Geologic Map of Medicine Lake Volcano, Northern California

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View of Medicine Lake volcano from northeast. Photo by Julie M. Donnelly-Nolan, 1978

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Introduction

Medicine Lake volcano forms a broad, seemingly nondescript highland, as viewed from any angle on the ground (fig. 1, on sh. 1). Seen from an airplane, however, as in figure 2 (on sh. 1), treeless lava flows are scattered across the surface of this potentially active volcanic edifice. Lavas of Medicine Lake volcano (MLV), which range in composition from basalt through rhyolite, cover more than 2,000 km^2 east of the main axis of the Cascade Range in northern California. Across the Cascade Range axis to the west-southwest is Mount Shasta, its towering volcanic neighbor (fig. 3, on sh. 1), whose stratocone shape contrasts with the broad shield shape of MLV. Hidden in the center of MLV is a 7 km by 12 km summit caldera in which nestles its namesake, Medicine Lake. The flanks of MLV, which are dotted with cinder cones, slope gently upward to the caldera rim, which reaches an elevation of nearly 8,000 ft (2,440 m). The maximum extent of lavas from this half-million-year-old volcano is about 80 km north-south by 45 km east-west. In postglacial time, 17 eruptions have added approximately 7.5 km^3 to its total estimated volume of 600 km^3, and it is considered to be the largest by volume among volcanoes of the Cascades arc. The volcano has erupted nine times in the past 5,200 years, a rate more frequent than has been documented at all other Cascades arc volcanoes except Mount St. Helens.

Geography and Access

Few other volcanoes combine such well-exposed young lava flows with such a range of compositions, variety of flow and vent types, and excellent access as MLV. Access is by paved roads from the south, east, north, and northwest, and thereafter by graveled U.S. Forest Service roads. Major roads, land management boundaries, and some place names are shown on figure 4 (on sh. 1). Most place names are shown on figure 5 (on sh. 1). Nearly all of MLV is public land managed primarily by the U.S. Forest Service. About 10 percent of the area is contained within Lava Beds National Monument, located on the north flank of the volcano. Established in 1925, the monument was managed initially by the Forest Service, but later it was transferred to the National Park Service. Modoc National Forest occupies most of the east half of the volcano and encompasses the caldera; Klamath National Forest is on the northwest side; and Shasta-Trinity National Forest is on the southwest. The three national forests converge at Little Mount Hoffman, where a former fire lookout station surmounts a glaciated cinder cone that may mark the poorly defined westernmost boundary of the caldera. The views north, west, and south from the lookout are spectacular. On a clear day the view encompasses Lassen Peak 110 km to the south, the rim of Crater Lake 150 km to the north, and Mount Shasta looming large 50 km to the west-southwest beyond the barren rocky surface of the late Holocene Little Glass Mountain rhyolite flow (fig. 2, on sh. 1).

Small inholdings of private land are scattered around the volcano. Some of the larger ones are owned by logging companies. Private land on the shores of Medicine Lake is used for summer cabins. Few other usable buildings are present on the main edifice of the volcano except in Lava Beds National Monument; at Forest Service ranger stations located at Medicine Lake, Long Bell, and Harris Spring; and in the small community of Tionesta, on the far east flank.

Road access generally is excellent after the winter snow has melted, especially with high-clearance or four-wheel-drive vehicles. Paved roads from the east and south extend to Medicine Lake, but those from the west and north are partly graveled. Many good graveled roads exist in addition to numerous small roads and tracks, although some have been closed by the Forest Service. Most of the roads were originally built for logging. Some of the best graveled roads and their subsidiary roads are parts of the former railroad logging system. Because of the cuts required to establish level railroad grades, these roads provide some of the best opportunities for studying rocks.

Few designated hiking trails exist except in Lava Beds National Monument. Improved campsites are available only where drinking water is provided in the monument, as well as at Medicine Lake and at Harris Spring. Lodging is available in Tionesta and in the town of Tulelake northeast of the volcano (fig. 4, on sh. 1). No telephone or electric lines extend above the lowest flanks of the volcano, although important power lines and a major gas pipeline cross the southeast side (see Donnelly-Nolan and others, 2007, fig. 1).

The upper part of the volcano is covered much of the year by snow, which typically blocks road access across the caldera from November through May. Sometimes heavy snowfalls occur as early as October, and snowmelt can be delayed until mid-July. Precipitation in the summer typically is limited to occasional late-afternoon thunderstorms, although larger storm systems can produce rain. Freezing temperatures can occur any night of the year. Daytime temperatures commonly reach 80°F on the upper slopes and into the 90’s on the lower flanks, for example, in Lava Beds National Monument. The highest parts of the monument are covered with thickets of mountain mahogany interspersed with small stands of pine trees. At a lower elevation, Lava Beds National Monument is very dry, covered mostly with sagebrush and scattered juniper trees. The lower northwest flank of the volcano, as well as its lower east side, are similar to the sagebrush and juniper areas of the monument.

The abundance of trees at MLV increases with elevation. The species are dominated by several types of pine, but fir, cedar, and hemlock also are important at higher elevations.

Name of the Volcano

The name “Medicine Lake” apparently derives from “big medicine” rites held at the lake by the local Native Americans (Gudde, 1960). The name of the lake appeared on maps as early as 1890. Stearns (1928) referred to the volcanic edifice as “Medicine Lake Mountain.” Peacock (1931) used the term “Central Volcanic Dome” to describe what Powers (1932) called the “Medicine Lake Highland.” C.A. Anderson (1941) also used the name “Medicine Lake Highland.” This highland is the geographic feature that has Medicine Lake near its center and dominates the skyline as a broad shield-shaped form seen from the north, east, and south. The term “Medicine Lake volcano” was first applied by Mertzman (1977b) and is used herein to describe not only the obvious geographic feature that forms a volcanic shield but also the widespread lava flows that originated from the edifice and covered large areas of the Modoc Plateau. The name "Medicine Lake volcano" conveys the idea that this is a single large volcanic center having a central focus and, although it comprises many individual vents, is not just a set of overlapping smaller volcanoes.

Methods

Geologic mapping, which began in 1979, was funded by the Geothermal Program of the U.S. Geological Survey. Field seasons typically lasted 8 to 10 weeks each summer, and most mapping was completed by 1987. The 1984 field season was devoted to detailed mapping at 1:24,000 scale in Lava Beds National Monument (Donnelly-Nolan and Champion, 1987). From 1987 to 1992, much effort during shorter field seasons was focused on detailed mapping and sampling of individual compositionally zoned lavas, as well as units containing suites of magmatic and granitic inclusions. The emphasis of these efforts was on deciphering the sequence of events and the processes involved in these eruptions (see, for example, Donnelly-Nolan and others, 1991; Baker and others, 1991; Champion and Donnelly-Nolan, 1994; Wagner and others, 1995; Grove and others, 1997; Kinzler and others, 2000). Subsequent mapping has involved trying to sort out difficult stratigraphic problems. After completion of the initial mapping over most of the volcano and compilation onto base maps, parts of several field seasons were used to field check and complete difficult areas and resolve discrepancies with adjacent mapping. New field work was undertaken elsewhere in 1993, but each year short field periods also were spent at MLV resolving mapping problems, completing detailed mapping, and collecting samples of individual flows.

Geologic mapping was recorded on 1974 U.S. Forest Service color aerial photographs at a scale of about 1:16,000 and later, in some areas, on 1984 1:24,000-scale air photos. Geologic information on the air photos was transferred to stable base materials using PG-2 stereo plotters. The 15' topographic maps available at the time were mostly published in the early 1950’s and did not show the present road network. Larger scale 7.5' topographic maps were published after mapping was mostly completed. After final compilation on individual 1:24,000-scale stable base maps, the geology was scanned and converted to a GIS digital map database.

Units were distinguished in the field using a hand lens, but because of the relative paucity of phenocrysts in many lava flows and the compositional and petrographic variability of others, chemical analyses were utilized to provide additional certainty in delineating eruptive units; chemical analyses of pre-Holocene MLV rocks are published in Donnelly-Nolan (2008). Roadcuts and old railroad cuts allowed access to rocks below the surface of many lava flows, but rarely were these cuts deep enough to expose the underlying flow(s). Exposures displaying one lava flow or tephra layer on top of another are extremely rare at MLV. In general, silicic lavas have been erupted near the center of the volcano, whereas the most mafic lavas have been erupted on its flanks. Lavas having less than 0.20% K_2O have been erupted throughout the history of the volcano, but typically on its flanks and not from its center. Drill holes for geothermal exploration have penetrated large volumes of silicic lava, as much as 30 percent of the volcano’s volume, whereas only about 5 percent of the surface area of the volcano is covered by such lavas (Donnelly-Nolan, 1990a, 2006).

The boundaries of the mapping on the north, east, and south largely are defined by the contact of obviously younger MLV lavas onto older lavas of the Modoc Plateau. Directly east of Medicine Lake, however, MLV lavas overlie the (age-equivalent) basalt of Damons Butte (bdb), which probably is a back-arc basalt. Where this basalt lies west of 121° W. longitude, it has been included on the map.

On the west and southwest sides of the volcano, the map boundary is also somewhat arbitrary. Obviously porphyritic lavas, especially those bearing hornblende, were assigned pre-MLV status. In some areas straight lines were drawn arbitrarily to define the extent of detailed mapping. Mapping on the west overlaps with that of R.L. Christiansen (unpub. data, 2005).

The map area covers about 2,200 km^2. Comparison of the size of MLV to that of two volcanoes in the Cascade Range of southern Washington State is shown on figure 6 (on sh.1).

Previous Geologic Work

The first geologic studies that focused on MLV were those of Peacock (1931) and Powers (1932), who jointly mapped the Modoc Lava Bed one-degree quadrangle and then published slightly different versions of their reconnaissance geology. Other early geologic studies of the volcano include a descriptive article by Stearns (1928) about Lava Beds National Monument, as well as studies by Finch (1933) on the Burnt Lava Flow and by C.A. Anderson (1933) on Glass Mountain. In 1941, C.A. Anderson published his classic study, entitled “Volcanoes of the Medicine Lake Highland, California” (C.A. Anderson, 1941); this volume included a geologic map of much of the volcano at an approximate scale of 1:130,000, which was considerably more detailed than the mapping of Peacock (1931) and Powers (1932). On his map, C.A. Anderson (1941) identified about 15 volcanic units.

Other topical and petrologic studies that have been done since publication of C.A. Anderson (1941) include Fisher (1964), Eichelberger (1975), Condie and Hayslip (1975), and Heiken (1978). S.A. Mertzman and colleagues published a series of petrologic papers (Mertzman, 1977a,b, 1978, 1979, 1981; Mertzman and Williams, 1981) that were based on new geologic mapping, parts of which are on file as senior theses at Franklin and Marshall College in Lancaster, Pennsylvania. Mertzman initiated a potassium-argon dating effort (Mertzman, 1981, 1982, 1983) and paleomagnetic work (Brown and Mertzman, 1979). In 1982, T.L. Grove and his students and colleagues began a new series of petrologic studies of the volcano that were based on experimental laboratory work (Gerlach and Grove, 1982; Grove and others, 1982, 1988, 1997; Grove and Baker, 1984; Grove and Donnelly-Nolan, 1986; Baker and others, 1991; Bartels and others, 1991; Wagner and others, 1995; Kinzler and others, 2000; Donnelly-Nolan and Grove, 2008). Grove and coworkers utilized mapping compiled herein, as well as detailed maps of individual lava flows (Donnelly-Nolan, unpub. data, 1990). Additional petrologic and topical work was done by A.T. Anderson (1973, 1974, 1976), A.T. Anderson and others (1984), and Brophy and others (1996). J.H. Fink and his students published studies (Fink, 1980, 1981, 1983; Fink and Pollard, 1983; Fink and others, 1992; Anderson and Fink, 1992; Ondrusek and others, 1993; Anderson and others, 1998; Ramsey and Fink, 1999) on the emplacement of young silicic lava flows at MLV. Detailed studies of granitic inclusions collected at the volcano were published by Lowenstern and others (2000, 2003).

Donnelly-Nolan and Champion (1987) published a 1:24,000-scale geologic map of Lava Beds National Monument, in part revised herein. Donnelly-Nolan and colleagues also published geologic reports about the volcano that were based on new geologic mapping of MLV (Donnelly-Nolan and Nolan, 1986; Donnelly-Nolan, 1988, 1990a,b, 1998, 2002; Donnelly-Nolan and others, 1990, 1991, 2003, 2005, 2007, 2008; Champion and Donnelly-Nolan, 1994; Donnelly-Nolan and Ramsey, 2001, 2002; Ramsey and Donnelly-Nolan, 2002; Champion and others, 2005; Nathenson and others, 2007).

Geologic and Tectonic Setting

Medicine Lake volcano (MLV) lies within a tectonically active terrane behind the volcanic front of the Cascades arc, at the west edge of the Basin and Range tectonic province. Located within a zone of dominantly north-south-trending, regional-scale normal faults, the volcano is undergoing east-west extensional deformation. The volcano sits at the south end of the Klamath graben, a topographically low extensional basin that extends northward to Crater Lake caldera. MLV is cut by active faults that include the Mayfield Fault (Wills, 1991; Jennings, 1994; Donnelly-Nolan and others, 2007, fig. 6), one of several strands of an active fault system (Wills, 1991; Guffanti and others, 1994) that extends from the Lassen Peak region on the south to west of Crater Lake on the north.

Many of the mapped faults are simply open ground cracks that have no vertical offset but may show many meters of horizontal separation of the two sides. These north- to northeast-trending cracks are common on the volcano. They are most pronounced high on the west side, where they are associated with the Little Glass Mountain eruption, and they are interpreted as indicating shallow dike emplacement (Fink and Pollard, 1983). One of these cracks was shown in Muffler and others (1989, fig. 14, p. 196, stop 2), and another was shown in Donnelly-Nolan and others (2007, fig. 7). Another photograph of a crack high on the west side of the volcano was shown in the May 1998 issue of National Geographic Magazine (see p. 34). Open ground cracks also are found on the lower east side of the volcano near Tionesta (Muffler and others, 1989, p. 200, stop 9) and at Big Crack in northeastern Lava Beds National Monument. Other excellent places for seeing the cracks are on the southwest side of Lyons Peak at about 7,550 ft (2,300 m) elevation just east of the road to the top of Red Shale Butte, as well as in the north end of Lava Beds National Monument about 3 km southwest of Captain Jacks Stronghold. The latter cracks are on trend with the vents for the late Holocene basalt of Black Crater and Ross Chimneys (bbr). Similar features can be seen elsewhere at "Earthquake Fault" in east-central California near the town of Mammoth Lakes, as well as at Crack in the Ground and nearby parallel cracks north of Christmas Valley, Oregon, where open cracks aligned with vents for young lavas may represent extensional features above dikes.

Most of the evidence for regional-scale faulting has been buried by lavas of the volcano, but some faults continue onto the edifice. The steep eastern margin of MLV suggests that the volcano is built over a major north-northwest-trending normal fault whose offset is down to the east (Donnelly-Nolan, 1983). Few of the volcano's vents are found east of this structure, although many vents are located along it. Most of the many eruptions at MLV that had multiple vents took place from vents aligned within 35° of north. Exceptions are found around the margins of the caldera and on the southwest side of the volcano. Eruptions of such units as the Holocene dacite of pit craters (dpc) reflect local stress fields related to the caldera. The basalt of Giant Crater (bgc) was erupted high on the southwest flank of the volcano from vents aligned both nearly north-south and N. 55° E.; the latter direction reflects the influence of the east-northeast-trending highland of vents that connect MLV and Mount Shasta (Christiansen, 1996). This linear array of vents connecting the two volcanoes probably indicates a zone of structural weakness across the Cascades arc (Donnelly-Nolan and others, 1991). It lies above the northeast-trending Shasta gravity lineament defined by Blakely and others (1997).

Despite abundant evidence of faulting, few earthquakes have occurred at or near MLV. In general, the Modoc Plateau has been very quiet seismically. Dzurisin and others (1991) summarized the seismicity of the area around MLV and included descriptions of earthquake swarms in 1978 and 1981 that had events as large as magnitude 4.6, centered just west of MLV at Stephens Pass and Tennant. Another swarm included a magnitude 4.1 earthquake under Medicine Lake caldera in 1988 (Walter and Dzurisin, 1989). In addition, three earthquakes of magnitude 5.4 to 6.0 occurred in 1993 about 25 km northwest of Klamath Falls, Oregon, on faults that project under MLV (Blakely and others, 1997). Furthermore, active subsidence has been documented at the volcano (Dzurisin and others, 1991, 2002; Poland and others, 2006).

Petrologic research (Kinzler and others, 2000) has identified the presence of a subduction component, as indicated by significant water contents in some MLV lavas, although dry (Sisson and Layne, 1993) tholeiitic basalts are more abundant (Elkins Tanton and others, 2001). An indication of an intraplate mantle component also is present (Bacon and others, 1997). MLV overlies the projection of a subducted slab, which has been geophysically modeled (Harris and others, 1991) at a depth of about 200 km below the volcano. MLV appears to be a rear-arc volcano (Donnelly-Nolan, 1990b; Donnelly-Nolan and others, 2008) that is strongly influenced by a Basin and Range extensional tectonic overprint.

The presence of only a single major explosive unit, an ash-flow tuff herein named the dacite tuff of Antelope Well (dta), suggests that buildup of volatiles enough to generate major explosive eruptions is a rare event. Instead, eruptions are small, are minimally explosive, and commonly form fluid lava flows, resulting in the shield shape of MLV. Mapped lavas most commonly are mafic and poorly porphyritic; hornblende is nearly absent, and biotite is found only in inclusions. These characteristics probably reflect frequent tapping of the magmatic system within an actively extending tectonic environment.

Pre-MLV Volcanic Activity

Volcanism has been long-lived and relatively continuous in northeastern California, although no pre-Pliocene ages have been measured near Medicine Lake volcano. Two ages for older (pre-MLV) Pliocene units (odh, 2.95±0.09 Ma; otg, 2.023±0.020 Ma) are listed in table 1. Several pre-MLV Pleistocene ages listed in table 1, as well as others published previously (Luedke and Lanphere, 1980; Mertzman, 1982, 1983; Donnelly-Nolan and others, 1996; Donnelly-Nolan and Lanphere, 2005), may indicate an episode of volcanism at about 1 Ma. Among the older (pre-MLV) units located on the west side of MLV, whose compositions range from basalt to rhyolite, one rhyolitic ash-flow tuff is present, the older tuff of Box Canyon (otb, 1.006±0.025 Ma; table 1). The vent location for this tuff is unknown, although a site under MLV is possible; an alternative vent location would be in the highland between MLV and Mount Shasta, where another older rhyolite unit, the older rhyolite of Red Cap Mountain (orr, 965±24 ka; table 1) is located. Also nearby are other silicic domes of the older rhyolite near Dock Well unit (ord), as well as the (undated) older dacite of Squaw Peak unit (ods), suggesting the possible existence of a small, one-million-year-old center of silicic activity located at the west edge of MLV.

On the east side of MLV is the "Hackamore center" (Donnelly-Nolan and others, 1996), dominated by basalt that was erupted about 1 Ma. Located in the back-arc Devils Garden area, the center consists of several closely spaced vents that erupted widespread low-K_2O basalt flows. These basalt flows were mapped originally (Powers, 1932; C.A. Anderson, 1941) as part of the Warner Basalt but later were broken out as part of the basalt of Devils Garden (McKee and others, 1983). An age of 1.62±0.15 Ma was obtained by Luedke and Lanphere (1980) on one of the stratigraphically older flow units. More recently (Donnelly-Nolan and Lanphere, 2005), an age of 629±176 ka was determined on the basalt of Plum Ridge, one of the youngest flow units, as were several ages from 0.975 to 1.205 Ma. All of these ages are much younger than the 6 Ma K-Ar ages previously determined by McKee and others (1983).

Two other monogenetic mafic shields immediately predate MLV. The older basaltic andesite of Black Mountain (omb), enclosed within eastern lavas of MLV, yielded a K-Ar age of 599±16 ka (table 1). Just west of MLV is Garner Mountain, which yielded one K-Ar age of 520±30 ka (Donnelly-Nolan and Lanphere, 2005).

Eruptive History of MLV

Medicine Lake volcano began to grow about 500,000 years ago. The sequence of eruptive events at a volcano as large as MLV is not easily determined. Although argon dating (both K-Ar and $^{40}Ar/^{39}Ar$), combined with geologic mapping and drill-core study, has provided significant constraints on the sequence of eruptive events, only about 40 of the 199 Pleistocene volcanic units have been successfully argon dated. Argon ages of these units are found in table 1, organized alphabetically by unit symbol; additional argon data can be found in Donnelly-Nolan and Lanphere (2005). Of the 106 Pleistocene units of MLV that have lava flows of basalt or basaltic andesite, only about 15 percent provided reasonable argon ages. More silicic lavas yielded better results, producing successful argon ages for about 28 percent of andesite units that have lava flows, about 78 percent of all dacite units, and 90 percent of all rhyolite units. Note that these proportions are crudely inverse to the relative abundances of the rock types as shown on the geologic map.

The geographic distribution of units on MLV provides important clues to the volcanic stratigraphy. To help visualize the relations between units, the geologic map has been divided into thirteen sectors (see Sector Location Map, on sh. 2), and these have been used to make stratigraphic associations on MLV (see Correlation of Map Units, on sh. 2). Lava flows typically are confined to narrow sectors of the volcano's flanks; however, some units extend into several sectors and provide stratigraphic constraints on the sequence of eruptions. The most significant "marker" unit is the volcano's only ash-flow tuff, the dacite tuff of Antelope Well (dta), found in 9 of the 13 sectors. Some additional stratigraphic constraints were provided by drill-hole data (Donnelly-Nolan, 1990a, 2006), although few of the lava flows and minor tuffs that were penetrated by geothermal drilling could be correlated conclusively to mapped units. Units lacking measured ages or stratigraphic constraints on their age (for example, the isolated cinder cones) were positioned on the Correlation of Map Units on the basis of their morphology, soil development, and degree of weathering in comparison with units of known age. Units identified by their morphology as postglacial have, in many cases, been dated by radiocarbon methods, as described in the Description of Map Units; ages of other postglacial units have been constrained by stratigraphy and (or) paleomagnetic data (see, for example, Champion and others, 2005).

Compositions of MLV lavas range from primitive basalt having 47.2% SiO_2 to rhyolite having 77.1% SiO_2. The full range of silica contents is present, although dacites are relatively rare. Despite this, one of the largest single eruptions at MLV was the dacite tuff of Antelope Well (dta), which had an estimated erupted volume that could have been as large as 10 km^3; this volume reflects the abundance of the tuff present in geothermal drill holes located in places on the volcano where the tuff is not exposed at the surface. On the basis of geologic mapping alone, the largest individual eruptions were basaltic lava flows, some having volumes as large as 5 km^3. Examples include the basalt of Mammoth Crater (bmc), the basalt of Giant Crater (bgc; see also, Donnelly-Nolan and others, 1991),

Table 1. Argon ages of map units on Medicine Lake volcano
[See Donnelly-Nolan and Lanphere (2005) for additional data]

Map Unit	**Age** (in ka, except as noted)	**Sample No.**	**Method** (1=K-Ar; 2= $^{40}Ar/^{39}Ar$)	**Latitude** (in minutes above 41° N.)	**Longitude** (in minutes west of 121° W.)
aac	114±5	114M	2	34.81	32.98
adh[1]	171±4	471M	2	46.77	33.97
aes	307±24	160M	2	41.36	43.27
aib	22±13	1620M	2	38.49	27.03
anr[2]	100±3	999M	2	36.78	37.05
asb	65±23	MLV-021-92	2	44.46	31.45
asr[2]	124±3	1013M	2	33.67	34.82
atm	282±11	479M	2	32.60	46.75
	254±25	505M	1	32.48	48.20
bdb	144±15	1799M	2	30.64	18.03
bhp	445±25	1521M	2	49.15	31.35
bl	126±14	1724M	2	33.97	29.91
	123±27	MLV-014-92	2	33.97	29.91
	65±10	MLV-016-92	2	35.22	25.45
	(avg=89±13)				
blh	146±11	1326M	2	34.72	39.54
bls	97±13	701M	2	40.05	24.17
bmc	36±16	MLV-020-92	2	41.58	32.73
bp	273±18	1268M	1	50.91	23.20
bug	445±27	1797M	2	22.17	35.41
byb	86±14	1919M	2	25.55	28.33
dec	200±2	1360M	2	40.69	34.29
deg	203±6	1247M	1	36.17	26.81
dls	182±4	517M	1	30.95	46.23
drs	88±7	1355M	1	34.79	29.70
ds	159±30	912M-c	2	32.50	32.12
dsk	244±20	1654M	2	38.90	41.75
dta[3]	171±43	194M	2	32.58	43.42
men	114±10	1403M	2	45.28	33.77
mfh	130±36	1474M	1	39.98	39.25
mnl	289±13	383M	2	40.27	38.64
mrr	251±6	2058M	2	24.33	35.63
msp	168±7	928M	2	33.47	31.45
mug	180±28	1094M	2	31.74	39.67
mwr	309±17	455M	2	34.91	46.53
oap	949±29	460M	1	34.80	43.78
ob	910±49	448M	1	47.05	37.03
odh	2.95±0.09 Ma	135M	1	26.90	44.67
om	1.211± 0067 Ma	1223M	1	44.77	39.10
omb	599±16	1229M	1	32.11	25.98
omt	1.820±0.042 Ma	776M	1	38.40	16.95
ord	840±51	381M	1	38.20	43.07
orr	965±24	469M	1	33.51	44.26
otb	1.006±0.025 Ma	94CSJ780	2	46.91	42.88
otg	2.023±0.020 Ma	1079M	2	47.30	33.92
rcb	437±7	MLV-004-92	2	39.68	27.36
rec[4]	313±22	18M	1	40.81	35.38
	335±21	19M	1	40.77	35.37
	(avg=322±22)				
reg	475±29	1707M	2	36.62	28.02
rgf	383±1	253M	2	31.24	42.00
	391±2	MLV-008-92	2	41.62	39.10
	(avg=387±6)				
rmh	28±5	MLV-017-92	2	35.95	32.87
rng[5]	105±3	675M	1	36.97	31.40
rse[6]	330±40		1		
rsl	327±16	256M	1	38.38	24.71
	308±6	1365M	1	37.81	24.22
	(avg=313±11)				
rwc	349±7	684M	1	40.69	38.90

[1] Sample collected from unmappable exposure in fault scarp
[2] From Donnelly-Nolan and others (1994)
[3] From Herrero-Bervera and others (1994)
[4] Samples collected from talus downslope from mapped unit
[5] Sample collected from block of unit exposed beneath surficial unit p
[6] From Mertzman (1982), who did not specify latitude or longitude

the Lake Basalt (bl; see also, Wagner and others, 1995), and the basalt of Yellowjacket Butte (byb), which covers an area of more than 300 km^2 (Donnelly-Nolan and others, 2005).

The following discussion of the eruptive history of MLV focuses on five relatively well-constrained eruptive stages: (1) early history, approximately 500 ka to 300 ka, (2) approximately 300 ka to 180 ka, approximate time of the eruption of the dacite tuff of Antelope Well (dta), (3) approximately 180 ka to 100 ka, (4) approximately 100 ka to 13 ka, and (5) postglacial eruptions (less than 13 ka).

Eruptive Stage 1: Approximately 500 ka to 300 ka

$^{40}Ar/^{39}Ar$ dating, combined with study of drill core and cuttings from more than a dozen geothermal drill holes, indicates that this early history of MLV was dominated by the eruption of silicic domes and flows (Donnelly-Nolan, 1990a, 2006). Mafic lavas were erupted as well, as documented in drill holes; however, fewer than 10 basaltic to andesitic units of this time period were mapped at the surface. Two basalt units—the basalt of Hovey Point (bhp) and the basalt under Giant Crater lava field (bug)—have essentially identical $^{40}Ar/^{39}Ar$ ages (445±25 ka and 445±27 ka, respectively; table 1). The oldest dated lava of MLV is a rhyolite dome, the rhyolite east of Glass Mountain (reg), which has a $^{40}Ar/^{39}Ar$ age of 475±29 ka (table 1). K-Ar dating also was performed on rhyolites of this time period (Mertzman, 1982, 1983; Donnelly-Nolan and Lanphere, 2005), although results were variable and inconsistent (see table 5, Donnelly-Nolan and Lanphere, 2005). Ages have been measured on seven of the eight early rhyolite units (rcb, rec, reg, rgf, rse, rsl, rwc) that crop out at MLV; the ages range from 475±29 ka to 313±11 ka (table 1).

