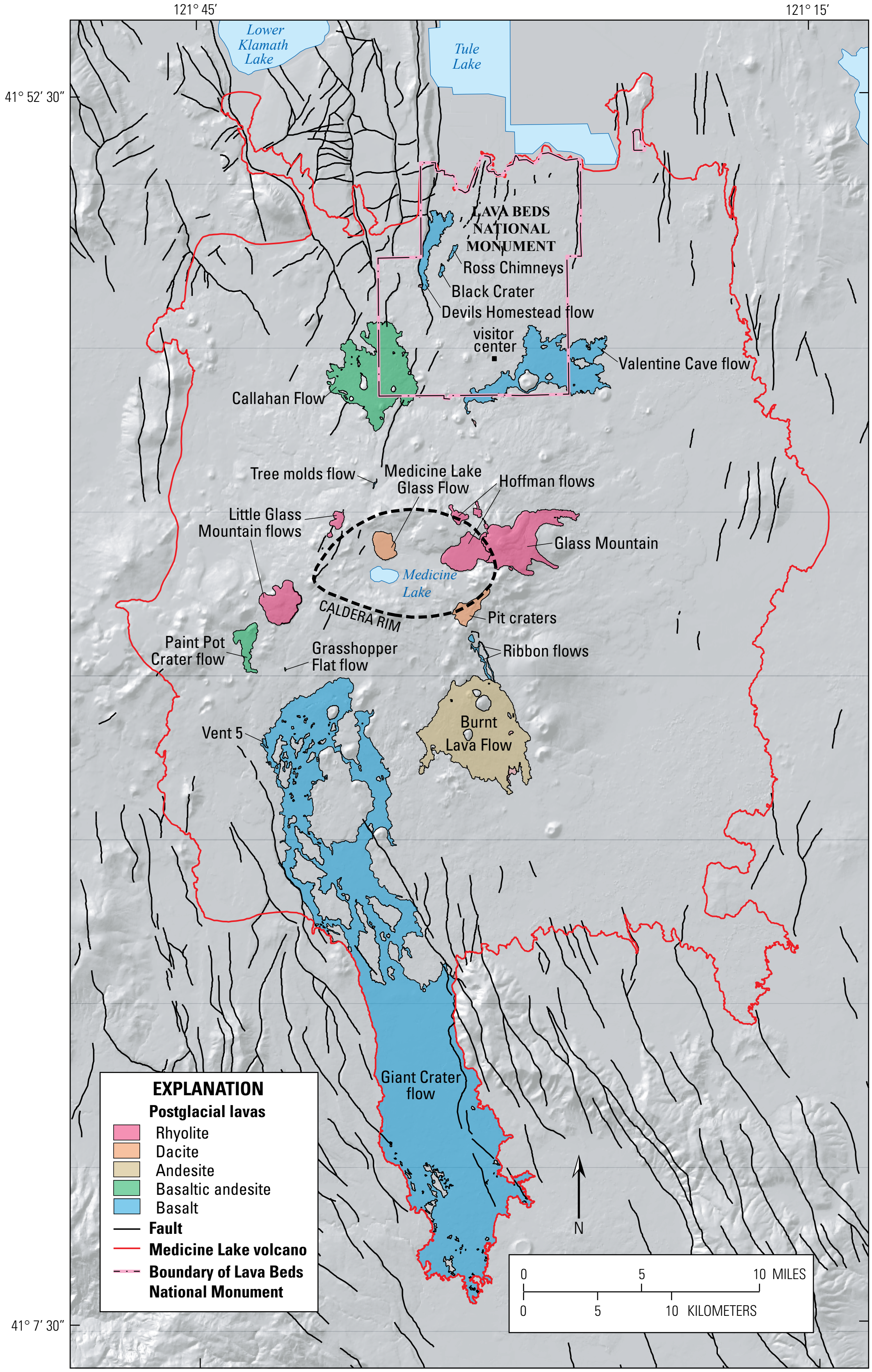


Figure 4. Map from Donnelly-Nolan and others (2007, their fig. 3B) showing the outline of Medicine Lake volcano and the distribution of postglacial lavas (color coded by composition).

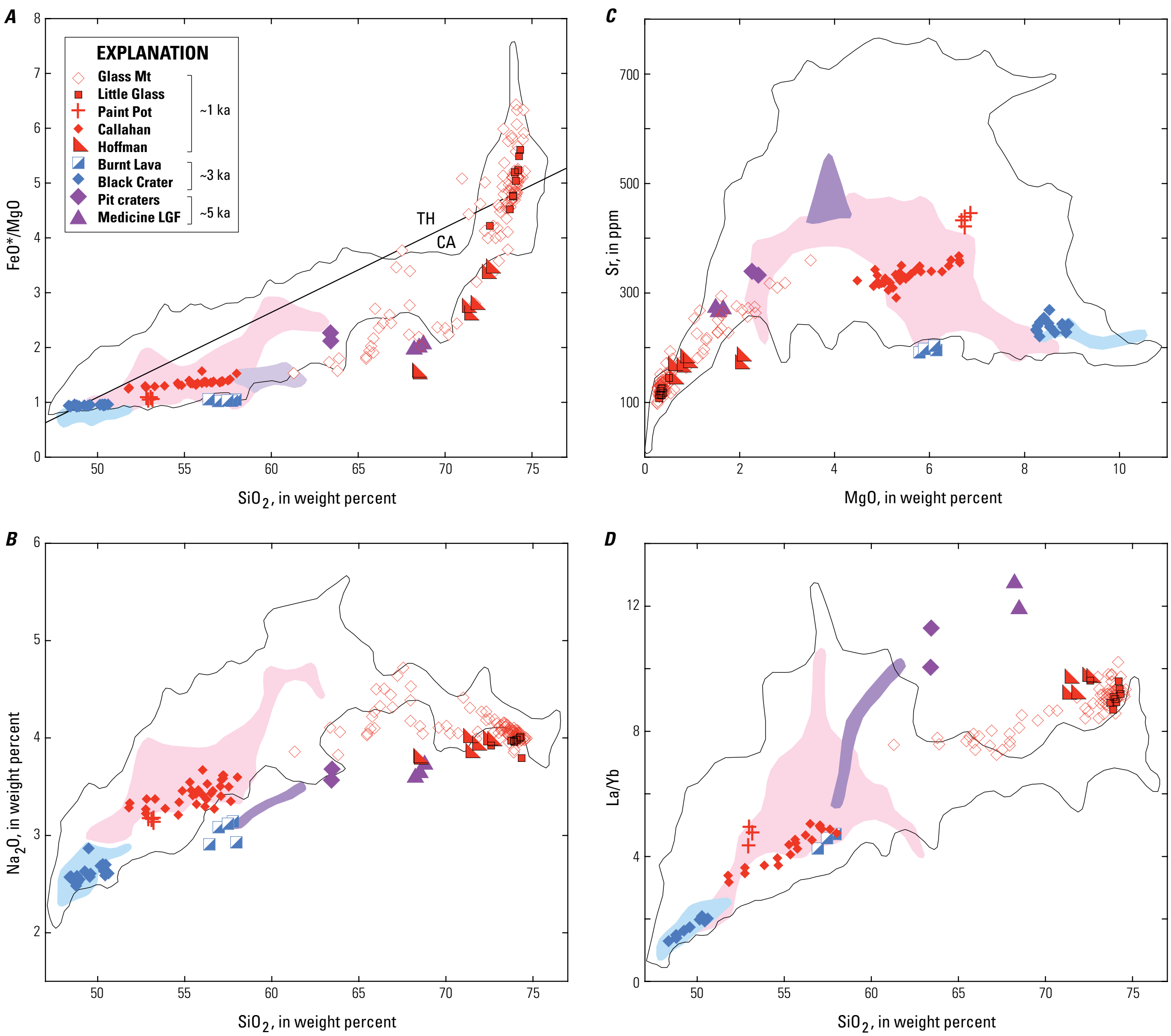


Figure 5. Plots showing the compositional range of lavas erupted at Medicine Lake volcano, highlighting materials erupted since ~5,200 years ago (Donnelly-Nolan and others, 2016, their fig. 5). Black line in (*A*) separates fields designated as tholeiitic (TH) and calc-alkaline (CA) by Miyashiro (1974). In explanation, Mt is mountain; LGF is Lake Glass Flow.

Our work at Medicine Lake volcano began independently, but for both of us coincidentally, in 1979, the year we first met in Lava Beds National Monument. Donnelly-Nolan focused on geologic mapping and hazards evaluation. Publication of the hazards assessment (Donnelly-Nolan and others, 2007), was followed soon after by an overview paper (Donnelly-Nolan and others, 2008), and the geologic map at a scale of 1:50,000 (Donnelly-Nolan, 2010). Grove was intrigued by the full spectrum of compositions from rhyolite to primitive basalt that had been identified by Anderson (1941). Grove and his students took advantage of the spectacularly exposed and compositionally interesting lava flows to do detailed petrology and geochemistry on the origin of the lavas and the nature of the magma system. They published numerous papers that are cited below at stops along the field trip route. Our first collaborative paper (Grove and Donnelly-Nolan, 1986) is a study of the late Holocene Little Glass Mountain rhyolite flow and its inclusions. This study demonstrated to us the value of looking for included material in lava flows. Subsequent detailed studies of compositionally zoned lava flows demonstrated the power of using both the erupted compositional range and petrologic information from inclusions to identify and constrain the magmatic processes that generated the lava (for example, Baker and others 1991; Grove and others, 1997; Kinzler and others, 2000).

The petrologic work by Grove and his students has played an important role in the evolution of thought about

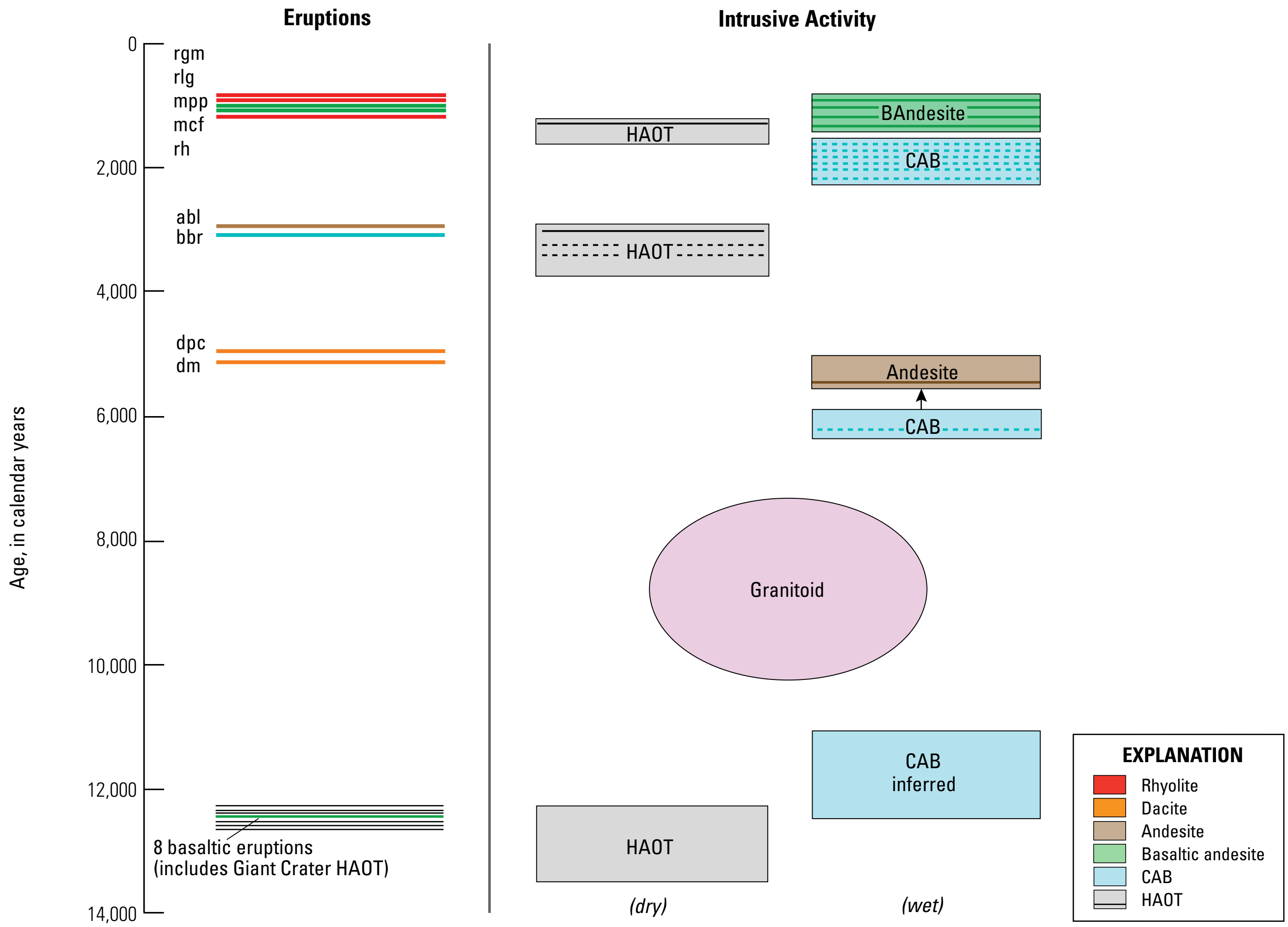


Figure 6. Illustration showing Holocene eruptive episodes color-coded by composition (Donnelly-Nolan and others, 2016, their fig. 55). The dense cluster of lines at about 12.5 ka represents the eight basaltic eruptions that occurred in a short span of ~200 years in immediate postglacial time. On the right side of the figure is a diagrammatic representation of intrusive events, some documented by the presence of quenched magmatic inclusions of a range of compositions (solid horizontal lines), some by petrologic evidence (dashed horizontal lines). HAOT, high-alumina olivine tholeiite basalt (Hart and others, 1984); CAB, calc-alkaline basalt; BAndesite, basaltic andesite. Evidence for granitoid intrusion is from the dating of zircons in granitoid inclusions found in the rhyolite of Little Glass Mountain and in the dacite of Medicine Lake Glass Flow (Lowenstern and others, 2000, 2003). The CAB on lower right of diagram is inferred based on the petrologic and geochemical arguments of Kinzler and others (2000) that wet (calc-alkaline) magmas differentiate to produce silicic melts, whereas dry (HAOT) magmas can differentiate only to andesite.

magmatic sources and processes. High-pressure experimental studies on near-primary primitive basalts at Medicine Lake volcano (Bartels and others, 1991) show that these low-potassium, high-alumina olivine tholeiite (HAOT; Hart and others, 1984) magmas were produced in the mantle near the crust-mantle boundary and most likely originated by dry adiabatic decompression melting of shallow mantle. Grove and others (1982) and Gerlach and Grove (1982) used a combination of experimental, petrologic, and geochemical studies on basalts and andesites of Medicine Lake volcano to recognize that a combination of fractional crystallization, assimilation, and magma mixing was important in generating the calc-alkaline differentiation trend preserved in the lavas of the volcano (Grove and Baker, 1994). Continued investigations with students and with U.S. Geological Survey (USGS) collaborators provided evidence to develop quantitative models of the fractionation, assimilation, and mixing process (Grove and others, 1988; Donnelly-Nolan and others, 1991; Baker and others, 1991). The petrologic, geochemical, and field evidence for the importance of these combined processes is spectacularly preserved in the young mafic lavas including the Burnt Lava Flow (Stop 22), Giant Crater lavas (Stop 23), the Callahan Flow (Stop 8), and the Paint Pot Crater flow (Stop 6). In addition, quenched mafic inclusions preserved in some of the young silicic lava flows (Glass Mountain, Stop 2; Little Glass Mountain, Stop 5;

Medicine Lake Glass Flow, Stop 21) exhibit petrologic and geochemical evidence revealing that wet, near-primary mantle-derived magmatic inputs are also coming from hydrous melting processes that begin in the mantle near the slab-mantle wedge interface (Kinzler and others, 2000). The wet fractional crystallization story at Glass Mountain (Grove and others, 1997) is a classic example showing how wet basaltic magmas are needed to make granite by fractional crystallization.

Geophysical Summary

A variety of geophysical studies including gravity (Finn and Williams, 1982), seismic refraction (Zucca and others, 1986; Fuis and others, 1987), magnetotelluric (Stanley and others, 1990), and tomographic (Evans and Zucca, 1988; Chiarabba and others, 1995; Ritter and Evans, 1997) document the presence of intrusive bodies under the volcano. Donnelly-Nolan (1988) argued that the lack of geophysical evidence for a large magma body indicated a distributed system of small magma bodies. Seismic tomography identified a small silicic magma body under the eastern part of the caldera (Evans and Zucca, 1988; Chiarabba and others, 1995). Seismic monitoring has identified earthquake swarms (Walter and Dzurisin, 1989) as well as long-period earthquakes (Pitt and others, 2002). Subsidence focused on the center of the caldera has been documented and explained by the cooling of hot rocks (Dzurisin and others, 1991, 2002; Poland and others, 2006).

