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A Magmatic Model of Medicine Lake Volcano, California

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Medecine Lake volcano is a Pleistocene and Holocene shield volcano of the southern Cascade Range. It is located behind the main Cascade arc in an extensional tectonic setting where high-alumina basalt is the most commonly erupted lava. This basalt is parental to the higher-silica calc-alkaline and tholeiitic lavas that make up the bulk of the shield. The presence of late Holocene, chemically identical rhyolites on opposite sides of the volcano led to hypotheses of a large shallow silicic magma chamber and of a small, deep chamber that fed rhyolites to the suface via cone sheets. Subsequent geophysical work has been unable to identify a large silicic magma body, and instead a small one has apparently been recognized. Some geologic data support the geophysical results. Tectonic control of vent alignments and the dominance of mafic eruptions both in number of events and volume throughout the history of the volcano indicate that no large silicic magma reservoir exists. Instead, a model is proposed that includes numerous dikes, sills, and small magma bodies, most of which are too small to be recognized by present geophysical methods.

INTRODUCTION

Medicine Lake volcano is a Quaternary shield volcano that lies about 50 km east-northeast of Mount Shasta, the largest of the Cascade stratovolcanoes (Figure 1). It is located east of the axis of the Cascade volcanic arc. Its low shield shape, similar to Newberry volcano of central Oregon which is also behind the arc, contrasts with the stratovolcanoes that dot the length of the Cascade chain. Medicine Lake volcano could be considered a Basin and Range volcano unrelated to the Cascades, but chemical and temporal similarities as well as close spatial association indicate that Medicine Lake and Newberry volcanoes are indeed Cascadian. The setting of these two volcanoes behind the arc in a more extensional environment has contributed to their physical differences from the more impressive stratocones. The Medicine Lake shield was built mostly by numerous very fluid lavas that flowed relatively long distances from their sources. More viscous lavas constitute a smaller volume.

The presence of several late Holocene, high-silica lava flows on the upper parts of Medicine Lake volcano (Figure 2) has been used to argue for the existence of a moderately large silicic magma chamber [*Eichelberger*, 1981; *Christiansen*, 1982]. Eichelberger proposed a silicic reservoir about 10 km across, with a flat bottom underplated by mafic magma (Figure 3). However, geophysical evidence discussed below indicates that no large silicic magma body exists. Large magma bodies have apparently been found by geophysical methods at Yellowstone, at Long Valley, and at Clear Lake, California, but in many cases the geophysical search for magma bodies has been fruitless, notably in the Cascade Range [*Iyer*, 1984]. In some instances the magmatic system may be temporarily depleted, but in most the magma bodies are probably small. Geophysical data (J. R. Evans, written communication, 1986) indicate the presence of a small low-velocity zone under the center of Medicine Lake volcano. Taken together with geologic evidence, the data are consistent with an underlying complex of dikes, sills, and small magma bodies.

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PREVIOUS STUDIES

Numerous geologic and petrologic studies of the volcano have been published. Early studies by *Peacock* [1931] and *Powers* [1932] described its main features and were followed by the classic study of *Anderson* [1941]. Anderson's geologic map remains the primary source of published geologic mapping for much of the volcano. Some K-Ar dates have been published by *Luedke and Lanphere* [1980], *Mertzman* [1982, 1983], and *Hart et al.* [1984]. Other geologic studies include *Anderson* [1933], *Eichelberger* [1975], *Heiken* [1978], and *Ciancanelli* [1983]. Petrologic studies include *Barsky* [1975], *Condie and Hayslip* [1975], *Mertzman*, [1977*a*, *b*], *Mertzman and Williams* [1981], and recently a series of papers by Grove and coworkers: *Gerlach and Grove* [1982], *Grove et al.* [1982], *Grove and Baker* [1984], and *Grove and Donnelly-Nolan* [1986]. This recent petrologic work together with remapping of the volcano [*Donnelly-Nolan and Champion*, 1987; J. M. Donnelly-Nolan, unpublished mapping, 1979–1987] has led to new interpretations, some of which are published here.