In addition, K-Ar ages (not listed in table 1) were obtained on four rhyolite samples collected from geothermal drill holes: two samples from drill hole 68-16 yielded ages of 397±8 ka and 297±6 ka; one sample from drill hole 52-4 has an age of 382±8 ka; and one sample from 57-13 has an age of 324±7 ka. See Donnelly-Nolan and Lanphere (2005) for additional data related to these age determinations; also see Donnelly-Nolan (2006) for more information about these drill holes.

Eruptive Stage 2: Approximately 300 ka to 180 ka

Beginning at about 300 ka, eruption of mafic lavas dominated at MLV. Forty-six basalt and basaltic andesite units, as well as 16 andesite units and 8 total dacite and rhyolite units, are identified as belonging to this eruptive stage. In addition, more than half of the isolated cinder cones on MLV are assigned to this time period, although none are dated. Of the handful of mafic units from this eruptive stage that have been dated successfully, most are located around the periphery of the volcano. For example, the basalt of Prisoners Rock (bp, 273±18 ka; table 1) is located in the far northeast extremity of the volcanic field; no stratigraphic constraints exist for this unit, but the age is similar to those of other early mafic lava flows of MLV that are found on the far northwestern, western, and southern parts of the volcano.

On the far northwestern side of MLV, the oldest mafic units are the andesite east of Six Shooter Pass (aes) and the basaltic andesite north of Lookout Butte (mnl); unit aes (307±24 ka; table 1), which directly overlies much older pre-MLV rocks, lies stratigraphically below unit mnl (289±13 ka; table 1). Near the west edge of the volcano, the basaltic andesite west of Red Cap Mountain (mwr, 309±17 ka; table 1) overlies only one other MLV unit. At the far west edge of the map, the andesite of Typhoon Mesa (atm) has yielded two overlapping (within analytical error) ages: a $^{40}Ar/^{39}Ar$ age of 282±11 ka and, from a different area, a K-Ar age of 254±25 (see table 1). These ages lie within the cold period of between about 280 and 240 ka, as indicated by marine oxygen-isotope stage 8 (Martinson and others, 1987; Bassinot and others, 1994); this age range is compatible with the interpretation, which is based on morphologic evidence, that this unit (atm) was erupted under ice (see fig. 7, on sh. 2, for map of ice distribution). On the far south side of the volcano, the basaltic andesite of railroad (mrr, 251±6 ka; table 1) directly overlies the basalt under Giant Crater lava field (bug, 445±27 ka; table 1) of eruptive stage 1. These two flows are the stratigraphically lowest units on the south flank.

Of the eight silicic units that were erupted in this time period, all are dacitic except for one low-silica rhyolite, the rhyolite west of Crater Glass Flow (rcg, 70.9% SiO_2). The dacite units in this eruptive stage constitute 7 of the volcano's 11 mapped dacite units; 5 of the 7 have been dated. The oldest unit in this apparent dacite eruptive episode is the dacite southwest of Kelley Pass (dsk, 244±20 ka; table 1). The others span a short interval of time, from the age of the dacite east of Glass Mountain (deg, 203±6 ka; table 1) and the dacite east of Callahan Flow (dec, 200±2 ka; table 1) to that of the dacite east of Lost Spring (dls, 182±4 ka; table 1), culminating with the eruption of the (widespread) dacite tuff of Antelope Well (dta, 171±43 ka; table 1); unit dta was erupted from within the caldera, spilling ash flows in all directions and creating the volcano's only "marker" bed.

Eruption of the Dacite Tuff of Antelope Well (dta): Approximately 180 ka

The dacite tuff of Antelope Well (dta) is the only widespread stratigraphic marker on MLV, and so it is the most important single unit at MLV. It also is the only known ash-flow tuff on the volcano. Originally mapped by C.A. Anderson (1941) as the "andesite tuff," this ash-flow tuff was regarded as one of the basal units of the volcano. Geologic mapping presented herein, however, indicates that the eruption of the tuff occurred midway in the history of the volcano. In addition, chemical analyses of pumice lumps demonstrate that the juvenile components of the tuff are dacitic (63.1–67.1% SiO_2), although whole-rock analyses typically are andesitic. Recognition of its dacitic composition has resulted in its renaming herein as the dacite tuff of Antelope Well (dta).

The dacite tuff unit dta was erupted from the caldera and probably flowed outward into all sectors of the volcano, although no evidence is available for the northeast flank, where younger lavas are abundant and, apparently, completely cover the tuff. Exposures of unit dta are found on the north flank of the volcano and continue westward around to the southwest, as well as within the summit caldera. Unit dta also can be found directly east of the caldera, as small patches on two units: the dacite east of Glass Mountain (deg) and the rhyolite east of Glass Mountain (reg). Drill-hole data indicate that unit dta also was deposited on the south flank, although it is covered almost entirely by younger lavas on the south and southeast sides of the volcano. No tuff is present on the caldera rim.

The eruption of the dacite tuff of Antelope Well (dta) also produced an initial ash-fall tephra deposit, although it is lacking in the few localities where the base of the ash-flow tuff is exposed. The tephra was found (A. Sarna-Wojcicki, written commun., 1984) in a quarry about 13 km north of Timber Mountain, just east of Highway 139 beyond the east edge of the map. Distal tephra also has been correlated to ash layer KK at Summer Lake, Oregon (Sarna-Wojcicki and others, 1991) and to ash found in a deep core in Tule Lake (Rieck and others, 1992).

Eruption of unit dta took place when ice was present over the caldera (Donnelly-Nolan and Nolan, 1986). Marine oxygen-isotope climate records (Martinson and others, 1987; Bassinot and others, 1994) indicate a cold period from 185 to 130 ka (see fig. 7, on sh. 2, for distribution of ice on MLV). Argon dating of a pumice lump (Herrero-Bervera and others, 1994) resulted in a whole-rock $^{40}Ar/^{39}Ar$ plateau age of 171±43 ka; despite the large analytical error, the age is consistent with the eruption having taken place when ice was present on the volcano.

At Schonchin Spring just northwest of Medicine Lake, a small outcrop of unit dta contains flattened and unusually elongated (≤1 m) welded pumice lumps and many large (≤20 cm) included lithic fragments, which suggests that this outcrop is located close to the vent. Donnelly-Nolan and Nolan (1986) interpreted the andesite units on the northwest rim to be older than unit dta, suggesting that the tuff had been removed by ice; however, four fairly extensive units on the north, south, and east rims are now known to be younger than unit dta: the andesite of north rim (anr), the andesite of south rim (asr), the dacite of Red Shale Butte (drs), and the Lake Basalt (bl). The age of unit dta is constrained by the age of the overlying unit, the basaltic andesite under Giant Crater lava field (mug, 180±28 ka; table 1), and by the presence of ice on the summit region of the volcano (after 185 ka); the most likely age of unit dta is considered herein to be approximately 180 ka.

Eruptive Stage 3: Approximately 180 ka to 100 ka

More than 80 units are assigned to eruptive stage 3 in the Correlation of Map Units. The apparent eruption rate for this approximately 80,000-yr time period is, thus, one per thousand years, more frequent than is known for any other time period except postglacial time. Eruptive activity was dominated by basalt and basaltic andesite, but 20 andesite units also were erupted, more than half the total number of andesite units identified at MLV. In addition, one small rhyolite unit was erupted during this time, the rhyolite northwest of Glass Mountain (rng, 105±3 ka; table 1), a low-silica rhyolite (71.1% SiO_2) located just outside the northeast caldera rim. A single dacite unit, the dacite of south flank (ds), also was erupted during this time; unit ds has a $^{40}Ar/^{39}Ar$ age of 159±30 ka (table 1), measured on a mafic magmatic inclusion contained within the somewhat altered host glass.

Two of the most extensive units of this eruptive stage are the andesite units of the caldera rim: the andesite of north rim (anr) and the andesite of south rim (asr). Together they form the well-defined northern and southern topographic boundaries of the caldera. Each unit was erupted from several vents, probably cinder cones that have been mostly removed by subsequent glaciation. The lava flows consist of spatter-fed high-Na_2O (approx 4.6–5.6 wt.%) andesite and minor amounts of low-silica dacite. The andesite of south rim (asr) apparently was erupted first, followed by the andesite of north rim (anr), on the basis of the $^{40}Ar/^{39}Ar$ ages in table 1 (asr, 124±3 ka; anr, 100±3 ka), although no stratigraphic relation constrains the relative age of the two units. Numerous K-Ar age measurements (not reported here) also have been made on these units (see Donnelly-Nolan and others, 1994; Donnelly-Nolan and Lanphere, 2005). Paleomagnetic data (D.E. Champion, written commun., 1999) indicate similar but not identical directions of magnetization, confirming that the two units are different ages despite their similar distinctive high-Na_2O chemical compositions.

Eruption of the two extensive, rim-forming andesite units (asr and anr) at approximately 120 ka to 100 ka apparently culminated this 80,000-yr time period, which was otherwise dominated by relatively small and frequent eruptions. No ash-flow tuffs were erupted after the (180-ka) dacite tuff of Antelope Well (dta) was erupted, and so the caldera as seen today was not formed by collapse following a major explosive eruption. Instead, it was formed by eruption of rim-forming lavas that presumably traveled up ring faults, arcuate pathways that define and control the existence of the central basin; these ring faults could have been created during the eruption of unit dta.

Eruptive Stage 4: Approximately 100 ka to 13 ka

Only 24 eruptions took place during this approximately 85,000-yr time period, far fewer than during the previous 80,000-yr period. Eruptions, which occurred dominantly on the east side of the volcano, include five at about 90 ka. These include the low-silica, high-Na_2O dacite unit, the dacite of Red Shale Butte (drs, 88±7 ka; table 1), which forms an important component of the poorly defined east rim of the caldera. Unit drs is the only dacite that was erupted in this time period. The high-Na_2O signature of unit drs suggests that it is petrologically related to the andesite lavas of the north and south rim and may have been erupted from the same magma reservoir.

Another unit from this time period is the basalt of Little Sand Butte (bls), which has a $^{40}Ar/^{39}Ar$ age of 97±13 ka (table 1). Unit bls apparently is overlain by the basalt of Tionesta (bt), which forms a broad, flat area low on the far east side of the volcano. Unit bt was considered to be part of the Pliocene Warner Basalt by C.A. Anderson (1941) and was thought to underlie the volcano. It is one of the petrologically most primitive basalts that were erupted from MLV, comparable in composition to the most primitive lavas of the basalt of Giant Crater (bgc). The fresh pahoehoe surface of the basalt of Tionesta (bt) is mantled by glacial-outwash gravel and by pumice of late Holocene eruptions, making the unit appear older than it is. It clearly underlies several widespread basaltic units, including the Lake Basalt (bl), which has an approximate age of 90 ka (see discussion below), and the basalt of Yellowjacket Butte (byb, 86±14 ka; table 1). Thus, the basalt of Tionesta (bt) is constrained to be older than about 90 ka (approximate age of unit bl) but younger than approximately 97 ka (age of unit bls).

The Lake Basalt (bl) is a large, compositionally zoned unit of basalt and basaltic andesite (Wagner and others, 1995), much of it rich in plagioclase phenocrysts. It was erupted from numerous vents that form a 15-km-long, north-northwest-trending linear array through Lyons Peak and Red Shale Butte, near the east rim of the caldera. Additional vents for this compositionally variable unit are located on an east-west alignment through these two peaks. The age of this unit is not known precisely. A previous K-Ar date by Luedke and Lanphere (1980) gave an age of 130±100 ka. Two $^{40}Ar/^{39}Ar$ ages from a site in the caldera lobe of the Lake Basalt (equivalent to the Lake Basalt as mapped by C.A. Anderson, 1941) give essentially identical ages of 123±27 and 126±14 ka (table 1). A third dated sample of Lake Basalt (bl) from comparably porphyritic lava on the east flank gives an age of 65±10 ka (table 1). Although paleomagnetic data (D.E. Champion, written commun., 1999) indicate a time gap of perhaps hundreds of years between the caldera lobe of Lake Basalt and the remainder of the unit, the outcrop where the 123- and 126-ka samples were collected shares the same direction of magnetization with two other sites in the caldera lobe, indicating that the dated site is part of the same eruptive event as the remainder of the caldera lobe; however, the caldera lobe overlies the andesite of north rim (anr, 100±3 ka; table 1; see also, Donnelly-Nolan and others,1994). Thus, the measured ages of 123 and 126 ka are too old if the more precise age of unit anr (100 ka) is correct. The remainder of the Lake Basalt (bl), which has a different magnetic direction, includes a southern lobe that underlies the basalt of Yellowjacket Butte (byb, 86±14 ka; table 1), a northern lobe that overlies unit bt (approximate age, between 97 ka and 90 ka), and a late aphyric facies that is stratigraphically younger than the caldera lobe. Therefore, the measured age of this part of the Lake Basalt (bl, 65±10 ka; table 1) is too young. The time span that separates the early caldera lobe of the Lake Basalt from the later parts of the unit is constrained by the age of the underlying andesite of north rim (100±3 ka) and that of the overlying basalt of Yellowjacket Butte (86±14 ka). The weighted average of the three $^{40}Ar/^{39}Ar$ ages for the Lake Basalt is 89±13 ka (see table 1), which fits the stratigraphic constraints. In conclusion, on the basis of geologic mapping and geochemistry (Wagner and others, 1995), the Lake Basalt (bl) is a single stratigraphic unit whose age is best characterized by the weighted average of its three $^{40}Ar/^{39}Ar$ age determinations, approximately 90 ka.

Subsequent to eruption of unit bl, the basalt of Yellowjacket Butte (byb) was erupted at 86±14 ka (table 1) from numerous vents on the south flank of the volcano (Donnelly-Nolan and others, 2005). Unit byb covers an estimated 300 km^2, making it the largest single unit at the volcano in terms of area. Another very large basalt flow, the basalt of Mammoth Crater (bmc, 36±16 ka; table 1), was erupted later in this time period, covering about 250 km^2.

Only two andesite units were erupted during this time period, one tenth the number of andesite units that were erupted during the previous time period, which spans approximately the same length of time. One of these units is the andesite of Schonchin Butte (asb), found on the far north flank of the volcano in Lava Beds National Monument. Unit asb, which underlies the basalt of Mammoth Crater (bmc), has an age of 65±23 ka (table 1). The second andesite unit is the andesite of Indian Butte (aib) on the upper northeast flank of the edifice. Its age is 22±13 ka (table 1), which overlaps with that of both unit bmc (36±16 ka) and the rhyolite of Mount Hoffman (rmh, 28±5 ka; table 1).

The rhyolite of Mount Hoffman (rmh) is the single rhyolite unit that was erupted during this time period. The glaciated vent dome for this rhyolite forms the highest point on the volcano, at 7,913 ft (2,412 m). Unit rmh and the rhyolite northwest of Glass Mountain (rng, 105±3 ka; table 1) are the only two mapped rhyolite units known to have been erupted at MLV between approximately 300 ka and late Holocene time. The stratigraphic relation between unit rmh and the nearby unit aib is unknown; in addition, unit aib does not come in contact with unit bmc. Therefore, units rmh, aib, and bmc have been shown at equivalent positions on the Correlation of Map Units because their stratigraphic relations are unknown.

Three other units were erupted near the end of this time period. One is the basalt of Water Caves (bwc), also described as the "basalt of Horse Caves-Water Caves" in Donnelly-Nolan and others (1991). Another is unit bup, the basalt under Paint Pot Crater flow; unit bup is a very small basalt flow that lies immediately south of the basaltic andesite of Paint Pot Crater (mpp), and its vents have the same northeast trend as those of unit mpp (Donnelly-Nolan and others, 1990). The third unit is the basaltic andesite northeast of Aspen Crater (mna), whose lavas surrounded, but did not cover, a circular area of apparently wet, bedded gravel (later quarried) interpreted as glacial outwash. All three units are undated and their relative ages are unknown, but they all are morphologically youthful and could be postglacial in age.

Eruptive Stage 5: Postglacial Eruptions, Approximately 13 ka to Present

Since the retreat of the Pleistocene glaciers, at least 17 eruptions have occurred at Medicine Lake volcano, resulting in the venting of about 7.5 km^3 of lava (Donnelly-Nolan and others, 1990). These postglacial lava flows, which are scattered widely across the volcano, include a broad range of compositions, from 47.2% to 74.6% SiO_2, with a gap between 58.1% and 63.3% SiO_2; however, quenched mafic magmatic inclusions found in the Little Glass Mountain and Glass Mountain flows bridge this gap in erupted compositions, indicating that andesitic liquids were present under the volcano and were involved in the eruptions. The postglacial eruptions took place episodically, beginning with a cluster of eight basaltic events that span approximately 200 years in very latest Pleistocene time, about 12,500 years ago (Champion and others, 2005; Donnelly-Nolan and others, 2007; Nathenson and others, 2007). Among these early mafic eruptions is the large-volume (4.35 km^3), compositionally zoned unit, the basalt of Giant Crater (bgc) (Donnelly-Nolan and others, 1991; Baker and others, 1991; Champion and Donnelly-Nolan, 1994). Unit bgc also includes one very small postglacial basalt identified in Donnelly-Nolan and others (1990) as "spatter vents surrounded by Double Hole flow."

Both mafic and silicic eruptions took place at MLV during late Holocene time, although silicic eruptions were more frequent. Late Holocene eruptions (Donnelly-Nolan and others, 2007; Nathenson and others, 2007) began about 5,200 calendar years ago with emplacement of the dacite of Medicine Lake Glass Flow (dm) on the floor of the caldera; about 100 years later, lava was erupted explosively along the southeast caldera rim, forming the dacite of pit craters (dpc). Subsequently, about 3,000 years ago, two mafic eruptions took place within an estimated 200-year interval: (1) a basaltic fissure eruption on the lower north flank of the volcano in Lava Beds National Monument, forming the small flows known as the basalt of Black Crater and Ross Chimneys (bbr), and (2) the andesite of Burnt Lava Flow (abl), which was erupted on the south flank of the volcano.

The most recent episode of volcanic activity is estimated to have lasted less than 300 years, producing five more eruptions between about 1,230 and 950 years ago. First was tephra and the two flows of the rhyolite of "Hoffman flows" (rh), vented from a north-northwest-trending fissure near the northeast caldera rim, partly on the shoulder of the rhyolite of Mount Hoffman (rmh). Two mafic eruptions followed: (1) the compositionally zoned (basalt to andesite) Callahan Flow (mcf), on the north flank about 1,180 years ago, and (2) the (smaller) basaltic andesite of Paint Pot Crater (mpp), shortly thereafter on the west side of the volcano. Less than a century later, the rhyolite of Little Glass Mountain (rlg) was erupted northeast of Paint Pot Crater. The several domes of this 8-km-long fissure eruption lie just outside the caldera, but some of the cracks (Fink and Pollard, 1983) that apparently opened during the eruption step down to the southeast into the western part of the caldera. Finally, about 950 years ago on the opposite side of the caldera, the youngest eruption at MLV took place at Glass Mountain. Eruption of the rhyolite of Glass Mountain (rgm) produced an initial rhyolitic tephra (Heiken, 1978), followed by dacite lava and a large flow of rhyolite; to the north and south of the main flow, additional small domes were erupted along a 5-km-long, north-northwest-trending fissure parallel to, and about 1 km east of, the fissure from which erupted the rhyolite of "Hoffman flows" (rh).

The Caldera

Medicine Lake caldera is elongated in the east-west direction, measuring approximately 12 km east-west by 7 km north-south. It is defined by constructional topography that forms high rims to the north and south. The east rim is not as well defined, but it is delineated approximately by Red Shale Butte and Lyons Peak. To the west, the location of the caldera boundary is unclear and may be located as far west as Little Mount Hoffman.

The elevation of Medicine Lake officially is 6,676 ft (2,035 m), as shown on the 1988 Medicine Lake 7.5' topographic map, although the lake level can vary by 10 ft (3 m) or more from drought years to heavy snow years. Childs and others (2000) published a bathymetric map of the lake that also includes information from shallow cores, some of which was interpreted in Starratt and others (2003). The highest unit at any point on the caldera rim is the glaciated dome of the late Pleistocene rhyolite of Mount Hoffman (rmh), at 7,913 ft (2,412 m). Other units at high points include the highest elevations of the andesite of north rim (anr), at 7,719 ft (2,353 m), and the andesite of south rim (asr) on Medicine Mountain, at 7,580 ft (2,310 m). Red Shale Butte on the east rim has an elevation of 7,834 ft (2,388 m); adjacent Lyons Peak is slightly higher, at just over 7,880 ft (2,402 m). On the west, most elevations lie below 7,300 ft (2,225 m), although Little Mount Hoffman has an elevation of 7,310 ft (2,228 m).

The volcano in its guise as a dominantly mafic shield apparently was in existence by the time the dacite tuff of Antelope Well (dta) was erupted. It is likely that eruption of the tuff initiated formation of the caldera; subsequent development mostly consisted of construction of the andesite rim, combined with downwarping of the basin floor as a result of withdrawal of magma from directly under the caldera floor and its net transfer down the slopes of the volcano (as suggested by C.A. Anderson, 1941). The andesite eruptions on the rim certainly contributed to the formation of the caldera, but they are probably not the whole story. At present, the floor of the caldera at its center is subsiding at the rate of 8.6±0.9 mm/yr (Dzurisin and others, 2002); hypotheses to explain the subsidence are proposed and discussed in Dzurisin and others (1991, 2002) and in Poland and others (2006). Most likely, the process of caldera formation has been intermittent, perhaps alternating between periods of inflation and deflation that may, in turn, have been related to eruptions that occurred on the flanks and not necessarily in or near the caldera.

Glacial History

Ice clearly has modified the upper portions of Medicine Lake volcano (MLV) by scraping, transporting, and depositing material, as recognized by C.A. Anderson (1941). Evidence includes glacial striations and polish that are most noticeable on the dense, hard andesitic lavas of the caldera rim. In addition, deposits of glacial till were found and mapped where they cover areas large enough to obscure the underlying units. However, the small volume of till, as well as the presence of only a few small cirques and the lack of U-shaped valleys or other major landscape changes, indicates that glacial modifications mostly involved removing the surfaces of lava flows. Despite this, it is obvious that more than one period of glaciation affected the volcano, although the timing and extent of each ice advance are poorly known. Figure 7 (on sh. 2) shows the interpreted maximum ice limit, as well as the limit of ice in post-100-ka time, after eruption of the andesite lavas of the caldera rim (units asr and anr).

The timing of glaciations in the Cascade Range is not well known, although times of worldwide cooling are fairly well constrained by oxygen-isotope variations measured in oceanic sediments (see, for example, Martinson and others, 1987; Shackleton and others, 1990; Bassinot and others, 1994; Worm, 1997). More proximal climate records are available for Nevada (Winograd and others, 1992) and for the California margin (Herbert and others, 2001; Lyle and others, 2001). These records provide some constraints as to when ice likely was present on MLV.

Evidence of the most recent glaciation, representing marine oxygen-isotope stage 2 in latest Pleistocene time, is relatively abundant. Ice apparently not only flowed outward from the rim of the volcano but also inward into the caldera, where it, as it accumulated, forced its way south out the lowest caldera exit, which is located in the area of Paynes Spring. This ice advance left a set of low morainal ridges, located about 2 to 3 km southwest of Paynes Spring, that are the best such features on the volcano. Ice probably extended down to as low as about 6,000 ft (1,829 m) in this area. It also traveled west out of Medicine Lake basin, as evidenced by the morphology of the scraped and modified terrain west and southwest of the lake. Even Little Mount Hoffman (elevation 7,310 ft; 2,228 m) probably was overridden. Evidence of poorly developed cirques that were sculpted by ice feeding the sheet in the caldera can be seen as topographic scallops along the north side of Medicine Mountain, which forms much of the south rim of the caldera.

In addition to deposits of till (unit t) shown on this map, smaller (unmapped) deposits are exposed along paved Forest Road 97 near Telephone Flat, and more are scattered across the caldera and south to the Burnt Lava Flow. Some of these deposits include boulders and cobbles derived from the late Pleistocene rhyolite of Mount Hoffman (rmh). Till also is present at Little Medicine Lake, which may be a kettle lake created by melting of ice that was caught up in the till.

Excellent examples of striations and polish can be seen on the north rim, just west of paved Forest Road 49. Just to the northwest is Grouse Hill, which is surrounded by a “moat” created when ice scoured away the less resistant cinders of the cone rather than the more resistant younger andesite flow (unit anr) that surrounds the cone. The cinder cone of Badger Peak (7,354 ft; 2,241 m) near the northwest caldera rim also was overtopped by ice. C.A. Anderson (1941) estimated an ice thickness of about 150 m; fluid-inclusion studies of deep drill-hole samples (Bargar, 2001) support this amount of ice or perhaps even more.

South-facing portions of the north rim ridge west of Mount Hoffman consist dominantly of talus, much of it glassy blocks from flow surfaces. Perhaps these talus slopes represent remains of former rock glaciers. The small lake located on the caldera rim north of the Medicine Lake Glass Flow apparently occupies a cirque left behind when ice scraped out a cinder cone. Another cirque on the north edge of Mount Hoffman probably is the best developed such feature on the volcano. However, evidence of extensive ice to the north is scanty, although it may be covered by pumice from more recent eruptions. Roadcuts along the major east-west-trending graveled road south of Fourmile Hill display poorly developed till deposits. A small deposit of till containing cobbles of the rhyolite of Mount Hoffman (rmh) is present about 0.4 km south of Aspen Crater. Ice probably did not extend below about 6,200 ft (1,890 m) on the north flank.

Evidence of glaciation also is present on the east rim where cinder cones have been modified considerably. One deposit of till was mapped on the lower northeast flank of Red Shale Butte adjacent to the rhyolite of Glass Mountain (rgm). Ice probably also moved through the gap now occupied by Glass Mountain, between Mount Hoffman to the north and vents of Red Shale Butte and Lyons Peak on the east rim to the south, although the evidence is buried by the late Holocene silicic lava flows of Glass Mountain and the “Hoffman flows.” Within the east end of the caldera, Alcohol Crater probably was created when ice excavated a cinder cone surrounded by more resistant lavas. Some glacial evidence almost certainly has been buried by proximal late Holocene tephra deposits, which include those of the dacite of pit craters (dpc), the rhyolite of Little Glass Mountain (rlg), the rhyolite of “Hoffman flows” (rh), and the rhyolite of Glass Mountain (rgm).

Glacial-outwash gravel extends east of the MLV edifice to the lower flanks where it mantles much of the basalt of Tionesta (bt), making the already subdued basalt surface look much older than its actual late Pleistocene age, which probably is a major reason why it was assigned a Pliocene age by C.A. Anderson (1941). In places along the east side of the railroad tracks north of Tionesta, borrow pits in the gravel and in the overlying pumice deposit have exposed the original surface of the basalt, showing it to be remarkably fresh in appearance. The Lake Basalt (bl) on the east flank of the volcano also is partly mantled by glacial-outwash gravel, although the steep topography on the upper parts of this unit has constrained the gravel’s distribution to limited areas.

Evidence for glacial-outwash gravel to the north is found in three localities. One is in Hidden Valley, an amphitheater on the east flank of the Mammoth Crater shield, where gravel containing pebbles of the latest Pleistocene rhyolite of Mount Hoffman (rmh) is found on the floor of the valley; it is shown as a small elongate area of unit g just east of Mammoth Crater. The gravel apparently was transported down a channel later filled by the (postglacial) basalt of Valentine Cave (bvc). A second small area of unit g is found about 3 km farther uphill from the first, where a quarried deposit of glacial-outwash gravel probably was wet when the (overlying) basaltic andesite northeast of Aspen Crater (mna) surrounded it. Unit mna has a very youthful morphology and, although it underlies the Valentine Cave flow (unit bvc), probably is postglacial or late glacial in age. A third such deposit was exposed by quarrying about 0.5 km east of Caldwell Butte, where it also is shown as unit g. Here, bedded gravel containing abundant pumice pebbles that have the same chemical composition as the rhyolite of Mount Hoffman (rmh) was deposited prior to eruption of the basalt of Valentine Cave (bvc). Lava flows of unit bvc surrounded but did not cover the gravel deposit, which was most likely wet. The quarry was located in Lava Beds National Monument where it was used as a landfill after quarrying ceased; the refuse later was covered over, filling the quarry and, unfortunately, eliminating the exposure of these gravels.