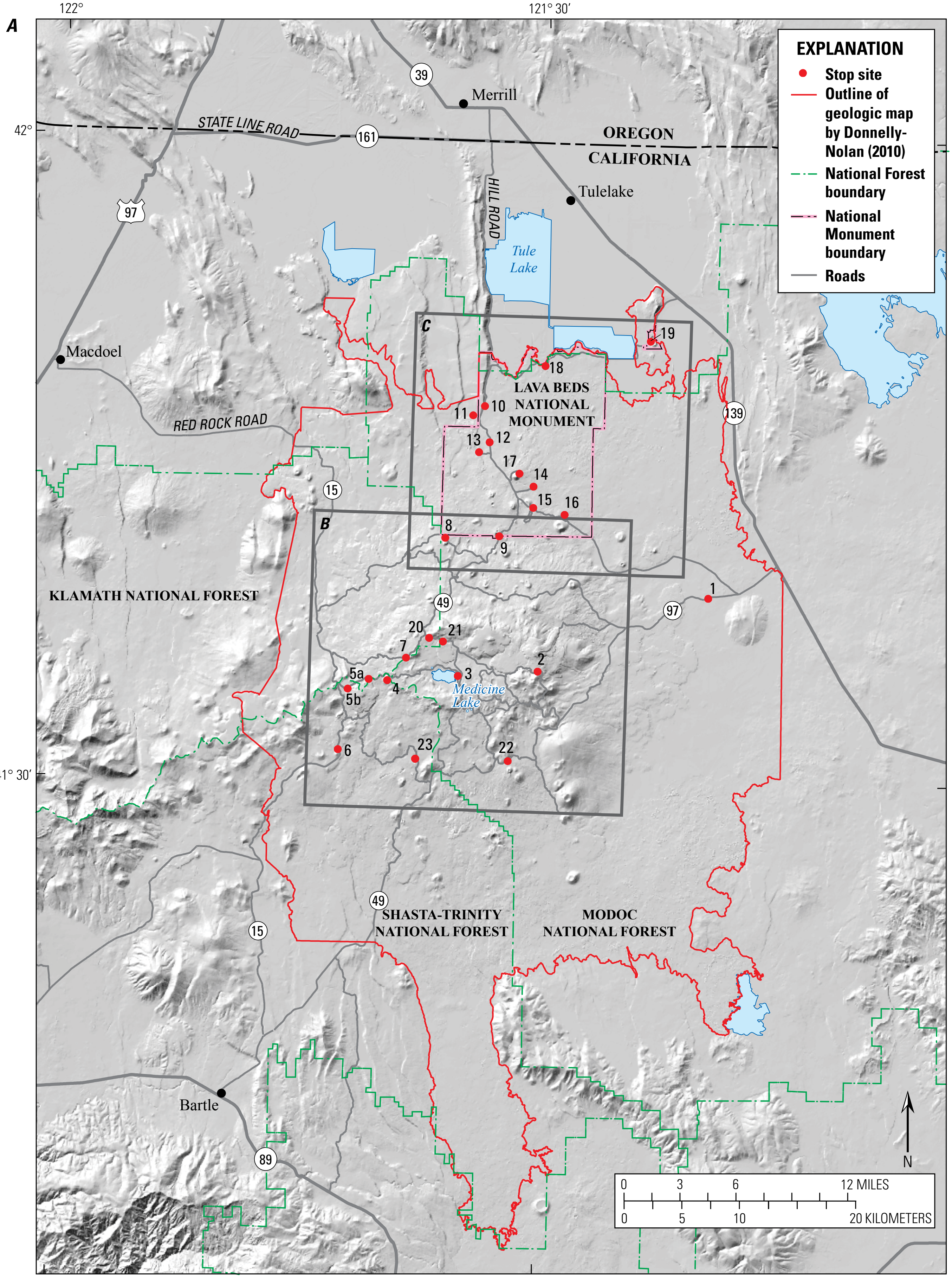
Regional seismic evidence (McCrory and others, 2012) indicates a depth to the subducting Juan de Fuca Plate of ~90 km, less than half the previous estimated depth (Harris and others, 1991). Warm mantle temperatures are indicated at shallow depths beneath the southern Cascades (Bartels and others, 1991; Bacon and others, 1997; Elkins Tanton and others, 2001) and explained by Till and others (2013) as a result of subduction-induced corner flow combined with toroidal flow around the south edge of the slab and crustal extension. Evaluation of regional gravity, seismicity, and fault trends in the southern Cascades indicates partitioning of strike-slip and extensional strain among domains defined by gravity anomalies (Blakely and others, 1997). For the domain defined at Medicine Lake volcano, the edifice is located at the intersection of structural features where extension is focused under the caldera (Donnelly-Nolan and others, 2008).

Logistics

The 23 stops shown on figure 7 and described in this guide are organized into 3 days, each beginning in Klamath Falls, Oregon (the nearest large city), which has lodging, food, and gas. Because the volcano is so large, each day involves considerable driving and even with short times at the stops (for example, half an hour or less), the days are long. The route need not be followed in the particular order listed here, but as organized in this guide, Day 1 begins with crossing the volcano from east to west by way of the caldera and returning to Klamath Falls by a number of different routes. Most of the Day 2 stops are in Lava Beds National Monument. The third day traverses the volcano from north to south, and ends at California Highway (CA Hwy) 89 on the far south side. Camping at Medicine Lake or in Lava Beds National Monument offers the best option for maximizing the amount of time at stops and minimizing the travel time, although no gas or food are available on the volcano. As of this writing (May, 2016) additional lodging options for visiting the volcano include staying in the city of Mount Shasta or in the community of McCloud and approaching the volcano from Hwy 89 on the south; renting the lookout on Little Mount Hoffman (Stop 4; rental information on Shasta-Trinity National Forest website); staying in rustic lodging in Tionesta on the east side of the volcano near Stop 1; staying in a motel in Tulelake, Calif. (CA Hwy 139) or Merrill, Oreg. (Oregon [OR] Hwy 39). The town of Tulelake offers lodging and food, but no gas; Merrill provides all three.

This guide is best used from Fourth of July into early October, although Lava Beds National Monument is open year round. Accumulation of snow at higher elevations typically prevents access to the upper parts of the volcano from late fall into early summer. Lava Beds National Monument is located on the lower north flank and occupies about 10 percent of the area of the volcano. Most of the volcano is managed by three National Forests (Klamath, Shasta-Trinity, and Modoc) that converge near the center of the volcano (Stop 4 and fig. 7). Information about current road conditions is available at district Forest Service offices including the Doublehead Ranger District of Modoc National Forest (just south of Tulelake on CA Hwy 139), McCloud Ranger District of Shasta-Trinity National Forest (about 16 miles [mi] west of Bartle on CA Hwy 89), and the Goosenest Ranger District of Klamath National Forest (about 3.5 mi southwest of Macdoel

Figure 7. Shaded relief map showing the locations of the 23 stops described in this field guide, as well as important roads. Red line is outline of published geologic map (Donnelly-Nolan, 2010). Land management boundaries are shown in green for three National Forests (Klamath, Modoc, Shasta-Trinity) and in orange for Lava Beds National Monument. Box labeled "B" encompasses figure 7*B*, showing the central part of the volcano where all stops from Days 1 and 3 are located except Stop 1, which lies outside the box to the east. GM is Glass Mountain; GC is Giant Crater. Box labeled "C" encompasses all stops in and near Lava Beds National Monument, most of which are included in Day 2. An enlarged and modified version of "C" is shown as figure 29.



A
122°
121° 30′
42°
41° 30′
EXPLANATION
Stop site
Outline of geologic map by Donnelly-Nolan (2010)
National Forest boundary
National Monument boundary
Roads
Merrill
STATE LINE ROAD
OREGON
CALIFORNIA
Tulelake
HILL ROAD
Tule Lake
Macdoel
RED ROCK ROAD
LAVA BEDS NATIONAL MONUMENT
KLAMATH NATIONAL FOREST
Medicine Lake
SHASTA-TRINITY NATIONAL FOREST
MODOC NATIONAL FOREST
Bartle
B
C
39
161
97
139
15
49
89
1
2
3
4
5a
5b
6
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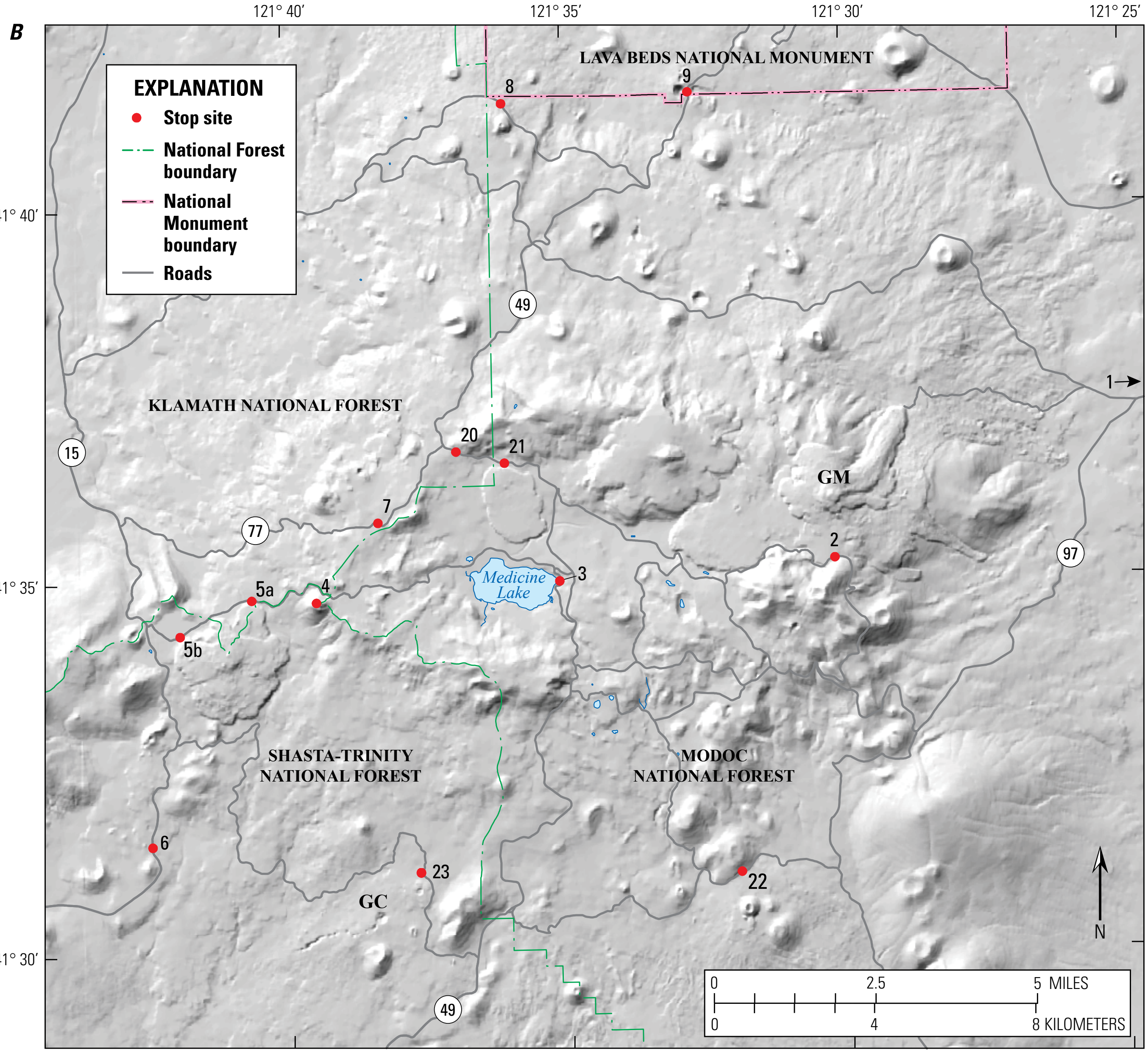

Figure 7.—Continued

on CA Hwy 97). This guide is accompanied by an online location map in a georeferenced PDF (portable display format) file, which can be downloaded and used as an aid in navigating the roads. Only the main roads are shown. There are many more roads on the volcano, but no single detailed road map. The roads in Lava Beds National Monument are few and well defined, but for travel in the National Forests, we advise users of this guide to obtain the latest Forest Service maps because roads and access routes could change. Many of the roads shown on figure 7 and in the accompanying georeferenced PDF map are paved or good-quality gravel roads and can usually be driven by passenger cars, although high clearance is recommended. Descriptions of less suitable road conditions (as of fall 2015) are added as indicated. Road numbers and names in the three National Forests are derived from U.S. Forest Service maps available to the authors in 2016 and are labeled, for example, as Road 44N01 or Road 49 (two-digit road numbers indicate the most important roads). Parts of the route will be on the Volcanic Legacy Scenic Byway (VLSB), a designated All-American Road that traverses 500 mi of volcanic terrain from the Lassen area to Crater Lake. At Medicine Lake volcano, the Forest Service has added the Modoc Volcanic Scenic Byway that connects portions of the VLSB from Lava Beds National Monument to CA Hwy 89.

Be sure to have a full tank of gas along with a spare tire and jack, a shovel, extra food and water, first aid supplies including sunscreen and insect repellant, and warm clothing before venturing to the upper parts of the volcano. Elevations range from about 4,000 feet (ft) on the lower slopes of the volcano to almost

8,000 ft at Mount Hoffman on the north caldera rim. Medicine Lake sits at nearly 6,700 ft within the 7- by 1km summit caldera. Cell phone coverage is very limited on the volcano and is not available within the caldera. Weather conditions can be extremely variable, with temperatures ranging on a typical summer day from highs in the 90s (°F) to freezing temperatures at night. Summer rains commonly arrive as thunderstorms from buildup of afternoon clouds. Heavy thunderstorms can damage roads, high winds can knock down trees, and lightning can cause fires. Drinking water is available in the Medicine Lake campgrounds and at the campground and Visitor Center in Lava Beds National Monument. A warm jacket and a flashlight (or a headlamp) are essential gear for visits to nearly all of the lava-tube caves. Most of the stops involve little or no walking, however some stops (notably Stop 23) require foot travel across rough and uneven surfaces of sharp-edged lava. We strongly recommend wearing leather gloves and long pants while hiking, in addition to taking the usual field precautions (wearing a hat and boots with good soles, as well as carrying a pack with food, water, first aid supplies, and an extra jacket). Be especially careful to wear eye protection and use leather gloves when handling obsidian (Stops 2, 5, and 21). Don't forget your camera!

Vegetation varies from dry sagebrush and juniper on the lower slopes to pine, fir, and hemlock forest at higher elevations. Large mammals include mostly deer and coyotes, but rarely include pronghorn antelope, bears, mountain lions, and elk; rattlesnakes can be found in the lower country. Both bald eagles and golden eagles are present, as well as numerous hawks, owls, and a wide variety of smaller birds. The Tule Lake National Wildlife Refuge, a major stop for migrating birds along the Pacific Flyway, abuts the volcano at the north edge of Lava Beds National Monument.

Sites of historical importance along the route include Captain Jacks Stronghold (Stop 18), and both Camp Tulelake and the Tule Lake Segregation Center of the WWII Valor in the Pacific National Monument, which are mentioned along the route.

Information To Take With You

In addition to the Forest Service maps, we suggest that if you have an electronic tablet or other device, download the georeferenced PDF (appendix 1) and use it to help navigate. Online geologic references that you may also wish to download include (1) the geologic map of Medicine Lake Volcano (Donnelly-Nolan, 2010, http://pubs.usgs.gov/sim/2927/); (2) the hazards assessment parts A (Donnelly-Nolan and others, 2007, http://pubs.usgs.gov/sir/2007/5174/a/) and B (Nathenson and others, 2007, https://pubs.usgs.gov/sir/2007/5174/b/); and (3) USGS Professional Paper 1822, which describes the late Holocene eruptive activity at the volcano and includes online appendices of chemical analyses and paleomagnetic data (Donnelly-Nolan and others, 2016, https://pubs.er.usgs.gov/publication/pp1822). Stops 2, 5, 6, 8, 12, 21, and 22 feature late Holocene lavas. Other online data sources that may be useful can be found in the reference list.

About The Units Used In This Guide

The published data listed in the references have latitude and longitude locations in the NAD27 datum, but the stop locations listed in this guide are in the WGS84 datum. Road distances are given in miles because vehicle odometers are in miles (note that interval mileages are given in bold type). Because odometers can vary slightly, be aware that the mileages can vary by ~0.1 mi. Elevations are given in feet because topographic maps show elevations in feet. All other areas, distances, and dimensions are given in metric units.

Road Log (in miles)

Day 1 (East to west across the volcano, then return to Klamath Falls, OR)

0.0 Intersection of Washburn Way and South 6th Street, Klamath Falls, Oregon. Proceed southeast on South 6th Street. **3.5**

3.5 Junction with OR Hwy 140 on left to Reno; ignore and continue south on OR Hwy 39. **14.0**

17.5 Merrill, Oregon. Road turns east. Slow down and obey speed limits. Gas, food, and lodging available. Continue east. **2.3**

19.8 Intersection on right (south) with Malone Road. Ignore for now and continue east, but route will return by way of this road at end of day. **2.9**

22.7 California border. Just after crossing into California, the highway becomes CA Hwy 39. Note junction on right with State Line Road (CA Hwy 161). Ignore and continue south. **3.7**

26.4 Town of Tulelake on right (food, but no gas available). About 1.5 mi farther south along Hwy 139, the Doublehead District office of Modoc National Forest is on the east side of the road. **8.2**

34.6 Newell, on the left, is located on the site of a World War II Japanese Relocation Camp. Road on right to Lava Beds National Monument and Stop 19. Day 2 route uses this road to return to CA Hwy 139. **16.6**

51.2 Turn right on paved County Road 97 to Tionesta, Medicine Lake, and southern route to Lava Beds National Monument. **2.3**

53.5 Road to Tionesta on left (rustic lodging available). **0.3**

53.8 Road on right to Lava Beds National Monument. Ignore and continue west. Pass pumping station on right for major natural gas pipeline and cross under first of two major power lines. **1.5**

55.3 Railroad tracks. **Stop and look both ways before crossing**, then park on left just beyond the tracks. Gravel road south from parking area leads to the pumice processing plant for material mined from the Glass Mountain pumice quarry. **0.1**

55.4 Park in open area on left.

Stop 1. Tionesta Cracks

Walk a short distance west along the paved road until you see the open ground crack (fig. 8) on your right (41°38.75′ N., 121°19.69′ W.). This deep crack (don't fall in!) is one of many such open ground cracks scattered across Medicine Lake volcano and reflects the strongly extensional tectonic environment here at the west edge of the Basin and Range Province. Most large open cracks, like this one, are north-to-northeast-trending. After following and viewing this ~0.3-km-long crack, walk east to the railroad cut and examine the high-alumina basalt of Tionesta. This primitive basalt contains (in weight percent) 47.7 SiO_2, 0.07 K_2O, 18.3 Al_2O_3, and 0.70 TiO_2. Similar basalts are common across the Modoc Plateau to the east of the volcano and in the Pacific Northwest, including along the Cascades Arc axis, near Mount Shasta (Christiansen and others, 2017) and at the Lassen Volcanic Center (Clynne and others, 2017). These basalts are usually labeled HAOT (high-alumina olivine tholeiite; Hart and others, 1984) or LKOT (low-potassium olivine tholeiite). The basalt at this location was originally labeled as "Warner Basalt" by Anderson (1941) because of its similarity to widespread aphyric diktytaxitic-textured basalt that covers much of the Modoc Plateau to the east and is present in the Warner Mountains of northeastern California. The "Warner Basalt" is now known to be older than Medicine Lake volcano and to consist of multiple basalt flows erupted from numerous vents (Donnelly-Nolan and others, 1996). The lava flow exposed here was erupted from now-buried vents on the east flank of Medicine Lake volcano. Samples from this locality were studied in petrologic papers including Yoder and Tilley (1962). Very similar primitive basalt was erupted from Giant Crater (see description of Stop 23).