GEOLOGIC SETTING

Lavas from the volcano cover nearly 2000 km^2, and their volume is estimated at 600 km^3. Tholeiitic and calc-alkaline lavas are represented, including the silica range from 47 to 77%, although dacites are rare. Temporal patterns of eruption are poorly understood because of limited K-Ar data, lack of incision and stratigraphic exposure, and near absence of significant marker beds for stratigraphic control. However, some patterns can be discerned. Growth of the volcano began about a million years ago (J. M. Donnelly-Nolan and L. B. Pickthorn, unpublished data, 1980–1987), following eruption of a large volume of tholeiitic high-alumina basalt that is the principal rock type of the Modoc Plateau. High-alumina basalt has continued to erupt around the flanks of Medicine Lake volcano throughout its history. The main edifice consists mostly of calc-alkaline lavas, dominantly basaltic andesite and andesite. Rhyolite and dacite are typically found on the higher parts of the volcano. Few eruptions have been explosive. Most eruptive events have produced lavas and their associated spatter vents and cinder cones. Ashfall tephra deposits are uncommon and only one ash flow tuff is known.

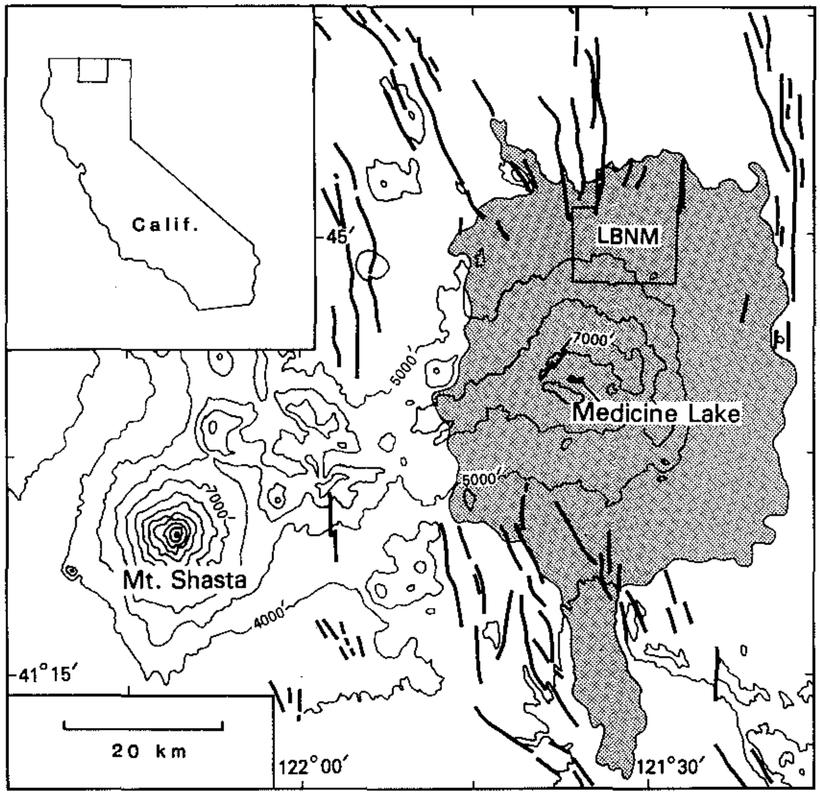

Fig. 1. Location map showing extent of lavas of Medicine Lake volcano in lined pattern. LBNM is Lava Beds National Monument. Contour interval is 1000 feet. Medicine Lake volcano is entirely below 8000 feet and mostly above 4000 feet. Heavy lines are faults [*Gay and Aune*, 1958].