On the south side of MLV, glacial-outwash gravel must have been carried by streams that flowed down low areas, now occupied by the basalt of Giant Crater (bgc), because the edge of the (underlying) basalt of Water Caves (bwc) is covered by gravel where it is exposed at the eastern margin of Hambone Island. Gravel also was carried south under the present Burnt Lava Flow, down narrow channels now filled by the (post-glacial) basalt of ribbon flows (brf) and later covered by the andesite of Burnt Lava Flow (abl). These channels may have transported the gravel that mantles the area east of Snell Butte and south of the Burnt Lava Flow, as well as additional areas on the basalt of Yellowjacket Butte (byb).

On the lower northwest flank of the volcano, gravels are common and are present as a thin veneer over wide areas of low terrain. Much of this gravel probably was deposited by flooding following eruption of the dacite tuff of Antelope Well (dta), on the basis of evidence presented by Donnelly-Nolan and Nolan (1986), who argued that the tuff was erupted at a time when ice capped the volcano. This event probably also explains the presence of gravel in low areas west of Red Cap Mountain and at Tamarack Flat, where it likely buries unit dta. At approximately 180 ka, eruption of unit dta would have taken place near the beginning of marine oxygen-isotope stage 6 (Martinson and others, 1987; Bassinot and others, 1994; Worm, 1997).

Evidence for ice representing marine oxygen-isotope stage 8 can be found at the far west edge of MLV, in some of the oldest lavas of the Medicine Lake mafic shield. The andesite of Typhoon Mesa (atm, two ages of 282±11 ka and 254±25 ka; table 1), which is partially shown on the map, consists of a flat-topped mesa surrounded by steep talus slopes, as well as two small conical hills and other flow remnants that lack obvious vents. These compositionally distinct lavas probably were erupted on a northeasterly trend under an ice cap. No obvious vents remain on either Typhoon Mesa itself or on the flow farthest northeast, but the two small conical hills probably represent the interior remnants of vent cones. The Six Shooter Butte cinder cone (see unit m19) on the south flank of the volcano has an unusual elongate shape and may also have been scoured by this earlier, more extensive ice.

Under the present climatic conditions, no ice is present on the volcano, although some areas of protected snow may not melt completely from year to year. Snow covers most of the upper part of MLV for many months, from late fall through late spring and sometimes even into early July. Despite this, very little surface water is seen at MLV. The only creek is the one below Paynes Springs, which carries water a limited distance of one or two kilometers before the water disappears into the highly permeable ground of the volcano. Elsewhere on the volcano, water sometimes runs short distances on the ground surface during very heavy thunderstorms, although this more typically occurs on the packed surfaces of graveled roads. In general, modification of the landscape by water-caused erosion has not been a process of much significance at MLV.

Hazards, Resources, and Recreation

Potential volcanic hazards at MLV are most likely to take the form of a lava flow in a forested or brush-covered area, possibly accompanied by a local tephra fall and probably attended by fire. Donnelly-Nolan and others (2007) published a hazards assessment for the volcano that was based in part on analysis of the eruption record and probabilities as calculated by Nathenson and others (2007).

Early in the 20th century, much of MLV was logged by railroad. Some stands of large Ponderosa pine and red fir remain, but much of the volcano is now covered by second-growth forest. One of the old logging railroads is shown on the 1952 Medicine Lake 15' topographic map, which was the only available topographic map of the central part of the volcano when this mapping project began. However, by that time (late 1970's), the old railroad routes had been transformed into roads to accommodate logging trucks. Old railroad ties were tossed aside, and they commonly are still found along with other railroad debris such as spikes and bolts, although the rails have been taken away.

The only surface evidence for a geothermal system within the volcano is at the Hot Spot northwest of Glass Mountain, where high-temperature fumaroles are located. Other indications of hydrothermal alteration are scarce, but some altered rocks are present near Schonchin Spring and Crystal Springs in the caldera. Exploration for geothermal energy at MLV began in the 1980's; a high-temperature hot-water system confined primarily to the caldera was confirmed by drilling (Hulen and Lutz, 1999). Considerable evidence for alteration was found in core samples from the drill holes, especially from caldera drill holes 28-32 and 45-32, where minerals such as epidote and actinolite were found at depth (Bargar and Keith, 1997; Bargar, 2001); temperatures over 300°C at depths of about 1,200 m are indicated by their studies. Geothermal exploration continues, although political decisions about development of the resource have changed through time and may change again.

Surface water on the volcano is a scarce resource. Only a few standing bodies of water exist on the volcano, and springs are rare. Water, a precious commodity, is sometimes found at "wells" such as Antelope Well and Dock Well, where naturally wet low areas have been developed as water holes for cattle and wildlife; these "wells" actually are shallow holes commonly dug out over welded parts of the dacite tuff of Antelope Well (dta). The welded tuff is impermeable to water except when it is disturbed, as in the case of the southwesternmost outcrop of unit dta, near the edge of the map (sector B), which was deepened artificially in order to hold more water and now consequently holds none.

Recreational resources for tourists include campgrounds, fishing, and water sports at Medicine Lake, as well as camping, caving, and historical presentations at Lava Beds National Monument. Viewing of birds and wildlife also is an attraction for many people. A number of viewpoints that can be reached easily by road include the top of Little Mount Hoffman and lookouts at Round Mountain and Timber Mountain. A hiking trail is maintained to the lookout at the top of Schonchin Butte. In addition, unmarked hiking routes to the top of Lyons Peak and Mount Hoffman among other high points on the caldera rim provide spectacular views. Roads take the visitor to some of the youngest and most spectacular lava flows, such as Glass Mountain and Little Glass Mountain, the Medicine Lake Glass Flow, the Burnt Lava Flow, and through the Paint Pot Crater flow. A graveled road, one of the former logging-railroad routes, cuts through the rugged late Holocene Callahan Flow. Jot Dean Ice Cave and Valentine Cave are located within the postglacial Giant Crater and Valentine Cave flows, respectively, and paved roads reach to within a few meters of these caves. The (postglacial) basalt of Devils Homestead (bdh) flow and its vents at Fleener Chimneys, as well as Black Crater (unit bbr), are both easily accessible by road and trail and are well marked in Lava Beds National Monument. The paved road from Highway 139 and Tionesta on the east side of the volcano has a marked scenic overlook that has a view south across the Burnt Lava Flow to Lassen Peak, more than 100 km away. As the road continues west toward Medicine Lake, it cuts through the Holocene dacite of pit craters (dpc). Short side excursions on good graveled roads take the sharp-eyed visitor to within meters of some of the explosion craters that erupted the unit. Additional geologic features are described in various field guides (see, for example, Donnelly-Nolan and others, 1981; Donnelly-Nolan, 1987; Muffler and others, 1989), but travelers should be aware that road access changes from year to year.

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Introduction to Description of Map Units

This geologic map of Medicine Lake volcano (MLV) displays 237 units that are divided among surficial deposits, volcanic rocks, and units older than MLV. The map area is about 2,200 km^2 and covers all or part of twenty-seven 7.5' quadrangles; comparison of MLV's size to that of two volcanoes in the Cascade Range in southern Washington State is shown on figure 6 (on sh. 1). Approximately 60 percent of the map area is covered by MLV basalt; another 26 percent is composed of MLV basaltic andesite and andesite in subequal amounts (Donnelly-Nolan and Ramsey, 2001); silicic lavas (dacite plus rhyolite) of MLV cover only about 5 percent; the remaining 9 percent consists of surficial deposits and older (pre-MLV) volcanic units.

The geologic map portrays 208 volcanic rock units of MLV: of these, 13 are rhyolite, 11 are dacite, 39 are andesite, 63 are basaltic andesite, and 82 are basalt. Included among the 208 units are 45 isolated cinder cones of basalt, basaltic andesite, and andesite. Four surficial units of MLV age also are mapped. In addition, 25 older (pre-MLV) volcanic and surficial units are shown.

The volcanic rock units represent, as much as possible, individual eruptive events. Most consist of a lava flow and the single vent (or multiple vents) that spawned it. A few units represent packages of very similar lava flows that cannot be mapped separately and appear to reflect a single stratigraphic horizon. It is possible that some lava flows whose vents are unknown could be correlated to isolated cinder cones, but if the unit is compositionally heterogeneous and the physical connection between vent and flow is buried by younger flows, then the correlation cannot be made with any certainty. Additional units, including their vents, undoubtedly are buried by younger flows.

Silica content, based on one or more chemical analyses, is given for all eruptive units; chemical analyses were recalculated to 100 percent on a volatile-free basis. The volcanic rock units of MLV have been subdivided into compositional categories, as indicated by the first letter of the unit symbol (a, andesite; b, basalt; d, dacite; m, basaltic andesite; r, rhyolite). Unit symbols have been limited to three letters in order to minimize clutter; because of this limitation, the letter "m" (for "mafic") has been used for units that are basaltic andesite in composition (rather than the combined letters "ba").

Within each compositional category, MLV volcanic rock units have been listed alphabetically by unit symbol, here and in the List of Map Units (on sh. 2). On the map, colors for MLV volcanic rock units primarily reflect composition. Basalt (≤52.9% SiO_2) is shown in shades of blue and purple; basaltic andesite (53.0–56.9% SiO_2), in greens; andesite (57.0–62.9% SiO_2), in browns; and dacite (63.0–69.9% SiO_2), in oranges. Rhyolite (≥70.0% SiO_2) is shown in shades of pink and red. In addition, sixteen units that were erupted in postglacial time are highlighted on the map with an overlay "v" pattern.

Isolated cinder cones are identified by a dot pattern, and all cones of the same composition (either basalt, basaltic andesite, or andesite) are shown in the same color. For example, all nine isolated cinder cones of andesite composition are shown with the same brown color and overlying dot pattern. All cones are labeled with a letter indicating their composition (b for basalt, m for basaltic andesite, a for andesite), followed by a number that increases from north to south. None of these cones has been correlated with a lava flow; most likely, the flows have been buried by younger eruptions. The ages of the isolated cones are poorly constrained.

Surficial deposits of MLV are mapped only where they completely obscure underlying units or, occasionally, where identification of the deposit is important to the geologic history of MLV. Much of the volcano is covered by a mantle of pumice, especially the north half. In low places within the higher terrain, pumice commonly mantles colluvial material that may be principally glacial in origin. Surficial deposits of MLV are shown either in shades of yellow, for different types of deposit (gravel, lake deposits, and till), or in pale pink, for pumice deposits thick enough to obscure underlying units.

Older (pre-MLV) units are subdivided into surficial and volcanic units; their unit symbols begin with the letter "o," and they also are listed in alphabetical order. Decisions about which units are older (in other words, not part of MLV) were based on measured ages, age gaps, petrographic criteria such as presence or absence of hornblende (rare at MLV), degree of erosion and (or) weathering, and contiguity. All older units are shown in shades of gray: older surficial units (gravel and lake deposits) are shown in the two palest gray shades; older volcanic units generally are shown in lighter shades for more mafic units and darker shades for units that have a higher silica content.

Vents are identified on the map with star symbols. Some units have single vents, such as a cinder cone or a dome, but many have multiple vents; the linear arrays of rhyolite domes in units rgm and rlg are examples, as are the mafic fissures that are vents for units bbr, bc, and bgc.

Faults are indicated by heavy black lines on the map. Some faults have normal offset, as indicated on the map by the bar and ball symbol on the downthrown side. No faults having lateral offset have been recognized on MLV.

Other features to note on the map include the caldera boundary and lava tubes. The caldera boundary is defined primarily by topography and vent locations, not by faults; its estimated position, which is known only approximately, is indicated by a thick, gray-dashed line on the map and on figures 4, 5, and 6 (on sh. 1) and 7 (on sh. 2). Lava tubes are shown as magenta crosshatched lines. They are found only in basaltic flows on the flanks of the volcano, in units such as the basalt of Mammoth Crater (bmc), which covers much of Lava Beds National Monument, and the basalt of Giant Crater (bgc), on the south side of MLV. A lava tube in unit bmc fed the littoral cones of Hospital Rock, located in northeastern Lava Beds National Monument. Here the tube emptied into ancient Tule Lake, where steam explosions fragmented the lava on contact with the water, forming small cones that are superficially similar to cinder cones. At the northeast edge of the monument, the lava flow margin displays pillow lava, indicating that the lava flow entered the lake. Additional discussion of features in Lava Beds National Monument can be found in Donnelly-Nolan and Champion (1987).

Most units are named informally: for example, the basalt of Giant Crater, the basaltic andesite near Tickner Cave, and the dacite tuff of Antelope Well. A few units, such as the Lake Basalt, have formal names derived from prior publications; however, some previously used names have been changed herein because chemical analyses show that the unit either has a different composition than originally thought (for example, the andesite tuff of C.A. Anderson (1941) became the dacite tuff of Antelope Well because it contains dacitic pumice) or is not related to the larger unit in which it was originally included (for example, the basalt of Tionesta is not part of the Warner Basalt).

Units that have been dated by argon methods are indicated, here and in the Correlation of Map Units (on sh. 2), by an asterisk (*) following the unit symbol. All argon ages cited herein, which are listed alphabetically by unit symbol in table 1, are from Donnelly-Nolan and Lanphere (2005) unless otherwise noted. When both K-Ar and $^{40}Ar/^{39}Ar$ ages were generated on the same sample, only the latter is included in table 1, as the $^{40}Ar/^{39}Ar$ ages are considered to be the preferred ages; see Donnelly-Nolan and Lanphere (2005) for additional data. Time boundaries for the subdivisions early, middle, and late Pleistocene (Richmond and Fullerton, 1986) are indicated on the Correlation of Map Units.

Most units depicted on the map have not been dated directly. Stratigraphic relations have been used to constrain ages, but the position on the Correlation of Map Units of many units is an informed guess that is based on such characteristics as degree of weathering and erosion and thickness of soil mantle. One critical factor is whether an undated unit underlies or overlies the dacite tuff of Antelope Well (dta), the only widespread marker bed on the volcano. In estimating relative age, the location of a unit on the volcano also is a factor: for example, the northern and eastern parts of MLV are much drier than the western and central parts, resulting in better preservation of surface features; in addition, surfaces of lava flows are better exposed on the southern part because the pumice cover is thinner there.

Lava flow morphology is closely related to chemical composition; for example, as silica content increases, so typically does the height of the flow front. Basalts that have the lowest silica contents (in other words, less than 49% SiO_2) may have flow fronts less than a meter high, whereas a typical basaltic andesite will have a flow front several meters high, commonly 3 to 10 m; andesite flows typically will be even higher and more rugged. For comparison, the flow front of the dacite of Medicine Lake Glass Flow (dm) is about 30 m high, and that of the rhyolite of Glass Mountain (rgm) is at least twice that high. One clear exception is the dacite tuff of Antelope Well (dta), which was erupted as a mixture of gas and hot fragments of lava. The variable thickness of the tuff is dependent upon topography because the ash flow traveled down small valleys and filled basins and also spread thinly across flat surfaces.

Vent type and size also are related to chemical composition. Vents for low-silica basalts typically are spatter cones, lava lakes, and pit craters, reflecting the fluid nature of these lavas. Eruptions of high-silica basalts, as well as of basaltic andesites and andesites, usually produce cinder cones; these eruptions also may produce dispersed tephra, but no such tephra deposits are shown separately on this map. More silicic lava flows typically form viscous flows that have domes at their vents, although their initial explosive eruptions may yield tephra (for example, surficial unit p) and tephra cones. Only the most fluid basaltic lavas form lava tubes.

Rock texture also is related directly to chemical composition. No attempt has been made here to describe groundmass textures as seen in thin section; however, basaltic rocks tend to display a granular groundmass in hand specimen, such that tiny individual crystals commonly can be discerned using a hand lens. Some of the most primitive basalts show a diktytaxitic texture, having irregular open spaces between groundmass crystals. As silica content increases from that of basalt to that of rhyolite, so does the glassiness of the rocks, such that broken surfaces will be progressively smoother. In addition, textures can vary within the same lava flow, depending on position in the flow; for example, surface samples may have much glass between crystals, whereas completely crystallized interior samples may have none. A typical andesite flow having about 60% SiO_2 will display (where preserved at its top) dense glassy blocks that show satiny black surfaces. Interior blocks also will be smooth and dense, but they will be gray and dull in appearance. True obsidian—the black volcanic glass, transparent in thin broken slivers, that was used by Native Americans to make arrowheads—is found only among rhyolites.

In the field, color alone cannot be used to distinguish between different rock types. At MLV, the most primitive basalts commonly are light gray; basaltic andesites most commonly are dark gray; and andesites can be gray to black, as can dacite and rhyolite, which also can have a beige or white, pumiceous facies. In addition, any of the rock types can be oxidized to various shades of red.

Many lava flows contain chilled magmatic inclusions that represent blobs of more mafic magma that have been incorporated into the host unit, most likely during magmatic recharge. Descriptions of these inclusions can be found in Grove and Donnelly-Nolan (1986) and Grove and others (1988, 1997); see also, Bacon (1986). Some inclusions display cumulate textures (for example, in Little Glass Mountain), but they typically are fine grained and display quench textures; photographs of both types are shown in Grove and Donnelly-Nolan (1986). These kinds of inclusions also are known as enclaves.

Percentages of phenocrysts for most units were estimated from thin sections or, in some cases where thin sections were unavailable, from hand specimens. Phenocrysts are considered to be crystals 1 mm in size or larger, although some descriptions include comments about microphenocrysts. General terms used to describe phenocryst abundance are as follows: poorly porphyritic, approx 1% or less; sparsely porphyritic, 1–3%; moderately porphyritic, 3–5%; porphyritic, 5–15%; and very porphyritic, greater than 15%. Some lava flows are variably porphyritic, typically when they also are compositionally variable.

Estimated areas and volumes are given primarily for the youngest eruptive units. Some data were published in Donnelly-Nolan and others (1990), as were radiocarbon dates for many of the postglacial units. More recently, revised and calibrated ages for all of the postglacial units were presented in Donnelly-Nolan and others (2007) and Nathenson and others (2007).

DESCRIPTION OF MAP UNITS

[Map units are listed in same order as “List of Map Units” (on sh. 2). Argon-dated units are shown with asterisk (*), here and in “List of Map Units”; ages of units are listed (alphabetically by unit symbol) in table 1. Radiocarbon ages, both measured number and calibrated age, are given in years before present (yr B.P.), where “present” is 1950 by convention. Capital letter(s) listed at ends of descriptions indicate sector(s) of volcano where unit can be found (see “Sector Location Map” on sh. 2). Mineral abbreviations: opx, orthopyroxene; cpx, clinopyroxene; pyx, pyroxene (seen in thin section but of uncertain composition); ol, olivine; plag, plagioclase; hb, hornblende; xls, crystals; MI, magmatic inclusion(s). Other abbreviations: MLV, Medicine Lake volcano; LBNM, Lava Beds National Monument; USGS, U.S. Geological Survey. Detailed information about how MLV map units have been classified and interpreted and also how they are portrayed on map can be found in "Introduction to Description of Map Units" (see p. 13)]

SURFICIAL DEPOSITS

g **Gravel (Pleistocene)**—Includes boulders as much as a meter across, but dominant size range consists of pebbles to small cobbles; deposited in widely scattered areas distributed on middle to lower flanks of MLV. Consists primarily of glacial-outwash gravel associated with deglaciation, as well as gravels deposited by flood that was generated when the dacite tuff of Antelope Well (dta) erupted onto summit ice cap (Donnelly-Nolan and Nolan, 1986) about 180,000 years ago (age of unit dta). All sectors except D, H, K

l **Lake deposits (Holocene and Pleistocene)**—Fine-grained, water-laid sediments in low, flat areas scattered around MLV. All sectors

p **Pumice (Holocene)**—Mapped only where thick deposits of pumice obscure underlying units and contacts. Consists of pumice deposited by air fall from eruptions at Little Glass Mountain and Glass Mountain. Isopach maps and detailed descriptions of these pumice deposits are included in Fisher (1964) and Heiken (1978). Little Glass Mountain tephra deposit is strongly elongated southwest-northeast, whereas Glass Mountain tephra is found mainly north and northeast of lava flows and domes emplaced after tephra. Deposits are depicted on map in following areas: adjacent to Glass Mountain, Little Glass Mountain, and Crater Glass Flow; in basin that contains Pumice Stone Well; in two low areas west of Squaw Peak; and in two low areas within caldera, notably at Arnica Sink. Sectors D, E, F, J, K, L

t **Glacial till (late Pleistocene)**—Includes boulders, cobbles, gravel, and interstitial finer grained material deposited directly by glaciers that formerly existed on top of MLV. Only better defined and more extensive deposits are mapped. Other till is present only in small patches or is poorly exposed. Because of poor exposure and limited extent of deposits, no attempt has been made to separate glacial deposits of different ages (see fig. 7, on sh. 2, for approximate distributions). Several mapped areas are younger than volcanic units on caldera rim, including areas on unit anr, areas on and near Medicine Mountain on unit asr, and one area at edge of Red Shale Butte that is younger than the Lake Basalt (bl) and thus is less than about 89 ka in age. Mapped area on north side of Mount Hoffman is deposited in cirque cut by latest Pleistocene glaciers and is younger than 28±5 ka, which is age of the rhyolite of Mount Hoffman (rmh); cobbles of unit rmh are present in till on south side of caldera. Till at Little Medicine Lake is mapped as younger than unit anr. Largest area of till, about 3 km south-southeast of Medicine Lake, includes several low morainal ridges and thin scattering of till over lava of unit asr. Sectors A, B, C, E, F, J, L, M

VOLCANIC ROCKS

BASALT

b1 **Basalt of Hardin Butte (middle Pleistocene)**—Very porphyritic basalt (52.1% SiO_2) of Hardin Butte cinder cone, oxidized and partially buried, in central part of LBNM. Phenocrysts, 20–25%: 1–4 mm plag+ol, plag>ol; includes approx 5% 1–3 mm ol. Surrounded by the (younger) basalt of The Castles (bc); several vents of unit bc are located on lower west flank of Hardin Butte. Sector I

b2 **Basalt cone at northeast edge of Sharp Mountain (middle Pleistocene)**—Porphyritic basalt (51.1% SiO_2) cinder cone west of Three Sisters (in northwestern part of map area), at northeast edge of Sharp Mountain. Phenocrysts: 5–10% 1–2 mm plag+ol, commonly in clots, plag≥ol. Underlies unit bts. Sector F b3 **Basalt cone at east edge of Sharp Mountain (middle Pleistocene)**—Poorly porphyritic basalt (51.5% SiO_2) cinder cone between Sharp Mountain and Three Sisters (in northwestern part of map area). Phenocrysts: ≤1% 1 mm ol. Underlies units dta and bts. Sector F

b4 **Basalt of Caldwell Butte (middle? Pleistocene)**—Very porphyritic basalt (51.6% SiO_2) of Caldwell Butte cinder cone, as well as of satellite vent, Caldwell Minor, on its north flank. Lava flows, if present, are entirely buried by younger lavas. Phenocrysts: approx 20% 1–4 mm plag; 1% 1–2 mm ol. Underlies unit bvc. Sector J

b5 **Basalt cone southeast of Mammoth Crater (middle? Pleistocene)**—Poorly porphyritic basalt (52.1% SiO_2) cinder cone just southeast of Mammoth Crater, south of southwest end of Hidden Valley. Phenocrysts: <1% 1–2 mm plag. Underlies units bma and bmc. Sector I

b6 **Basalt cone at southeast end of Hidden Valley (middle Pleistocene)**—Nearly aphyric basalt (51.4% SiO_2) cinder cone less than 1 km southeast of Mammoth Crater and south of southeast end of Hidden Valley. Phenocrysts: rare ≤4 mm plag. Underlies units bma and bmc. Sector I

b7 **Basalt cone southwest of Bonita Butte (middle Pleistocene)**—Porphyritic basalt (50.4% SiO_2) cinder cone approx 5 km southwest of Bonita Butte and approx 6 km northeast of Dock Well. Phenocrysts: 8–10% 1–3 mm plag; 1–2 mm ol; plag>>ol. Completely surrounded by younger unit mnl. Sector F

b8 **Basalt cone east of Cinder Butte (middle Pleistocene)**—Moderately porphyritic basalt (51.4% SiO_2) cinder cone approx 2 km east of Cinder Butte at east edge of Callahan Flow (unit mcf). Phenocrysts: ≥5% 1–2 mm plag+ol, plag>ol. Underlies units dec, bmc, and mcf. Sector H

b9 **Basalt cone north of Aspen Crater (middle Pleistocene)**—Porphyritic basalt (50.5, 51.1% SiO_2) cinder cone approx 2.5 km southeast of Mammoth Crater and an equal distance north-northeast of Aspen Crater. Phenocrysts, 10–15%: mostly 1–3 mm plag; includes approx 2–3% 1–2 mm ol; rare cpx. Underlies units asm and mna. Sector J

b10 **Basalt cone southwest of Dock Well (middle Pleistocene)**—Porphyritic basalt (52.7% SiO_2) cinder cone, quarried, about 2.5 km southwest of Dock Well along major paved east-west road. Phenocrysts: 5–10% 1–3 mm ol+plag, ol>plag. Underlies unit dta; probably underlies unit mtr. Sectors E, F

b11 **Basalt cone northeast of Six Shooter Butte (middle Pleistocene)**—Poorly porphyritic basalt (52.1% SiO_2) cinder cone approx 3.5 km northeast of Six Shooter Butte. Phenocrysts: approx 1% 1 mm plag+ol, plag>>ol. Underlies units as and asr. Sector A

b12 **Basalt cone northeast of Doe Peak (middle Pleistocene)**—Porphyritic basalt (52.6% SiO_2) cinder cone approx 1.5 km northeast of Doe Peak. Phenocrysts: 5–10% 1–3 mm plag+ol, plag>ol. Probably overlies unit mnd; underlies units mdp and bnp. Sector C

b13 **Basalt cone east of Six Shooter Butte (middle Pleistocene)**—Sparsely porphyritic basalt (52.2% SiO_2) cinder cone approx 2 km east of Six Shooter Butte. Phenocrysts: 1–2% 1–2 mm plag; sparse 1 mm ol xls. Underlies and is completely surrounded by unit as. Sector A

b14 **Basalt cone east of Doe Peak (middle Pleistocene)**—Moderately porphyritic basalt (52.3% SiO_2) cinder cone less than 2 km east of Doe Peak. Phenocrysts small, >5%: mostly 1 mm plag, some ol. Underlies units mnd, mdp, and bsl. Sector C

b15 **Basalt cone south of High Hole Crater (middle Pleistocene)**—Porphyritic basalt (52.0% SiO_2) cinder cone approx 2.5 km south of High Hole Crater within Burnt Lava Flow (unit abl). Phenocrysts: 5–10% 1–3 mm plag+ol, plag>ol. Completely surrounded by much younger unit abl. Sector M

b16 **Basalt of Snell Butte (middle Pleistocene)**—Porphyritic basalt (49.4% SiO_2) of Snell Butte cinder cone, south of Burnt Lava Flow (unit abl); quarried. Extent of alteration and depth of soil suggest that cone is relatively old. Phenocrysts, ≥10%: 1–3 mm plag+ol, plag>ol. Underlies unit bdc, as well as later glacial-outwash gravel of surficial unit g. Sector M

b17 **Basalt of Round Mountain (middle Pleistocene)**—Moderately porphyritic basalt (51.7% SiO_2) forming large cinder cone at Round Mountain. Lava flows, if present, are buried by the basalt of Yellowjacket Butte (byb) that surrounds cone. Phenocrysts, approx 5%: 1–3 mm plag; 1–2 mm ol; plag>ol. Underlies unit byb. Sector M