Figure 8. Photograph looking south-southwest of large open ground crack near the small community of Tionesta. Crack projects toward area where pumice from Glass Mountain quarry is processed. This crack is ~0.3 kilometers in length, extends to unknown depth, and is one of many open cracks at Medicine Lake volcano that reflect the overall east-west extensional tectonic regime.

Drive west on paved County Road 97, which becomes paved (Forest Service) Road 97. At about 3.6 mi, cross under second major power line. **5.2**

60.7 Road 44N01 on right. This road is used by large, fast-moving trucks for transporting pumice mined from a quarry at the north edge of the Glass Mountain flow (fig. 9). The quarry is private property now that it has been patented under the 1872 Mining Act, so we do not include it as a field trip stop, although previous guides (Donnelly-Nolan, 1987; Muffler and others, 1989) included the location where the final rhyolite lobe (~73 weight percent SiO_2) sits directly over the earlier dacite lobe (~67 weight percent SiO_2 at that location) of the flow. At that location an old road climbs south, up the front of the high rhyolite lobe, and provides easy walking onto this very rugged lava flow. The road continues upward through the marginal obsidian facies and high onto the finely vesicular upper surface of the aphyric, inclusion-free rhyolite lobe. The dacite lava lobe, by contrast, contains phenocrysts and numerous basaltic andesite quenched magmatic inclusions (typically about 54 to 56 weight percent SiO_2). The rhyolite and dacite lava postdate the initial rhyolitic tephra of this 1-km^3 silicic eruption, which is being quarried just north of the big rhyolite lobe. The ongoing quarrying (fig. 10) frequently changes the location and exposure of the pumice fall deposits, which are as much as 15 meter (m) thick. See Heiken (1978) for an isopach map of near-vent Glass Mountain

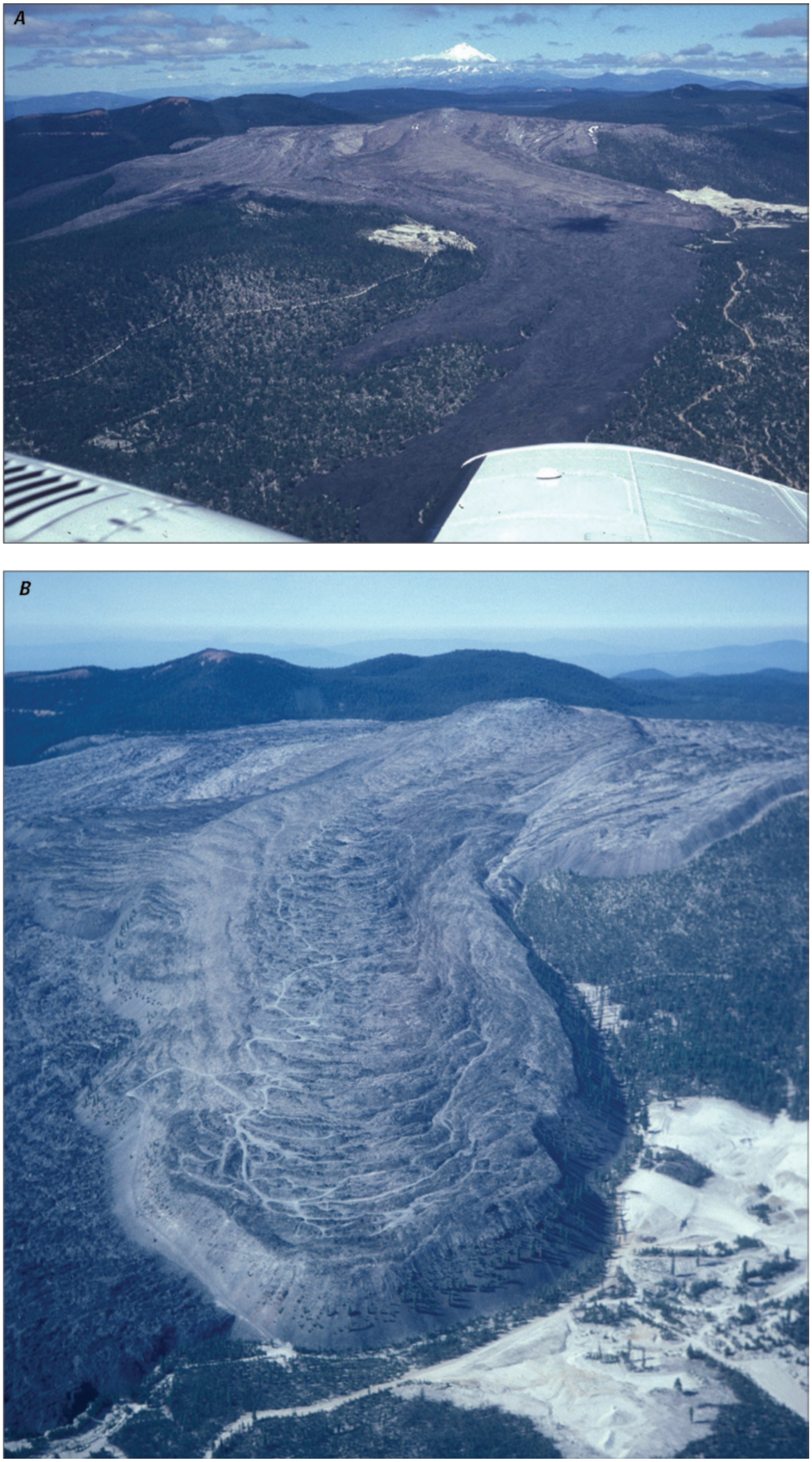

Figure 9. Aerial views of the ~950-year-old Glass Mountain flow showing (*A*) view west-southwest toward Mount Shasta shows the Glass Mountain flow draped over the east side of the Medicine Lake volcano edifice. The lighter gray is rhyolite; the darker gray above the airplane wing is dacite. To the right, north of the flow, is the quarry where pumice is currently mined from the initial tephra deposit of this youngest eruption at Medicine Lake volcano. The haul road can also be seen just to the north of the dacite. (*B*) View southwest, looking up the final rhyolite lobe shows the pumice quarry in the lower right and in the lower left the contact of the rhyolite lobe over the earlier, darker dacitic lobe of the eruption. Walkable road climbs up onto the rhyolite.

Figure 10. Glass Mountain pumice quarry in October 2015. View is looking south toward the northern, high margin of Glass Mountain rhyolite. Photograph by John Tinsley, USGS.

pumice. Current work by T. Giachetti and T. Shea (written commun., 2015) involves detailed study of the tephra deposits in an effort to understand the eruptive processes.

Continue on the paved road and follow directions to Stop 2 on the upper part of the Glass Mountain flow. At ~950 years old, Glass Mountain is the largest and youngest silicic lava flow in the United States. Any visit to Medicine Lake volcano should include a visit to this spectacular young lava flow.

67.7 At big right-hand bend in road, note turnoff on left to well graded gravel Road 43N12 that leads to Burnt Lava Flow and Stop 22. **7.0**

Ignore Road 43N12 and continue on Road 97. **3.0**

70.7 Where paved road bends sharply to left, turn sharp right onto gravel Road 43N99 to access upper Glass Mountain. **3.4**

See southernmost small rhyolite dome (fig. 11) from the Glass Mountain fissure below road on right at about 73.7 mi. Roadcut on left is in coarse tephra generated early in the eruption. If you have time, stop briefly here to see large “puff bombs” with highly inflated cores and breadcrust rinds.

74.1 Park in wide area adjacent to Glass Mountain rhyolite flow.

Stop 2. Upper Glass Mountain Rhyolite Flow

At this location (41°35.24′ N., 121°30.20′ W.) an old bulldozer track provides easy walking access onto the flow (fig. 12). The bulldozer track can be followed north across several internal flow facies, including two zones of pumice breccia indicated by linear growth of trees (fig. 13) that likely represent disaggregated early pumice cone deposits (Anderson, 1941). Depending on how much time you have, you can follow this track north toward the main Glass Mountain vent. The track ends before reaching the last, high rhyolite lobe in a zone of the rhyolite flow that contains numerous quenched magmatic inclusions. Along the way, a number of branching paths can take you east and west from the main bulldozer track. Nighthawks sometimes lay their pair of eggs directly on the bulldozer track, so watch where you step.

Early workers thought Glass Mountain was perhaps only a few hundred years old, but radiocarbon dating of a large dead tree caught in the end of one of the flow lobes and dating of other samples yielded a range of older ages. Nathenson and others (2007) discuss the evaluation of the data, including the paleomagnetic data, that resulted in the ~950-year age.

Be very careful if you pick up pieces of the obsidian. Leather gloves and eye protection are strongly recommended for handling these very sharp rocks.

This complex and fascinating compositionally zoned lava flow was first studied by Anderson (1933), who described the range of products produced during the Glass Mountain eruption and discussed the petrographic evidence for mixing. He also

Figure 11. Aerial view taken in 1985 looking north-northwest toward the dome of Glass Mountain. In the foreground is “South dome”, the southernmost dome along the Glass Mountain eruptive fissure.

Figure 12. Photograph at parking area for Stop 2, at the south edge of upper Glass Mountain, where walkable bulldozer road provides easy access onto the rugged rhyolite flow.

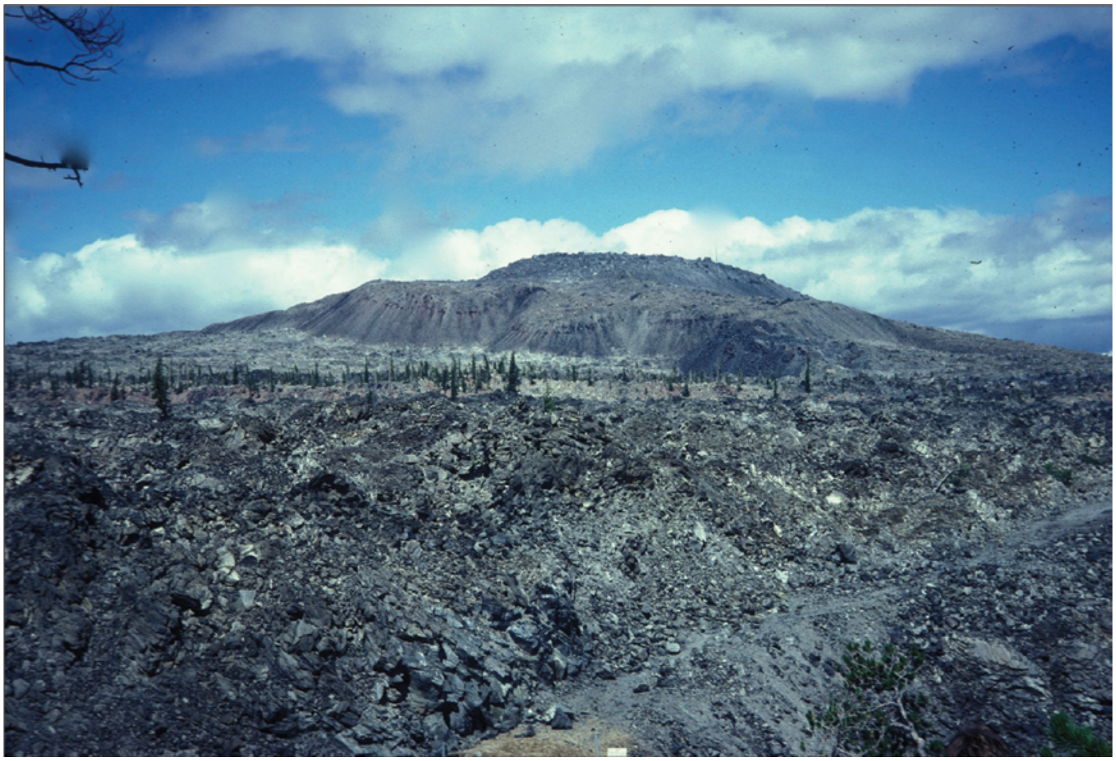

Figure 13. Photograph looking north across the upper rhyolite flow to the dome of Glass Mountain. Beginning of bulldozer road shown in figure 12 is at bottom center of photo. In the middle distance are trees showing the location of a zone of pumice breccia (Anderson, 1941) within the flow. Photo taken from north side of Lyons Peak, a Pleistocene cinder cone.

showed the general distribution of rock types in the main flow and in the small domes along the 5-km vent fissure. More than four decades later, for his Stanford Ph.D. work and subsequent papers, Eichelberger (1974, 1975) described in more detail the mineral compositions and evidence for mixing. He also mapped out the various compositional types (Eichelberger, 1975) in greater detail, showing their sequential emplacement. These papers were instrumental in refocusing attention on magma mixing as a process in generating intermediate volcanic compositions. Both Anderson and Eichelberger saw the mafic inclusions, but understood them as lithic material, incorporated and disaggregated. Then Eichelberger (1980, 1981) recognized that mafic magma had intruded, vesiculated, and chilled against the host rhyolite. Despite these studies, few chemical analyses had been performed, although the rhyolite of Glass Mountain has been used as a rock standard (RGM-1, Tatlock and others, 1976).

In 1979 Donnelly-Nolan began the systematic collection of host and inclusion samples used to create the maps (fig. 14) previously published in Donnelly-Nolan and others (2016), which show the distribution of the various lava compositions and included material. In addition to the quenched magmatic inclusions, cumulate and rare plutonic (both gabbro and granite) inclusions were also identified, primarily in the northern small domes and the southernmost dome along the 5-km-long vent fissure. Chemical analyses of the Glass Mountain materials are published as online table 1 of Donnelly-Nolan and others (2016). Grove and others (1997) characterized many of the inclusions and lava samples and described the petrology and geochemistry of the lavas and inclusions. Hornblende-bearing quenched inclusions and cumulates display a variety of grain sizes, but the most common inclusions that you will see are fine-grained, equi-granular, and vesicular, and contain olivine + plagioclase + augite + glass. Grove and others (1997) performed experiments on a quenched andesitic inclusion that is closest to the parental melt that produced the rhyolite of Glass Mountain. The experiments showed that parental calc-alkaline basaltic andesite contained 3 to 4 weight percent H_2O. The authors concluded that fractionation of the parental melt was accompanied by significant assimilation of shallow silicic crustal material to generate the rhyolite, followed by magma mixing to produce the range of erupted silicic compositions (fig. 5)

Continue driving west around the edge of the rhyolite flow. **1.8**

75.9 On your right is a good view of the rhyolite of the Hoffman flows. This fissure-fed rhyolite flow erupted about 300 years prior to eruption of the parallel Glass Mountain fissure. When the Glass Mountain eruption occurred, it deposited a thick fall of silicic tephra over the east end of the Hoffman flow. Also visible through the trees on the right is a bleached area known as the Hot Spot (fig. 15), where hot gases emerge at the

A

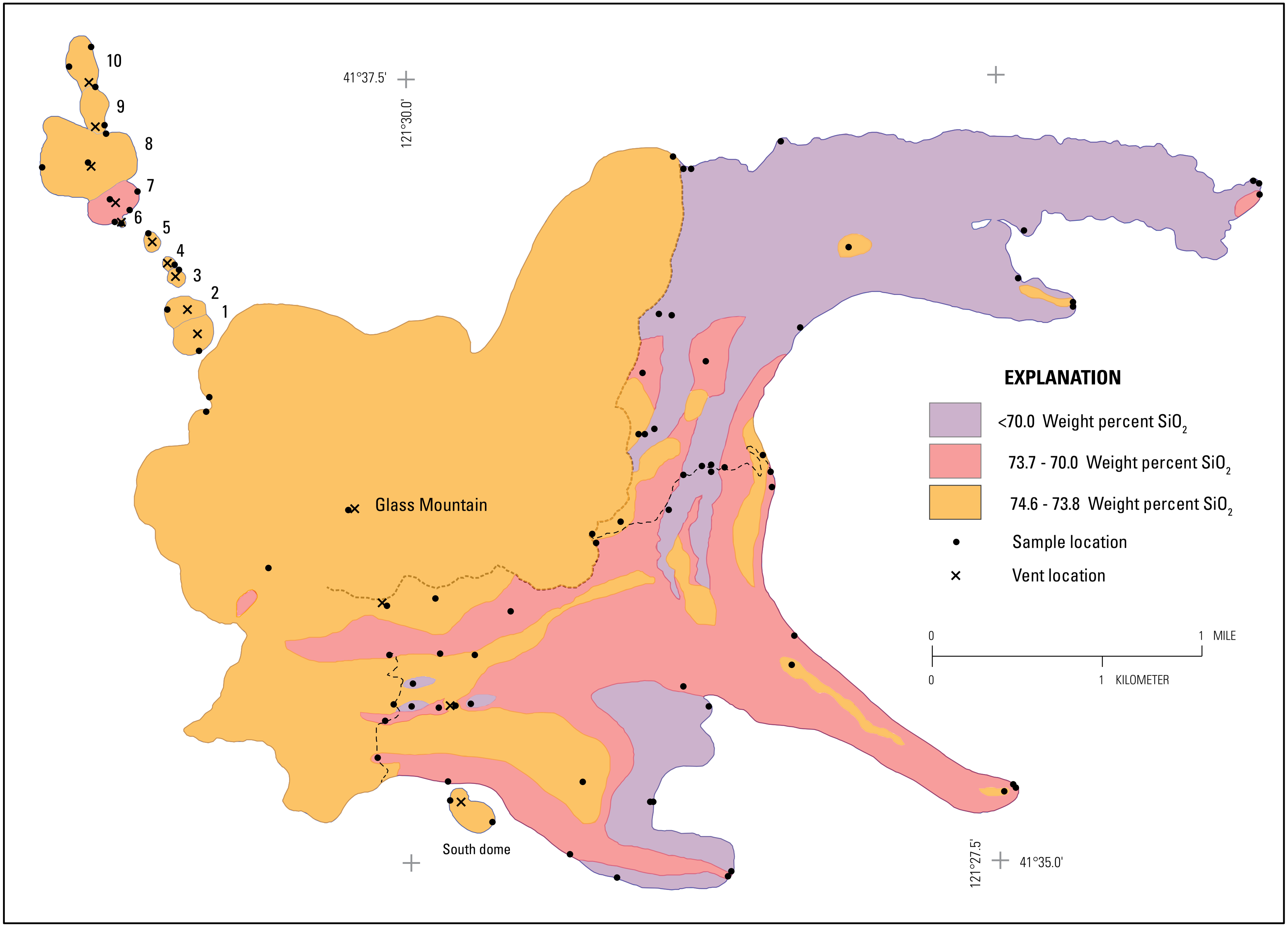

Figure 14. Maps showing (*A*) compositional variation within the Glass Mountain flow and domes. Small domes along the eruptive fissure are numbered 1–10, south to north from the northern edge of the main Glass Mountain flow. Heavy dashed lines are bulldozer tracks; track at Stop 2 begins just northwest of “South dome”; (*B*) Distribution of inclusions found in Glass Mountain lavas. Maps are figures 13 and 17, respectively, in Donnelly-Nolan and others (2016), which includes online tables of chemical analyses.