GEOLOGIC EVIDENCE FAVORING A LARGE SILICIC MAGMA BODY

The presence across the top of the volcano of several young silicic lava flows erupted in late Pleistocene and Holocene time strongly suggests the presence of additional silicic magma at depth. Two of the late Holocene silicic eruptions, at Glass Mountain and Little Glass Mountain, occurred on opposite sides of the caldera, 16 km apart, and yet the rhyolitic products of these eruptions are essentially identical in composition for the 10 major elements and about 30 minor and trace elements that have been determined. No primitive basalts are known to have have erupted since late Pleistocene time within the area where young silicic flows occur, although they have erupted to the south and north. Two late Pleistocene vents within the caldera have produced basaltic flows with silica contents of 50.2 and 52.3%. However, most of the lava in the area of the caldera is late Pleistocene andesite.

GEOPHYSICAL DATA AND INTERPRETATIONS

Gravity

Medicine Lake volcano lies at the edge of a regional, roughly circular gravity low that also includes Mount Shasta [*LaFehr*, 1965]. A gravity high characterizes Medicine Lake volcano and is modeled by *Finn and Williams* [1982] as a high-density intrusive body, located 2 to 4 km below the surface approximately centered under and extending beyond the 7 × 12 km central caldera. They state that the body may extend below 4-km depth but cannot confirm this structure using gravity data.

Magnetotelluric Data

Magnetotelluric soundings by *Stanley* [1982] show that a resistive body lies 1.5 km below the caldera, not the conductive body expected if magma is present.

Seismic Refraction

Modeling of a seismic refraction survey across the volcano [*Zucca et al.*, 1986] indicates a shallow high-velocity body under Medicine Lake volcano. A horstlike or pluglike structure of high-velocity material explains the travel time advance seen there. The authors propose a shallow pluton consisting of dikes and sills of basalt and small bodies of rhyolite.

Teleseismic P Wave Residuals

Preliminary analysis of teleseismic *P* wave travel time residuals from an array across the volcano indicates high-velocity anomalies in the crust and possibly the upper mantle to 100 km beneath the volcano [*Evans*, 1982]. One small low-velocity feature was identified near a young lava flow on the southeast side of the volcano, but the absence of any other significant low-velocity region suggested to Evans that melt or partial-melt pockets forming before an eruption must be either very small, very short lived, or both. The 3-km station spacing employed along the center of the array is sufficient to resolve features larger than 3 to 5 km across at any depth in the crust.

Active Seismic Imaging Experiment

In September 1985, 140 seismometers were deployed over a 17 × 12 km area centered over the caldera and the youngest eruptive center at Medicine Lake volcano, the thousand-year-