bac **Basalt of Aspen Crater (late Pleistocene)**—Sparsely porphyritic basalt (50.1–51.8% SiO_2; avg of 5 = 50.8%), in three separate, relatively small outcrop areas, both within caldera and on north flank of MLV. One area is in caldera at southeast edge of Arnica Sink; another lies between Mount Hoffman and Aspen Crater; and third and smallest patch is approx 2 km northwest of Aspen Crater. One vent location is unknown but is probably on north caldera rim under unit rmh. Pyroclastic deposits from probable explosive activity at Aspen Crater likely were removed by glacial ice; small unmapped deposit of glacial till overlies unit and is exposed in roadcut approx 1 km south-southwest of Aspen Crater. Phenocrysts: 1–3% 1–2 mm plag+ol, plag>ol; occasional 2–3 mm plag+ol clots. Overlies units m9, m10, and mnm; underlies units aac and bl; presumably underlies unit rh, and surficial unit p within caldera; presumably underlies units asm, anr, aib, and mna north of caldera. Sectors I, J, K, L

bbr **Basalt of Black Crater and Ross Chimneys (Holocene)**—Very porphyritic basalt (48.3–50.6% SiO_2; avg of 21 = 49.5%), found in two small areas in northern part of LBNM. Covers approx 0.45 km^2, having total volume of approx 0.001 km^3. Was erupted from numerous north-northeast-trending spatter cones that form en echelon linear arrays. Vents for topographically lower, more northerly patch of lava, known as Ross Chimneys, produced basalt that ranges in composition from 48.3 to 49.6% SiO_2. Vents for upper patch, known as Black Crater, and its associated spatter vents erupted lava that ranges in composition from 49.2 to 50.6% SiO_2. In general, silica content decreases with decreasing elevation. Lava from topographically higher Black Crater vents overlies lava from topographically lower Black Crater vents, suggesting that higher silica lava erupted after lower silica lava. Open ground cracks, which are on same trend and have same orientation as vents, extend north toward boundary of LBNM and may have opened during this eruption. Phenocrysts, 20–25%: mostly 2–4 mm plag, some plag ≤1 cm; includes 2–4% 1–2 mm ol. Overlies all adjacent units (bmc, men, msc). Calibrated radiocarbon age is 3,080 yr B.P. (Donnelly-Nolan and others, 2007; Nathenson and others, 2007). Sector I

bc **Basalt of The Castles (late Pleistocene)**—Aphyric, diktytaxitic basalt (48.6% SiO_2) fed from many tens of spatter cones, including The Castles near west base of Schonchin Butte. One major vent is lava lake west of Semi Crater. Most vents are aligned north-northeast, but some are oriented north-northwest to northwest. Most of unit is located west of Schonchin Flow (unit asb), but one area is located at its northeast edge. Unit contains small lava tubes and lava-tube caves. Overlies all adjacent units (b1, bcb, msc, asb, bmc). Degree of spatter-vent breakdown indicates that unit is not Holocene. Sector I

bcb **Basalt of Canby Bay (middle Pleistocene)**—Sparsely porphyritic basalt (50.0% SiO_2), in northern part of LBNM. Phenocrysts: 2% 1–3 mm plag; rare ol ≤3 mm. Petrographically distinct because of its more abundant phenocrysts when compared to adjacent and morphologically similar, but nearly aphyric, lava of the basalt of Mammoth Crater (bmc). Underlies all adjacent units (msc, bmc, bc, bdh) except unit bhp to north, which it overlies. Vent is unknown and presumably is buried to south under younger lava flows. Sector I

bci **Basalt of Caldwell Ice Caves (late Pleistocene)**—Aphyric basalt (52.8% SiO_2) flow, which includes mostly collapsed lava tube that is host to Caldwell Ice Caves near southeast corner of LBNM. Tube and flow directions indicate buried vent(s) to southwest. Overlies units mc, mni, anh, and bng; underlies units aib and bvc. Sector J

bco **Basalt of Cougar Butte (middle Pleistocene)**—Moderately porphyritic basalt (51.2% SiO_2) lava flow and Cougar Butte cinder cone, midway up northeast flank of MLV. Phenocrysts: 5% 1–3 mm plag+ol; large ol more abundant than large plag, small ol less abundant than small plag. Overlies unit rcb; underlies units bls and aib; probably underlies unit bng. Sector K

bcu **Basalt of unnamed crater (middle Pleistocene)**—Poorly porphyritic basalt (52.2, 52.5% SiO_2) exposed in collapse(?) or explosion(?) pit and in one other small outcrop area about 2.5 km southwest of Mammoth Crater. Unit may have been erupted from unknown vent to south. If crater was created by explosion, pyroclastic deposits were likely removed by glacial ice. Phenocrysts: 1% 1 mm plag; trace 1 mm ol. Underlies units mnm and asm. Sector I

bdb* **Basalt of Damons Butte (middle Pleistocene)**—Variably porphyritic basalt (47.8–48.3% SiO_2; avg of 13 = 48.0%) at easternmost edge of MLV; only western part of unit is shown on map. Unit may be a back-arc basalt not directly related to MLV, although it is age equivalent. Several (about 5) spatter vents form north-northeast trend, approx 4 km east of map boundary. Fine grained and aphyric to moderately porphyritic. Phenocrysts (when present): ≤5% 1–2 mm ol+plag, commonly in clots ≤1 cm that give rock a spotted appearance; in addition, single 5 mm cpx+plag clot present. Overlies unit ob; underlies units bt and byb. $^{40}Ar/^{39}Ar$ age is 144±15 ka (table 1). Sectors K, L

bdc **Basalt of Deep Crater (middle Pleistocene)**—Poorly porphyritic basalt (two analyses, 50.3% SiO_2) forming large complex of lava flows and numerous (≥10) cinder and spatter vents at south edge of Burnt Lava Flow (unit abl). Vents, including Deep Crater, are aligned from slightly north of east to approx N. 30° W. One lava tube trends southeast from Deep Crater about 3 km, where it is buried by unit byb. Phenocrysts: <1% 1 mm plag+ol, commonly ol>plag. Rock typically is fine grained, having tiny plagioclase crystals that flash in groundmass on a sunny day. Overlies units b16, mrr, and bnr; underlies units bpb, byb, ms, bgc, and abl, as well as surficial unit g. Lack of unit dta on surface of this large unit may suggest that it is younger than unit dta. Sectors A, M

bdh **Basalt of Devils Homestead (late Pleistocene)**—Young, sparsely porphyritic basalt (51.3, 51.4% SiO_2) flow and spatter vents known as Fleener Chimneys. Aa flow makes up rugged Devils Homestead in LBNM, although much of lava near vent is pahoehoe. Area covered by unit is approx 4.1 km^2; volume is approx 0.04 km^3. Vents, located at bend along predominantly north-south-trending Gillem Fault, are aligned approx N. 20–25° E. Phenocrysts: 1–2% plag, mostly 1–3 mm, some ≥1 cm long. Overlies all adjacent units (adh, bcb, msc, awf, men, bmc). Age is postglacial, on basis of paleomagnetic data and morphologic comparison with other lava flows (Donnelly-Nolan and others, 1990). Calibrated age of 12,320 yr B.P. is based on estimate derived from comparison of paleomagnetic direction with other dated units (Donnelly-Nolan and others, 2007; Nathenson and others, 2007). Sectors H, I

bdp **Basalt of Doe Peak (middle Pleistocene)**—Moderately porphyritic, diktytaxitic basalt (48.9, 49.1% SiO_2) forming small lava flow on lower northwest flank of Doe Peak, as well as somewhat larger lava flow about 2 km southwest, adjacent to paved Harris Spring Road (Forest Road 15); vents trend approx N. 55° E. Both outcrop areas are mantled with pumice, and vents in both areas are broken down and eroded. Coarse diktytaxitic texture. Phenocrysts: 2–5% elongate 1–4 mm plag; <0.5% 1 mm ol. Overlies units mdp and bwd. Sector C

bea **Basalt east of Antelope Well (middle Pleistocene)**—Very porphyritic basalt (50.5% SiO_2) exposed in numerous outcrop areas that are scattered low on northwest flank of MLV. Vent location is unknown but presumably is uphill to southeast. Phenocrysts: ≥15% 1–4 mm plag; 3–5% 1–2 mm ol. Overlies units ord and aes; underlies units dsk, mnl, anl, awh, dta, and mfh. Sectors F, G

beb **Basalt east of Big Sand Butte (late Pleistocene)**—Aphyric basalt (51.0% SiO_2) that apparently was erupted from partially collapsed lava lakes located approx 1 km east of Big Sand Butte. Overlies units mes and bls; underlies unit bmc. Sector K

bec **Basalt east of Cinder Butte (late Pleistocene)**—Sparsely porphyritic basalt (51.6% SiO_2) that was erupted from quarried spatter vents located east of Cinder Butte. Overall trend of two closely spaced north-south-trending vents and a third, more northern vent is approx N. 30° E. Morphology is youthful; lava channels and small lava tubes are present. Phenocrysts: 1% 1–3 mm plag; sparse 1 mm ol xls; rare ≤4 mm plag+ol clots. Overlies units rse, rec, dec, and mnm; also overlies northeast-trending fault; underlies unit mcf. May have been erupted after latest glaciation. Sector H

beg **Basalt east of Glass Mountain (middle Pleistocene)**—Porphyritic basalt (51.0% SiO_2) covering relatively small area east of Glass Mountain flow (unit rgm); vent unknown and probably buried beneath Glass Mountain lava. Phenocrysts, approx 10%: ≤2 mm plag+ol, plag>>ol; plag+ol also in 2–3 mm clots. Groundmass crowded with <1 mm plag+ol xls visible to naked eye, plag>>ol. Overlies unit reg; underlies units deg, bl, and rgm. Sector L

bei **Basalt east of Indian Butte (middle Pleistocene)**—Porphyritic basalt (51.7% SiO_2) exposed in small area about 3 km southeast of Cougar Butte. Vent location unknown. Phenocrysts: 5–10% ≤3 mm, mostly plag; approx 1% 1–2 mm ol. Underlies unit aib; probably underlies unit bng. Sector K

bel **Basalt east of Lost Iron Well (middle Pleistocene)**—Poorly porphyritic basalt (51.4% SiO_2) occupying very small outcrop area about 3.5 km northeast of Harris Mountain. Phenocrysts rare: 1 mm plag+ol. Unit is exposed where it flowed against older unit rgf and where it was not completely buried by overlying unit mug. Sector B

bet **Basalt east of Timber Hill (middle Pleistocene)**—Porphyritic basalt (50.9, 51.0% SiO_2) in four patches of mostly cindery material northeast of Porcupine Butte. Implied vent alignment is approx north-south. Phenocrysts: approx 5% 1–2 mm plag; 1–2% 1–2 mm ol; sparse plag+ol clots to ≤4 mm. Underlies units as and bgc. Sector A

bgc **Basalt of Giant Crater (late Pleistocene)**—Variably porphyritic and chemically variable, postglacial basaltic (47.7–53.2% SiO_2; avg of 84 USGS analyses = 49.5%) lava field, extending 45 km south from numerous vents on south flank of MLV between 5,000 ft (1,524 m) and 6,000 ft (1,829 m) elevation. Many vents are aligned north-south; others, N. 55° E. (see Donnelly-Nolan and others, 1991, for vent locations and additional description). Area covered by unit is about 198 km^2; volume is about 4.35 km^3. Includes isolated spatter cones found within Double Hole Crater lobe. Six chemical subgroups within lava field have been mapped and described by Donnelly-Nolan and others (1991); their petrographic description (see p. 21,844) is quoted here:

> "Group 1 lavas are the most porphyritic with about 5% of phenocrysts of plagioclase and olivine and an occasional 1–3 mm quartz grain. Plagioclase crystals are as long as 6 cm. Group 2 and 3 lavas contain decreasing amounts of phenocrysts and the plagioclase megacrysts are typically smaller, usually 1–2 cm across in group 3 lavas. The distinctions between groups 1 and 2 and between groups 2 and 3 are difficult to make in the field. Group 4 lavas, however, are distinctive. They are typically massive and aphyric with rare plagioclase megacrysts to 1 cm across. Group 5 lavas are aphyric but diktytaxitic and can be distinguished fairly readily from group 4 lavas but not from group 6. All groups include both aa and pahoehoe lavas."

More detailed petrographic descriptions are given in Baker and others (1991; see p. 21,820). As depicted on this map, unit includes very small "spatter vents in Double Hole Crater flow" unit described in Donnelly-Nolan and others (1990, 1991). Unit also contains melted granitic inclusions and mafic cumulate inclusions (Baker and others, 1991). Underlies unit bv5; overlies all other adjacent units. Unit is displaced as much as 10 m down to west by Mayfield Fault. Calibrated age of 12,430 yr B.P. (Donnelly-Nolan and others, 2007; Nathenson and others, 2007) is based on two radiocarbon ages (Donnelly-Nolan and others, 1990). Sectors A, B

bgd **Basalt of Gold Digger Pass (late Pleistocene)**—Poorly porphyritic basalt (49.6–50.7% SiO_2; avg of 8 = 50.4%) on lower north flank of MLV. Has youthful, well-preserved morphology similar to the (underlying) basalt of Mammoth Crater (bmc). Exposed flow length approx 11 km. Broken by both northwest-trending and northeast-trending faults. Vent area presumably buried by Callahan Flow (unit mcf) to south. Phenocrysts: approx 1% 1 mm ol; sparse 1 mm plag xls. Overlies units om, ob, opt, dta, awf, awb, buc, and bmc; underlies unit mcf. Sectors G, H

bgf **Basalt west of Canby Cross at Gillem Fault (middle Pleistocene)**—Poorly porphyritic basalt (51.4% SiO_2) exposed in small upfaulted outcrops at base of Gillem Bluff in northwestern part of LBNM. Unit flowed against preexisting Gillem Fault, then it was covered in part by unit adh; subsequently, both units (bgf, adh) were upfaulted more than 10 m. Phenocrysts: 0.5% 1 mm plag. Younger than Pliocene units obg and omw of Gillem Bluff; underlies unit adh. Older than unit bmc, which flowed against upfaulted outcrops of this unit. See Donnelly-Nolan and Champion (1987) for additional information (on their map, mapped as "unit bwcc"). Sector H

bh **Basalt of Hill 22 (middle Pleistocene)**—Sparsely porphyritic basalt (51.9% SiO_2) that was erupted from cinder cone named Hill 22. Flow extends approx 1.5 km northwest of vent. Phenocrysts: 2–3% 1 mm ol+plag, ol>plag. Underlies units mtr, anl, and dta. Sector F

bhi **Basalt of Hambone Island (middle Pleistocene)**—Aphyric, fine-grained diktytaxitic basalt (48.4% SiO_2). Vent location unknown. Underlies all adjacent units (mrr, bwc, bgc). Broken by northwest-trending fault; may be older basalt flow underlying MLV. Sector A

bhp* **Basalt of Hovey Point (middle Pleistocene)**—Poorly porphyritic, diktytaxitic basalt (50.9% SiO_2) at north edge of LBNM. Appears to have been inundated at some time by ancient Tule Lake. Phenocrysts: 0.5% 1 mm plag+ol, plag>ol. Underlies both adjacent units (bcb, bmc). $^{40}Ar/^{39}Ar$ age is 445±25 ka (table 1). See Donnelly-Nolan and Champion (1987) for additional description of unit. Sector I

bl* **Lake Basalt (late Pleistocene)**—Variably porphyritic basalt and basaltic andesite (50.0–56.1% SiO_2; avg of 45 = 52.4%) flows and multiple (>15) cones along two trends: one is 15 km long and is north-northwest-trending; other extends approx 5 km east-west across eastern part of caldera floor to east rim of caldera. Unit covers approximately 150 km^2 and has an estimated volume of about 3 km^3: some is within eastern part of caldera; remainder is east and southeast of caldera on east slope of MLV. Unit is glaciated but is commonly scoriaceous in appearance, having a slightly purplish hue. Four subgroups have been defined by Wagner and others (1995), including sparsely porphyritic lava that has as little as 2–3 percent plag and trace of ol, as well as very porphyritic lava that contains as much as 33 percent phenocrysts consisting of 1–4 mm plag and 1 mm ol, which constitutes ≤2 percent of rock; plag>>ol; cpx is present but rare. One partially melted granitic inclusion was found. Overlies units obu, omb, reg, rsl, beg, deg, dta, mrs, msp, aug, bac, aac, asr, anr, drs, and bt; underlies units byb, aib, brf, dpc, dm, abl, rh, and rgm, as well as surficial units g, l, t, and p. Three $^{40}Ar/^{39}Ar$ measurements yield ages of 126±14 ka, 123±27 ka, and 65±10 ka (table 1): of four subgroups of this unit (Wagner and others, 1995), oldest (or "caldera") Lake Basalt has ages of 126±14 and 123±27 ka, but it overlies unit anr (100±3 ka); one age of 65±10 ka was measured on Lake Basalt lava that has same paleomagnetic direction (D.E. Champion, unpub. data, 1995) as southern subgroup of this unit, which underlies unit byb (86±14 ka). Thus, two older measured ages for this unit are too old, and youngest age is too young. However, weighted mean of three ages is 89±13 ka, which fits stratigraphic constraints of ages for underlying unit anr and overlying unit byb. Sectors I, J, K, L, M

blh* **Basalt of Little Mount Hoffman (middle Pleistocene)**—Porphyritic basalt (52.1% SiO_2) of glaciated cinder cone just northeast of Little Glass Mountain, on or near poorly defined west rim of caldera. Top of cone provides spectacular view, primarily to south, west, and north, and overlooks the late Holocene Little Glass Mountain rhyolite flow (unit rlg), with Mount Shasta about 50 km away on horizon behind it. Phenocrysts, approx 15%: plag, 1 mm to 1 cm; 1–3 mm ol; plag>ol. Overlies units mlh, awh, and aeg; underlies unit anr. $^{40}Ar/^{39}Ar$ age is 146±11 ka (table 1). Sector E

bls* **Basalt of Little Sand Butte (late Pleistocene)**—Poorly porphyritic basalt (51.1, 51.4% SiO_2) that was erupted from Little Sand Butte cinder cone and north-trending spatter rampart on its south flank. Phenocrysts, ≤1%: 1–2 mm, mostly ol; rare 1 mm plag. Overlies units rcb, m3, and mes; probably overlies unit bng; underlies units beb, aib, and bmc; probably underlies unit bt. $^{40}Ar/^{39}Ar$ age is 97±13 ka (table 1). Sector K

bma **Basalt southeast of Mammoth Crater (late Pleistocene)**—Poorly porphyritic, diktytaxitic basalt (48.6% SiO_2) of small flow that was erupted from spatter vent on south side of cinder cone (unit b5) just southeast of Mammoth Crater. Phenocrysts: <1% 1 mm plag+ol. Overlies unit bmc and isolated cinder cone units b5 and b6. Sector I

bmc* **Basalt of Mammoth Crater (late Pleistocene)**—Compositionally variable (48.4–55.9% SiO_2; avg of 45 = 52.3%) basalt and basaltic andesite. Unit is dominantly basalt and consists of widespread lava flows, mostly fed by lava tubes as far as 25 km from vent area. Vents are in southern part of lava field and include Mammoth Crater, Modoc Crater, and Bat Butte, as well as a spatter rampart on north side of Bearpaw Butte and other north- and northwest-aligned pit craters and spatter vents. At its northeast edge, unit entered ancient Tule Lake and formed pillow lavas and littoral cones of Hospital Rock. Numerous north-northwest- to north-northeast-trending faults, including open ground cracks, cut unit. Phenocrysts: most mafic samples (48.4% SiO_2) are essentially aphyric, having rare 1 mm ol±plag; most silicic samples, 1–2% 1–3 mm plag. Unit can sometimes be distinguished by reddish patina. Overlies numerous units, including dated units dta and asb; underlies units bgd, bc, bma, bdh, bvc, bbr, and mcf, as well as surficial unit g. $^{40}Ar/^{39}Ar$ age is 36±16 ka (table 1). See Donnelly-Nolan and Champion (1987) for more detailed description of unit. Sectors G, H, I, J, K

bnb **Basalt north of Burnt Lava Flow (middle Pleistocene)**—Moderately porphyritic basalt (49.2% SiO_2) flow and cones north of Burnt Lava Flow (unit abl). Phenocrysts: approx 5% 1 mm plag+ol, plag>ol. Probably overlies unit msp; underlies units brf and abl. Sector M

bnf **Basalt northeast of Fourmile Hill (late Pleistocene)**—Sparsely porphyritic basalt (52.3% SiO_2) consisting mostly of at least three N. 5° E.–aligned spatter cones approx 1.5 km northeast of Fourmile Hill. Phenocrysts: 2–3% 1 mm plag+ol, plag>>ol. Underlies unit anr; overlies unit mnm. Sector H

bng **Basalt northeast of Glass Mountain (middle? Pleistocene)**—Aphyric basalt (48.4–50.8% SiO_2; avg of 6 = 49.4%) whose primary vent(s) is (are) buried by younger flows above 4,900 ft (1,494 m) elevation on northeast flank of MLV. Two additional satellite vents aligned northeast are located in and near southeast corner of LBNM. Overlies units rsl, m3, bei, bco, bse, and anh; underlies units bci, aib, and bvc; probably underlies unit bls. See description of "unit db" in Donnelly-Nolan and Champion (1987). Sectors J, K

bnp **Basalt near Paint Pot Crater (late? Pleistocene)**—Very porphyritic basalt (49.3, 49.4% SiO_2) flow that was erupted from partially buried cone east of Paint Pot Crater. Largest outcrop area is southwest of Paint Pot Crater flow (unit mpp). Phenocrysts: approx 15% 1–5 mm plag; approx 3% 1–3 mm ol; common plag+ol clots ≤1 cm across. Overlies units orr, mnd, mwg, mdp, bwd, and b12; underlies units awl, bsl, bup, mpp, and rlg. Sectors C, D

bnr **Basalt north of railroad (middle Pleistocene)**—Aphyric, diktytaxitic basalt (47.2% SiO_2) flow that covers very small area on lower south flank of MLV, approx 2 km northwest of railroad siding at Lakin and 4 km southeast of Porcupine Butte. Vent location unknown. Overlies unit mrr; nearly surrounded by overlying unit bdc. Sector A

bnw **Basalt north of Whitney Butte (middle Pleistocene)**—Moderately porphyritic basalt (50.7% SiO_2) of eroded, northeast-trending set of small spatter cones; no lava flow visible. Phenocrysts, 3–5%: 1–6 mm ol+plag, ol>>plag. Underlies, and is nearly surrounded by, unit awb; probably underlies unit awf. Sector H

bp* **Basalt of Prisoners Rock (middle Pleistocene)**—Clot-bearing basalt (48.0–49.5% SiO_2; avg of 5 = 48.6%) that was erupted from north- and northeast-trending subaerial and subaqueous vents (including Prisoners Rock and The Peninsula), forming lava flows and spatter vents, in addition to tuff rings. Tuff rings were significantly eroded around west, north, and east sides by Tule Lake before lake was reclaimed for farmland beginning in the early 1900's. Well-exposed wave-cut benches can be seen along west and east sides. Phenocrysts (two lava flow samples): <1% 0.5–1 cm clots of plag+ol; 1% 1 mm ol. In addition, three samples of dikes exposed on eroded tuff rings display variable amounts of phenocrysts, and one sample is noticeably more porphyritic than lava flow samples. Unit lies beyond northeast margin of contiguous lavas of MLV. K-Ar age is 273±18 ka (table 1). See Donnelly-Nolan and Champion (1987), Lavine (1994), and Lavine and Aalto (2002) for additional description of unit. Sector J

bpa **Basalt of The Panhandle (late Pleistocene)**—Fine grained, diktytaxitic basalt (49.6–51.0% SiO_2; avg of 3 = 50.4%). Shows evidence at its northeast margin of having flowed into ancient Tule Lake; this and its petrographic and morphologic similarity to overlying unit bmc, which also flowed into ancient Tule Lake, make two units (bpa and bmc) difficult to distinguish in field. Vent is unknown but presumably is located south or southwest of outcrop area. Previously understood (see Donnelly-Nolan and Champion, 1987) as two units ("bo" and "bpa"), but subsequent paleomagnetic sampling (D.E. Champion, unpub. data, 1984) and chemical analyses (this study) indicate that more mantled lava (previous "unit bo") is same as lava having more youthful appearance (previous "unit bpa"). Unit is cut by open ground crack (Big Crack) that also breaks unit bmc. Phenocrysts: <0.5% 1 mm plag; rare 1 mm ol. Underlies units mts and bmc; overlies unit mj (Juniper Butte). Sector J

bpb **Basalt of Porcupine Butte and Timber Hill (middle Pleistocene)**—Moderately porphyritic basalt (51.3% SiO_2) flow that was erupted from two large cinder cones, for which unit is named, on south side of MLV. Cones are aligned N. 25° W., parallel to northwest-trending fault that cuts unit. Phenocrysts, approx 5%: 1–3 mm plag; 1–2 mm ol; plag>ol. Overlies units bdc and mrr; underlies units bwc and bgc. Sectors A, B

bph **Basalt of Papoose Hill (middle Pleistocene)**—Porphyritic basaltic (49.0, 54.3% SiO_2; avg = 51.7%) lava flow, as well as cinder cone for which unit is named. Phenocrysts: 10–15%, mostly plag, 1–4 mm; 1–2% 1–2 mm ol. Overlies units bug, mph, and asn; underlies units asr and bgc. Sectors A, B

bpw **Basalt near Pumice Stone Well (late Pleistocene)**—Sparsely porphyritic basalt (51.6% SiO_2) of relatively young flow and cones. Vents located just northwest of Little Glass Mountain. Two major cones are aligned N. 40° E. Flow extends nearly 8 km northwest from northwest edge of Little Glass Mountain. Flow front is unusually high (at least 60 m) for unit of basaltic composition. Overlies units oap, obw, atm, mtr, anl, awh, and dta; probably also overlies surficial unit g of Tamarack Flat, which was likely deposited by flood that followed eruption of unit dta (Donnelly-Nolan and Nolan, 1986). Underlies units rlg and surficial unit p; may underlie unit awl; age relation to unit anr is uncertain, but unit probably underlies unit anr. Sector E

brf **Basalt of ribbon flows (late Pleistocene)**—Sparsely to moderately porphyritic basalt (49.0–50.5% SiO_2; avg of 5 = 49.9%) forming narrow lava flows that occupy channels presumably cut by glacial meltwater. Was erupted from numerous spatter vents approx 3 km north of Burnt Lava Flow (unit abl). Vents, situated at north end of unit, are aligned slightly east of north to slightly west of north. Lava flows extend more than 10 km south-southeast from vent area and, for much of their length, are buried by Burnt Lava Flow; unit also crops out at southeast edge of Burnt Lava Flow. Estimated area and volume are 8 km^2 and 0.02

km^3. Phenocrysts: 1–5% plag+ol, typically 1–2 mm; some plag ≥4 mm; plag>ol; plag+ol also in clots ≤3 cm across. MI were seen but were too small to collect for chemical analysis. Overlies all adjacent units (msp, bnb, bl, byb) except Burnt Lava Flow (abl). Previously published radiocarbon age (Donnelly-Nolan and others, 1990), considered too young, has been calibrated, on basis of estimate derived from comparison with paleomagnetic data of dated flows of similar age, to be 12,480 yr B.P. (Donnelly-Nolan and others, 2007; Nathenson and others, 2007). Sector M

brh **Basalt of Red Hill (late Pleistocene)**—Nearly aphyric basalt (50.6% SiO_2) that was erupted from multiple spatter vents aligned approx N. 35° E., largest of which is Red Hill. Unit occupies three separate outcrop areas, each with its own vent(s). Phenocrysts: sparse 1 mm plag xls. Abundant <1 mm plag+ol visible in groundmass. Overlies units m17, acc, mug, and aeg; underlies units asr and bgc. Sectors B, C

bsc **Basalt southwest of Cinder Butte (late Pleistocene)**—Aphyric basalt (52.1% SiO_2) that has both aa morphology and youthful appearance, which belie its true age (older than unit anr). Very small outcrop area. Vent is unknown and presumably is buried by unit anr. Overlies unit asc; underlies units anr and mcf. Sector G

bse **Basalt southwest of East Sand Butte (middle Pleistocene)**—Aphyric, fine-grained basalt (50.2% SiO_2) lava flow. Some tiny plag+ol visible in groundmass. Unit is similar in composition and in stratigraphic position to unit bco, which lies uphill, but this unit exhibits higher MgO content, whereas unit bco has higher Sr content. Underlies all adjacent units (bt, bls, bng). Sector K