B

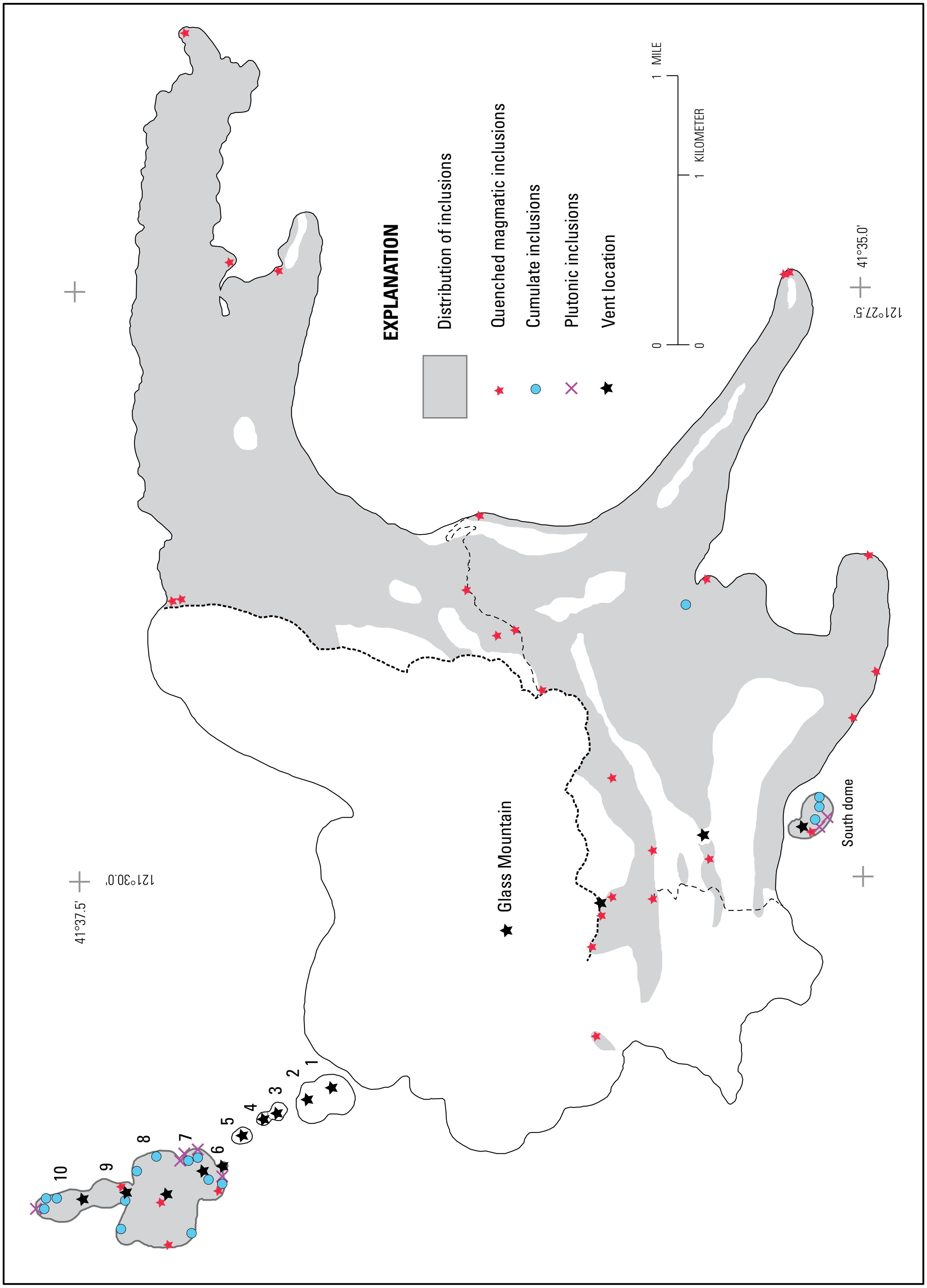

Figure 14.—Continued

Figure 15. Photograph taken at the Hot Spot, the single location at Medicine Lake volcano where hot gases emerge to the surface. Beyond the altered barren area is the treed surface of the southern Hoffman flow, a rhyolite flow erupted ~300 years prior to the Glass Mountain eruption; rising above it to the left is the barren talus slope of the west edge of the Glass Mountain flow. On the horizon is Lyons Peak. The road between Stop 2 and Stop 3 is south of both young rhyolite flows and on the north flank of Lyons Peak.

only known active surface thermal manifestation on the volcano. **0.6**

76.5 Arrive at T-junction of well-graded gravel roads and turn left onto Road 43N53. [If you turn right, you will continue on Road 43N99 past a geothermal drill site at ~1 mile for hole 17A6 (total depth 9,620 ft, Donnelly-Nolan, 2006), through the open area of Arnica Sink, onto a somewhat rocky extent of the road before it joins paved Road 49 about 1.5 mi north of Medicine Lake.]

After turning left, see a geothermal drill site on the left after half a mile, and a pit crater on the right at 1.4 mi. The crater is one of a northeast-trending set of vent craters for the ~5-ka dacite of the pit craters. [A left turn onto Road 97 takes you east 0.9 mi back to Road 43N99, the turnoff to Stop 2; if you choose to turn left, the road will also take you past a scenic viewpoint that allows a good vista to the south that, on a clear day, includes Lassen Peak).] **1.7**

78.2 Turn right (west) onto paved Road 97. **0.5**

78.7 Road 43N42 on left; ignore, but this is an alternate route to Stop 22. **2.2**

80.9 Road 43N21 on right; ignore, but this is an alternate route to Stop 2. **1.1**

82.0 T-junction with paved Road 49. Turn right and drive into the caldera (fig. 16) at this low, glaciated rim. Modoc National Forest manages the caldera and the eastern part of Medicine Lake volcano. **1.7**

Figure 16. Photograph showing distant view of Medicine Lake, nestled within the caldera. View looks west from the top of Glass Mountain across the uppermost part of the rhyolite flow. Mount Shasta is on the horizon.

83.7 Turnoff on left to Medicine Lake. Turn left. **0.3**

84.0 T-junction. Turn left; drive ~0.3 mi to the day use parking area. After Stop 3, return to this intersection. **0.3**

84.3 Park in day use parking.

Stop 3. Medicine Lake

This stop (41°34.99′ N., 121° 35.14′ W.) offers rest rooms, picnic tables, and a nice view of the eponymous lake at the center of the volcano (fig. 17). Rather than drain into the permeable volcanic rocks below, the lake probably exists because of a combination of fine tephra and glacial clay forming a seal on top of otherwise permeable volcanic rocks. The lake is fresh, fed by snow melt and spring water, but has no surface outlet. The water level varies from year to year; the elevation indicated on the 1988 Medicine Lake 7.5′ USGS topographic map is 6,676 ft. Childs and others (2000) studied lake cores and mapped the underwater topography. To the north, a short distance back along the road from the parking lot, is an exposure of the porphyritic Lake basalt of Anderson (1941), a multi-vent, late Pleistocene, compositionally zoned unit of cinder cones and lava flows generated by a combination of differentiation and plagioclase accumulation (Wagner and others, 1995). Geophysical studies (Dzurisin and others, 1991, 2002; Poland and others, 2006; Parker and others, 2014) indicate ongoing subsidence of the caldera.

From parking area, return ~0.3 mi to previous road junction just east of Medicine Lake. Reset odometer to 0.0.

Figure 17. Photograph of day-use picnic area and beach at the east end of Medicine Lake.

0.0 Continue straight ahead (north and then the road curves west) and follow paved road past campgrounds. Pavement ends just past the campgrounds; continue west on gravel Road 43N48. At junction with road to Schonchin overflow camping area, keep left. Parts of the road are rocky and narrow. **4.1**

4.1 Junction with road to top of Little Mount Hoffman. There is space for 1–2 vehicles to turn around and park adjacent to the upper gates, but if your group has large vehicles or several vehicles, park at the base of the cone and walk. The 0.6-mi road is steep, exposed, and narrow. The elevation gain is about 330 ft to the top at 7,310 ft elevation.

Stop 4. Little Mount Hoffman

The top of this glaciated Pleistocene cinder cone (41°34.73′ N., 121°39.50′ W.) offers one of the most spectacular and accessible viewpoints in the Cascades Volcanic Arc, although access is currently limited for vehicles, owing to gates installed as a result of the rental of the old fire lookout building at the summit (see Shasta-Trinity National Forest website for rental information). The view from Little Mount Hoffman is a must-see for any visit to Medicine Lake volcano as long as clouds do not completely obscure the view, but if you are walking, it is not necessary to go all the way to the top of the cone. About halfway up the road, an outcrop of welded spatter on the left provides a platform for a great view. The view west (fig. 18) encompasses the massive fore-arc volcano Mount Shasta on the horizon beyond the many dominantly basaltic andesite volcanic vents of the Cascades Arc axis. In the foreground below you is the rugged and barren surface of the late Holocene Little Glass Mountain rhyolite flow. On a clear day, Lassen Peak is visible to the south and the rim of Crater Lake caldera to the north.

If you ascend to the top of the cone, you may also be able to discern the rocky tops of the Crater Glass Flows just above the trees to the northeast. These are the northeastern domes of the ~1,000-yr-old Little Glass Mountain rhyolite fissure. And looking east toward Medicine Lake caldera, the upper parts of the north, east, and south caldera rims can be seen, but the lake is not visible. One of the few seismometers on the volcano is located on the upper side of Little Mount Hoffman. Little Mount Hoffman is at the triple junction of Modoc National Forest on the east, Klamath National Forest on the northwest, and Shasta-Trinity National Forest on the southwest.

Mileage continues from parking at the base of Little Mount Hoffman. Drive west down a rather steep and rocky part of Road 43N48. **1.5**

5.6 Ignore road on left and continue driving west to follow road around the north side of Little Glass Mountain.

Figure 18. Photograph looking west-southwest from Little Mount Hoffman. Mount Shasta is on the horizon; the late Holocene Little Glass Mountain rhyolite flow is the barren, rocky area in the middle ground.

Stop 5a,b. Little Glass Mountain

Road 43N48 around the north side of the late Holocene Little Glass Mountain rhyolite flow (Fink, 1983) offers several places to park close to the edge of the obsidian flow (fig. 19). Although no specific mileages are given, two such places are labeled on the accompanying location map as 5a (41°34.78′ N., 121°40.66′ W.) and 5b (41°34.30′ N., 121°41.95′ W.). As at Stop 2 at Glass Mountain, **handle the obsidian carefully and wear eye protection and leather gloves**. This ~1,000-yr-old rhyolite contains ~1–2 percent of 1–2 millimeter (mm) phenocrysts including plagioclase, orthopyroxene, and oxide crystals. Like the slightly younger Glass Mountain 16 km to the east on the opposite side of the caldera, this flow and additional smaller domes (fig. 20) along the northeast-trending 8-km vent fissure contain numerous inclusions. The inclusion suite varies from rare granitoid fragments to hornblende gabbro cumulates and a variety of quenched magmatic inclusions ranging from basaltic to andesitic in composition (Mertzman and Williams, 1981; Grove and Donnelly-Nolan, 1986; Brophy and others, 1996; Donnelly-Nolan and others, 2016).

Figure 19. Photograph of the north edge of the ~1,000-yr-old Little Glass Mountain rhyolite flow. One of several places where the road and parking are close to the flow (see Stops 5a,b, fig. 7).

Figure 20. Photograph of a crease structure in one of the Crater Glass flows near the northeastern end of the 8-kilometer vent fissure for the rhyolite of Little Glass Mountain. The structure was created by internal mushrooming of rhyolite as the margins of the lava flow were restricted by adjacent topography. Scientist is sampling the flow for its paleomagnetic direction. See Donnelly-Nolan and others (2016) for discussion of paleomagnetism in young lavas at Medicine Lake volcano.

Quenched magmatic inclusions (QMI) range in silica content from 52.2 to 62.2 weight percent SiO_2, and cumulate inclusions span a compositional range from 51.8 to 57.3 weight percent SiO_2. Texturally, the noncumulate QMI are typically aphyric and contain microphenocrysts of olivine, plagioclase, and clinopyroxene in a vesicular glassy groundmass. Andesitic inclusions with >57 weight percent SiO_2 contain orthopyroxene, plagioclase, and iron-titanium oxide phenocrysts ± hornblende ± clinopyroxene phenocrysts in a vesicular rhyolitic glass matrix. The cumulate inclusions are relatively common and vary from 53 to 56 weight percent SiO_2. They typically contain plagioclase, clinopyroxene, olivine, orthopyroxene, hornblende, and iron-titanium oxides forming a network of crystals set in a vesicular matrix of rhyolite glass. See Donnelly-Nolan and others (2016) for chemical analyses and photomicrographs of the range of erupted materials from both the Glass Mountain and Little Glass Mountain eruptions. Only a few of the Glass Mountain inclusions contain hornblende and closely resemble the hornblende gabbro cumulates found at Little Glass Mountain. The Little Glass Mountain QMI show a broader range of compositions.

Continue west around Little Glass Mountain on Road 43N48.

7.8 T-junction with paved Road 15. Turn left. **3.8**

11.6 Drive south to roadcut through end of late Holocene Paint Pot Crater flow. Along the way, a roadcut on east (left) side of road may expose the contact of 2–3 m of white Little Glass Mountain tephra over black tephra of the Paint Pot Crater eruption. On your right as you head south, you will be able to see Paint Pot Crater through the trees on the west side of the road.

Stop 6. Paint Pot Crater Basaltic Andesite Flow

Be careful here. The paved road that cuts through the lava flow carries a significant amount of traffic including log trucks. Park as far off the road as possible. This stop (41°31.48′ N., 121°42.49′ W.) features the small, rough-surfaced basaltic andesite flow that erupted from Paint Pot Crater (fig. 21) about 1,170 years ago. The lava flow is also known as the Tilted Rock Lava Flow because of the many rafted spires of agglutinate (fig. 22) carried from the vent cone. Paint Pot Crater is named for its colorful appearance of black and red scoria with a partial covering of white pumice from the Little Glass Mountain eruption. The lava contains about 53 weight percent SiO_2 and a relative abundance (~5 percent) of 1–2 mm magnesian olivine ($Fo_{85.5}$) and high-An plagioclase ($An_{87.1}$) suggesting pre-eruptive magmatic H_2O contents of 3–6 weight percent. Petrologic evidence,

Figure 21. View east-northeast across the top of Paint Pot Crater, which has a mantle of white pumice from the eruption of Little Glass Mountain. The Little Glass Mountain rhyolite flow can be seen as the bare rocky area beyond the cone. Barely visible on the horizon is Little Mount Hoffman.

Figure 22. Photograph of roadcut in basaltic andesite of Paint Pot Crater at Stop 6. This small ~1,170-yr-old very rugged flow is mantled with numerous hills and spines of rafted agglutinate carried from the vents.

including hydrous minerals found in melt inclusions within olivine, indicates that this is a hydrous calc-alkaline subduction-related lava flow (Kinzler and others, 2000; see also Stop 8 for additional discussion). This is the youngest mafic lava flow at Medicine Lake volcano, but not the youngest erupted mafic lava. That distinction belongs to the quenched mafic magmatic inclusions in Little Glass Mountain and Glass Mountain (Grove and Donnelly-Nolan, 1986; Grove and others, 1997; Donnelly-Nolan and others, 2016).

From this stop, options include (1) driving north on this paved road (Road 15) west through Red Rock Valley to CA Hwy 97 (about 35 mi) and then north ~45 mi to Klamath Falls to complete the loop, (2) driving south to CA Hwy 89 (~24 mi), (3) retracing your route to Medicine Lake, or (4) proceeding to Stop 7.

To continue to Stop 7, drive north on paved Road 15. **3.8**

15.4 Ignore junction with Road 43N48 that takes you east around Little Glass Mountain and back to Medicine Lake. Continue north on paved Road 15. **2.1**

17.5 Turn right on Road 77. This well-graded gravel road takes you east to Road 49. At about 2.7 mi, keep right at junction with Road 44N54 and continue on Road 77. **5.0**

22.5 Park as far off the road as possible, preferably not at the bend in the road.

Stop 7. Big Cracks

Road 77 crosses big open cracks (fig. 23) here (41°35.79′ N., 121°38.38′ W.). Cracks extend from both sides of the road. The May 1998 issue of National Geographic Magazine includes a photograph from this location. Other cracks along this same set were featured in previous guides, but tree growth and poor road quality for access make that stop difficult and this one preferable. These cracks are part of an extensional set (Fink and Pollard, 1983) associated with the 8-km-long northeast-trending rhyolite fissure eruption about 1,000 years ago that emplaced Little Glass Mountain and the Crater Glass flows. Although the cracks trend northeast, the extension direction is east-west, reflecting the overall tectonic setting of the volcano. The rocks exposed in the walls of the cracks are fountain-fed andesite of the north rim, one of several rim-building high-Na_2O andesites that erupted about 100,000 years ago to form the rim of the caldera. You will also see this nearly aphyric andesite at Stop 20.

Continue 2 mi east on Road 77. About 1 mi east of the cracks, there is a trailhead on the left for access to the Crater Glass flows. Another 0.5 mi farther east, pass a geothermal drill site on the left. Geothermal exploration has led to numerous drill holes including those studied by Bargar and Keith (1997) and Donnelly-Nolan (2006). Measured temperatures of ~300 °C were reported by Hulen and Lutz (1999). **1.8**

Figure 23. Photograph of a pair of large cracks located a short distance south of Road 77. Cracks also extend north of road. These northeast-trending open cracks are some of the many created during the fissure eruption of the late Holocene rhyolite of Little Glass Mountain (Fink and Pollard, 1983).

24.3 T-junction with Road 49. [Note that a right turn takes you south into the caldera and to Medicine Lake.] Reset odometer to 0.0.