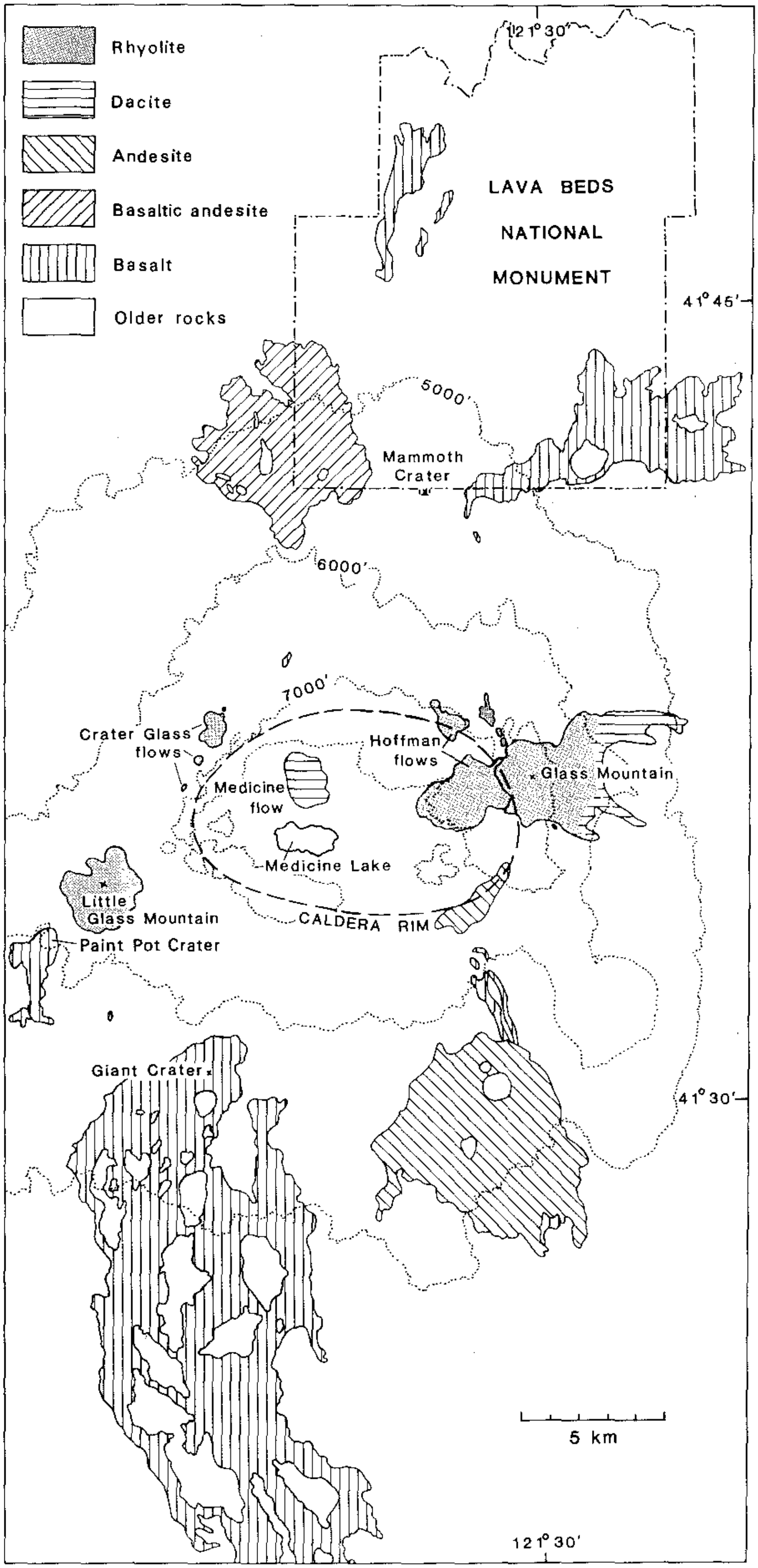

Fig. 2. Map of Medicine Lake volcano showing Holocene lavas, approximate location of caldera rim, and named locations referred to in text.

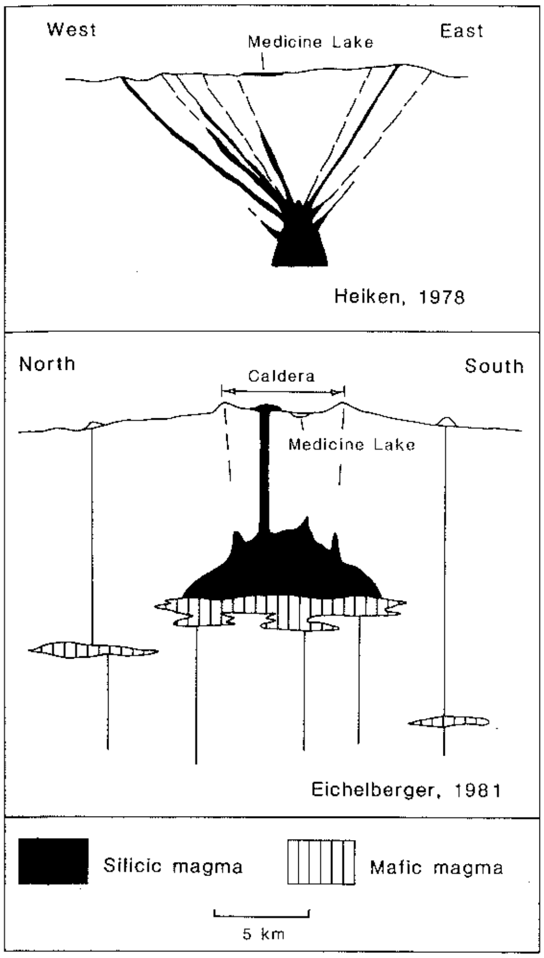

Fig. 3. Previously published models of Medicine lake magma system. Volume of *Heiken* [1978] magma reservoir as shown is approximately 10 km^3. Volume of *Eichelberger* [1981] silicic reservoir is approximately 140 km^3.