bsh **Basalt of Saddle Hills (middle Pleistocene)**—Moderately porphyritic basalt (50.6% SiO_2) of three cinder cones and one small area of lava flow southeast of Six Shooter Butte. Perhaps also scraped by south-southwest-moving ice. Two cones are aligned N. 30° E.; northernmost one is offset to west. Phenocrysts: approx 5%, mostly 1–3 mm plag; some 1 mm ol. Underlies units as and bgc. Sector A

bsl **Basalt south of Little Glass Mountain (late Pleistocene)**—Nearly aphyric basalt (49.3% SiO_2) that was erupted from vent built on north end of vent cone for unit bep. Vent is located just south of Little Glass Mountain rhyolite flow (unit rlg), which may have buried additional vents. Fluid flow traveled southwest in two lobes around preexisting obstacles. Phenocrysts, rare: 1 mm plag+ol. Overlies units orr, rgf, m15, m18, b14, mnd, dta, mwg, mdp, mug, aeg, and bnp; underlies units bup, mpp, and rlg. Sectors B, C, D

bsp **Basalt of Shotgun Peak (middle Pleistocene)**—Variably porphyritic basalt (51.8–53.3% SiO_2; avg of 4 = 52.6%) cinder cones aligned about N. 35° W.; no lava flows are visible. Shotgun Peak has glacial till on its north flank up to 6,500 ft (1,981 m) elevation, although till is not separately mapped. Cone immediately north of Burnt Lava Flow (unit abl) is most porphyritic, showing approx 10% phenocrysts: mostly plag ≤5 mm; minor ol ≤2 mm. Shotgun Peak itself and two cones farther southeast that are entirely surrounded by Burnt Lava Flow contain 1–3% 1–4 mm plag; 1% 1–2 mm ol. All four cones are chemically similar. Underlies all adjacent units (msp, asr, abl). Sector M

bsr **Basalt southwest of Red Cap Mountain (middle Pleistocene)**—Very porphyritic basalt (51.3% SiO_2) forming eroded (presumably glacially modified) cinder cone remnant on extension of ridge southwest of Red Cap Mountain. Phenocrysts, approx 25%: plag 1 mm to 1 cm, mostly 1–4 mm; 1–2 mm ol (approx 5% of rock); plag>>ol. Overlies unit orr; age relation to unit msr is uncertain, but this unit probably is older. Sector D

bss **Basalt south of Squaw Peak (middle Pleistocene)**—Very porphyritic basalt (50.4–51.7% SiO_2; avg of 3 = 51.2%) of one cinder cone immediately south of Squaw Peak and two other cones and accompanying lava flow on northeast end of Fisk Ridge. Phenocrysts: 15–25%, mostly 1–3 mm plag; a few percent 1–2 mm ol. Overlies units ods, orr, omf, msr, mwr, and atm; underlies units mrc, dls, and dta. Sector D

bst **Basalt southwest of Tickner Cave (middle Pleistocene)**—Moderately porphyritic basalt (52.6, 53.0% SiO_2) just south of LBNM, consisting mostly of large cinder cone and two outcrop areas of lava flow on lower northeast flank. Cinder cone is known locally as either “Berthas Butte” (for nearby Berthas Cupboard Cave) or “Railroad Butte” (for old railroad grade that wraps around cone). Phenocrysts, 3–5%: 1–4 mm plag; 1–2 mm ol; plag>ol; sparse 2–4 mm plag+ol clots. Underlies all adjacent units (asm, bmc, mna, bvc). Sectors I, J

bt **Basalt of Tionesta (late Pleistocene)**—Aphyric, fine grained, diktytaxitic basalt (48.1–48.4% SiO_2; avg of 7 = 48.3%) of primitive composition, as well as low-relief morphology indicative of fluid lava. Pattern of topographic contours and distribution of lava-tube caves indicate source buried to west under younger lavas on east flank of MLV. Unit was formerly (C.A. Anderson, 1941) considered part of the "Warner Basalt," a widespread series of Pliocene basalts making up much of surface of Modoc Plateau. More recent work (for example, Donnelly-Nolan and others, 1996) indicates that the Warner Basalt consists of numerous smaller, but very similar, diktytaxitic-basalt units, many of which are Pleistocene. Numerous north- to north-northeast-trending faults break unit, most of which show little offset or are open ground cracks having no vertical offset. Part of unit (amounting to <2 km^2) extends east beyond map boundary. Overlies units omt, obu, rsl, m13, bse, mes, bdb, and probably unit bls; underlies units bl, byb, and bmc, as well as surficial unit g. Sectors K, L

btm **Basalt of tree molds (late Pleistocene)**—Porphyritic basalt (51.9% SiO_2) that was erupted from N. 10° E.–trending spatter cones south of Callahan Flow (unit mcf) near east base of Fourmile Hill. Small thin flow surrounded several trees just downstream from vents, preserving tree molds. Total area covered by unit is approx 0.05 km^2; estimated volume is 0.0001 km^3. Phenocrysts: 5% plag, mostly 1–2 mm, some ≤2 cm; 1% 1 mm ol; scattered plag+ol clots. Overlies unit anr. Previously published radiocarbon age (Donnelly-Nolan and others, 1990), considered too young, has been calibrated, on basis of paleomagnetic direction and comparison with other dated units, to be 12,330 yr B.P. (Donnelly-Nolan and others, 2007; Nathenson and others, 2007). Sector G

bts **Basalt of Three Sisters (late? Pleistocene)**—Moderately porphyritic basalt (51.8–52.2% SiO_2; avg of 4 = 52.0%) that was erupted from several cinder cones, including three north-south aligned cones of Three Sisters (in northwestern part of map area). Two additional vents lie slightly north-northwest of three main cones, and two others are located to northwest and northeast. Phenocrysts: 3–5% 1–2 mm plag+ol, some in 2–3 mm clots; plag=ol. Overlies all adjacent units (otb, oap, aes, aut, b2, b3, dta, surficial unit g). Sectors F, G

btw **Basalt of Twin Sister (middle Pleistocene)**—Porphyritic basalt (49.6, 49.8% SiO_2) of two cinder cones aligned north-northeast: northern cone was quarried to below ground level by railroad mining before 1980; Twin Sister is unquarried southern cone. Phenocrysts, 10–15%: 1–4 mm ol+plag, large ol more abundant than large plag, small (1 mm) ol less abundant than small (1 mm) plag. Both cones lie east of LBNM and are entirely surrounded by unit bmc. Sector J

bu **Basalt near Undertakers Camp (late Pleistocene)**—Sparsely porphyritic basalt (50.4% SiO_2) forming two small areas that include lava flow and one vent, both of which are glaciated. At least one additional vent must be buried by younger lavas to north. Phenocrysts: approx 1% 1–2 mm plag; sparse plag+ol clots ≤1 cm. Also visible in groundmass are <1 mm ol. Overlies units asr and msp; underlies unit dpc and surficial unit t. Sector M

buc **Basalt under Callahan Flow (late Pleistocene)**—Very porphyritic basalt (50.9% SiO_2) flow displaying rugged morphology. Was erupted from cinder cone that is surrounded by Callahan Flow (unit mcf). Phenocrysts: 30–40% plag, mostly 2–5 mm; 1–3% 1–3 mm ol. Overlies units rgf, dta, and mfh; underlies units bgd and mcf. Sector G

bug* **Basalt under Giant Crater lava field (middle Pleistocene)**—Aphyric, fine-grained, diktytaxitic basalt (49.3, 50.8% SiO_2), found as patches extending nearly 20 km south and then southwest from its northernmost outcrop area west of Snag Hill. Large difference in Sr content of two samples suggests that unit may consist of two or more flows, which were erupted from multiple vents that presumably are buried north or northwest of Snag Hill. Probably younger than unit mhi. Underlies units mrr, bph, bwc, and bgc. $^{40}Ar/^{39}Ar$ age is 445±27 ka (table 1). Sectors A, B

bup **Basalt under Paint Pot Crater flow (late Pleistocene)**—Plagioclase-phyric, moderately porphyritic basalt (49.0% SiO_2) flow and N. 40° E.–aligned spatter cones that cover very small area. Very youthful in appearance and may be postglacial in age, but no material was found for radiocarbon dating. Unit is petrographically distinctive at MLV for its abundance of large (≤1 cm) plag phenocrysts, approx 3% total; abundant small (≤1 mm) plag+ol, plag>ol. Overlies units mwg, bnp, and bsl; underlies unit mpp. Sector C

bv5 **Basalt of "vent 5" (late Pleistocene)**—Sparsely porphyritic basalt (two analyses, 52.7% SiO_2) flow and spatter vents that may represent late tap of magma system responsible for Giant Crater lava field (unit bgc). Spatter vents are aligned N. 20–25° W., but they, in turn, are on trend (N. 55–60° E) with four vents of Giant Crater system (thus, "vent 5"). Very small flow covers about 0.12 km^2; estimated volume is 0.0002 km^3. Phenocrysts, approx 5%: mostly 1–4 mm plag; 1 mm ol; plag>>ol; numerous plag+ol clots ≤1 cm. Overlies units mug and bgc. Previously published radiocarbon age (Donnelly-Nolan and others, 1990), considered too young, has been calibrated, on basis of paleomagnetic direction and comparison with other dated units, to be 12,270 yr B.P. (Donnelly-Nolan and others, 2007; Nathenson and others, 2007). Sector B

bvc **Basalt of Valentine Cave (late Pleistocene)**—Sparsely porphyritic basalt and basaltic andesite (52.9, 52.9, 53.4% SiO_2; avg of 3 = 53.0%) of early postglacial flow that was erupted from northwest-trending linear array of spatter cones at 5,400 to 5,600 ft (1,646 to 1,707 m) elevation on north flank of MLV, just south of LBNM. Unit is estimated to cover 19.9 km^2 and to have volume of 0.2 km^3. Nearly all of flow was erupted from vents known as Tickner Chimneys, but separated from these are additional vents uphill to southeast that produced very small lava flow. Main flow hosts several lava-tube caves, including much-visited Valentine Cave in LBNM. It is unusual at MLV for flow that has such a high silica content to generate lava tubes, but the explanation may relate to its high iron and titanium contents, apparently resulting in lowered viscosity. Phenocrysts, variable: more abundant in vent lavas, 2–3% 1 mm plag, 1% 1–4 mm plag+ol clots; less abundant in downstream lavas, 1% plag+ol clots. Overlies all adjacent units: mc, mtc, bst, m3, b4, bng, bci, aib, bmc, and mna, as well as surficial unit g, which in this area is glacial-outwash gravel formerly exposed in quarry east of paved park road, about 0.5 km east of Caldwell Butte; white pebbles in glacial-outwash gravel are pumice that is compositionally identical to the rhyolite of Mount Hoffman (rmh). Previously published radiocarbon age (Donnelly-Nolan and others, 1990), considered too young, has been calibrated, on basis of paleomagnetic direction and comparison with other dated units, to be 12,260 yr B.P. (Donnelly-Nolan and others, 2007; Nathenson and others, 2007). Sectors I, J, K

bwc **Basalt of Water Caves (late Pleistocene)**—Poorly porphyritic basalt and basaltic andesite (49.9–53.7% SiO_2; avg of 8 = 52.4%) that was erupted from two large spatter vents aligned N. 20° W. on south flank of MLV. Tube-fed flows extend at least 17 km south-southeast from vent area. On Hambone Island, excavation revealed that glacial-outwash gravel overlies unit, much of which has aa morphology and very youthful appearance. Phenocrysts, <1%: ≤1 mm ol+plag, ol>plag; rare 2 mm plag. Overlies units bhi, bug, bpb, asn, and byb; underlies unit bgc. See Champion and Donnelly-Nolan (1994) for additional discussion of unit age. Sectors A, B

bwd **Basalt west of Doe Peak (middle Pleistocene)**—Porphyritic basalt (51.6, 53.0% SiO_2; avg = 52.3%) flow and cone along southwest edge of map area. Phenocrysts: ≥5% plag, typically 1–2 mm; some elongate plag ≤5 mm; ≤1% 1 mm ol. Overlies units orr, ael, mrl, mdp, and dls; underlies units bdp and bnp. Sector C

bwh **Basalt west of Mount Hoffman (late Pleistocene)**—Sparsely to moderately porphyritic basalt (52.9% SiO_2) flow and cone partially buried under west edge of Mount Hoffman rhyolite flow (unit rmh). Phenocrysts: 2–3% plag, mostly 1 mm, some ≤3 mm; a few 1 mm ol xls; scattered 2–3 mm clots of plag+ol. Groundmass contains abundant smaller plag+ol xls, plag>ol. Overlies unit anr; underlies unit rmh and surficial unit p. Sectors J, K

bwl **Basalt west of Lava Crack Spring (middle Pleistocene)**—Variably porphyritic basalt (47.5–48.0% SiO_2; avg of 5 = 47.7%) exposed primarily as narrow, approx 6-km-long flow west of Lava Crack Spring and southeast of Harris Mountain, as well as separate smaller tongue to east. Unit appears to have flowed against preexisting fault scarp of north-northwest-trending, down-to-east fault; unit is broken by north-trending, down-to-west fault. Phenocrysts: <1% 1–2 mm plag; ≤5% 1–4 mm plag (typically elongate) and 1 mm ol, plag>ol; plag+ol commonly in small clots. Overlies units ob, obd, and mlc; underlies units mdp and mug, as well as surficial unit g, which in this area forms small alluvial fan that obscures contact area between two lobes of unit. Probably younger than unit dta, which is found farther south on underlying unit obd. Sector B

byb* **Basalt of Yellowjacket Butte (late Pleistocene)**—Variably porphyritic, chemically variable basalt (49.5–53.1% SiO_2) forming very large flow, which has maximum extent of about 32 km northwest to southeast and total volume of 4–5 km^3 (Donnelly-Nolan and others, 2005). Was erupted from numerous vents, including five lying along 11-km-long northwest trend, which is intersected at its northwest end by similar number of vents lying along 2-km-long, approximately east-northeast trend. Some of these latter vents possibly are rootless vents over lava tube. Cones in upper vent area have been glaciated. Unit is broken by several faults, primarily in its southwestern part; most trend north-south to northwesterly and are dominantly down to west, including Mayfield Fault. Phenocrysts, variable: from <1% (total) of 1–2 mm plag+ol to ≥10% (total); includes 1–5 mm plag, 1–2 mm ol, typically plag>>ol; plag+ol commonly appear as 2–4 mm clots, which can give rock spotted look. Texture is sugary and granular to diktytaxitic. Overlies units mrr, b17, bdc, ay, bdb, as, asr, bt, and bl; underlies units ms, bwc, brf, bgc, and abl, as well as glacial-outwash gravel of surficial unit g. $^{40}Ar/^{39}Ar$ age is 86±14 ka (table 1). Sectors A, L, M

BASALTIC ANDESITE

m1 **Basaltic andesite spatter vent west-northwest of Bat Butte (late or middle Pleistocene)**—Porphyritic basaltic andesite (53.0% SiO_2) of single isolated spatter cone in LBNM, approx 1 km west-northwest of Bat Butte. Cone is broken down and mostly oxidized, suggesting that it is relatively old. Phenocrysts, approx 20%: mostly 1–2 mm plag; some oxidized 1 mm ol; rare plag+ol+cpx clots ≤4 mm. Small MI as large as 1 cm were observed in hand specimen. Underlies surrounding unit men. Sector H

m2 **Basaltic andesite of Crescent Butte (middle Pleistocene)**—Poorly porphyritic basaltic andesite (54.5% SiO_2) of Crescent Butte cinder cone, oxidized. Located short distance northwest of headquarters of LBNM. Phenocrysts: 1% 1 mm plag+ol, plag>ol. Underlies units mhi and bmc. Age relation to adjacent isolated andesite cinder cone (unit a1) is unknown. Sectors I, J

m3 **Basaltic andesite of Big Sand Butte (middle Pleistocene)**—Porphyritic basaltic andesite (54.0% SiO_2) of Big Sand Butte cinder cone and small satellite cone to northwest. Phenocrysts: 5–10% 1–3 mm plag+ol, plag>ol. Underlies four adjacent basalt units bng, bls, bmc, and bvc. Sector K

m4 **Basaltic andesite cone southwest of Cinder Butte (middle Pleistocene)**—Moderately porphyritic basaltic andesite (53.9% SiO_2) cinder cone about 3 km southwest of Cinder Butte. Phenocrysts, 5%: 1–2 mm, mostly plag; includes sparse 1 mm ol xls. Underlies units mnl and mfh. Sector G

m5 **Basaltic andesite cone north of Aspen Crater (middle Pleistocene)**—Moderately porphyritic, very small basaltic andesite (54.2% SiO_2) cinder cone less than 2 km north of Aspen Crater. Phenocrysts, 5%: some plag ≤3 mm, most 1 mm, typically elongate; some 1 mm ol. Underlies unit mna and glacial-outwash gravel of surficial unit g. Sector J

m6 **Basaltic andesite cone northwest of Lookout Butte (middle Pleistocene)**—Moderately porphyritic basaltic andesite (54.6% SiO_2) cinder cone approx 1.5 km northwest of Lookout Butte, on northwest flank of MLV. Phenocrysts, <5%: mostly 1–2 mm plag; includes <1% 1 mm cpx+ol. Underlies surrounding unit mfh. Sector G

m7 **Basaltic andesite cone northeast of Aspen Crater (middle Pleistocene)**—Porphyritic basaltic andesite (55.1% SiO_2) cinder cone approx 1.5 km northeast of Aspen Crater. Phenocrysts: approx 5% 1–4 mm plag; <1% 1–2 mm ol+cpx. Underlies surrounding unit mna. Sector J

m8 **Basaltic andesite cone northwest of Fourmile Hill (middle Pleistocene)**—Poorly porphyritic basaltic andesite (54.0% SiO_2) cinder cone approx 2 km northwest of Fourmile Hill. Phenocrysts, approx 1%: mostly 1 mm plag; rare 1 mm ol+cpx. Underlies surrounding unit mfh. Sector G

m9 **Basaltic andesite cone southwest of Aspen Crater (middle Pleistocene)**—Sparsely porphyritic basaltic andesite (55.1% SiO_2) cinder cone just southwest of Aspen Crater. Phenocrysts: approx 1% 1 mm plag; <1% 1 mm cpx+ol. Underlies units bac and anr. Sector J

m10 **Basaltic andesite cone southeast of Aspen Crater (middle Pleistocene)**—Nearly aphyric basaltic andesite (53.7% SiO_2) cinder cone approx 1.5 km southeast of Aspen Crater. Phenocrysts rare: 1 mm plag. Underlies units anh, bac, anr, and aib. Sector J

m11 **Basaltic andesite cone west of Medicine Lake (middle Pleistocene)**—Moderately porphyritic basaltic andesite (54.2% SiO_2) cinder cone approx 1 km west of west end of Medicine Lake; quarried. Phenocrysts: approx 5% 1–3 mm plag+ol, plag>ol. Underlies units mug and asr. Sectors D, E

m12 **Basaltic andesite cone southwest of Medicine Lake (middle Pleistocene)**—Nearly aphyric basaltic andesite (56.6% SiO_2) cinder cone just southwest of Medicine Lake. Phenocrysts: <<1% 1 mm plag+cpx+ol xls, plag>cpx+ol. Xenoliths as large as a few mm also present. Underlies units mug, asr, and surficial units t and l. Sectors C, D

m13 **Basaltic andesite southwest of Kephart (middle Pleistocene)**—Porphyritic basaltic andesite (55.1% SiO_2). Probable eroded remnant of vent cone; surrounded by the (overlying) basalt of Tionesta (bt). Phenocrysts: 10–15%, mostly 2–4 mm plag; <1% 1 mm ol. Noticeable weathering rind on rocks suggests that unit may be pre-MLV in age. Sector L

m14 **Basaltic andesite cone southeast of Paynes Springs (middle Pleistocene)**—Moderately porphyritic basaltic andesite (53.0% SiO_2) cinder cone approx 1 km southeast of Paynes Springs. Glacial till is present on top of cone, but till is not mapped separately. Phenocrysts, ≤5%: mostly 1–3 mm plag; approx 1% 1–2 mm ol. Underlies unit asr and mapped area of glacial till (surficial unit t) adjacent to cone. Sector M

m15 **Basaltic andesite cone south of Little Glass Mountain (middle Pleistocene)**—Nearly aphyric basaltic andesite (55.9% SiO_2) cinder cone remnant approx 1 km south of south edge of Little Glass Mountain rhyolite flow (unit rlg). Phenocrysts: <<1% 1 mm plag+cpx, plag>cpx. Scattered xenoliths of andesite are present. Underlies units mug, aeg, and bsl. Sector C

m16 **Basaltic andesite cone north-northeast of Six Shooter Butte (middle Pleistocene)**—Nearly aphyric basaltic andesite (55.7% SiO_2) cinder cone approx 3 km north-northeast of Six Shooter Butte. Phenocrysts, <1%: 1 mm plag; 1–2 mm ol. Underlies surrounding unit asr. Sector A

m17 **Basaltic andesite cone northeast of Cinder Cone (middle Pleistocene)**—Sparsely porphyritic basaltic andesite (54.0% SiO_2) cinder cone, mostly buried, approx 3 km north of Giant Crater. Phenocrysts, 2–3%: mostly 1 mm plag; <1% 1–2 mm ol. Underlies units mug and brh. Sector B

m18 **Basaltic andesite cone south of Paint Pot Crater (middle Pleistocene)**—Porphyritic basaltic andesite (53.5% SiO_2) cinder cone approx 3.5 km south of Paint Pot Crater, at south end of unit mpp. Phenocrysts, 10–15%: mostly 1 mm plag+ol, plag typically elongate, plag>ol; in addition, single 5 mm plag+ol+cpx clot present. Underlies units bsl and mpp; overlies unit rgf. Sector C

m19 **Basaltic andesite of Six Shooter Butte (middle Pleistocene)**—Sparsely porphyritic basaltic andesite (53.9% SiO_2) of large, eroded Six Shooter Butte cinder cone, approx 7 km south of Medicine Lake, just east of Giant Crater. Unusual elongate shape of cone suggests that it may have been glaciated. Phenocrysts: 1% 1 mm plag+ol+cpx xls, plag>ol+cpx. Underlies all adjacent units (as, asr, bgc). Sectors A, B

mbp **Basaltic andesite of Badger Peak (middle Pleistocene)**—Porphyritic basaltic andesite (54.4, 55.0% SiO_2) that flowed northwest from several vents located at and near poorly defined northwest margin of caldera. Five vents, including Badger Peak and Grouse Hill, are scattered in area of about 3.5 km by 2 km; some cones lie on possible northeasterly trends. Unit has been glaciated, as described by C.A. Anderson (1941). Phenocrysts: approx 5% 1–3 mm plag; <1% 1 mm ol. Northwest of caldera, overlies units rcg, dsk, anl, and awh; underlies units dta, mfh, anr, and rlg. Within caldera, overlies units awm and dwm; underlies units dta, mug, and anr, as well as surficial units l and p. Sectors E, F, G

mc **Basaltic andesite south and southwest of Caldwell Butte (middle Pleistocene)**—Sparsely porphyritic basaltic andesite (56.1% SiO_2) lava flow and small cinder cone at south boundary of LBNM. Phenocrysts: 1–2% 1–2 mm plag+ol, plag>ol. Underlies units bci, aib, and bvc. Previously designated “unit a” by Donnelly-Nolan and Champion (1987). Sector J

mcf **Basaltic andesite of Callahan Flow (Holocene)**—Compositionally variable (51.8–57.8% SiO_2; avg of 40 = 55.1%) and variably porphyritic, blocky lava flow consisting of basalt, basaltic andesite, and andesite (Mertzman, 1977a; Kinzler and others, 2000). Lava flows were erupted from Cinder Butte and adjacent smaller vents 6.5 km from northern terminus of flow. Estimated area covered is 23.7 km^2; volume is approx 0.33 km^3. Phenocrysts: basalt facies is nearly aphyric, <<1% 1–2 mm plag±ol; andesite facies, 2–5% 1–3 mm plag, a few 1 mm opx xls, rare 1 mm ol. Cinder Butte contains partially melted silicic inclusions; one MI was found in flow (Kinzler and others, 2000). Unit overlies all adjacent units and is one of youngest eruptive units at MLV; some pumice (not mapped) from Little Glass Mountain (unit rlg) and probably from Glass Mountain (unit rgm) is found on flow. Calibrated age of 1,120 yr B.P. (Donnelly-Nolan and others, 2007; Nathenson and others, 2007) is based on three radiocarbon ages (Donnelly-Nolan and others, 1990). Previously designated as “unit ba” of Donnelly-Nolan and Champion (1987). Sectors G, H, I

mdp **Basaltic andesite of Doe Peak (middle Pleistocene)**—Porphyritic basaltic andesite (55.2% SiO_2) forming large flow on southwest flank of MLV. Flow was erupted from its vent at Doe Peak, a large cinder cone that has two craters aligned N. 45° E. Phenocrysts, 10%: mostly 1–4 mm plag; minor 1 mm ol. Overlies units odh, oml, obd, rgf, b14, b12, mnd, bwl, and mhm; underlies units mug, bwd, bdp, bnp, and bsl, as well as surficial unit g. Probably younger than unit dta, which is not found on top of unit but is present to south of unit, indicating that it (dta) likely flowed through area now occupied by this unit. Sectors B, C

mel **Basaltic andesite east of Little Glass Mountain (late? Pleistocene)**—Sparsely porphyritic basaltic andesite (55.8% SiO_2) lava flow and spatter vents. Although glaciation has disturbed unit, vents appear to be aligned approximately N. 50° E. Phenocrysts: 2–3% 1–3 mm plag; <1% 1 mm ol. Overlies units a8, mug, and aeg; underlies unit anr. Sector D

men* **Basaltic andesite of Eagle Nest Butte (late Pleistocene)**—Sparsely porphyritic basaltic andesite flow and cinder cones (52.4–53.8% SiO_2; avg of 10 = 53.2%). Vents are Eagle Nest Butte and Bearpaw Butte. Phenocrysts: approx 1% 1 mm plag, some plag ≤3 mm; rare 1 mm ol; ol+plag in 1 cm clots. Overlies units msc, awf, awb, and m1; underlies units mhi, bmc, bdh, bbr, and mcf. $^{40}Ar/^{39}Ar$ age is 114±10 ka (table 1). Sectors H, I

mes **Basaltic andesite of East Sand Butte (middle? Pleistocene)**—Porphyritic basaltic andesite (54.6% SiO_2) lava flow that surrounds its own vent, East Sand Butte. Cinder cone has been quarried by railroad mining, exposing interior of cone, which contains both partially melted silicic inclusions and MI (two samples, 48.3, 49.5% SiO_2); see also, A.T. Anderson (1976). Phenocrysts: 5% 1–4 mm plag; 1% 1–2 mm ol. Underlies all adjacent units (beb, bls, bt, bmc). Sector K

mfh* **Basaltic andesite of Fourmile Hill (late or middle Pleistocene)**—Sparsely porphyritic basaltic andesite (54.1–55.7% SiO_2; avg of 6 = 55.3%) lava flow that was erupted from two northwest-aligned cinder cones and flowed down northwest flank of MLV. Fourmile Hill is larger and more southerly of two vents. Flow covers area of approximately 5 km by 10 km. Phenocrysts, 1–2%: 1–2 mm plag; 1 mm ol; plag>ol. Overlies adjacent units rgf, m4, m6, m8, bea, mnl, dsk, anl, mbp, and dta; directly underlies only units buc and anr. K-Ar age is 130±36 ka (table 1). Sectors F, G

mgf **Basaltic andesite east of Grasshopper Flat (late Pleistocene)**—Sparsely porphyritic basaltic andesite (54.3% SiO_2) of north-south-trending spatter rampart and very small lava flows (area, approx 0.02 km^2; estimated volume, less than 0.0001 km^3). Phenocrysts: 1–2% 1 mm plag; some 3–4 mm clots of plag+ol+cpx. Was erupted through and onto unit aeg (only unit with which it is in contact). Previously published radiocarbon ages (Donnelly-Nolan and others, 1990), considered too young, have been calibrated, on basis of paleomagnetic direction and comparison with other dated units, to be 12,490 yr B.P. (Donnelly-Nolan and others, 2007; Nathenson and others, 2007). Sector C