0.0 Turn left (north) onto Road 49, which almost immediately changes from paved to gravel. Proceed north toward Stop 8 and Lava Beds National Monument. **4.0**

4.0 At major junction of well-graded gravel roads, continue straight ahead. [If you turn right onto Road 44N01, the road takes you back to Stop 1, paved Road 97, and Tionesta]. In 1.1 mi, pass the Doorknob snowmobile parking area on the left; continue another 0.3 mi to a big bend in the road. **2.4**

6.4 Here the Medicine Lake-Lava Beds road (Road 49) crosses Road 44N53, which is an old railroad grade that was used for logging and has since been converted to a road. A left turn (to the west) takes you onto a poorly maintained part of the grade. **Be careful at this intersection because of limited visibility**. Reset odometer to 0.0.

0.0 For Stop 8, turn left onto Road 44N53. Stop 8 is worth a visit, but only if your vehicle has good clearance and you are willing to drive through vegetation that has encroached into the roadway. Watch for rocks and railroad debris along the 3 mi to Stop 8. Old railroad spikes can be hard on tires. This old railroad grade will take you past the quarried northeastern side of Cinder Butte, the main vent for the Callahan Flow. The quarried cinders were used in constructing the railroad grade. Continue another 0.1 mi. **3.1**

3.1 Park in small lava quarry on left, one of the few turnaround places along the old railroad grade through the lava flow.

Stop 8. Callahan Flow

This small quarry (41°41.41′ N., 121° 36.06′ W.) in a flow lobe (fig. 24) offers the opportunity to see drill holes for paleomagnetic sampling. The late Holocene Callahan Flow (fig. 25) erupted compositionally zoned lava about 1,180 years ago (fig. 26). At this location, the composition is basaltic andesite. The earliest erupted lava is andesite containing as much as 57.8 weight percent SiO_2; the last is basalt with as little as 51.8 weight percent SiO_2. Petrologic study (Kinzler and others, 2000) indicates that this lava flow, like the slightly younger Paint Pot Crater flow (Stop 6) and the amphibole-bearing mafic inclusions in Glass Mountain and Little Glass

Figure 24. Photograph taken at parking area for Stop 8. View south is toward vent cone of Cinder Butte. Quarrying for the old railroad grade exposed a cross-section of basaltic andesite flow lobe where one-inch-diameter drill holes for paleomagnetism can be found in the lava flow. Old railroad ties are remnants of the railroad logging that was done on the volcano.

Figure 25. Photograph looking south across the rugged andesitic northern end of the compositionally zoned Callahan Flow toward the main vent at Cinder Butte (partly covered by snow, photograph by Tanya Blacic).

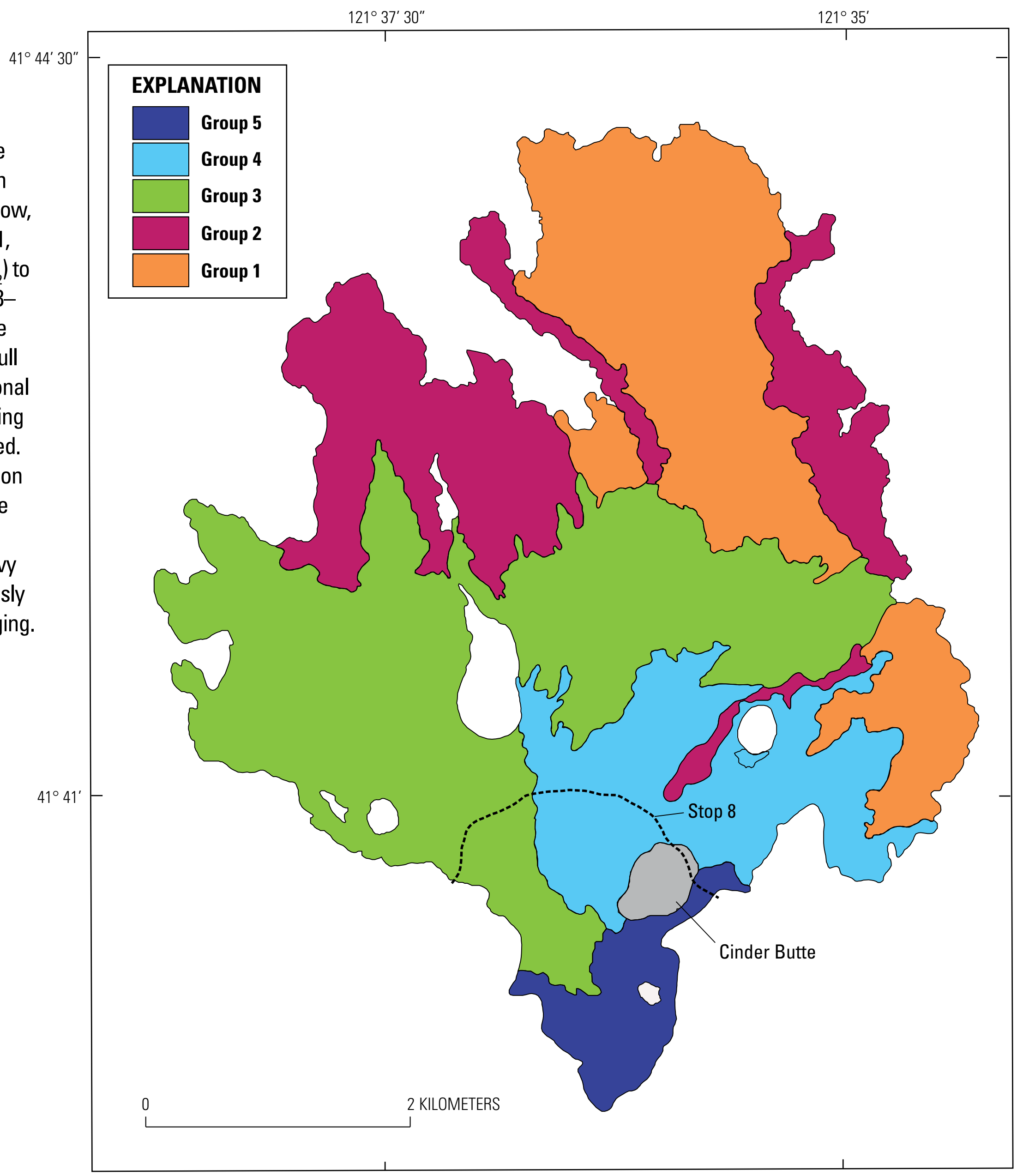

Figure 26. Map showing the distribution of compositions in the late Holocene Callahan Flow, from the earliest lava (group 1, 57.3–57.9 weight percent SiO_2) to the last-erupted (group 5, 51.8–53.3 weight percent SiO_2). See Kinzler and others (2000) for full explanation of the compositional zonation and for a map showing where samples were collected. Chemical analyses and location data for samples are available online in table 1 of Donnelly-Nolan and others (2016). Heavy dashed line is a road, previously a railroad grade used for logging.

Mountain, is calc-alkaline and was generated by hydrous subduction-related processes. Compositional evidence preserved in minerals in this basaltic andesite indicate magma mixing prior to eruption. Magnesium-rich olivine and calcic plagioclase are found with strongly resorbed and reacted orthopyroxene and sodium-rich plagioclase (Gerlach and Grove, 1982). These hydrous mafic lavas and inclusions contrast with previous mafic eruptions produced from dry tholeiitic basalt parental magma. You will see these latter basaltic lavas at the Tionesta crack (Stop 1), Black Crater (Stop 12), and Giant Crater (Stop 23) as well as andesitic lava (Burnt Lava Flow, Stop 22) derived from tholeiitic parental basalt. Evidence indicates that during postglacial time, the Medicine Lake magma system has alternated between dry and wet parental inputs (Kinzler and others, 2000; fig. 55 of Donnelly-Nolan and others, 2016, included here as figure 6).

This site provides an excellent view across this young mafic lava flow north toward the north-trending normal faults west of Tule Lake (fig. 27), and northeast toward Lava Beds and some of its large cinder cones such as Schonchin Butte (Stop 17). The northeastern part of the Callahan Flow is located within Lava Beds National Monument, where it is also called the “Black Lava.”

Retrace route and be very careful because of limited visibility at junction with Road 49. Reset odometer to 0.0.

0.0 Turn left on Road 49 and proceed north. **1.7**

1.7 Enter Lava Beds National Monument and leave Modoc National Forest.

Stop 9. Mammoth Crater

Just after entering Lava Beds National Monument, park on left (41°41.53′ N., 121°32.72′ W.) and take the short path uphill to the overlook into Mammoth Crater. This large pit crater (fig. 28) is one of the main vents for the late Pleistocene basalt of Mammoth Crater (Donnelly-Nolan and Champion,

Figure 27. Photograph looking north from Stop 8 across the rocky Callahan Flow, toward older faulted terrain west of Tule Lake and beyond the northern limit of lavas from Medicine Lake volcano.

Figure 28. Photograph of Mammoth Crater from south edge; crater is about 300 feet deep. Viewpoint for visitors and trail can be seen on far right, at and just below rim. This pit crater is one of the main vents for the basalt of Mammoth Crater, which covers about two-thirds of Lava Beds National Monument and hosts most of the lava-tube caves for which the monument is known. The lavas of this late Pleistocene eruption also extend both east and west from Lava Beds and cover a total area of about 250 square kilometers.

1987; Donnelly-Nolan, 2010). The eruption produced compositionally zoned basalt to basaltic andesite (48.4 to 55.9 weight percent SiO_2) tube-fed lava flows that cover two-thirds of the monument and extend both to the east and the west. Stops 14 (Skull Cave), 15 (Visitor Center and Mushpot Cave), and 18 (Captain Jacks Stronghold) are also in this unit, as are most of the iconic lava-tube caves featured in Lava Beds National Monument.

Continue north on the well-graded gravel road to T-junction with the paved Lava Beds Road. At this junction, you could turn right to access the visitor center and campground. Instead, the route described here turns left to drive north through the monument and return to Klamath Falls. Note that the route takes you by the entrance guard station, where an entrance fee is collected. **2.7**

4.4 Turn left and proceed north on the paved Lava Beds Road. **8.3**

12.7 Entrance guard station. After paying fee, continue 0.1 mi east. **0.1**

12.8 Junction on left with paved Hill Road. Turn left. [If you choose instead to drive east, the road will take you to Stop 18]. **0.6**

13.4 Road leaves Lava Beds National Monument and proceeds north within the west edge of the Tule Lake National Wildlife Refuge. **8.5**

21.9 Headquarters and visitor center on left for the Klamath Basin National Wildlife Refuges (including Tule Lake National Wildlife Refuge). **0.5**

22.4 Continue straight ahead (north) to return to Klamath Falls, but note this junction with East West Road, which can take you to the town of Tulelake and CA Hwy 139. **1.0**

23.4 On left is Camp Tulelake of the WWII Valor in the Pacific National Monument. World War II German and Italian prisoners of war were housed at the camp. Continue north. **2.4**

25.8 State Line Road (CA Hwy 161). Turn left and then immediately right onto Malone Road. **5.3**

31.1 Junction of Malone Road and OR Hwy 39. Turn left. Follow highway through Merrill to Klamath Falls and beginning of Day 1 route. **19.8**

50.9 Intersection of Washburn Way and South 6th Street, Klamath Falls, Oregon.

Day 2. Focus on Lava Beds National Monument

[Note: no sample collecting is allowed without a permit]

The second day is focused on geologic features of Lava Beds National Monument, which covers about ~180 km^2 on the north flank of Medicine Lake volcano. See map figure 29 for stop locations, including Stop 9 at Mammoth Crater from late on Day 1. The National Park Service has highlighted a variety of interesting locations within the park including cinder cones, spatter cones, and pit craters, some of which are described in this geologic guide, but the monument is perhaps best known for its caves. Hundreds of lava-tube caves have been discovered, primarily within the dozen or so lava tubes that form the distributary system for the late Pleistocene basalt of Mammoth Crater, which covers about two-thirds of the monument. The caves formed when lava continued to flow downhill by way of the tubes, but the supply of new lava from the vents ceased. Access to the caves is created when roof collapses occur along the tube systems. Multiple vents in the southern part of the monument, including Mammoth Crater itself, fed the basalt to the north, but also well beyond the monument to the west and east. Although much of the monument was resurfaced during this eruptive event, effectively burying older geologic terrain, one notable exception is the blocky Schonchin Flow near the center of the monument that acted to divert the more fluid basalt to the west and to the east. This rugged block lava flow is poorly vegetated and appears very young, but in reality it is older (~65,000 years old) than the adjacent and more fluid basalt of Mammoth Crater, which is poorly dated at ~35,000 years old (Donnelly-Nolan, 2010).

The basalt of Mammoth Crater also hosts Captain Jacks Stronghold (Stop 18), a natural fortress where Modoc Indians held off the U.S. Army for months during the Modoc War of 1872–73. The cracked and broken environment of the Stronghold was created when the basalt flow encountered the water of ancient Tule Lake, stopped, and inflated as lava continued to be fed from the vents. As the surface of the lava flow rose, some parts failed to rise, creating pits, while other lava squeezed out the front of the flow forming tumuli. To the south, the uplifted plateau surface is relatively smooth.

The youngest lava flows in the monument include two that erupted about 12,500 years ago after ice melted off the upper slopes of Medicine Lake volcano. One is the Devils Homestead flow on the west side of the monument, which was fed from the Fleener Chimneys spatter vents (Stop 13). The other is the Valentine Cave flow in the southeastern part of the monument. It hosts the eponymous cave (Stop 16), which is one of the most photogenic in Lava Beds and one of the relative few lava tube caves that is not located within the basalt of Mammoth Crater. The youngest eruption that occurred within the monument is the basalt of Black Crater and Ross Chimneys. These two small lava flows erupted about 3,140 years ago from a northeast-trending alignment of spatter cones including Black Crater (Stop 12). The youngest

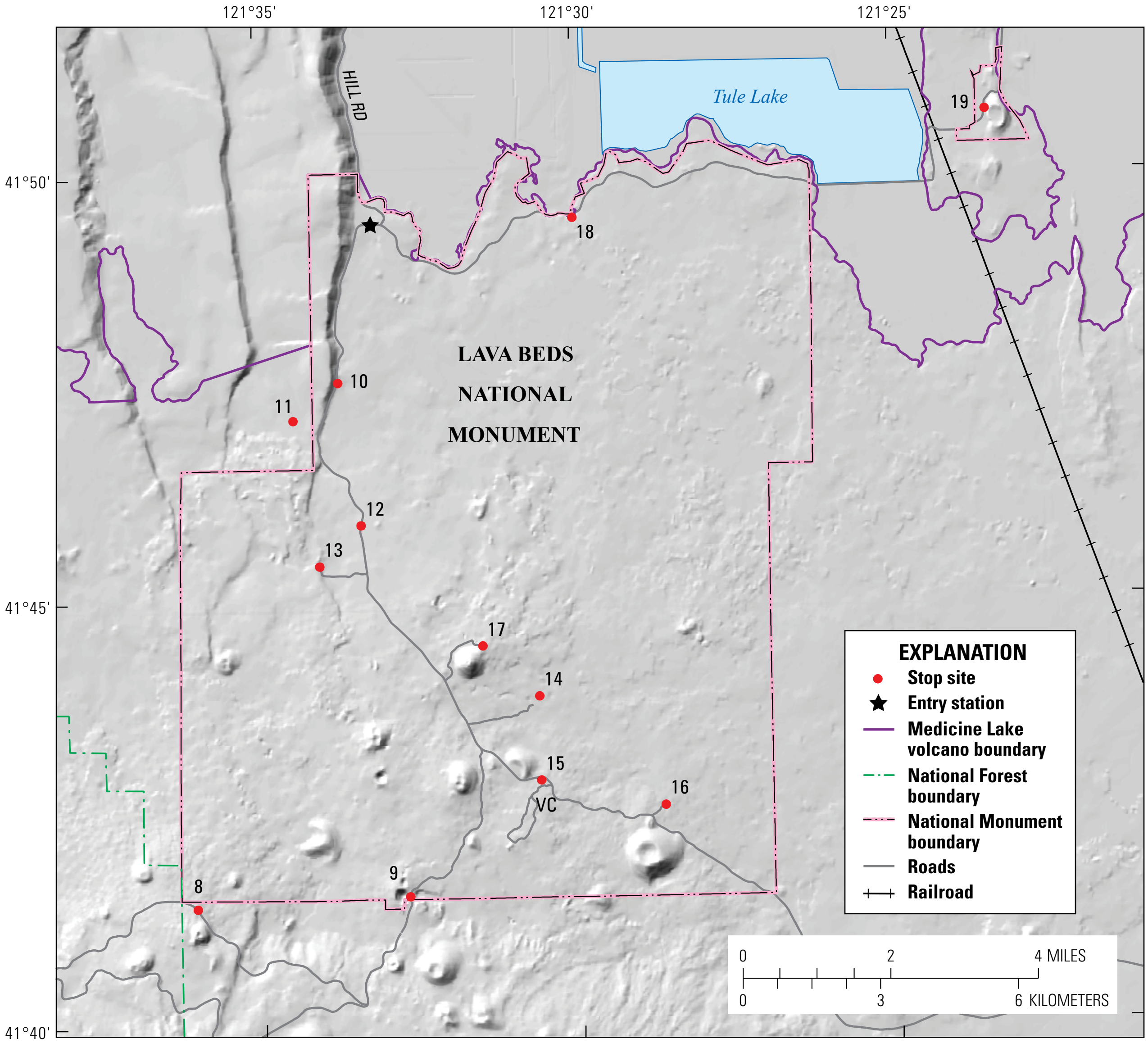

Figure 29. Shaded relief map showing stops in and near Lava Beds National Monument. VC, visitor center; star, location of entrance station. See figure 7*C* for location on Medicine Lake volcano.

lava flow, however, is in the southwest corner of Lava Beds National Monument where part of the 1,180-yr-old Callahan Flow (Stop 8) lies within the monument boundary. The park boundary extends almost to the vent at Cinder Butte (fig. 25), although most of the flow lies outside the monument. The youngest volcanic material in the park is pumice primarily from the Little Glass Mountain eruption (Stop 5) that took place to the southwest about 1,000 years ago.

The primary geologic reference for Lava Beds National Monument is a geologic map of the park (Donnelly-Nolan and Champion, 1987), which was later slightly modified and incorporated into the geologic map of Medicine Lake volcano (Donnelly-Nolan, 2010). Maps and descriptions of some of the caves can be found in Waters and others (1987).