old Glass Mountain, which is located near the poorly defined eastern caldera rim (Figure 2). About 1 km^3 of rhyolite and subordinate dacite erupted from at least 13 vents along a N25°W trend extending 5 km. These areas were considered the most likely on the volcano for a detectable shallow silicic magma chamber [*Berge et al.*, 1985].

A series of explosions were set off in a circular array about 50 km away from the study area to provide a high-frequency Pg phase at the array. Pg travel time anomalies were inverted to obtain a velocity structure (J. R. Evans, written communication, 1986). The method is capable of resolving, in three dimensions, velocity anomalies as small as 1 km^3 in the upper 4–6 km of the crust even when they are part of complex structures that make reflection seismology impractical. The experiment was designed to test the hypothesis that Cascades magma chambers are smaller than other magma bodies studied and simply cannot be seen by the previously applied methods of seismic refraction and teleseismic P wave tomography. A similar study at Newberry volcano in Oregon identified a small low-velocity anomaly that may be a silicic magma chamber containing about 1 km^3 to a few cubic kilometers, located about 3 km below the surface [*Evans et al.*, 1986]. Data from the Medicine Lake experiment are more equivocal but suggest a small, shallow low-velocity body under the east central caldera. This feature is located beneath a high-velocity caldera feature, suggesting that it is not simply caldera fill but probably is a magma chamber with a volume of a few to a few tens of cubic kilometers.

Discussion of Geophysical Findings

Several conclusions can be drawn from the results of these geophysical studies: (1) no large magma body of any kind is present; (2) very small magma bodies are probably present, and one has apparently been identified; and (3) a high-velocity, relatively high-density body is present at shallow depth under the volcano, perhaps as close to the surface as 1.5 km.

If we accept that the geophysical techniques that have been applied at Medicine Lake volcano should have been able to detect a large magma body such as the 10-km-diameter chamber suggested by *Eichelberger* [1981] (Figure 3), then we must conclude that no such body exists in spite of the apparent shadow zone. The model of *Heiken* [1978] (Figure 3) is similar in general to the seismic imaging findings of J. R. Evans (written communication, 1986), although the magma body as shown by Heiken is deeper than that modeled by Evans.

GEOLOGIC CONSTRAINTS ON SILICIC MAGMA BODIES

Young Silicic Lavas

Young rhyolite and dacite lavas dot the upper surface of Medicine Lake volcano (Figure 2). The largest and youngest flow is at Glass Mountain to the east of the caldera. The Glass Mountain (GM) event occurred about a thousand years ago and began with the eruption of a Plinian rhyolitic air fall tephra [*Heiken*, 1978] followed by 67% SiO_2 mixed dacite containing abundant mafic magmatic inclusions of basaltic andesite [*Eichelberger*, 1975, 1980, 1981]. As the eruption proceeded, rhyolite containing similar mafic magmatic inclusions formed part of the main flow as well as other domes to the south and north. Some of the domes to the north and south contain a broader range of inclusion compositions, sometimes in a rhyodacite host rather than rhyolite. Ten domes are present to the north and one to the south along a N25°W trend about 5 km long. Inclusion-free rhyolite containing 73.5–74% SiO_2 was the last lava to erupt at GM and at adjacent small domes to the north. Granitic inclusions have been found in the dome to the south and in the sixth and tenth domes to the north. The volume of the GM event including the initial tephra blanket is about 1.0 km^3.