mhi **Basaltic andesite of Hippo Butte (late Pleistocene)**—Sparsely porphyritic basaltic andesite (54.4–56.1% SiO_2; avg of 7 = 55.4%) lava flow and cones. Unit was erupted from Hippo Butte and from smaller cone south of Mammoth Crater. Rocks from two outcrop areas have similar chemical compositions. Most samples from Hippo Butte contain approx 1–2% phenocrysts: 1 mm plag, some larger plag occasionally; occasional 1 mm ol. Samples from smaller vent are more porphyritic, having 2–3% phenocrysts: 1–2 mm plag+ol, plag>ol. Overlies units m2, a1, awb, and men; may underlie unit mnm; underlies units asm, msm, and bmc. Previously designated as “unit bhb” of Donnelly-Nolan and Champion (1987), although this unit is more extensive than “unit bhb.” Sectors H, I

mhm **Basaltic andesite adjacent to Harris Mountain (middle Pleistocene)**—Sparsely porphyritic basaltic andesite (55.2% SiO_2) lava flow. Vent location is unknown and presumably is buried to north or northeast. Phenocrysts, 1–2%: mostly 1–3 mm plag; some clots of plag+ol+cpx. Overlies units odh, oml, and obd; probably overlies unit dta, which is found to south of unit but not on top of it, as would be expected if unit dta were younger; underlies unit mdp and surficial unit g. Sectors B, C

mj **Basaltic andesite of Juniper Butte (middle Pleistocene)**—Basaltic andesite (53.8% SiO_2) of eroded palagonite tuff ring in northeastern part of LBNM. Individual juvenile clasts are mud coated. Tuff ring probably formed by eruption through ancient Tule Lake. Unit is nearly surrounded by overlying unit bmc; remaining perimeter is overlain by unit bpa. Sector J

mlc **Basaltic andesite of Lava Crack Spring (middle Pleistocene)**—Sparsely porphyritic basaltic andesite (53.2–57.0% SiO_2; avg of 6 = 55.5%) flows and cone exposed on far south-southwest flank of MLV. North-northwest-trending major fault, which extends length of unit and beyond, bisects vent cone and offsets cone and lava flows down to east by at least 60 m. To east, a parallel but much shorter fault that has much less vertical offset also cuts unit and displaces it down to west. At least one additional vent to north must be buried by younger lava flows. Phenocrysts: 1–2% 1–3 mm plag; sparse 1 mm ol; rare plag+ol+cpx clots. One sample is slightly more porphyritic and has lowest silica content of samples collected. Overlies older diktytaxitic basalt of unit ob, which is interpreted to be pre-MLV in age; underlies units bwl, mug, and bgc, as well as surficial unit g. Sector B

mlh **Basaltic andesite of Little Mount Hoffman (middle Pleistocene)**—Porphyritic basaltic andesite (55.7% SiO_2) exposed on west flank of Little Mount Hoffman, under capping basaltic cinder cone of unit blh. Phenocrysts: 10–15% 1–2 mm plag; 1–2% 1–2 mm ol. Underlies units awh and blh. Sector E

mna **Basaltic andesite northeast of Aspen Crater (late Pleistocene)**—Porphyritic basaltic andesite (53.1–54.1% SiO_2; avg of 3 = 53.7%) that was erupted from north-northeast-trending alignment of spatter and cinder cones. Lava flow has youthful appearance. In addition, lava flow failed to cover flat area where unconsolidated glacial-outwash gravel (later quarried) was present in late-glacial, or immediately postglacial, time, and lava flow was diverted around wet area. All these factors suggest late Pleistocene age. Amount of soil that mantles unit near vent, as well as breakdown of lava tubes in unit, is greater than what is seen in other early postglacial flows. Phenocrysts, 5–10%: 1–4 mm plag; 1–2 mm ol; plag>ol; plag+ol clots ≤1 cm. Underlies unit bvc; overlies all other adjacent units (mtc, bst, m5, m7, b9, bac, asm, aib, surficial unit g). Sector J

mnd **Basaltic andesite northeast of Doe Peak (middle Pleistocene)**—Poorly porphyritic basaltic andesite (53.5% SiO_2); vent unknown. Composition does not match that of nearby isolated cinder cones (units b12 and m18), either chemically or petrographically. Phenocrysts: <1% 1–3 mm plag; rare ≤1 mm ol. Overlies units rgf and b14; age relation to unit mwg is uncertain, but this unit is probably older. May overlie unit b12; underlies units mdp, bnp, and bsl. Sector C

mni **Basaltic andesite north of Indian Butte (middle Pleistocene)**—Moderately porphyritic basaltic andesite (54.8, 55.0% SiO_2) lava flow exposed in three separate outcrop areas. Also includes vent cone at south end of largest area. Phenocrysts: 3–5% 1–3 mm plag; 1% 1–2 mm ol; sparse plag+ol clots ≤5 mm. May be younger than unit a4; older than surrounding units bci and aib. Sector J

mnl* **Basaltic andesite north of Lookout Butte (middle Pleistocene)**—Sparsely porphyritic basaltic andesite (53.4–55.7% SiO_2; avg of 4 = 54.1%) that was erupted from glaciated cinder cone approx 2.5 km southwest of Cinder Butte. Lava flow exists as several isolated outcrop areas on middle to lower northwest flank of MLV. Phenocrysts: 2–3% 1–3 mm plag; ≤1% 1–2 mm ol. Overlies units rgf, rwc, m4, bea, b7, aes, and arr; underlies units anl, dta, muc, mfh, anr, and mcf. $^{40}Ar/^{39}Ar$ age is 289±13 ka (table 1). Sectors F, G

mnm **Basaltic andesite north of Medicine Lake (late Pleistocene)**—Sparsely porphyritic basaltic andesite (56.4–57.6% SiO_2; avg of 8 = 56.9%) exposed in three areas, smallest of which (inside caldera) is probably part of vent cone. Other two areas lie to north, southeast of southeast margin of Callahan Flow (unit mcf). Larger, more westerly area is broken by north-northeast-trending fault that has ≤5 m of offset, down to east. Fault appears to be part of zone of northeast-trending faulting that extends across west and north sides of MLV. Phenocrysts: 1–2% of mostly 1 mm plag, some larger; minor 1 mm ol. Overlies units asc, dec, bcu, ama, and mhi; faulted against older units rec and rse. Underlies units bnf, bac, asm, anr, bmc, and bec. $^{40}Ar/^{39}Ar$ age of 75±8 ka (not listed in table 1) is apparently too young, on basis of its position underneath unit anr; see Donnelly-Nolan and others (1994) for discussion of argon ages of units; see also, Donnelly-Nolan and Lanphere (2005) for additional data. Sectors G, H, I

mnp **Basaltic andesite northwest of Paint Pot Crater (middle Pleistocene)**—Very porphyritic basaltic andesite (55.1, 55.4% SiO_2) that was erupted from two glaciated vents aligned N. 65° E., located about 2 km apart west of Little Glass Mountain. Phenocrysts, 20–25%: mostly 1–2 mm plag; 5% 1 mm ol; ol sometimes in clots ≤1 cm. Overlies units orr and oap; underlies units atm and mrc; probably underlies unit mwr. Sectors D, E

mph **Basaltic andesite of Powder Hill (middle Pleistocene)**—Porphyritic basaltic andesite (53.4% SiO_2) of Powder Hill cinder cone and also small area of lava flow exposed to southeast. Phenocrysts, approx 10%: 1–3 mm plag+ol; plag>ol. Underlies units bph and bgc. Sectors A, B mpp **Basaltic andesite of Paint Pot Crater (Holocene)**—Moderately porphyritic basaltic andesite (52.9–53.2% SiO_2; avg of 4 = 53.1%) that was erupted in late Holocene time from cinder cone and multiple spatter vents aligned N. 40° E. Length of flow is less than 4 km. Area covered is approx 2.7 km^2; volume is approx 0.04 km^3. At and near vents, unit has significant mantle of white pumice (not mapped) from eruption of nearby Little Glass Mountain. Distal end of flow is nearly bare of pumice and trees and is extremely rugged, displaying numerous 5- to 10-m-high spines and mounds of lava and spatter. Phenocrysts, approx 5%: 1–2 mm plag+ol, plag>ol. Partially melted granitic inclusions and MI as large as 3 cm are present. Overlies all adjacent units (oap, rgf, m18, dta, mwg, mug, bnp, awl, bsl, bup). Calibrated age of 1,110 yr B.P. is based on estimate derived from stratigraphic relation of its tephra (Donnelly-Nolan and others, 1990) to radiocarbon-dated tephras (its tephra overlies tephra of unit mcf and underlies tephra of unit rlg) and on paleomagnetic constraints (Donnelly-Nolan and others, 2007; Nathenson and others, 2007). Sectors C, D

mrc **Basaltic andesite of Red Cap Mountain (middle Pleistocene)**—Variably porphyritic basaltic andesite (53.0, 53.6% SiO_2) lava and cinder forms "red cap" on glaciated Red Cap Mountain; unit also has flows to east and west of crest. Three eroded vents have north-to-northeast alignments. More than one rock type is present: one is very porphyritic and tends to be found as large solid blocks and as cinders at vents; other is poorly to moderately porphyritic and is found as bombs, as smaller pieces of float rock, and as cinders at vent areas. Phenocrysts in porphyritic type: dominantly plag, approx 20%, 1–3mm; ≥1% ol; sparse 1 mm cpx. Phenocrysts in less porphyritic type: 1–5% 1–2 mm plag; ≤1% 1 mm ol; rare 1 mm cpx. Combination of factors, including glaciation, heavy mantle of pumice from late Holocene Little Glass Mountain eruption, extensive logging, and steep vegetation-covered slopes, has resulted in few real exposures and many float rocks, making mapping difficult. Overlies units orr, ods, oap, mnp, mwr, and bss; underlies unit dta. Sectors D, E

mrl **Basaltic andesite of road to Lost Spring (middle Pleistocene)**—Very porphyritic basaltic andesite (54.7% SiO_2) exposed in small outcrop area approx 1.5 km east of Lost Spring. Phenocrysts, 30–40%: mostly 1–3 mm plag; includes approx 5% 1–2 mm pyx (opx+cpx), opx>>cpx. Overlies units orr and ael; underlies units afr, dls, and bwd. Sector C

mrr* **Basaltic andesite of railroad (middle Pleistocene)**—Moderately porphyritic basaltic andesite (54.4, 55.8% SiO_2) on far south flank of MLV. Three vents aligned N. 25° W. are located south and southeast of Porcupine Butte. Vents have been downfaulted by about 100 m from easternmost extent of unit by northwest-trending fault. Phenocrysts: approx 3% plag ≤1 cm, typically elongate; <1% 1 mm ol. Overlies units bhi and bug; underlies units bnr, bdc, bpb, and byb. $^{40}Ar/^{39}Ar$ age is 251±6 ka (table 1). Sectors A, B

mrs **Basaltic andesite of Red Shale Butte (middle Pleistocene)**—Poorly porphyritic basaltic andesite (53.0–54.0% SiO_2) exposed as two small patches at base of Red Shale Butte. Phenocrysts: <1% 1 mm plag, some plag ≤4 mm; rare 1 mm ol. Underlies units drs, bl, and rgm. Sector L

ms **Basaltic andesite of Stud Hill (late Pleistocene)**—Moderately porphyritic basaltic andesite (56.8% SiO_2) cone and youthful-looking block-lava flow, located west of Burnt Lava Flow (unit abl). Phenocrysts, approx 5%: mostly 1–3 mm plag; includes approx 1% 1 mm ol. Overlies units bdc, ay, as, asr, and byb; underlies units bgc and abl. Sector A

msc **Basaltic andesite of Semi Crater (middle Pleistocene)**—Porphyritic basaltic andesite (55.0, 55.5% SiO_2) lava flows that were erupted from now-isolated and partially buried cinder and spatter cone of Semi Crater, which is surrounded on three sides by unit bc and is invaded on east by tongue of Schonchin Flow (unit asb). Phenocrysts, 10%: plag ≤5 mm; ol ≤2 mm; plag>ol; plag+ol±cpx clots ≤7 mm. Overlies unit bcb; underlies units men, asb, bmc, bc, bdh, and bbr. May be younger than unit dta, which does not overlie this unit. Previously designated "unit bsc" by Donnelly-Nolan and Champion (1987). Sectors H, I

msm **Basaltic andesite south of Mammoth Crater (late Pleistocene)**—Sparsely porphyritic basaltic andesite (53.4% SiO_2) of north-trending array of several spatter vents bisected by Lava Beds–Medicine Lake road (Forest Road 49) south of Mammoth Crater. Phenocrysts, ≤3%: 1–4 mm plag; 1 mm ol; plag>ol. Overlies units mhi and asm; underlies unit bmc. Sector I

msn **Basaltic andesite southwest of Snag Hill (middle Pleistocene)**—Poorly porphyritic basaltic andesite (55.1% SiO_2) lava flow forms several small kipukas west of Snag Hill andesite flow (unit asn). Phenocrysts: ≤1% 1 mm ol. Entirely surrounded by much younger unit bgc. Sector B

msp* **Basaltic andesite east and northeast of Shotgun Peak (middle Pleistocene)**—Poorly porphyritic basaltic andesite (52.6–53.6% SiO_2; avg of 5 = 53.2%) lava flows and cinder cones between Burnt Lava Flow (unit abl) and southeast margin of Medicine Lake caldera. Unit is glaciated in upper part and is partially buried by adjacent lava flows. Phenocrysts, ≤1%: 1–2 mm plag+ol; plag>ol. Overlies units bsp and ds; underlies units bnb, asr, bu, bl, brf, dpc, and abl. $^{40}Ar/^{39}Ar$ age is 168±7 ka (table 1). Sectors L, M

msr **Basaltic andesite southwest of Red Cap Mountain (middle Pleistocene)**—Poorly porphyritic basaltic andesite (53.3–53.9% SiO_2; avg of 3 = 53.7%) cinder cone and lava flow. Cone is approx 1.5 km southwest of Red Cap Mountain and approx 4 km east of Typhoon Mesa. Phenocrysts, approx 1%: 1 mm plag; 1 mm ol; plag>>ol. Probably younger than unit bsr. Overlies unit orr; underlies units mwr, atm, bss, and dta. Sector D

mtc **Basaltic andesite near Tickner Cave (middle Pleistocene)**—Poorly porphyritic basaltic andesite (55.6% SiO_2) lava flow and (mostly buried) cinder cone, found in one small, and another very small, outcrop area just south of LBNM. Phenocrysts: approx 1% 1–2 mm plag+ol; plag>ol. Underlies all adjacent units (aib, mna, bvc). Sector J

mtf **Basaltic andesite of Tamarack Flat (middle Pleistocene)**—Sparsely porphyritic basaltic andesite (56.2% SiO_2) lava flow that bounds south edge of Tamarack Flat. Partially buried vent cone is at south end of flow. Phenocrysts: 1–2% 1 mm plag+ol. Abundant <1 mm plag in groundmass. Overlies unit oag; underlies units mwr, atm, and dta, as well as gravel of Tamarack Flat (surficial unit g). Sector E

mtl **Basaltic andesite of Tamarack Lake (middle Pleistocene)**—Poorly porphyritic basaltic andesite (53.9–57.5% SiO_2; avg of 7 = 56.1%). Glaciated vent-cone remnant is located at east edge of unit. Flow forms fairly large (2 × 3 km) flat surface east of Typhoon Mesa. Glacial gravel is present on flow surface, but it is not mapped. Phenocrysts: <1% 1 mm plag+ol, plag>ol. Overlies units aet, mwr, and mws; underlies unit atm and surficial unit p. Sectors D, E

mtr **Basaltic andesite of "Tennant Road" (middle Pleistocene)**—Moderately porphyritic basaltic andesite (55.3% SiO_2) that was erupted from cinder cone approx 3 km southwest of Dock Well, south of road west to Tennant. Much of flow is mantled by unit dta. Phenocrysts: 2–3%, mostly 1 mm plag; plag+cpx+ol in clots; approx 1% 1 mm cpx+ol. Overlies units oap and bh; probably overlies unit b10; underlies units anl, dta, and bpw. Sectors E, F

mts **Basaltic andesite of Three Sisters (late? Pleistocene)**—Poorly porphyritic basaltic andesite (54.4% SiO_2) in eastern part of LBNM. Apparently was erupted from cluster of small cones in southern part of unit. Vents are atypical, in that they show no apparent alignment, although cones could be interpreted as lying on intersecting northeasterly and northwesterly alignments. Phenocrysts: 1% 1–2 mm plag. Overlies unit bpa; underlies unit bmc. Previously designated as "unit bts" of Donnelly-Nolan and Champion (1987). Sector J

muc **Basaltic andesite under Callahan Flow (middle Pleistocene)**—Porphyritic basaltic andesite (52.9–53.1% SiO_2; avg of 3 = 53.0%) lava flow and cinder cone approx 1.5 km west-southwest of Cinder Butte. Most of unit lies outside of much younger Callahan Flow (unit mcf), but one small outcrop area is surrounded by unit mcf. Unit is dropped down to southeast by northeast-trending fault. Phenocrysts: 10–15% 1–4 mm plag; 1% 1 mm ol. Overlies unit mnl; underlies units anr and mcf. Presence of unit dta on unit mnl but not on this unit suggests that this unit is younger than unit dta. Sector G

mug* **Basaltic andesite under Giant Crater lava field (middle Pleistocene)**—Variably porphyritic, from poorly porphyritic to porphyritic, basaltic andesite (53.4–56.6% SiO_2; avg of 8 = 55.0%) in part under Giant Crater lavas (unit bgc), although most of unit lies to west and north. Only one vent is exposed, approx 1 km east of Little Mount Hoffman, but others may be present under units aeg, asr, and perhaps anr. Unit is very similar chemically to unit mbp, but unit mbp is overlain by the dacite tuff of Antelope Well (dta). Phenocrysts: 1–15%, dominantly 1–3 mm plag; some plag ≤5 mm; <1% to 2% ol, typically 1–2 mm. Overlies units rgf, m15, m17, awm, dwm, bel, mlc, mbp, bwl, acc, mwg, mdp, m11, m12, and probably units a8 and a9; underlies units aeg, mel, brh, bsl, asr, anr, bgc, bv5, and mpp, as well as surficial unit g. Stratigraphic relations and drill hole information indicate that this unit overlies unit dta. $^{40}Ar/^{39}Ar$ age is 180±28 ka (table 1). Sectors B, C, D, E

mwc **Basaltic andesite in western Callahan Flow (middle Pleistocene)**—Porphyritic basaltic andesite (54.4% SiO_2) cone and lava flow forming two kipukas near west edge of late Holocene

Callahan Flow (unit mcf). Phenocrysts, 10%: dominantly 1–2 mm plag; includes 2% 1 mm ol. Entirely surrounded by overlying Callahan Flow (unit mcf). Sector G

mwd **Basaltic andesite west of Devils Homestead (middle Pleistocene)**—Poorly porphyritic fine-grained basaltic andesite (52.6, 54.2% SiO_2) lava that has scattered large tumuli. Vent(s) located to south is (are) are buried under younger lava flows. Phenocrysts: approx 1% ≤2 mm plag; sparse 1 mm ol xls. Overlies units ob and obg; underlies units dta, awf, and awb. Sector H

mwg **Basaltic andesite west and north of Grasshopper Flat (middle Pleistocene)**—Sparsely to moderately porphyritic basaltic andesite (55.0–57.0% SiO_2; avg of 6 = 56.1%) consisting mostly of eroded, probably glaciated cinder cones and some adjacent flow rock. Includes one large and three small outcrop areas. Phenocrysts, 2–5%: mostly 1–4 mm plag; minor ol, typically 1–2 mm. Overlies unit rgf and probably unit mnd; underlies units mug, bnp, bsl, bup, and mpp. Sector C

mwr* **Basaltic andesite west of Red Cap Mountain (middle Pleistocene)**—Poorly porphyritic and moderately porphyritic basaltic andesite (53.7–54.9% SiO_2; avg of 7 = 54.6%) that was erupted from cinder cone approx 1.5 km south-southwest of Squaw Peak. Lower part of cone and lava flow northwest of Squaw Peak are poorly porphyritic; upper part of cone and some nearby lava flow are noticeably more porphyritic. However, rocks are very similar chemically, despite their petrographic variability. Phenocrysts in more porphyritic facies: 5–10% 1–3 mm plag; <1% 1–2 mm ol. Phenocrysts in less porphyritic rocks, ≤1%: ≤2 mm plag+ol, plag>ol. Overlies units orr, ods, msr, and mtf; probably overlies unit mnp; underlies units mws, mtl, atm, bss, mrc, and dta, as well as surficial unit p. $^{40}Ar/^{39}Ar$ age is 309±17 ka (table 1). Sectors D, E

mws **Basaltic andesite west of Squaw Peak (middle Pleistocene)**—Sparsely porphyritic basaltic andesite (54.4% SiO_2) cinder cone approx 1.5 km west of Squaw Peak. Phenocrysts: 1–2% 1 mm plag; sparse 1 mm ol. Smaller plag obvious in groundmass. Overlies unit mwr; underlies units mtl and atm, as well as surficial unit p. Sectors D, E

ANDESITE

a1 **Andesite cone west of Crescent Butte (middle? Pleistocene)**—Sparsely porphyritic andesite (57.4% SiO_2) cinder cone adjacent to Crescent Butte (unit m2) and just northeast of Hippo Butte. Cone has been quarried and displays mostly red, oxidized cinders and bombs. Phenocrysts: approx 2% 1–4 mm plag; rare 1 mm ol. Age relation to unit m2 is unknown. Underlies unit mhi. Sector I

a2 **Andesite of Red Butte (middle Pleistocene)**—Moderately porphyritic andesite (59.1% SiO_2) of Red Butte cinder cone in LBNM, southwest of monument headquarters. Cone consists of oxidized bombs and cinders and appears to be old morphologically, having no crater remaining. Phenocrysts: approx 5% plag, mostly 1–2 mm, some ≤4 mm; 1% 1 mm ol. Underlies surrounding unit bmc. Sector I

a3 **Andesite of Island Butte (middle Pleistocene)**—Sparsely porphyritic andesite (57.5% SiO_2) of Island Butte cinder cone in southwest corner of LBNM. Phenocrysts: 2% 1–3 mm plag; <1% 1 mm ol. Cone is entirely surrounded by late Holocene Callahan Flow (unit mcf). Sector H

a4 **Andesite cone west of Cougar Butte (middle Pleistocene)**—Sparsely porphyritic andesite (62.0% SiO_2) cinder cone about 2 km west of Cougar Butte. Phenocrysts: approx 2% 1–2 mm plag. Probably underlies unit mni; underlies unit aib. Sector J

a5 **Andesite cone east of Fourmile Hill (middle Pleistocene)**—Poorly porphyritic andesite (57.4% SiO_2) cinder cone approx 2 km east of Fourmile Hill. Phenocrysts: approx 1% 1–2 mm plag+ol, plag>>ol. Cone is completely surrounded by younger unit anr. Sectors H, I

a6 **Andesite cone southwest of Fourmile Hill (middle Pleistocene)**—Poorly porphyritic andesite (57.6% SiO_2) cinder cone approx 3 km southwest of Fourmile Hill and about 2.5 km north of Crater Glass Flow. Contains numerous small xenoliths. Phenocrysts: <1% 1 mm plag. Underlies units mbp and anr. Sector F

a7 **Andesite cone west of Crater Glass Flow (middle Pleistocene)**—Poorly porphyritic andesite (57.2% SiO_2) cinder cone approx 2 km west of Crater Glass Flow. Phenocrysts: <1% 1 mm plag; rare 4–5 mm plag. Contains sparse 3–5 mm, partially melted, vesiculated, silicic inclusions. Cone is surrounded by younger unit mbp; underlies unit dta. Sector F

a8 **Andesite cone south of Little Mount Hoffman (middle Pleistocene)**—Poorly porphyritic andesite (59.7% SiO_2) cinder cone about 1 km south of Little Mount Hoffman and 1 km east of Little Glass Mountain. Phenocrysts, <1%: mostly 1 mm plag. Numerous small xenoliths. Underlies units mug, mel, and anr. Sector D

a9 **Andesite cone southwest of Little Mount Hoffman (middle Pleistocene)**—Very porphyritic andesite (58.0% SiO_2) cinder cone partially buried by Little Glass Mountain rhyolite flow (unit rlg) and airfall tephra that preceded it. Phenocrysts (in solid blocks exposed in small quarry): approx 20% 1–2 mm, mostly plag; 1 mm ol+cpx+opx(?) constitute approx 5% of rock. Probably underlies adjacent unit mug; underlies units anr and rlg. Sector D

aac* **Andesite of Alcohol Crater (late Pleistocene)**—Porphyritic andesite (58.0–58.5% SiO_2; avg of 4 = 58.2%) flow and vents in eastern part of caldera. Alcohol Crater may represent vent area for this unit, as well as for unit bl, both of which have been excavated by ice at crater. Small window of this unit is exposed in canyon of Paynes Creek, where it underlies unit asr. Phenocrysts: 5% 1–2 mm plag; ≤1% 1 mm ol. Overlies unit bac; underlies units asr, bl, and rh, as well as surficial unit l (in this area, lake deposits in Alcohol Crater and in adjacent depression to north); probably underlies unit drs. $^{40}Ar/^{39}Ar$ age is 114±5 ka (table 1). Sectors L, M

abl **Andesite of Burnt Lava Flow (Holocene)**—Sparsely porphyritic andesite (56.4–57.9% SiO_2; avg of 5 = 57.3%) flow, mostly aa, that was erupted from High Hole Crater cinder cone and from spatter vents to north. Covers approx 34.3 km^2 and has volume of approx 0.5 km^3. Compositional variation is present within lava flow, but no attempt has been made to map areal distribution of compositions because of limited petrographic variability visible in hand specimens; however, examination of aerial photographs together with analyses given for 20 sample localities in Grove and others (1988) indicates that earlier erupted lava is more mafic than later erupted lava. Unit contains common fine-grained MI that range in size from microscopic to 20 cm across and in composition from 47.5 to 51.4% SiO_2; partially melted granitic inclusions also are present (Grove and others, 1988). Early geologic description of lava flow was published by Finch (1933). Phenocrysts: 1–2% 1–3 mm plag; a few 1 mm ol; sparse plag+ol clots. Overlies all adjacent units (b15, bsp, bdc, ay, msp, asr, bu, bl, byb, ms, brf); underlies only rhyolitic pumice (not mapped) from Little Glass Mountain (unit rlg) (and possibly from Glass Mountain, unit rgm). Because of youthful appearance of this rugged, mostly unvegetated lava flow, unit originally was thought to have been erupted as recently as 300 years ago (Finch, 1933). Calibrated age of 2,950 yr B.P. (Donnelly-Nolan and others, 2007; Nathenson and others, 2007) is based on two radiocarbon ages (Donnelly-Nolan and others, 1990). Sectors A, M

acc **Andesite of Cinder Cone (middle Pleistocene)**—Sparsely porphyritic andesite (58.8% SiO_2) flow and cone (Cinder Cone) located on south flank of MLV. Phenocrysts: 1–2% 1–2 mm plag; larger plag+ol+cpx clots; minor 1 mm ol. Underlies all adjacent units (mug, brh, bgc). Sector B

adh* **Andesite near Devils Homestead (middle Pleistocene)**—Variably porphyritic andesite (56.5–57.8% SiO_2; avg of 3 = 57.3%) lava flows exposed at and near base of Gillem Fault in northwestern part of LBNM. Three flows are exposed at and near Devils Homestead overlook: uppermost is least porphyritic (1–3% phenocrysts); middle flow contains 3–5% phenocrysts; and top of lowermost flow is most porphyritic (5–10% phenocrysts). All three contain 1–4 mm plag; 1–2 mm ol; plag>>ol. Additional small patches of unit are found farther north along Gillem Fault. In two places near Gillems Camp at north edge of LBNM, uppermost flow of unit overlies unit bgf. Both units flowed against preexisting fault scarp and were subsequently uplifted by more recent movements. Vent is unknown and presumably is buried farther south. Underlies units awf and bmc; overlies unit bgf. $^{40}Ar/^{39}Ar$ age of uppermost flow is 171±4 ka (table 1). See Donnelly-Nolan and Champion (1987) for additional information; mapped as "unit adha" on their map. Sector H