0.0 As with Day 1, this trip begins in Klamath Falls, but after passing through Merrill, Oregon on OR Hwy 39, the route turns south on Malone Road (see also road log for end of Day 1). **19.8**

19.8 About 2.3 mi east of Merrill, turn right onto Malone Road. At State Line Road (CA Hwy 161 and Oregon-California border), turn left and then immediately right to continue south on paved Hill Road into Lava Beds National Monument, which abuts the south side of Tule Lake National Wildlife Refuge. See additional description of this route on Day 1 after Stop 10. **18.3**

38.1 At T-junction of Hill Rd with Lava Beds Road, turn right (west). Note that a left turn (east) would take you to Stops 18 and 19. **0.1**

38.2 Entrance guard station. Stop and pay fee. Continue west and south on the paved Lava Beds Road. **2.5**

40.7 Parking for Devils Homestead Overlook.

Stop 10. Devils Homestead Overlook

This stop (41°47.59′ N., 121°33.73′ W.) on a bench along the Gillem Fault at the west boundary of the Tule Lake basin allows views north along the fault (fig. 30). The fault exposes much older lavas, primarily basalts, which are capped here by welded silicic tuff dated at about 2 million years (Donnelly-Nolan, 2010). This overlook also provides a broad overview south (fig. 31) toward the shield-shaped summit profile of Medicine Lake volcano. The view east-northeast is across lavas including basalt of Mammoth Crater and underlying lavas, and then beyond to the lake basin and the palagonite tuffs of the Petroglyphs section of the park (Stop 19). Directly below you is the rugged surface of the ~12,500-yr-old Devils Homestead lava flow that erupted from spatter vents at Fleener Chimneys farther south on the fault (Stop 13).

Exit the overlook parking lot, turn left (south) and continue for a short distance to Road 46N21 on the right. **0.8**

Figure 30. Photograph looking north from Devils Homestead Overlook (Stop 10) along the Gillem Fault, which forms the west edge of the Tule Lake basin.

Figure 31. Photograph looking south from Devils Homestead Overlook (Stop 10) toward the shield-shaped edifice of Medicine Lake volcano. Dark, rubbly area below overlook is the Devils Homestead flow, a postglacial basaltic lava flow erupted at the Fleener Chimneys spatter vents (Stop 13), which are located farther south along the extension of the Gillem Fault. The overlook is located on an uplifted bench of the fault (photograph by Tanya Blacic).

41.5 Turn right (west) onto road indicated as “not maintained.” The paved surface soon turns to gravel and the road leaves Lava Beds National Monument. **0.4**

41.9 Take the right fork and continue for about 0.2 mi. **0.2**

Stop 11. Tuff of Antelope Well

Park (41°47.14′ N., 121°34.45′ W.) and walk into the shallow ditch on the west side of road. This partly welded dacitic ash-flow tuff (fig. 32) erupted from the center of the volcano ~180,000 years ago. It is the only known ash-flow tuff at Medicine Lake volcano and forms the volcano’s single distinctive marker bed (Donnelly-Nolan, 2010). It can be found in small outcrops scattered around the volcano, although it is most abundant on the northwest flank, where it was first recognized by Anderson (1941) who named it the “andesite tuff.” Donnelly-Nolan and Nolan (1986) documented postemplacement flooding they attributed to eruption of the tuff through an ice cap on the upper part of the volcano. At this field trip stop, black partly welded pumices are visible in the brownish

Figure 32. Photographs showing the ~180-ka tuff of Antelope Well, the only ash-flow tuff known to have erupted at Medicine Lake volcano, at Stop 11. *A*, Quarried exposure in small draw just outside of Lava Beds National Monument; *B*, close-up shows texture of tuff. The base of the tuff is exposed at the northern water-washed end of this draw.

matrix. At the north end of the gully, the rarely seen base of the tuff is exposed in a water-washed outcrop.

Retrace route about 0.6 mi to T-junction with paved Lava Beds Road. Reset odometer to 0.0.

0.0 Turn right (south) on the paved Lava Beds Road. The road climbs down the east-facing fault scarp of Gillems Fault before turning east across the Devils Homestead flow where a wayside marker asks, “What in the world is aʻā?” Continue on the paved road to the parking area for Stop 12. **1.5**

1.5 Parking for Black Crater

Stop 12. Black Crater

A short trail from the parking lot (41°45.91′ N., 121°33.40′ W.) to Black Crater (fig. 33) allows visitors to climb up a few of the many spatter vents and walk on the pahoehoe lava of this ~3,140-yr-old basaltic fissure eruption. Tree molds can be seen along some of the paths. One large tree mold was excavated and pieces of charcoal from a burned juniper tree were found, providing material for radiocarbon dating (Donnelly-Nolan and others, 1991; Nathenson and others, 2007), which yielded an age of the eruption. This lava flow and the separately named Ross Chimneys flow that is located farther northeast along the vent fissure constitute the youngest eruption that has taken place entirely within Lava Beds National Monument (note that part of the 1,180-yr-old Callahan Flow is in the southwest corner of the monument). A map showing compositional zonation within this small unit was published in Donnelly-Nolan and others (2016) along with the chemical analyses. The detailed sampling for compositional variation was prompted by information in Condie and Hayslip (1975). Petrologic work (Sisson and Layne, 1993) documented the low water content of this tholeiitic basalt.

Turn left out of parking area and drive south on the paved road. **0.6**

2.1 Turnoff on the right to Fleener Chimneys. Turn right and follow well-graded gravel road directly west toward the fault scarp. The road turns north at the scarp into the parking lot. **0.8**

2.9 Parking lot for Stop 13. A restroom and picnic area make this a pleasant place for lunch.

Stop 13. Fleener Chimneys

The parking lot (41°45.42′ N., 121°34.06′ W.) and adjacent picnic area are built over near-vent fluid pahoehoe lava from the spatter vents that are accessed by a short trail up (fig. 34) onto the fault scarp. Farther north down the flow, the lava breaks up into aʻā and is crossed by the paved road on the route between Stops 11 and 12. This lava flow is not directly dated, but its age is constrained by its paleomagnetic direction, a near-identical match to the directions of seven other basaltic eruptions that occurred on the volcano (Champion and Donnelly-Nolan, 1994) in postglacial time ~12,500 years ago (Nathenson and others, 2007). The basaltic andesite of Valentine Cave in the southeast corner of the monument (Stop 16) is also part of this postglacial mafic event. The picnic tables are of geologic interest because the rock slabs supporting the tables (fig. 35) were quarried from the tuff of Antelope Well.

Figure 33. Photograph of person standing on pahoehoe lava at the base of the Black Crater spatter vent, where a path ascends and allows a close-up view of the vent. The small, late Holocene basalt of Black Crater and Ross Chimneys erupted ~3,140 years ago from multiple vents along a north-northeast trend.

Figure 34. Photograph of paved path ascending from parking area and picnic area to the Fleener Chimneys spatter vents (Stop 13), which are located on the southern extension of the Gillem Fault. The vents produced the basaltic Devils Homestead flow ~12,500 years ago, which can be seen from Stop 10.

Figure 35. Photograph of table at picnic area located at base of Fleener Chimneys (Stop 13) that is supported by slabs of the tuff of Antelope Well, seen at Stop 11 (photograph by John Tinsley, USGS).

Retrace route to paved Lava Beds Road. **0.8**

3.7 Turn right onto paved Lava Beds Road and proceed south. **2.5**

6.2 Road on left to Skull Cave. Turn left and follow the paved road east. **1.1**

7.3 Parking area for this very large lava-tube cave.

Stop 14. Skull Cave

A well-trodden pathway and stairs take you from the parking area (41°43.87′ N., 121°30.64′ W.) into the very large collapse trench (fig. 36) and then into the cave itself. A light source is a necessity for exploring this cave and especially for climbing down into the lower level that typically contains ice. Lights can be borrowed at the visitor center. Even if you don't have a light, you can walk into the cave entrance and experience the size of this lava tube that carried large volumes of lava from its vent at Modoc Crater about 2 mi to the southwest (one of many vents for the basalt of Mammoth Crater) around the east side of the Schonchin Flow out to the northern part of the monument and to Captain Jacks Stronghold (Stop 18). See also Stops 9 and 15 in the basalt of Mammoth Crater.

Drive back to the paved Lava Beds Road. **1.1**

8.4 Turn left (south). **0.5**

8.9 On right, note gravel road to Mammoth Crater and Medicine Lake. Continue straight ahead on the paved road. **0.8**

9.7 At sign for the visitor center, turn right, then left into the parking lot. If you continue straight ahead, the road takes you up Cave Loop Drive to a variety of additional caves you can explore. **0.1**

Figure 36. Photograph of the entrance to Skull Cave (Stop 14), one of the largest lava-tube caves in Lava Beds National Monument and one of the main distributary channels for basalt of Mammoth Crater. Note waist-high railing for scale along path from parking area to cave.

Stop 15. Visitor Center and Mushpot Cave

The visitor center (41°42.88′ N., 121°30.63′ W.) has restrooms, water, and indoor displays about biology, history, and geology (fig. 37). Items such as books, maps, and t-shirts are available to purchase. Entrance fees can be paid here and flashlights for exploring caves can be borrowed. The entrance to Mushpot Cave (fig. 38) is located along a short trail past the entrance to the visitor center. It is the only lighted cave in the monument and well worth a visit. Many interesting cave features are described on the interpretive signs. The cave ceiling is low, so be careful of your head while walking on the paved pathway to the end of the cave. The vent for this lava tube is Mammoth Crater.

Return to the paved Lava Beds Road. **0.1**

9.9 Turn right and drive east past the road on your left to the campground. **1.9**

11.8 At sign for Valentine Cave, turn left [If you continue straight ahead this road will take you 12.1 mi southeast to Road 97 and to Tionesta]. **0.2**

12.0 Drive 0.2 mi on paved road to the parking area for Stop 16 (41°42.56′ N., 121°28.68′ W.).

Figure 37. Photograph of the visitor center at Lava Beds National Monument, which has displays of biology, geology, and history, along with sales of books and other items. Restrooms and water available here at Stop 15. Short path to lighted Mushpot Cave begins at left side of building.

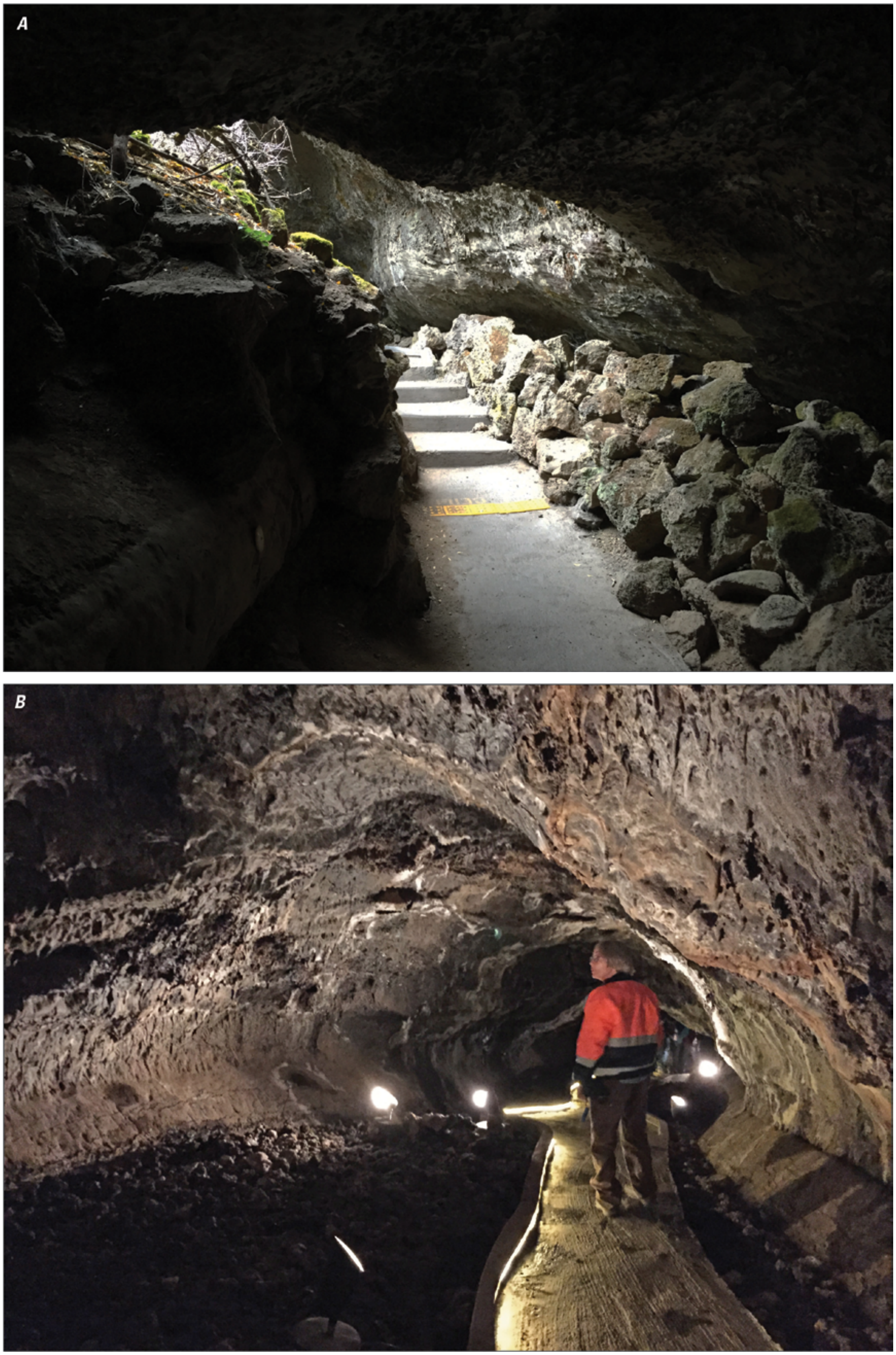

Figure 38. Photograph of Mushpot Cave, the only lighted cave in the monument. Stairs into the cave entrance (*A*) and a paved path (*B*) with multiple interpretive signs make this a must-see stop. The vent for this lava tube is Mammoth Crater.

Stop 16. Valentine Cave

This accessible and very photogenic cave displays beautiful high-lava marks on the walls and central column that can be seen at the entrance even without a light (fig. 39). This is one of the limited number of lava tube caves in Lava Beds National Monument that is not located in the basalt of Mammoth Crater. Instead, the Valentine Cave flow is postglacial and ~12,500 years old. The vents for this flow are located uphill to the southwest just outside the monument.

Return to the paved Lava Beds Road. **0.2**

12.2 Turn right (north).

Follow the paved road past the visitor center and continue north. **3.8**

16.0 Road on right to Schonchin Butte. A gravel road takes visitors around to the northeast side of this very large cinder cone to the base of the walking trail to the top. **4.8**

Figure 39. Photograph of entrance (*A*) to Valentine Cave (Stop 16). This very accessible cave is one of the few in the monument that is not in the basalt of Mammoth Crater. Instead, this lava tube is in the ~12,500-year-old postglacial basalt of Valentine Cave. *B*, View from the entrance of the cave, without addition of artificial light, shows high-lava marks on wall of central pillar (on right).

Stop 17. Schonchin Butte

This is an optional and time-consuming stop, but if you are ready for a hike and not concerned about time, then a walk from the base of the cone (41°44.47′ N., 121°31.52′ W.) to the fire lookout at the top of this large andesitic cinder cone (fig. 40) is worth the effort. Views from the top (fig. 41) are spectacular and encompass all of Lava Beds National Monument and the Tule Lake basin, Mount Shasta, and the north rim of Medicine Lake volcano. The andesite of Schonchin Butte is the most silicic lava erupted within the monument and contains about 57.2 weight percent SiO_2. The high margin of the blocky Schonchin Flow diverted the younger and more fluid basalt of Mammoth Crater to the east and west around its southern side.

Retrace your route to the paved Lava Beds Road. Reset odometer to 0.0. **1.0**

0.0 Turn right and follow the paved road north past the entrance guard station. **7.4**

7.4 Junction with Hill Road on your left. Continue straight ahead to the east. **3.2**

10.6 Parking area on right for Captain Jacks Stronghold (41°49.49′ N., 121°29.99′ W.).

Figure 40. Photograph looking south of Schonchin Butte (Stop 17), taken from near Skull Cave (Stop 14). The fire lookout on top of this nearly 500-foot-high andesitic cinder cone is visible perched atop the right side of the cone.

Figure 41. Stop 17 is an optional walk to the top of Schonchin Butte. Here the view from the top looking northwest across Lava Beds National Monument shows the Gillem Fault and parallel fault scarps to the west.

Stop 18. Captain Jacks Stronghold

A dramatic confluence of geologic and human history took place here in the winter of 1872–73 when Captain Jack and his band of Modoc Indians occupied the Stronghold during the Modoc War. With adjacent water in Tule Lake (now drained for agriculture), and shelter and protection in the Stronghold, the Modocs held off the U.S. Army for months. The key to that occupation is the geology. The Stronghold is located in the end of the basalt of Mammoth Crater flow, where the lava stopped when it reached the lake water, inflated, and cracked to form a rugged landscape of tumuli, lift-up caves, and noninflation pits—in effect, a natural fortress. Two paths, one longer, one shorter, are available to walk easily through the terrain. The short path allows the visitor to walk along the connected central axes of a semi-circular array of tumuli that provided natural fortifications (fig. 42). Waters (1981) described the critical influence of the geology on the Modoc War, although his understanding of how the broken topography was formed has since been revised by studies of inflated basalt flows. Excellent descriptions of basalt flows such as these that are fed by tubes flowing across relatively flat terrain are found in Chitwood (1994) and Hon and others (1994). This stop also provides good views south across the plateau surface of the inflated flow, which allowed an easy escape route for the Modocs. South of the plateau surface are numerous cinder cones and on the horizon the broad profile of Medicine Lake volcano (fig. 43) dominates. To the west is the Gillem Fault; to the north the Tule Lake basin.

Restrooms and a few picnic tables are available.

Turn right out of the parking lot and drive east on the paved road. Short roads to viewpoints are available on the left. **3.8**

14.4 Leave Lava Beds National Monument and continue east. **1.7**

16.1 T-junction with County Road 111, turn left. **0.7**

16.8 Immediately after you cross the railroad tracks, turn right onto County Road 126. Follow this well-graded gravel road 0.9 mi to the west-facing cliff ahead of you. **0.9**

Stop 19. Petroglyphs and Wave-cut Bench in Tuff Ring

This stop in the Petroglyphs section of Lava Beds National Monument is listed last in the Day 2 sequence because it is best viewed in the late afternoon. Sunlight on the west-facing cliff illuminates the petroglyphs carved into the wall of caliche that has formed on the vertical surface of the eroded tuff ring (fig. 44). The parking area (41°50.71′ N., 121°23.48′ W.) is on the beautifully exposed wave-cut bench (fig. 45) created by ancient Tule Lake. Eruptions through the lake along a dominantly north-south eruptive fissure ~275,000 years ago (Donnelly-Nolan, 2010) produced this tuff ring (Prisoners Rock) and the next one to the north (The

Figure 42. Stop 18 at Captain Jacks Stronghold features the interplay of geology and history. During the Modoc War, the Modoc Indians held off the U.S. Army here during the winter of 1872–73. The photographs (*A*,*B*) show protected paths within tumuli at the end of the inflated basalt of Mammoth Crater. This broken terrain was created when the lava reached the water of Tule Lake, chilled, and stopped flowing northward, while to the south the lava surface rose upward as tube-fed lava continued to flow from the vents upslope. The view in (*B*) is northeast toward the Peninsula tuff ring (see description of Stop 19).

Figure 43. Photograph looking south from the shorter of two trails in Captain Jacks Stronghold, toward the broad rim of Medicine Lake volcano. View is across the relatively gentle topography of the uplifted surface of basalt of Mammoth Crater.

Figure 44. Aerial view of the eroded Prisoners Rock tuff ring, part of the ~275-ka eruption through ancient Tule Lake at the far northeastern extent of eruptions associated with the Medicine Lake volcano magma system. The north-south vent trend reflects east-west extension here at the west edge of the Basin and Range Province. The Petroglyphs section of Lava Beds National Monument features petroglyphs carved into the caliche that formed on the wall of eroded tuff adjacent to a wave-cut bench in the tuff (Stop 19). Native Americans were thought to have accessed the wall by canoes when the lake water stood higher. View is to the southeast.

Figure 45. Photograph of wave-cut bench in palagonite tuff at the Petroglyphs (Stop 19). View is north toward The Peninsula, another eroded tuff ring that formed as part of the same eruption. The Peninsula overlooks the World War II Japanese Relocation Camp to the east and is now, in part, included in the WWII Valor in the Pacific National Monument.

Peninsula). The basaltic feeder dike is exposed at the top of this tuff ring. Once the deposits of tuff were high enough to keep lake water away from the vents, a lava flow emerged between the two primary tuff vents (Lavine, 1994; Lavine and Aalto, 2002).

From the parking area, turn right (north) and follow the gravel road about 0.4 mi across the alignment of the eruptive fissure. **0.4**

18.1 County Road 120. Turn left. Follow the paved road as it curves along the east side of the tuff rings. Cross railroad tracks and arrive at CA Hwy 139. **2.7**

20.8 Turn left. About 0.6 mi north, a historical monument on the east side of the road commemorates a World War II Japanese internment camp. The camp was the largest of 10 such camps and housed as many as 18,700 people. Some of the original buildings remain and the Tulelake airfield is located on the grounds of the former camp. This is the second site (along with Camp Tulelake described prior to Stop 10) of the Tule Lake Unit of the WWII Valor in the Pacific National Monument.

Follow CA Hwy 139 about 10 mi north past the town of Tulelake into Oregon, where the same highway becomes OR Hwy 39, goes through the town of Merrill, and continues northwest into Klamath Falls (see also directions for beginning of Day 1). **34.6**

55.4 Intersection of Washburn Way and South 6th Street, Klamath Falls, Oregon.

Day 3 (North to South Across the Volcano)

Follow the same route south from Klamath Falls as on the morning of Day 2 (before Stop 10). After you enter Lava Beds National Monument, turn right from Hill Road onto the Lava Beds Road, pay entrance fee at the small guard station, and follow the paved road south past Schonchin Butte. Continue 0.5 mi south beyond the turnoff to Skull Cave. **47.5**

0.0 Reset odometer at junction with gravel road to Medicine Lake. Turn right. Follow the road past Mammoth Crater (Stop 9) and leave Lava Beds National Monument. Enter Modoc National Forest and continue south on Road 49. **10.8**

10.8 Junction with Road 77 on your right just after gravel turns into pavement. [If you turn right here, a 1.9-mi drive on Road 77 takes you to Stop 7]. Continue straight ahead onto one-lane paved road. **0.2**

11.0 Drive a short distance south. Paved Road 49 is narrow here and parking is limited, so find space as far off the road as possible.

Stop 20. North Rim Caldera View and Glacial Evidence

Park at or near 41°36.73′ N., 121°36.96′ W. On the right side of the road before it curves and heads downhill, walk west through the small trees at the edge of the road and onto a smooth, polished, and striated surface (fig. 46) of the glaciated andesite of the north rim (also seen in the walls of the cracks at Stop 7). Look around and you will find 1-inch-diameter drill holes from sampling for paleomagnetism. The glassy carapace of this dense aphyric andesite flow was removed by ice, and the striations here indicate a north-northwest azimuth of ice movement. The Na_2O content of this andesite is unusually high for Medicine Lake volcano (~5 weight percent at ~60 weight percent SiO_2). Recent petrologic work by Mandler and others (2014, including a supplemental data file of chemical analyses of the andesite of the north rim) showed that this composition can be generated by fractionation from a mafic parent containing moderate amounts of water. Walk north along the road a short distance for a view into the caldera. The view is now (2016) partly obscured by trees, so you may wish to climb uphill for a better view (fig. 47). The caldera view includes Medicine Lake and the ~5-ka Medicine Lake Glass Flow (Stop 21).

Figure 46. Photograph of glacial polish and striations visible at Stop 20, on andesite of the north rim. View is approximately east-southeast across northwest-trending striations.

Figure 47. A short climb uphill from the parking for Stop 20 yields a good view south across the Medicine Lake caldera. The south rim, constructed of andesite similar in age and composition to the andesite of the north rim, is visible just beyond Medicine Lake. The rocky lava flow in the middle ground is the ~5-ka dacitic Medicine Lake Glass Flow (see Stop 21).

Drive down the one-lane paved road approximately into the caldera. **1.0**

12.0 Park in turnout on right.

Stop 21. Medicine Lake Glass Flow

The turnout (41°36.58′ N., 121°36.10′ W.) is just north of the flow margin. If you have already seen Glass Mountain and Little Glass Mountain, you could skip this stop, but this is an interesting young dacitic (~69 weight percent SiO_2) lava flow (fig. 48). This ~5 ka lava flow contains a sparse suite of inclusions, notably both mafic and silicic plutonic rocks as well as hornblende-bearing andesitic quenched magmatic inclusions (Grove and Donnelly-Nolan, 1986; Donnelly-Nolan and others, 2016).

Follow the single-lane paved road around the east side of the Medicine Lake Glass Flow. [At 1.1 mi past Stop 21, note narrow dirt Road 43N99 on left. It connects through Arnica Sink to the upper part of Glass Mountain (Stop 2).] Continue south on the paved road, which widens to two lanes about 0.3 mi north of the turnoff to Medicine Lake. **2.6**

14.6 Turnoff to Medicine Lake. Continue straight ahead. **1.7**

16.3 Junction on left with paved Road 97 from Tionesta [see route from east side on Day 1]. **0.5**

16.8 Turn left onto gravel Road 43N17. Remain on this road heading first east and then south. The road transitions from gravel to dirt, but the road should be adequate for a passenger car that has reasonable clearance. Pass

Figure 48. Two photographs of the Medicine Lake Glass Flow show an aerial view and a close-up of the surface topography. Aerial view (*A*) looks west across the flow; (*B*) shows sampling for paleomagnetism in one of the many crease structures on the surface of the flow. Stop 21 is close to the northern margin, near the right side of the flow as seen in (*A*).

junctions on the right to Bullseye Lake at 1.1 mi and to No Name Lake at 1.3 mi, and on the left at 1.5 mi to Paynes Spring. Continue straight ahead. **1.9**

18.7 Junction with Road 43N42 on left [note that a left turn here takes you northeast to paved Road 97]. Continue straight ahead on Road 43N17 to Burnt Lava Flow. **1.1**

19.8 Junction with Road 43N54 on left; ignore and continue straight ahead. **1.8**

21.6 T-junction with Road 56 that skirts the north edge of the Burnt Lava Flow. Turn left (east). [Note also instructions on Day 1 between Stops 1 and 2 for access to Burnt Lava Flow from Road 97 by way of Road 43N12] **0.8**

22.4 Park near spatter rampart on north side of road.

Stop 22. Burnt Lava Flow and Spatter Vents

This stop (41°31.04′ N., 121°31.96′ W.) is located directly north of the prominent vent cone of High Hole Crater and at the south end of a spatter rampart that formed part of the north-south vent alignments for this ~3-ka andesite flow (fig. 49). Burnt Lava Flow covers about 34.3 km^2 and has a volume of about 0.5 km^3. The rugged and barren surface suggested an age of only a few hundred years to previous workers (for example, Finch, 1933), but tephra from Little Glass Mountain can be seen on relatively flat surfaces on the lava flow and charcoal dug from the base of a tree mold gave a radiocarbon age of 2,950 years before present (Nathenson and others, 2007). Despite the similar youthful, rugged appearance of the Callahan Flow on the north flank of the volcano (Stop 8), the magmatic processes generating these two lava flows are quite different. Petrologic study (Grove and others, 1988) of the andesitic lava and of quenched basaltic magmatic inclusions, together with the presence of partly melted granitic inclusions led to the interpretation that the andesite was created by fractional crystallization of dry parental HAOT basalt combined with assimilation of granitic crustal material. Diagrams of two geometries that could lead to the generation of the andesite (Grove and others, 1988, their fig. 4) are shown in figure 50.

The andesite of Burnt Lava Flow is sparsely porphyritic, containing about 4 volume percent phenocrysts, which display unequivocal evidence of magma mixing. The textures of some of phenocrysts in backscatter images (Grove and others, 1988, their fig. 3*A-D*) are shown in figure 51. There are two populations of olivine phenocrysts, one with magnesium-rich cores and the other with iron-rich cores. Three plagioclase populations, calcium-rich, intermediate in anorthite content, and anorthite-poor, are present. There is also iron-augite and iron-rich orthopyroxene with magnesium-rich overgrowth rims. Also present are quenched blobs of HAOT that display a sugary gray texture. As you look around at the blocky margin of the andesite of Burnt Lava Flow, you can find small (millimeter to centimeter-sized) blobs of HAOT and rarer, white centimeter-sized irregular inclusions of highly melted granitic crust in this a‘ā lava flow.

Analyzed whole-rock samples from the andesite of Burnt Lava Flow (Grove and others, 1988) indicate that a small amount of compositional variation is present (56 to 58 weight percent SiO_2). The spatial distribution of the samples suggests that the higher-silica magma erupted last (Donnelly-Nolan and others, 2016).

Turn around and retrace your route. **0.8**

Figure 49. Photograph looking south toward High Hole Crater, the main vent for the ~3,010-yr-old Burnt Lava Flow. The photograph was taken from the northern spatter vents, which are part of the north-south vent alignment for this a‘ā andesite flow (Stop 22). Photograph by Dominique Weis.

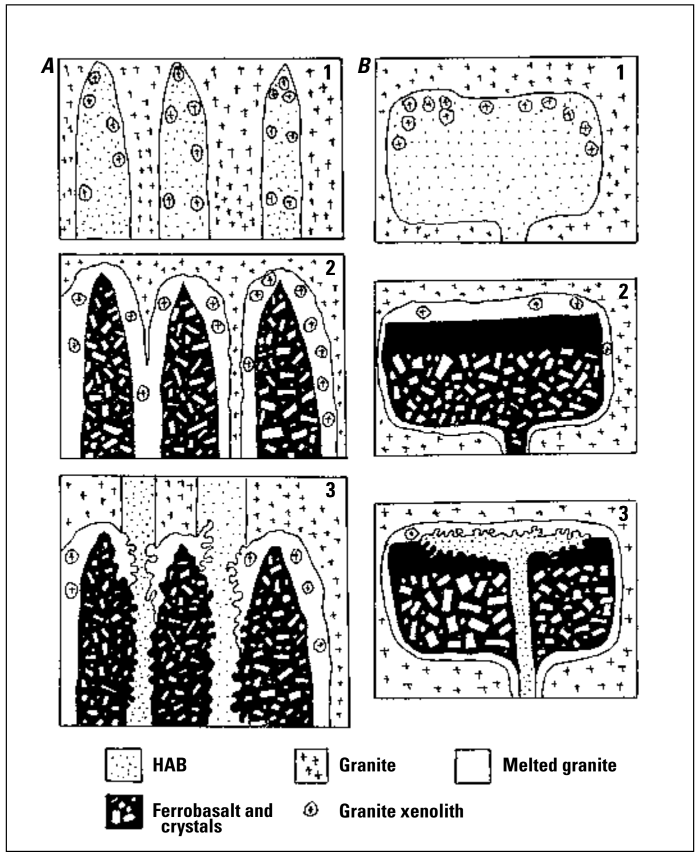

Figure 50. Diagram from Grove and others (1988, their fig. 15) models two possible scenarios that could produce decoupling of heat and mass transfer in the generation of the andesite of the Burnt Lava Flow. (*A*) Depicts a dike swarm and (*B*) shows a shallow magma chamber. Both involve assimilation of granite, which is present as inclusions in the andesite. HAB is high-alumina basalt, also known as high-alumina olivine tholeiite (HAOT).

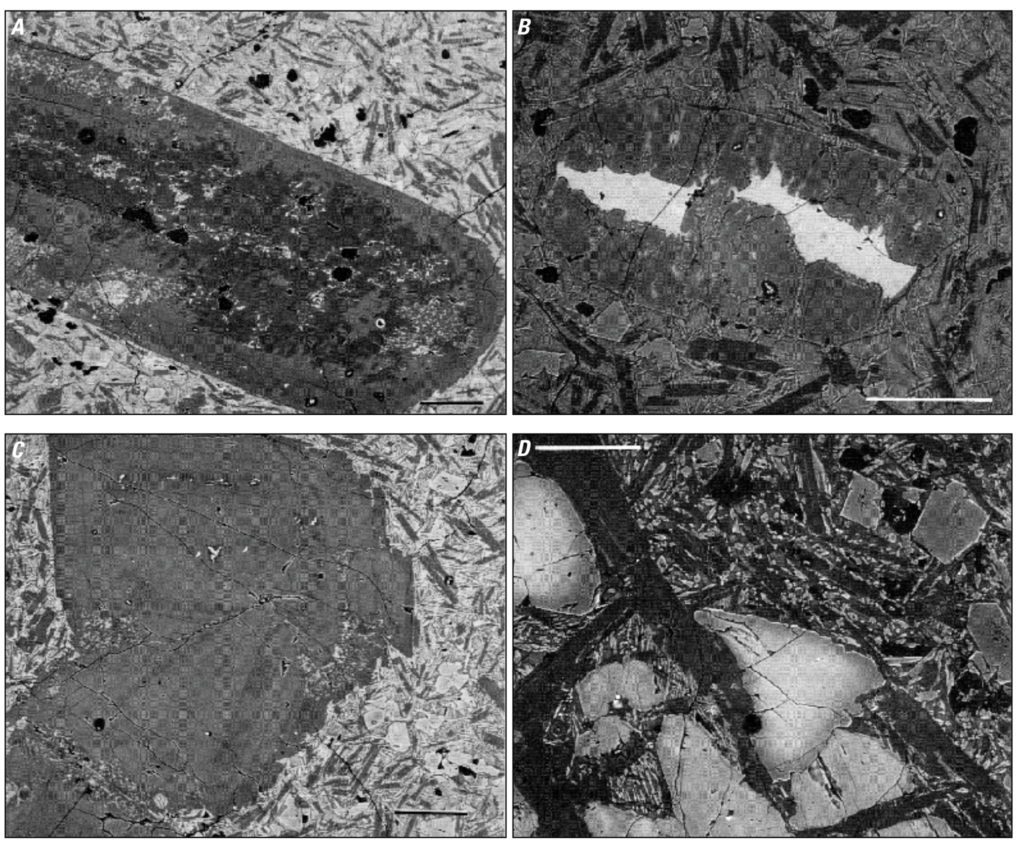

Figure 51. Back scattered images of textures in mixed andesite of the Burnt Lava Flow (Grove and others, 1988, their figs. 3*A*–*D*). *A*, is a plagioclase xenocryst of andesine composition with a sodium-rich core enclosed by calcium-rich overgrowths. *B*, shows light-colored iron-rich orthopyroxene with magnesium-rich reaction rim. *C*, is an oscillatory-zoned anorthosite-rich plagioclase crystal. *D*, shows elongate plagioclase together with large, slightly rounded olivine and smaller blocky pyroxene. There are two populations of olivine phenocrysts, one with magnesium-rich cores and the other with iron-rich cores along with both iron-rich augite. Scale bars are 100 microns in length.

23.2 Junction with Road 43N17 on right. Continue straight ahead on well-graded gravel Road 56. **0.3**

23.5 Entrance to Yellowjacket Cave below road on left (fig. 52). This entrance into a lava tube in the older basalt of Yellowjacket Butte was nearly buried by the Burnt Lava Flow. Continue to follow the road around the margin of the Burnt Lava Flow and then west to paved Road 49. **3.8**

27.3 T-junction with paved Road 49. Turn left. **1.0**

28.3 Junction with Road 43N11. Turn right and follow the good graveled road; see Double Hole Crater (one of the vents for the basalt of Giant Crater) on your left at about 0.5 mi. **2.2**

30.5 Turn left into a quarried area, or continue another 0.1 mi and turn left on small dirt road to Shastine Crater.

Stop 23. Giant Crater, Chimney Crater, and Shastine Crater

These three named locations are among the vents for the basalt of Giant Crater. From a geologic and petrologic perspective, a stop to see lavas from this eruption is a must for any geologic field trip to Medicine Lake volcano. As described here, this is a walking trip that involves a loop from Chimney Crater to Giant Crater to Shastine Crater (figs. 53, 54). The walk will take the visitor through a variety of the rock types produced by this compositionally zoned eruption (figs. 54, 55). There is ample parking, but little shade in the quarried area (41°30.95′ N., 121°37.62′ W.) just east of Chimney Crater so you may choose to park instead ~0.1 mi farther north in the shaded area adjacent to the Shastine Crater spatter vents (41°31.09′ N., 121°37.70′ W.; location of dot on fig. 7). Shastine Crater and Chimney Crater form a north-south line of vents for the initial (group 1) lavas of the basalt of Giant Crater. Whether you park on the quarried welded agglutinate just east of Chimney Crater or on the shaded road adjacent to the Shastine Crater spatter vents, we recommend that you begin by climbing up to the north rim of Chimney Crater (fig. 56). If you have only a limited amount of time, be sure to at least visit Chimney Crater (north rim, 41°30.91′ N., 121°37.74′ W.).