aeg **Andesite east of Grasshopper Flat (middle Pleistocene)**—Poorly porphyritic andesite (56.4–57.5% SiO_2; avg of 3 = 57.1%) flow and glaciated caldera-rim vent cones. Extends south and south-southwest from caldera rim as far as 8 km. Phenocrysts: approx 1% mostly 1 mm plag, some larger; minor ol+cpx. Overlies units mug and isolated cinder cones a8, a9, and m15; underlies units mel, brh, bsl, asr, anr, mgf, bgc, and rlg. $^{40}Ar/^{39}Ar$ age of 236±33 ka (not listed in table 1) is considered too old, on basis of stratigraphic constraints. See Donnelly-Nolan and Lanphere (2005) for additional data. Unit overlies unit mug, which has $^{40}Ar/^{39}Ar$ age of 180±28 ka (table 1). Sectors B, C, D, E ael **Andesite east of Lost Spring (middle Pleistocene)**—Very porphyritic andesite (60.4% SiO_2) lava flow forming very small outcrop area approx 2 km east of Lost Spring. Vent unknown. Phenocrysts, 25–30%: mostly 1–2 mm plag, some larger. Rock contains approx 5% opx+cpx, opx>cpx. Underlies units mrl and bwd; overlies unit orr. Sector C

aes* **Andesite east of Six Shooter Pass (middle Pleistocene)**—Poorly porphyritic andesite (58.3–60.7% SiO_2; avg of 3 = 59.3%) exposed on lower northwest flank of MLV. Numerous patches are found over area of approx 10 km by 3 km. Vent unknown. Phenocrysts: 1% ≤2 mm plag; much smaller amount of 1 mm cpx. Overlies units ob, om, and oap; also in fault contact with older unit ob. Underlies units bea, mnl, dta, and bts, as well as surficial unit l (in this area, lake deposits of Bonita Lake basin). $^{40}Ar/^{39}Ar$ age is 307±24 ka (table 1). Sectors F, G

aet **Andesite east of Typhoon Mesa (middle Pleistocene)**—Porphyritic andesite (59.1% SiO_2) cone at east edge of Typhoon Mesa andesite flow (unit atm). Phenocrysts, approx 10%: mostly 1–3 mm plag; includes approx 2% 1–2 mm opx. Underlies units mtl, atm, bss, and dta; overlies unit omf. Sector D

afr **Andesite of Fisk Ridge (middle Pleistocene)**—Very porphyritic andesite (60.8% SiO_2), consisting of glaciated lava flow at northeast end of Fisk Ridge. Phenocrysts, approx 25%: mostly (more than half) 1–3 mm plag; also, in decreasing abundance, 1–2 mm opx, 1–5 mm hb needles, ≤1% cpx. Underlies unit dls; overlies units orr and mrl. Sectors C, D

aib* **Andesite of Indian Butte (late Pleistocene)**—Variably porphyritic andesite and basaltic andesite (56.1–59.5% SiO_2; avg of 11 = 57.6%) that was erupted from Indian Butte, adjacent cinder cone to west, and additional cones farther to north-northwest. Covers significant area on upper northeast flank of MLV. Phenocrysts: 1–10% 1–4 mm plag+ol; plag>ol. Overlies all adjacent units except mna, bvc, rgm, and surficial unit p. $^{40}Ar/^{39}Ar$ age is 22±13 ka (table 1). Sectors J, K, L

ama **Andesite southwest of Mammoth Crater (middle Pleistocene)**—Sparsely porphyritic andesite (56.7, 57.4% SiO_2) that was erupted from cinder cone approx 4 km southwest of Mammoth Crater. Phenocrysts: 1–2% 1–2 mm plag; less abundant ol. Overlies unit dec; underlies units mnm, anr, and bmc. Sector I

anh **Andesite northeast of Mount Hoffman (middle Pleistocene)**—Porphyritic andesite (57.7, 58.0% SiO_2) flow exposed in three separate areas and extending at least 11 km from northeast edge of unit rmh, which directly overlies this unit. Vent is not exposed and presumably is buried to south or southwest. Unit is cut by two small northeast-trending faults. Phenocrysts: approx 15% 1–4 mm plag; 1–3% 1–2 mm ol. Overlies isolated basaltic andesite cone of unit m10; in outcrop area immediately northeast of Mount Hoffman, underlies units anr, aib, rmh, rgm, and surficial unit p; probably underlies unit aug in area west of northernmost domes of unit rgm; in two smaller areas southeast of Caldwell Butte, underlies units bng, bci, and aib. See also description of “unit pa” in Donnelly-Nolan and Champion (1987). Sectors J, K

anl **Andesite north of Little Glass Mountain (middle Pleistocene)**—Poorly porphyritic andesite (8 samples, 58.0–60.2% SiO_2; 1 sample, 63.0% SiO_2; avg of 9 = 59.8%) exposed in several outcrop areas over an area of approx 6 km by 9 km on northwest flank of MLV. Vent is unknown but presumably is near northwest caldera rim. One area about 3 km west of Callahan Flow (unit mcf) is more porphyritic and has more rugged morphology than other outcrop areas, but it occupies similar stratigraphic position. Uppermost outcrop area has been glaciated, exposing interior dull-gray blocks and removing black glassy exterior blocks present in other outcrop areas. Phenocrysts: most samples have approx 1% plag ≤2 mm and a few 1 mm ol xls; sample from more porphyritic area has approx 2% of 1–3 mm plag and ≤1% of 1 mm ol. Contains granitic inclusions that display significant melting. Overlies units bea, mnl, bh, and mtr; underlies units mbp, dta, mfh, bpw, and anr. Sectors E, F, G

anr* **Andesite of north rim (late Pleistocene)**—Poorly porphyritic andesite and subordinate amounts of dacite (57.5–64.3% SiO_2; avg of 11 = 60.7%) lava flows that were erupted as fountain-fed flows from several vents that define north rim of Medicine Lake caldera. At and near caldera rim, unit is glaciated, displaying smooth, sometimes polished and striated surfaces on dull-gray andesite. Farther away from caldera, unit typically displays blocky surface; many individual blocks have black, glassy appearance. Unit covers area approx 15 km southwest-northeast by 5 to 10 km northwest-southeast. Typical phenocrysts: <<1% 1–2 mm plag;

rare opx±ol±cpx. Also typical are small lithic fragments of variety of rock types, including white fragments of rhyolite. Two lava flow samples collected on or near north caldera rim are more silicic (62.7, 64.3% SiO_2) than other samples and are noticeably more porphyritic, having approx 2% 1–2 mm plag and approx 0.5% pyx. Two MI were collected and analyzed (both contain 55.2% SiO_2). Overlies numerous units: in northeastern part of unit, overlies m10, a5, asc, dec, dta, m9, anh, ama, mnm, bnf, bac, bsc, and asm; in northwest, overlies units rgf, rcg, arr, mnl, awh, mbp, a6, dta, muc, and mfh; in southwest, overlies awh, aeg, mug, blh, and mel. In west, unit abuts unit bpw, which is probably older. Underlies units bl, bwh, rmh, btm, dm, mcf, rh, and rlg, as well as surficial units t, l, and p. $^{40}Ar/^{39}Ar$ age is 100±3 ka (table 1; see also, Donnelly-Nolan and others (1994) for discussion of this age and other argon ages for this unit). Sectors D, E, F, G, H, I, J

arr **Andesite of old railroad (middle Pleistocene)**—Poorly porphyritic andesite (57.3% SiO_2) lava flow of small outcrop area approx 3 km west of Cinder Butte. Vent unknown. Phenocrysts: 1% plag+ol; includes 1–3 mm plag, 1 mm ol. Underlies all adjacent units (mnl, dta, anr). Sector G

as **Andesite of south flank (late? Pleistocene)**—Moderately porphyritic andesite (57.5–58.0% SiO_2; avg of 3 = 57.8%) lava flow, probably from vent(s) under Medicine Mountain. Phenocrysts, approx 5%: mostly 1–3 mm plag; includes approx 1% 1 mm ol. Overlies units bet and bsh, as well as three isolated cinder cones (units b11, b13, m19); underlies units asr, byb, ms, and bgc, as well as surficial unit g. Sectors A, M

asb* **Andesite of Schonchin Butte (late Pleistocene)**—Sparsely porphyritic andesite (56.8–57.4% SiO_2; avg of 3 = 57.2%) block lava flow (Schonchin Flow) that has steep margin, rugged morphology, and little vegetative cover. Unit also includes tephra erupted from Schonchin Butte, which is prominent landmark in LBNM and is location of monument fire lookout (foot trail to top). Phenocrysts: approx 2% 1–4 mm plag; <1% 1 mm ol. More extensive description was given in Donnelly-Nolan and Champion (1987); see also, Mertzman (1977a). Schonchin Flow overlies unit msc; in hole dug at south edge of the basalt of Mammoth Crater (unit bmc), tephra of this unit overlies unit mhi; unit underlies units bmc and bc. $^{40}Ar/^{39}Ar$ age is 65±23 ka (table 1). Sector I

asc **Andesite from cone at southeast edge of Callahan Flow (middle Pleistocene)**—Moderately porphyritic andesite (58.5, 59.0% SiO_2) in five separate outcrop areas: cinder cone at southeast edge of Callahan Flow (unit mcf); isolated part of another cone that is entirely surrounded by Callahan Flow; and three outcrop areas of lava flow adjacent to southern tip of Callahan Flow. Phenocrysts, 5%: 1–3 mm plag; 1–2 mm pyx; plag>pyx. Overlies unit rse; underlies units dec, mnm, bsc, anr, and mcf. Sectors G, H

asm **Andesite south of Mammoth Crater (late Pleistocene)**—Moderately porphyritic andesite (58.6% SiO_2) flow and unnamed cinder cone approx 1.5 km northwest of Aspen Crater. Phenocrysts: 5% 1–4 mm plag; much less 1 mm ol; scattered ≤0.5 mm clots of plag+ol+cpx. Overlies units bcu, bst, b9, mhi, mnm, and bac; underlies units anr, msm, bmc, and mna. Sectors I, J

asn **Andesite of Snag Hill (middle Pleistocene)**—Moderately porphyritic blocky andesite (61.6% SiO_2) flow and cinder cone of Snag Hill on south flank of MLV. Phenocrysts, approx 5%: mostly 1–2 mm plag; some ≤5 mm plag; <1% 1 mm ol. Underlies all adjacent units (bph, bwc, bgc). Sector B

asr* **Andesite of south rim (late Pleistocene)**—Aphyric to poorly porphyritic andesite (60.3–62.0% SiO_2; avg of 5 = 61.4%) that was erupted from arc of vents along south rim of Medicine Lake caldera. Southern analogue of the andesite of north rim (anr). Covers more than 20 km^2 of upper south flank of MLV. Appears to make up bulk of Medicine Mountain. Vents for unit as, and probably unit aeg, are buried beneath this unit. Locally steep areas, particularly on north edge and east end of Medicine Mountain, probably resulted from glacial erosion. Area of relatively gentle, irregular topography on north flank of Medicine Mountain, at southeast end of Medicine Lake, likely is a landslide made up entirely of this unit; it extends approx 1 km south of lake and is bounded on east by unit bl and on west by till of unit t. Most private cabins adjacent to Medicine Lake are located in this area. Except for its southernmost lobes, which still retain their carapace of glassy blocks, most of unit exhibits evidence of glacial ice (for example, striations; top of flow removed; glacial lakes such as Bullseye Lake; presence of meadows; and till that includes low morainal ridges; all present about 3 km south-southeast of Medicine Lake).

Phenocrysts, typically ≤1%: mostly 1–2 mm plag, some ≤4 mm, elongate; rare 1 mm opx, cpx, ol(?). Age relation to units anr and drs is uncertain, but, on basis of argon ages, this unit is older. Similarity of paleomagnetic direction (D.E. Champion, unpub. data, 2003) between this unit and unit anr, as well as their distinctive high-Na_2O contents, suggests that they are close in age. Overlies units m11, m12, m14, m16, m19, b11, dwm, bsp, bph, mug, aeg, ay, msp, as, brh, and aac; probably underlies unit bu; underlies units bl, byb, ms, bgc, and abl, as well as surficial units t and l. $^{40}Ar/^{39}Ar$ age is 124±3 ka (table 1); see also, Donnelly-Nolan and others (1994) and Donnelly-Nolan and Lanphere (2005) for additional data. Sectors A, B, C, D, E, M

atm* **Andesite of Typhoon Mesa (middle Pleistocene)**—Nearly aphyric to sparsely porphyritic andesite (59.1–62.4% SiO_2; avg of 8 = 60.4%) that probably was erupted under ice; present in several locations west of Little Glass Mountain. Typhoon Mesa, flat-topped tableland that has high, steep talus slopes, lies mostly west of map area. Isolated small conical hill, which probably represents inner core of a cinder cone, is present approx 0.5 km northwest of Tamarack Lake. About 1.5 km farther east is another such hill that includes large spindle bombs in coarse talus; this hill apparently vented lava flow that extends south and west of Squaw Peak and is now topographically higher than vent. Unit includes additional area to northeast, located between Pumice Stone Mountain and Tamarack Flat, that has same petrography and distinctive chemical composition; this area has topographic expression that suggests that andesite was constrained to flow north by ice located to west. Unit also includes isolated lobe of andesite west of Squaw Peak that is petrographically very similar to other rocks of this unit but has higher silica content (62.0%). If any cinders of vent cones existed, they apparently have been removed by ice. Phenocrysts: <1% to 2% 1–2 mm plag; ≤1% 1–2 mm hb needles; rare 1 mm ol±pyx. Underlies units bss, dta, and bpw, as well as surficial units g and p; overlies units orr, ods, oap, mnp, aet, msr, mtf, mwr, mws, and mtl. K-Ar age is 254±25 ka (table 1) at Typhoon Mesa. $^{40}Ar/^{39}Ar$ age is 282±11 ka (table 1) at area southwest of Squaw Peak. Ages are compatible with time of global cooling (oxygen-isotope stage 8 of Martinson and others, 1987; see also, Shackleton and others, 1990; Bassinot and others, 1994; Worm, 1997; Herbert and others, 2001). Sectors D, E

aug **Andesite under Glass Mountain (middle Pleistocene)**—Sparsely to moderately porphyritic andesite and basaltic andesite (53.6–58.3% SiO_2; avg of 4 = 55.1%) lava flow and at least three unnamed cinder cones that are mostly mantled by pumice from late Holocene eruption of Glass Mountain. Unit includes strip of basaltic andesite flow directly east of Glass Mountain, as well as another directly west of northernmost domes of Glass Mountain (unit rgm). Phenocryst contents vary: three samples have 1–5% plag+ol xls, typically 1–2 mm, plag>ol. Overlies units reg, beg, and deg; probably overlies unit dta; may overlie unit anh; underlies units aib and rgm, as well as surficial unit p. Sectors K, L

aut **Andesite under Three Sisters (middle Pleistocene)**—Sparsely porphyritic andesite (57.4% SiO_2) that flowed over, and was later displaced by, northwest-trending fault in northwest corner of map area. Despite single andesite chemical analysis, much of unit appears to be more mafic. Vent location is unknown and presumably is buried under Three Sisters lava (unit bts). Phenocrysts: 1–2% 1–2 mm plag+ol. Overlies units otb, ob, and dta; underlies unit bts. Sectors F, G

awb **Andesite of Whitney Butte (middle Pleistocene)**—Moderately porphyritic andesite (58.4% SiO_2) that was erupted from Whitney Butte at northern edge of late Holocene Callahan Flow (unit mcf). Cut by north- and northeast-trending normal faults whose offsets are more commonly down to east than down to west. Faulting has revealed flow thicknesses of at least 10 m, although flow margins are typically 2–3 m high. Phenocrysts: approx 3–5% 1–6 mm plag; rare 1 mm ol. Overlies units ob, dta, mwd, bnw, and awf; underlies units men, mhi, bmc, bgd, and mcf. Sectors G, H

awf **Andesite west of Fleener Chimneys (middle Pleistocene)**—Glassy andesite (60.8% SiO_2) lava flow that has highly irregular, blocky surface; flow margin is 10–20 m high. Vent is buried by younger flows to south. Phenocrysts rare, <1%: ≤1 mm ol+plag. Rock typically contains small (≤1 cm) inclusions, mostly MI but also xenoliths. Ash-flow tuff of unit dta is lacking on top of this unit, while at same time is found immediately to north, farther from vent area of unit dta, indicating that this unit overlies unit dta. Also overlies units obg, opt, bwg, mwd, and adh; probably overlies unit bnw; underlies units awb, men, and bdh. Sector H awh **Andesite west of Little Mount Hoffman (middle Pleistocene)**—Porphyritic andesite and minor dacite (61.1–64.4% SiO_2; avg of 4 = 62.5%) flow extending nearly 9 km to northwest from edge of Little Mount Hoffman. Vent location is unknown but probably is buried just north or northeast of Little Mount Hoffman. Unit contains numerous MI, two of which contain 57.9 and 59.2% SiO_2. Phenocrysts: approx 5% 1–2 mm plag; 1% 1 mm cpx+opx; rare ol, in ol+pyx+plag clots; some xls are from disaggregated inclusions. Largest MI (12 cm across) are found at south end of unit, nearer to presumed vent location; north end of flow contains only ≤1 cm clots of xls. Overlies units ord, rcg, bea, mlh, and anl; underlies units mbp, dta, blh, bpw, anr, and rlg. Sectors D, E, F

awl **Andesite west and north of Little Glass Mountain (late Pleistocene)**—Sparsely porphyritic andesite (58.5% SiO_2) flow that was erupted from cone at northwest edge of Little Glass Mountain. Flow is partially surrounded by Little Glass Mountain rhyolite (unit rlg) and is nearly buried by initial pumice eruption of unit rlg. Flow contains fine-grained MI to 8 cm in size, two of which contain 50.2 and 51.6% SiO_2. Phenocrysts: 2–3% 1–2 mm plag; 1% 1 mm ol; rare cpx. Overlies units oap and bnp; probably younger than unit bpw; underlies units mpp and rlg, as well as surficial unit l. Sectors D, E

awm **Andesite west of Medicine Lake (middle Pleistocene)**—Very porphyritic andesite (59.1% SiO_2). Unit is glaciated, but it has thick soil. East end of unit is hydrothermally altered; small landslide has taken place in this material. Phenocrysts, approx 30%: mostly 1–2 mm plag; includes 5% 1 mm cpx. Probably underlies unit dwm; underlies units mbp, dta, and mug, as well as surficial units p and l. Sectors E, F

ay **Andesite under basalt of Yellowjacket Butte (middle Pleistocene)**—Porphyritic andesite (58.5% SiO_2) lava flow. Vent is unknown and is presumed to be buried uphill to north. Phenocrysts, 10%: mostly 1–3 mm plag (some elongate); includes approx 2% 1 mm ol+cpx, ol>cpx. Underlies all adjacent units (asr, byb, ms, abl). Sector A

DACITE

dac **Dacite in Aspen Crater (middle Pleistocene)**—Porphyritic dacite (64.0% SiO_2) from single outcrop exposed on north wall of Aspen Crater. Contains MI in range of sizes, from <1 cm to several centimeters; one was analyzed (55.5% SiO_2). Phenocrysts are abundant and include xls from disaggregated MI. Phenocrysts, approx 10%: mostly plag, 1–2 mm; subordinate smaller ol. Underlies unit bac. Sector J

dec* **Dacite east of Callahan Flow (middle Pleistocene)**—Sparsely porphyritic dacite (67.3, 70.2% SiO_2) in two outcrop areas: one south, and another southeast, of southeast edge of late Holocene Callahan Flow (unit mcf). Vent location is unknown and presumably is to south. Significant northeast-trending fault zone, down to east, lies between two outcrop areas of this unit. Contains MI (55.0–57.8% SiO_2). Phenocrysts, approx 3%: plag ≤3 mm; opx ≤2 mm; plag>opx. Overlies units rse, b8, and asc; underlies units dta, ama, mnm, anr, bmc, bec, and mcf. $^{40}Ar/^{39}Ar$ age is 200±2 ka (table 1); see also, Donnelly-Nolan and Lanphere (2005) for additional data. Sectors G, H, I

deg* **Dacite east of Glass Mountain (middle Pleistocene)**—Porphyritic dacite (69.3% SiO_2) flow directly east of Glass Mountain. Vent location is unknown but probably is buried under Glass Mountain lava (unit rgm). Phenocrysts: 5–7% 1–4 mm plag, commonly elongate; ≤1% 1 mm opx. Overlies units reg and beg; underlies units dta, aug, bl, aib, and rgm. K-Ar age is 203±6 ka (table 1). Sector L

dls* **Dacite east of Lost Spring (middle Pleistocene)**—Sparsely porphyritic dacite (68.7% SiO_2) flow that was erupted from small vent dome less than 1.5 km east-northeast of Lost Spring. Phenocrysts, 3%: 1–2 mm plag. Small (<2 cm) MI are scattered throughout rock, but none were large enough for analysis. Overlies units orr, mrl, afr, and bss; underlies unit bwd. K-Ar age is 182±4 ka (table 1). Sectors C, D

dm **Dacite of Medicine Lake Glass Flow (Holocene)**—Porphyritic dacite (68.2–68.8% SiO_2; avg of 3 = 68.5%) of young, rugged and unmodified, pancake-like flow that covers approx 2.4 km^2 of caldera floor between Medicine Lake and north caldera rim. Volume is approx 0.08 km^3. Also known as “Medicine flow” (Powers, 1932), “Medicine dacite” (C.A. Anderson, 1941), and “Medicine dacite flow” (Donnelly-Nolan and others, 1990). Entire flow is edged by unstable talus slopes 25–40 m high of mostly glassy blocks. Two vent areas are defined by abundance of vertical spines of lava and by enclosing concentric or aligned pressure ridges; vents are aligned N. 45° W. Flow contains variety of sparsely distributed inclusions: granitic and mafic plutonic xenoliths, cumulate gabbroic inclusions, and fine-grained MI (one contains 60.4% SiO_2; Grove and Donnelly-Nolan, 1986). Phenocrysts, host lava: 5–7% 1–3 mm plag; approx 1% 1–2 mm opx. Sparse microscopic hb xls (rare at MLV) are present in groundmass. Overlies units anr and bl, as well as surficial unit l (in this area, lake sediments deposited by former high stand of Medicine Lake). Calibrated age of 5,140 yr B.P. is based on estimate derived from sedimentation rate and stratigraphy in Medicine Lake sediments (Donnelly-Nolan and others, 2007; Nathenson and others, 2007). Sectors G, H, I, J

dpc **Dacite of pit craters (Holocene)**—Nearly aphyric, low-silica dacite (two analyses, 63.4% SiO_2) that was erupted as tephra and spatter from numerous pit craters aligned approx N. 30–40° E. One of largest craters, located just northwest of junction of major roads approx 1 km northeast of Undertakers Camp, displays good exposures of welded-spatter “flows” of this unit on northwest wall of crater. Most of unit as shown on map consists of near-vent vesicular blocks as much as 1 m across; farther from vent, tephra of unit is mapped where it obscures underlying units. Tephra of this unit is more extensive than is shown in 1 km by 3 km mapped area and is noticeable on Red Shale Butte and Lyons Peak. Approximate area and volume of unit are 2.4 km^2 and 0.02 km^3, respectively. Northeast-trending cracks beyond northeasternmost extent of unit apparently opened during eruption but did not erupt magma. Phenocrysts: <<1% 1 mm plag; rare small pyx xls in groundmass. Angular lithic fragments of underlying lava flows also are present, including car-sized blocks of Lake Basalt (bl) that were thrown out of crater at northeast end of map unit. Overlies all adjacent units (msp, bu, bl, surficial unit t). Calibrated age of 5,040 yr B.P. (Donnelly-Nolan and others, 2007; Nathenson and others, 2007) is based on two radiocarbon ages (Donnelly-Nolan and others, 1990). Sectors L, M

drs* **Dacite of Red Shale Butte (late Pleistocene)**—Moderately porphyritic, low-silica dacite (62.3–64.5% SiO_2; avg of 7 = 63.1%) that was erupted from Red Shale Butte at or near east rim of caldera. Unit probably forms bulk of Red Shale Butte, although Lake Basalt (bl) was erupted through (and flowed over) this unit, such that this unit now exists only as half dozen isolated patches. Both this unit and unit bl have been glaciated. Total exposed area extends as far as 6 km west-southwest to east-northeast. Phenocrysts: 5% 1–2 mm plag; ≤1% 1 mm cpx+opx. Age relation to unit asr is uncertain. Overlies units mrs and aac; underlies units bl and rh, as well as surficial units t and p, latter of which in this area includes late Holocene tephra deposits but dominantly consists of Glass Mountain tephra. K-Ar age of 88±7 ka (table 1) may be too young, on basis of arguments discussed in Donnelly-Nolan and others (1994). Sectors L, M

ds* **Dacite of south flank (middle Pleistocene)**—Porphyritic, high-silica dacite (69.9% SiO_2) lava flow or dome exposed in small outcrop area on upper south flank of MLV at about 6,300 ft (1,920 m) elevation. Vent location is unknown but probably is uphill to north. Rock consists of streaky vitrophyre containing abundant fine-grained MI as much as 20 cm across. Two MI contain 51.2 and 51.3% SiO_2. Phenocrysts, host lava: ≥5% 0.5–3 mm plag; approx 1% ≤1 mm opx commonly associated with smaller opaque grains; 5% plag+cpx+ol (plag>cpx>ol) are probably disaggregated fragments of inclusions. Underlies, and is mostly buried by, unit msp. $^{40}Ar/^{39}Ar$ age of one MI is 159±30 ka (table 1); however, this unit and unit dsk could be part of same eruptive event, on basis of close similarity in chemical composition of both host silicic lava and sampled MI. If so, argon age of this unit likely is too young, whereas argon age of unit dsk (244±20 ka) likely is too old; both are part of approx 200-ka-old dacite event at MLV. Sector M

dsk* **Dacite southwest of Kelley Pass (middle Pleistocene)**—Moderately porphyritic, high-silica dacite (69.7, 70.2% SiO_2) flow containing numerous andesitic and basaltic MI (51.3–57.4% SiO_2). May correlate with unit rcg uphill to south; see also, unit ds for discussion of possible correlation with that unit. Phenocrysts: approx 5% 1–2 mm plag. Overlies unit bea; underlies units mbp, dta, and mfh. $^{40}Ar/^{39}Ar$ age of one MI is 244±20 ka (table 1), but this age may be too old; see discussion in unit ds description above. Sector F

dta* **Dacite tuff of Antelope Well (middle Pleistocene)**—Dacite ash-flow tuff found in many sectors around MLV, which makes it stratigraphically most important unit at MLV. Tuff is widespread unit that washed across preexisting topography, depositing thickly enough in low topographic areas to become welded and so to remain as recognizable unit today. Previously named “andesite tuff” by C.A. Anderson (1941). Analyses of 15 pumice samples range in composition from 63.1 to 67.1% SiO_2 (avg 64.9%); 10 whole-rock analyses range in composition from 61.0 to 64.9% SiO_2 (avg 63.3%). Sizes of lithic fragments and pumice lumps increase toward caldera (Donnelly-Nolan and Nolan, 1986; Donnelly-Nolan, 1987), indicating intracaldera source, perhaps where Medicine Lake is located or under Medicine Lake Glass Flow (unit dm) on caldera floor north of Medicine Lake. However, nearly all units on rim and floor of present-day caldera are younger than this unit, and so recognition of specific vent site is problematic. Three outcrops of this unit have been found within caldera; all are west-northwest of Medicine Lake and all overlie units mbp and awm. Outcrop at east end of unit awm is remarkable for having flattened, welded pumice lumps that are a meter long but are only 2 to 4 cm thick. This same locality also exhibits sparse lithic fragments and MI as much as 20 cm across. Outcrop appears to be welded and plastered onto northeast-facing slope, as though it was deposited by southwest-directed eruption. Donnelly-Nolan and Nolan (1986) presented evidence that deposition of this unit was followed by catastrophic flooding that cut anastomosing channels, primarily in northwest quadrant of MLV. Most tuff outcrops are present in this quadrant. Some of unit did travel east through caldera-rim gap now filled by unit rh and by Glass Mountain flow (unit rgm). Pieces of ash-flow tuff also are present in ejecta from explosion pits near east edge of the rhyolite of Mount Hoffman (unit rmh), indicating that this unit underlies unit rmh. In addition, single outcrop of welded tuff of this unit, as well as another of nonwelded tuff probably of this unit, have been found far south, approx 6 km south of Harris Mountain, near southwest edge of map area. Between welded outcrop south of Harris Mountain and caldera are several lava flows not overlain by this unit, which must have been deposited by pyroclastic flow southwest from caldera prior to emplacement of units mug, mdp, aeg, and others. Drill hole 62–21 on upper southwest flank of MLV begins in younger unit asr and intercepts unit dta at depth of approx 575 to 695 ft (175 to 212 m) below surface, indicating that considerable amount of this unit traveled southward (Donnelly-Nolan, 2006). Unit is variable in appearance, ranging in color from light gray and beige to red to brown and brownish black. Outcrops having darker colors typically are more welded and usually form thinner layer of tuff; no vitrophyre has been found in outcrop, but boulders of vitrophyre are present in gravel deposited by flood (for example, at Antelope Well). Where deposits are thicker and are cut by channels (for example, upstream from Antelope Well), typical exposure displays 1- to 2-m-high rounded walls. More commonly, unit is in reddish, flat tablets that are a meter or so wide and only 0.3 m or less thick. In many cases, blocks of tuff are scattered about in shallow depressions on surface of older units. Distribution of tuff typically is generalized on this map because of intermittent nature of outcrops; mapping and portraying each small outcrop area is not appropriate at scale of this map. Unit is significant in that it is impervious to water where it is welded and intact and thus provides water storage (for example, at Dock Well, Antelope Well, and other water holes). Phenocrysts (pumice lumps): 1–3% 1–2 mm plag; <<1% opx+cpx. Unit overlies many units, some of which are as follows: on north flank, units aes, bea, mnl, anl, mbp, and dec, as well as older surficial unit og; east of caldera, units reg, rsl, and deg; within caldera, units awm and mbp; to west, units obw, mtf, mwr, and atm; and to south, unit obd. This unit underlies numerous units as well: to northwest and north, units mf, bts, bpw, bmc, and aib; to east, units bls, bt, bl, and aib; and caldera-rim lavas of units asr, anr, and drs. $^{40}Ar/^{39}Ar$ age is 171±43 ka (table 1), which correlates with marine oxygen-isotope records that indicate cooler time about 180,000 years ago (Martinson and others, 1987; Bassinot and others, 1994; Worm, 1997). Stratigraphic relation to other dated units, together with climate constraints, indicates that this unit must be between 180 and 185 ka and is more likely the former. The 180-ka age is used herein as likely age for unit. Sectors B, C, D, E, F, G, H, K, L

dwm **Dacite west of Medicine Lake (middle Pleistocene)**—Porphyritic dacite (67.9% SiO_2) forming southeast side of glaciated hill that consists primarily of vent cone for unit mbp. Phenocrysts, as individual xls and as clots of xls, 10%: dominantly 1–3 mm plag; includes approx 2% 1 mm cpx+opx. Underlies units mug, mbp, and asr, as well as surficial unit p; probably overlies unit awm. Sector E