The basalt of Giant Crater is a 45-km-long compositionally zoned basaltic lava field that erupted ~12,500 years ago during an ~200-yr-long episode when 8 basaltic eruptions took place (Donnelly-Nolan and others, 1990; Champion and Donnelly-Nolan, 1994; Nathenson and others, 2007) across the volcano in immediate postglacial time—possibly related to pressure release associated with melting of the ice (Donnelly-Nolan and others, 2008). Donnelly-Nolan and others (1991, their figs. 2*C* and 7) recognized and mapped six sequential compositional groups (figs. 54, 55) beginning with eruption of higher SiO_2

Figure 52. Photograph looking east across the rubbly margin (~2-meters high) of the Burnt Lava Flow toward High Hole Crater shows the entrance, in foreground, to Yellowjacket Cave, which is in an older basalt flow.

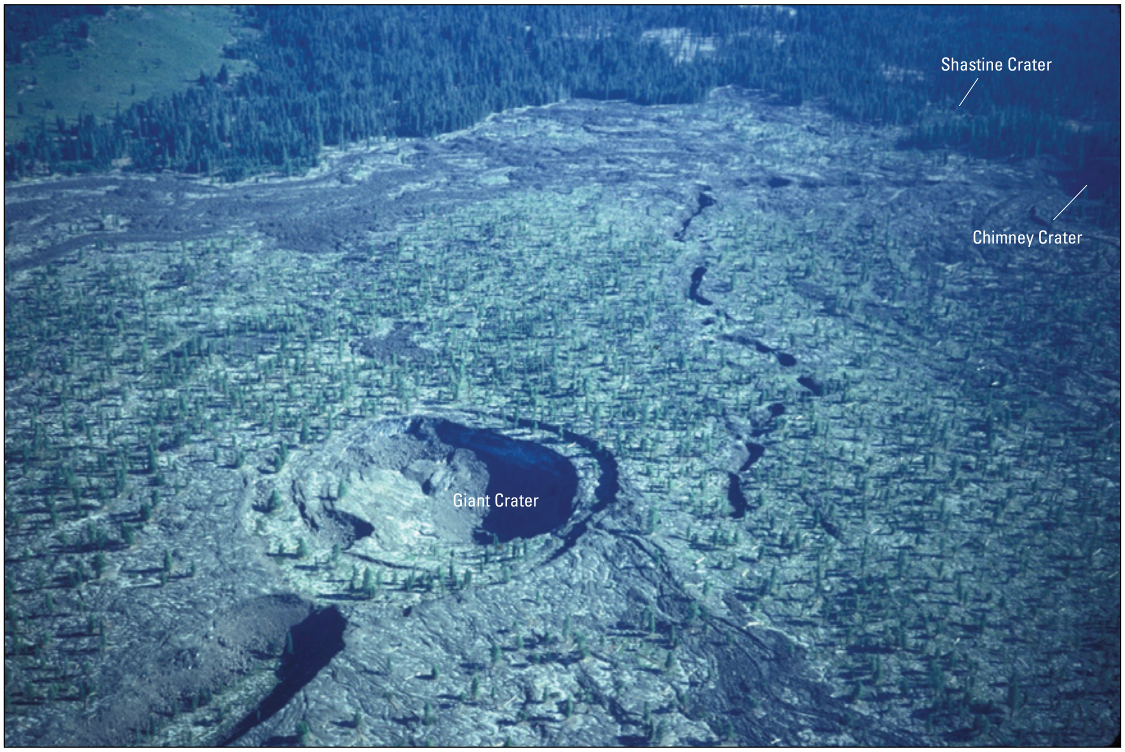

Figure 53. Aerial view north across Giant Crater. Straight-line distance from Chimney Crater to Giant Crater is ~1 kilometer. Major tube collapse is in lower left of photograph.

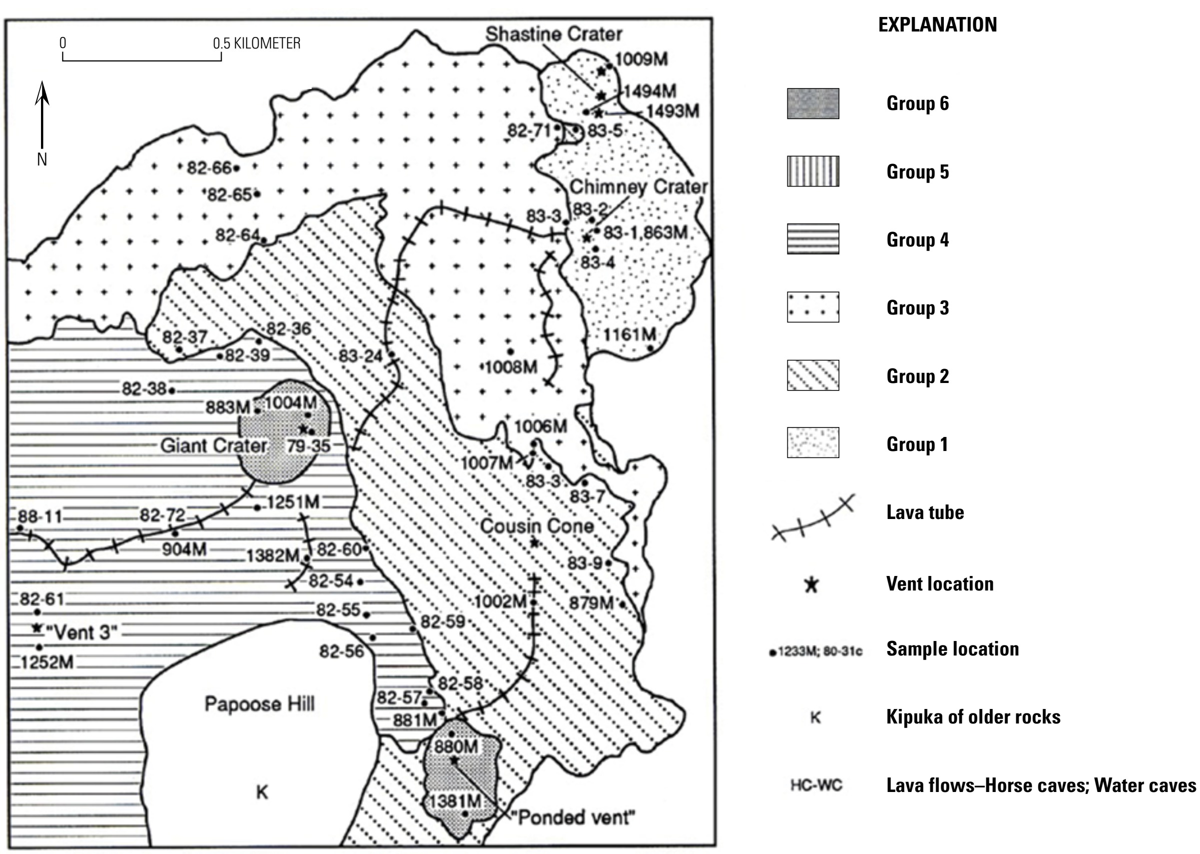

Figure 54. Map of vent area (Donnelly-Nolan and others, their fig. 2*C*) showing distribution of group 1–4 and group 6 lavas (group 5 is only seen at distal end of flow field) as well as the principal locations for Stop 23 sites (Shastine Crater, Chimney Crater, and Giant Crater).

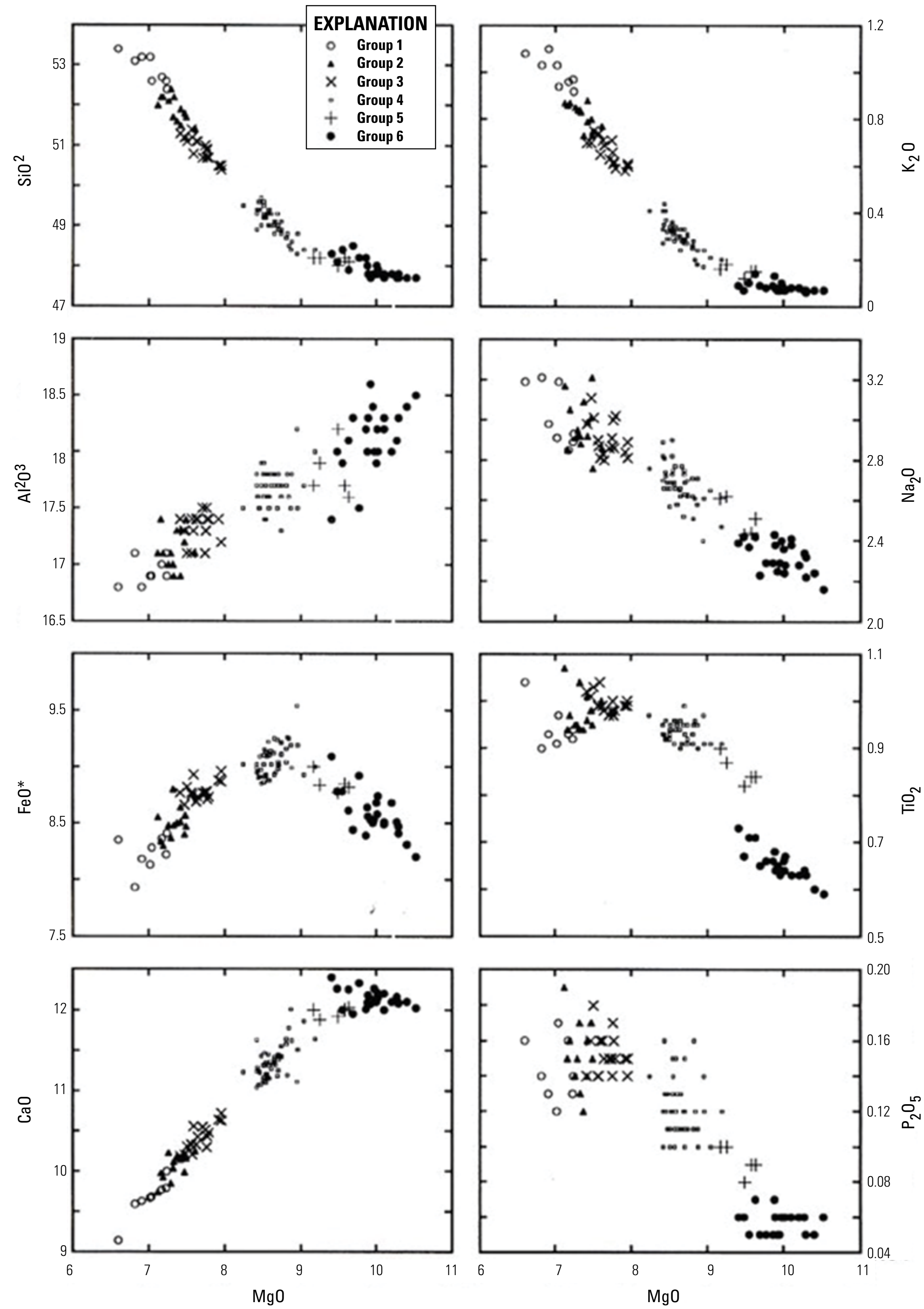

Figure 55. MgO variation diagrams (Donnelly-Nolan and others, 1991, their fig. 7) showing ranges of major element compositions in the compositionally zoned Giant Crater flow.

Figure 56. Photograph looking west from rim of Chimney Crater toward Mount Shasta. Chimney Crater is in group 1 lava (~53 weight percent SiO_2, ~1.1 weight percent K_2O), the highest-SiO_2 lava of the basalt of Giant Crater. Together with the spatter vents of Shastine Crater, which are located just to the north, these two group 1 vents are the highest in elevation (~5,900 feet) among the numerous vents for this ~12,500-yr-old lava field. Both vents are easily accessible (parking for Stop 23). Giant Crater is about a 1-hour walk to the southwest.

(~53.5 weight percent), lower MgO (~6.5 weight percent) porphyritic lava spatter that built the Shastine Crater spatter vents and Chimney Crater. Subsequent groups are characterized by increasingly lower SiO_2 and higher MgO, reaching the last-erupted lava with ~48 weight percent SiO_2 and ~10.5 weight percent MgO in group 6 lavas. The total volume of the eruption is estimated at about 4.4 km^3, covering ~200 km^2. The elapsed time for the eruption was <30 years based on paleomagnetic data (Champion and Donnelly-Nolan, 1994). Much of the lava was emplaced by way of lava tubes, including the group 5 lava that is only exposed in the southernmost part of the flow where it was transported by way of the group 4 lava tube. In walking from Chimney Crater to Giant Crater, you will walk downhill from group 1 lavas to Giant Crater, where group 6 lavas are present in the crater. Along the way, you will see group 2, 3, and 4 lavas.

Detailed petrographic descriptions and petrologic models describing the origin of the compositional variation are in Baker and others (1991). Group 1 lavas contain visible evidence of having mixed with melted silicic crustal material. In the parking area, the silicic crust can be seen in the welded agglutinate as “popped” highly melted inclusions that are centimeter-sized. Also present in the group 1 lavas are mafic inclusions that exhibit iron-rich olivine + iron-rich augite + plagioclase – a ferrogabbro- and forsterite-rich olivine intergrown with An_{80} plagioclase. These assemblages provide evidence for the presence of three magmatic components: melted silicic crust, cumulates from a differentiated ferrobasalt, and primitive HAOT (Hart and others, 1984).

The phenocryst percentage decreases from groups 1 to 4, as does the amount of melted crust and ferrobasaltic liquid in the mixed magma. Group 4 lavas are typically rather dense and aphyric, although scattered 1–2 cm plagioclase are also present. Group 5 and 6 lavas are typically diktytaxitic and nearly aphyric, characteristics of primitive tholeiitic basalts (see also Stop 1). The compositional evolution of this flow field can be explained (Baker and others, 1991) by repeated cycles of (1) injection of primitive HAOT into the magma chamber, (2) fractional crystallization to ferrobasalt, which releases heat to, (3) melt silicic crust, (4) replenishment of the chamber by a new batch of primitive HAOT, and (5) mixing of the HAOT, ferrobasalt, and silicic crust. A diagram of possible geometries that could lead to the generation of the Giant Crater lavas as well as the Burnt Lava Flow is shown in figure 50.

To continue from Chimney Crater to Giant Crater, find your way about 0.6 mi southwest to the east or northeast rim of Giant Crater (for example, 41°30.52′ N., 121°38.36′ W.) where you will be standing on group 4 lavas (fig. 57). Group 6 lavas are found inside the ~0.3-km-wide crater (fig. 58). A major lava tube exits the crater on the southwest side. The most primitive sample of Giant Crater lava was collected from the lava tube below Giant Crater. This sample (82–72f) and another group 6 sample from Giant Crater (79–35g) were used in high pressure experiments that showed (Bartels and others, 1991) the compositions are multiply saturated with olivine+augite+plagioclase+spinel±orthopyroxene at about 11 kilobars, near the depth of the crust-upper mantle boundary below Medicine Lake volcano (Zucca and others, 1986).

Retrace your path to Chimney Crater, or divert slightly north to Shastine Crater. Use your GPS (global positioning system) device if you have one, but some lava channels will block your route so a straight path between measured locations is not possible. Allow at least 1 hour each way.

Retrace route to Road 49. Reset odometer to 0.0.

0.0 Turn right (south) on paved Road 49. **9.3**

9.3 Road crosses over lava tube in Giant Crater group 4 lava. See tube collapse on left. Road leaves lavas of Medicine Lake volcano. **9.5**

18.8 Junction with paved Road 15. Turn left to proceed south to CA Hwy 89. [A right turn would take you north to Stop 6] **4.5**

23.3 Junction with CA Hwy 89. Turn right to drive west to the city of Mount Shasta and Interstate Hwy 5.

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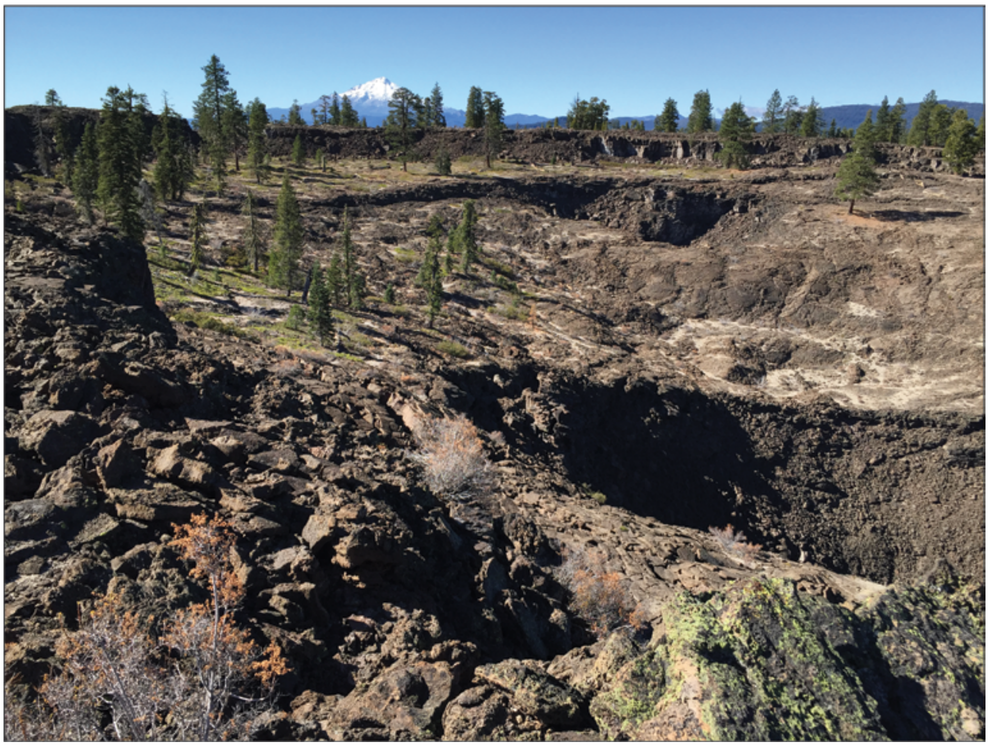

Figure 57. Photograph looking west, standing on group 4 lava on the eastern rim of Giant Crater, toward Mount Shasta on horizon.

Figure 58. Photograph looking south across 0.3-kilometer diameter Giant Crater toward older cinder cone of Papoose Hill. Person stands on group 6 lava within the crater (yellow circle). Photograph by Dominique Weis.

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