RHYOLITE

rcb* **Rhyolite near Cougar Butte (middle Pleistocene)**—Aphyric rhyolite (77.2% SiO_2), mostly stony but, in part, lithophysal and, in part, distinctive obsidian displaying scattered spherulites. Vent location is unknown although probably is buried by younger lavas not far to southwest of larger of two outcrop areas. Underlies all adjacent units (bco, bls, aib). $^{40}Ar/^{39}Ar$ age is 437±7 ka (table 1). Sector K

rcg **Rhyolite west of Crater Glass Flow (middle Pleistocene)**—Moderately porphyritic rhyolite (70.9% SiO_2) in small outcrop area equidistant (approx 3.5 km) from west edge of Crater Glass Flow and from northern margin of Little Glass Mountain. Petrographic characteristics suggest possible correlation with downslope unit dsk, which has lower silica content than this unit. Phenocrysts: approx 5% 1–2 mm plag; minor ≤1 mm opx. Also contains ≤3 cm MI. Vitric groundmass typically is hydrated. Underlies adjacent units awh, mbp, and anr. Sector E

rec* **Rhyolite east of Callahan Flow (middle Pleistocene)**—Aphyric rhyolite (72.3–72.6% SiO_2; avg of 3 = 72.5%) at southeast edge of Callahan Flow (unit mcf). Is faulted against, and also overlies, unit rse; also is faulted against stratigraphically younger unit bec; underlies units asc, bec, and mcf. Weighted average of two K-Ar ages is 322±22 ka (table 1). Sector H

reg* **Rhyolite east of Glass Mountain (middle Pleistocene)**—Aphyric rhyolite (two analyses, 76.4% SiO_2) of older dome that has lost much of its original carapace of pumice and glass. Only exposed directly east of Glass Mountain, where young flows did not completely surmount older dome but instead deviated around to north and south. Underlies all adjacent units: beg, deg, dta, aug, bl, aib, and rgm. $^{40}Ar/^{39}Ar$ age is 475±29 ka (table 1). Sectors K, L

rgf* **Rhyolite of Grasshopper Flat (middle Pleistocene)**—Aphyric or nearly aphyric rhyolite (75.2–75.7% SiO_2; avg of 6 = 75.5%) exposed as kipukas, dominantly of obsidian, across nearly 30 km of west side of MLV. Outcrops west of Callahan Flow (unit mcf) are identical chemically to those south of Little Glass Mountain. If all these outcrops resulted from coeval eruptions, and if they represent highest parts of otherwise buried flows and domes, then north-northeast vent trend is suggested. Phenocrysts (sparse outcrops): <<1% 1 mm plag. Underlies all adjacent units. $^{40}Ar/^{39}Ar$ age is 387±6 ka (table 1; see also, Donnelly-Nolan and Lanphere, 2005). Sectors B, C, G

rgm **Rhyolite of Glass Mountain (Holocene)**—Aphyric to variably porphyritic, compositionally zoned rhyolite to andesite, but dominantly rhyolitic (61.3–74.6% SiO_2). Initial tephra eruption formed deposits as thick as 10 m that were subsequently exposed by pumice mining. Flows and multiple domes were erupted from about 15 vents along northwest-trending fissure high on east rim of MLV. Glass Mountain was known originally as “Big Glass Mountain” (Powers, 1932); it was studied and mapped by C.A. Anderson (1933), by Eichelberger (1975, 1981), and by Donnelly-Nolan and Grove (2008). Lavas that have highest silica contents are aphyric. Phenocrysts in rhyolitic (70–73% SiO_2) lava: typically, 1–2% 1 mm plag; rare ≤1 mm opx; ±MI and their debris. Phenocrysts in dacitic (<70% SiO_2) lavas and in andesitic scoria (incorporated within zones of disrupted initial pumice cone deposits): typically, 1–3% 1–3 mm plag; 1% 1 mm opx. Rare partially melted granitic inclusions have been found in two small domes. Also present in main flow and in many domes are MI (<1–70 cm) and 5–10% of disaggregated MI material (plag+ol+cpx, plag>ol>cpx), amount of such material increasing as silica content of unit decreases; see Grove and others (1997), as well as Grove and Donnelly-Nolan (1986), for additional chemical analyses. Flow and domes cover approximately 14.0 km^2. Unit has estimated volume of 1 km^3, including tephra, which is estimated to constitute 10 percent of total volume (Heiken, 1978). Maximum thickness of lava flows varies from approx 30 m for dacite lobes to approx 100 m for last-erupted rhyolite lobe. Three areas of surficial unit p immediately north and south of unit consist dominantly of tephra of this unit. Overlies all adjacent units and is youngest unit at MLV. Calibrated age of 890 yr B.P. (Donnelly-Nolan and others, 2007; Nathenson and others, 2007) is based on radiocarbon ages published in Donnelly-Nolan and others (1990) and Champion and others (2005). Sectors K, L

rh **Rhyolite of “Hoffman flows” (Holocene)**—Porphyritic rhyolite and dacite (68.4–72.4% SiO_2; avg of 7 = 70.9%) of two young, steep-sided flows that were erupted from N. 25° W.–trending, en echelon alignments of nearly a dozen vents, including aligned explosion craters located on east edge of the rhyolite of Mount Hoffman (unit rmh). Lava was erupted near caldera rim, flowing both inward and outward. Estimated area is 5.5 km^2; estimated volume is 0.2 km^3. Unit is significantly mantled near Glass Mountain by pumice of Glass Mountain (unit rgm) eruption and by vegetation that has grown on pumice. Farther away, at west end of unit, flow has very youthful appearance. Tephra deposit ascribed to this unit has been exposed by quarrying in surficial unit p north of Glass Mountain. Rock contains abundant MI (commonly disc shaped), most of which are fine grained, but some are cumulate in texture; rock also contains scattered xenoliths. MI are so common, and many MI are so small, that it is not possible to remove them all, thus resulting in lowered silica content when host rock is analyzed by whole-rock methods. Phenocrysts: 5–10% 1–2 mm plag; ≤1% 1 mm opx, commonly in vitric groundmass. Overlies all adjacent units (anh, bac, aac, anr, drs, bl, rmh) except unit rgm and surficial unit p; underlies tephra of units mcf and rlg. Calibrated age of 1,170 yr B.P is based on radiocarbon ages not previously ascribed to this unit (Donnelly-Nolan and others, 2007; Nathenson and others, 2007). Sectors J, K, L

rlg **Rhyolite of Little Glass Mountain (Holocene)**—Poorly porphyritic rhyolite (72.6–74.2% SiO_2; avg of 9 = 73.9%) consisting of tephra and multiple lava flows and domes that were erupted from more than a dozen vents along two en echelon fissures having approx N. 30° E. trends. Estimated area covered is 6.3 km^2; estimated volume is approx 0.4 km^3. Unit contains obsidian and variably vesicular pumice. No stony interior rhyolite is exposed. Location is west and northwest of caldera. Extent of unit from southwest edge of largest and southwesternmost lava flow to northeast end of eruptive fissure is approx 10 km. Northeastern domes include Crater Glass Flow and additional domes farther along northeast trend. Emplacement of Little Glass Mountain was described by Fink (1983), as were its surficial features. Eruption was accompanied by formation of open ground cracks, as described by Fink and Pollard (1983). Tephra plume that extended both northeast and southwest preceded eruption of lava flows and domes (Fisher, 1964; Heiken, 1978). Phenocrysts: approx 1% 1–2 mm plag, mostly 1 mm; <<1% 1 mm opx. Unit also contains <1% inclusions: lithic fragments that are dominantly granite; MI to 0.8 m in diameter of basaltic andesite to andesite composition; and cumulate inclusions (see Mertzman and Williams, 1981; Grove and Donnelly-Nolan, 1986; Brophy and others, 1996). Overlies all adjacent units: awh, mbp, aeg, bnp, bpw, awl, bsl, and anr, as well as surficial unit p, which in this area consists dominantly of tephra from initial explosive eruption that resulted in emplacement of lava flow. Calibrated radiocarbon age is 940 yr B.P. (Donnelly-Nolan and others, 2007; Nathenson and others, 2007). Sectors C, D, E, F

rmh* **Rhyolite of Mount Hoffman (late Pleistocene)**—Porphyritic rhyolite (71.7–71.9% SiO_2; avg of 3 = 71.8%) lava flow that was erupted from vent marked by dome of Mount Hoffman, highest point on volcano at 7,913 ft (2,412 m). Lava flow margins are as high as 100 m. Perlitic texture present in glassy facies may reflect ice contact; scallop out of north-northeast side of flow is glacial cirque. Glacial debris of this unit is present as rounded pebbles 7 km to north on floor of Hidden Valley, just east of Mammoth Crater; rounded pebbles of this unit also are present in former gravel quarry (now filled) east of Caldwell Butte; rounded cobbles of this unit also are present in till of surficial unit t, south of caldera between Shotgun Peak and south caldera rim. Unit contains sparse MI ≤15 cm, five of which range in composition from 60.0 to 63.6% SiO_2; many contain hb xls (see also, Grove and Donnelly-Nolan, 1986). Phenocrysts: ≥5% 1–3 mm plag; 1–2% 1–2 mm opx. Overlies units anh, anr, and bwh; underlies unit rh and surficial unit p. May have been erupted early in latest glaciation. $^{40}Ar/^{39}Ar$ age is 28±5 ka (table 1). Sectors J, K

rng* **Rhyolite northwest of Glass Mountain (late Pleistocene)**—Aphyric rhyolite (71.1% SiO_2) found as large (as large as 1.5 m) blocks adjacent to Glass Mountain (unit rgm) domes 6, 7, and 8 (6th, 7th, and 8th domes of unit rgm north of main Glass Mountain lava flow). Blocks are most abundant immediately west of dome 7 and south of southwest corner of dome 8. No continuous outcrop is visible because area is mostly buried by Glass Mountain pumice of surficial unit p. Underlies unit rgm and surficial unit p. K-Ar age is 105±3 ka (table 1). Sector K

rse* **Rhyolite at southeast edge of Callahan Flow (middle Pleistocene)**—Moderately porphyritic rhyolite (73.9–74.1% SiO_2; avg of 3 = 74.0%) lava flow, commonly perlitic and (or) spherulitic, exposed in upfaulted block at southeast edge of Callahan Flow (unit mcf) and as spires protruding through overlying unit dec farther east. Phenocrysts, 5%: 1–3 mm plag, 1 mm opx, plag>opx. Underlies all adjacent units (rec, asc, dec, bec, mcf); faulted against stratigraphically younger units rec and mnm. K-Ar age is 330±40 ka (table 1; see also, Mertzman, 1982). Sectors H, I

rsl* **Rhyolite south of Little Sand Butte (middle Pleistocene)**—Aphyric stony rhyolite (75.0% SiO_2) and obsidian lava flow heavily mantled by pumice (not mapped) of Glass Mountain (unit rgm) eruption. Vent is unknown and presumably is located to southwest. Underlies units dta, bng, bt, bl, and aib, as well as surficial unit p; probably underlies unit bse. Weighted average of two K-Ar ages is 313±11 ka (table 1). Sector K rwc* **Rhyolite west of Callahan Flow (middle Pleistocene)**—Aphyric rhyolitic (73.4% SiO_2) obsidian exposed in small area west of upper Callahan Flow (unit mcf) and uphill from several exposures of unit rgf, which has different trace-element composition. Underlies unit mnl. K-Ar age is 349±7 ka (table 1). Sector G

UNITS OLDER THAN MEDICINE LAKE VOLCANO

SURFICIAL DEPOSITS

og **Older gravel deposits (middle and early Pleistocene)**—Well-rounded cobbles and pebbles. Mapped in one small and two very small areas in northwest corner of map; also exposed north of mapped area. Overlies unit otb; underlies unit dta and surficial unit g. Age is greater than 180 ka (age of unit dta) but less than 1.006±0.025 Ma (age of unit otb). Contains bluish rhyolite cobbles and other rock types not recognizable as MLV lavas, indicating age is probably greater than about 500 ka. Sectors F, G

ol **Older lake sediments (middle and early Pleistocene)**—White, powdery lake sediments, much eroded, occupying low area south and southwest of Mount Dome. Sediments are at least in part younger than Mount Dome itself. Underlies units ob, otb, omb, dta, and bmc. Age is greater than about 500 ka. Sector G

VOLCANIC ROCKS

oag **Older andesite of Garner Mountain (middle Pleistocene)**—Porphyritic to very porphyritic andesite (59.6% SiO_2) lava exposed under lower east side of Garner Mountain, an edifice of significant size just west of MLV. Phenocrysts, 10–20%: dominantly plag, 1 mm to 1 cm; <1% 1 mm opx+cpx(?). Underlies all adjacent units: mtf and dta, as well as surficial unit g in Tamarack Flat. Unit is undated; however, K-Ar age on lava from west side of Garner Mountain is 520±30 ka (sample 78C4, Donnelly-Nolan and Lanphere, 2005); in addition, Brown and Mertzman (1979) listed K-Ar age of 520±210 ka for Garner Mountain lava (this unit). Sector E

oap* **Older andesite of Pumice Stone Mountain (middle or early Pleistocene)**—Porphyritic andesite (57.3–58.7% SiO_2; avg of 6 = 57.7%) lava flow that has distinctive speckled appearance. Was erupted from Pumice Stone Mountain, as well as from probable second vent to northwest (now buried under unit mnp) and apparently from third vent on Wild Horse Mountain, about 14 km northwest of Pumice Stone Mountain. Vent alignment is approx N. 25° W. Lava flow traveled north at least 15 km from Pumice Stone Mountain and 6 km northeast of Wild Horse Mountain. Phenocrysts, 10–15%: 7–10% 1 mm plag; 2–5% ol+cpx+opx. Overlies unit orr; probably overlies domes of unit ord; underlies units obw, mnp, aes, atm, mtr, mrc, dta, bts, bpw, awl, and mpp, as well as surficial units g and l. K-Ar age is 949±29 ka (table 1). Sectors D, E, F

ob **Older basalt (middle and early Pleistocene)**—Typically aphyric or nearly aphyric basalt flows, commonly diktytaxitic in texture, exposed around margins of MLV. Many separate flows from different vents are represented in this lumped unit; all predate MLV, although ages of most are unknown, which is reason that this unit is not shown with asterisk added. However, one K-Ar age is 910±49 ka (table 1) for this unit near Gold Digger Pass, north of Callahan Flow (unit mcf). Sectors B, F, G, H, J, K, L

obc **Older basalt of Casuse Mountain (middle or early Pleistocene)**—Moderately porphyritic basalt (52.0% SiO_2) of eroded cone of Casuse Mountain and its surrounding lava flow. Phenocrysts: 3–5% 1–2 mm plag; <1% 1 mm ol; rare ≥3 mm plag+ol+cpx clots. Probably overlies unit ob but predates MLV; underlies and is mostly surrounded by unit bmc. Sector J

obd **Older basalt of Dry Lake (middle Pleistocene)**—Aphyric, diktytaxitic basalt (48.5–49.4% SiO_2; avg of 16 = 49.0%) at far southwest edge of MLV; unit also extends south of map area. Vent area located to west of MLV, as is most of unit (R.L. Christiansen and D.E. Champion, unpub. data, 2002). Unit is broken by north-trending faults, one of which displays offset down to west. Overlies units odh and ob; underlies units dta, bwl, mhm, and mdp, as well as surficial unit g. Sector B

obg **Older basalt of Gillem Bluff (Pliocene)**—Aphyric, diktytaxitic basalt (47.7, 47.9% SiO_2) flow forming rimrock that caps upthrown fault block of Gillem Fault. Unit also includes pillow lavas exposed in Gillem Bluff in northernmost LBNM. Overlies unit omw, exposed by fault;

underlies units omg, otg, bwg, mwd, dta, awf, and awb; may correlate with part of unit ob. Corresponds to “unit bgb” of Donnelly-Nolan and Champion (1987). Sector H

obp **Older basalt on west side of Gillem Fault (early Pleistocene)**—Very porphyritic basalt (52.2% SiO_2) in three small patches overlying Pliocene basalt (unit obg) that caps much of Gillem Bluff. Vent location unknown. Phenocrysts, approx 30%: dominantly plag, 1–4 mm; includes 2–3% 1–3 mm ol; scattered larger plag+ol clots. Overlies unit obg; underlies unit awf. Paleomagnetic data (D.E. Champion, written commun., 2005) indicates that unit has reversed polarity. See “unit pb” in Donnelly-Nolan and Champion (1987). Sector H

obu **Older basalt under Black Mountain (early Pleistocene)**—Sparsely porphyritic basalt (52.8% SiO_2) underlying east side of Black Mountain; also appears as patches under the Lake Basalt (bl) and the basalt of Tionesta (bt). Phenocrysts are clots a few millimeters across of ol+plag, in coarse-grained groundmass made up mostly of ≤1 mm plag and minor amounts of 1 mm ol. Underlies all adjacent units: omb, bt, and bl, as well as glacial-outwash gravel of surficial unit g. Sectors L, M

obw **Older basalt of Garner Mountain (middle Pleistocene)**—Moderately porphyritic basalt (two analyses, 51.7% SiO_2) that was erupted from vents aligned approx N. 45° E., forming northeast ridge of Garner Mountain, edifice that lies just west of, and just predates, MLV. Lava extends to northeast and is found approx 2 km northwest of Hill 22. Phenocrysts, approx 5%: mostly 1 mm ol; includes some ol+plag clots and sparse 1 mm plag xls. Underlies units dta and bpw, as well as surficial unit g; overlies unit oap. Unit is undated; however, K-Ar ages of about 520 ka have been determined on other lavas from Garner Mountain (see description of unit oag above). Sectors E, F

odh* **Older dacite of Harris Mountain (Pliocene)**—Porphyritic dacite (63.2, 63.9% SiO_2) of large eroded dome and small dome to northwest that are encompassed by MLV lavas at southwest edge of volcano. Unit is broken by north-trending fault. Phenocrysts: approx 15% 1–5+ mm plag; approx 2% 1–3 mm altered hb; rare 1 mm cpx. Contains rare <3 mm plutonic-textured inclusions. Underlies all adjacent units (oml, obd, mhm, mdp). K-Ar age is 2.95±0.09 Ma (table 1). Sectors B, C

ods **Older dacite of Squaw Peak (early? Pleistocene)**—Poorly porphyritic dacite (67.1% SiO_2) of glaciated dome that is largely surrounded by deposits of talus, most of which consists of pinkish, oxidized dacite. At base of western talus deposit is well-developed protalus rampart. Phenocrysts: <1% 1 mm plag. Underlies all adjacent units (mwr, atm, bss, mrc). Unit is aligned with domes of unit ord and may be similar in age to them and (or) to units orr and oap. Interpreted as older than MLV. Sectors D, E

om* **Older basaltic andesite of Bonita Butte (early Pleistocene)**—Porphyritic basaltic andesite (53.0% SiO_2) lava and large vent cone of Bonita Butte. Phenocrysts: 10% 1–2 mm plag+ol, plag>ol. Most porphyritic lava is found at, and just north of, Bonita Butte. Underlies units ob, opt, aes, dta, bmc, and bgd, as well as surficial unit l. Predates MLV. K-Ar age is 1.211±0.067 Ma (table 1). Sector G

omb* **Older basaltic andesite of Black Mountain (middle Pleistocene)**—Moderately porphyritic basaltic andesite (55.1% SiO_2) forms large shield edifice southeast of caldera; unit is encompassed by lavas of MLV and is interpreted herein as predating MLV. Phenocrysts, 5%: 1–2 mm plag, 1 mm ol, plag>ol. Overlies unit obu; underlies unit bl and glacial-outwash gravel of surficial unit g. K-Ar age is 599±16 ka (table 1). Sectors L, M

omf **Older basaltic andesite of Fisk Ridge (middle Pleistocene)**—Sparsely porphyritic basaltic andesite consisting of one isolated cinder cone and at least one additional cinder cone to southwest outside map boundary. Phenocrysts: 1–2% 1 mm plag+ol. Abundant smaller plag xls in groundmass. Underlies adjacent units aet, bss, and dta. Probably predates MLV. Sector D

omg **Older basaltic andesite of Gillem Bluff (Pliocene)**—Nearly aphyric basaltic andesite (56.9% SiO_2) lava flow remnants on Gillem Bluff. Phenocrysts: <1% 1 mm plag+ol. Overlies unit obg; underlies unit otg. See Donnelly-Nolan and Champion (1987) for additional information about this unit. Sector H

oml **Older basaltic andesite of Lost Iron Well (middle or early Pleistocene)**—Poorly porphyritic basaltic andesite (55.1% SiO_2) exposed as isolated area of lava flow adjacent to Harris Mountain; outcrop displays thick red soil. Vent unknown. Phenocrysts: <1% 1–2 mm plag. Overlies unit odh; underlies units mhm and mdp. Interpreted herein as predating MLV. Sector B omt* **Older basaltic andesite of Timber Mountain (late Pliocene)**—Aphyric basaltic andesite (53.4% SiO_2) of large, older, faulted shield that is surrounded by the basalt of Tionesta (bt) on lower east side of MLV. K-Ar age is 1.820±0.042 Ma (table 1). Sectors K, L

omw **Older basaltic andesite in western Lava Beds National Monument (Pliocene)**—Sparsely to moderately porphyritic basaltic andesite (53.7% SiO_2) exposed in face of Gillem Bluff. Phenocrysts: 2–5% 1–2 mm plag; minor ≤1 mm ol. Rock has speckled appearance. Underlies unit obg. Sector H

opt **Older palagonite tuff (middle? Pleistocene)**—Four separate outcrop areas of palagonite tuff, including Yellow Butte, which is a vent. All four areas are located low on north flank of MLV at margin of volcano; all probably predate MLV and likely represent eruptions through ancient lake. One analysis of vesicular clast from westernmost outcrop area is basaltic andesite (56.4% SiO_2). Underlies adjacent units except om and ob. Sectors G, H

ord* **Older rhyolite near Dock Well (early Pleistocene)**—Moderately porphyritic older rhyolite (71.1, 72.3% SiO_2) domes forming two kipukas on northwest flank of MLV. Total exposed area is about 2 km^2. The dacite tuff of Antelope Well (dta) flowed part way up, and welded onto, caldera-facing (southeast) sides of both domes. Phenocrysts: 3–5% 1–3 mm plag; approx 1% 1 mm cpx+opx. Underlies units bea, awh, and dta; probably underlies unit oap. Four K-Ar age determinations on single sample of smaller dome range in age from 814±46 to 959±73 ka (Donnelly-Nolan and Lanphere, 2005); weighted mean average is 840±51 ka (table 1). In addition, Mertzman (1982) gave whole-rock K-Ar ages of 1.18±0.06 Ma, for larger dome, and 0.95±0.14 Ma, for smaller dome. Sector F

orr* **Older rhyolite of Red Cap Mountain (early Pleistocene)**—Moderately porphyritic rhyolite (73.6% SiO_2) forming bulk of Red Cap Mountain west of Little Glass Mountain, although “red cap” is formed by overlying unit mrc. Predates MLV. Exposed in three outcrop areas that extend approx 5 km north-south and slightly less than 5 km east-west. Greatest exposed thickness exceeds 350 m. Probable vents for this glaciated unit are indicated at high points to south-southwest of Red Cap Mountain proper and approx 1.5 km to north. Phenocrysts, 5%: dominantly 1 mm plag, some to 2 mm; 1% 1 mm hb (needles) + opx (xls), hb>opx. Rock also contains small hb-bearing MI typically a few millimeters to 1 cm across; one plutonic-textured xenolith also was observed. Underlies all adjacent units (oap, mnp, bsr, msr, ael, mwr, mrl, afr, atm, bss, mrc, dls, dta, bwd, bnp, and bsl). All nearby units are much younger than this unit, except for unit oap, which is only slightly younger. K-Ar age is 965±24 ka (table 1). Sectors C, D, E

otb* **Older tuff of Box Canyon (early Pleistocene)**—Rhyolitic ash-flow tuff (five pumice lumps, 68.9–71.2% SiO_2; avg of 5 = 70.4%; one whole-rock analysis, 69.3% SiO_2) near Box Canyon south of Mount Dome. Partially welded to nonwelded, pink-to-white ash-flow tuff as much as 10 m thick containing pinkish pumice lumps as large as 0.5 m in maximum dimension. Vent location unknown. Unit is broken by numerous faults that have varying trends and offsets. Phenocrysts (pumice lumps): approx 1% 1–2 mm plag; <1% 1 mm opx. Overlies surficial unit ol; interbedded with basalt of unit ob; underlies units aes, dta, aut, and bts, as well as surficial units og and g. $^{40}Ar/^{39}Ar$ age on plag is 1.006±0.025 Ma (table 1). Sectors F, G, H

otg* **Older tuff of Gillem Bluff (Pliocene)**—Dacitic ash-flow tuff (six pumice lumps, 66.9–69.3% SiO_2; avg of 6 = 68.0%; one whole-rock analysis, 66.9% SiO_2) exposed in four closely spaced outcrop areas, each a few meters thick, at top of Gillem Bluff. Tuff is welded and typically is reddish. Phenocrysts: 1% 1–3 mm plag; 1 mm opx, plag>opx. Overlies units omw, obg, and omg. $^{40}Ar/^{39}Ar$ age on plag is 2.023±0.020 Ma (table 1). Sector H

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