Just prior to the GM event, Little Glass Mountain, located 16 km west of GM, erupted rhyolitic magma of identical chemical composition at about 10 sites including the Crater Glass flows along a 7.5 km N30°E trend. No noticeable chemical variation is known to occur within these 73.5–74% SiO_2 lavas, but in contrast to the GM rhyolite, Little Glass and Crater Glass rhyolites are porphyritic, containing about 1% of phenocrysts, mostly plagioclase together with a scattering of orthopyroxene and oxide minerals. The suite of inclusions also differs somewhat from the suite at GM, having a slightly higher average silica content and an apparently random spatial distribution. Granitic inclusions have been found in both of the flows at Little Glass Mountain and in several of the domes of the Crater Glass flows. The identical chemical composition of Little Glass Mountain (LGM) and Crater Glass flows together with identical inclusion suites and the same petrographic character indicates that these rhyolites erupted during a single event, referred to here as the LGM event. Volume of the LGM event, including the initial tephra deposit, is estimated at 0.3 km^3.

Hundreds of years before the GM event at an unknown time in the late Holocene, a dike-fed silicic eruption occurred parallel to the trend of the GM dike. The dike that emplaced the Hoffman dacite of *Anderson* [1941] trends N25°–30°W and lies less than 2 km west of the GM dike. Two flows are included in this event based on morphologic, petrographic, and chemical criteria: the Hoffman dacite flow of Anderson and a flow to the north, shown as the Hoffman flows in Figure 2. Both flows have silica contents of 71–72% SiO_2, a value that would be higher if all of the mafic inclusions could be removed from the analyzed samples and thus are classified here as rhyolite rather than dacite. The inclusion suites are not so variable as those of the GM and LGM events, but the inclusions are more mafic. The Hoffman flows together with a probable preceding tephra deposit (C. D. Miller, written communication, 1986) are here referred to as the Hoffman event. Volume of this event is estimated at 0.2 km^3.

The Medicine dacite flow is the only young silicic flow to erupt through the floor of the caldera. It contains 68–69% SiO_2 and possesses granitic and gabbroic fragments together with andesitic magmatic inclusions. The dacite erupted from two closely spaced vents on the northern floor of the caldera in late Holocene time prior to the GM and LGM events. Its age relation to the Hoffman event is unknown. The Medicine dacite apparently erupted nonexplosively, as it appears to lack an associated tephra deposit. Volume of the flow is about 0.1 km^3.

The total volume of Holocene silicic magma erupted to the surface at Medicine Lake volcano is about 1.5 km^3. Even if 10 times this amount still resides in a single silicic magma body under the volcano, the volume of the body would be only 15 km^3. Such a body could be represented by a cylinder 2.5 km in diameter and 3 km high. A magma body of this size is near the limit of detection of geophysical techniques used to search for magma.

Eruptive Patterns

Medicine Lake volcano is dominantly mafic. The volume ratio of mafic to silicic eruptive products during Holocene time is about 10 to 1, and it is about 20 to 1 in late Pleistocene time. The largest known eruptions at Medicine Lake volcano are basaltic, with volumes of about 5 km^3. The largest known silicic eruption probably has a volume of about 1 km^3. A rhyodacitic ash flow tuff initially interpreted to be an early eruptive product of the volcano [*Donnelly-Nolan*, 1983] may be much older based on tephrostratigraphy (A. M. Sarna-Wojcicki, oral communication, 1986). This tuff may be the unit dated by *Mertzman* [1982] as 1.25 ± 0.24 m.y. old.

This pattern contrasts sharply with the eruptive products of volcanoes inferred to have large silicic magma chambers, e.g., Yellowstone, Wyoming, and Long Valley, California, and even the much smaller Crater Lake, Oregon, whose magma body emptied about 50 km^3 to the surface about 6850 years ago [*Bacon*, 1983]. Since the eruption of the andesite tuff from Medicine Lake caldera in late Pleistocene time [*Donnelly-Nolan and Nolan*, 1986], additional andesite has erupted from the caldera rim and at least two basaltic lavas have erupted through the caldera floor. Since then, the only caldera eruptions have been silicic: the late Pleistocene rhyolite of Mount Hoffman from the north rim of the caldera, the late Holocene Medicine dacite flow through the floor of the caldera, and the late Holocene Hoffman event near the eastern edge.

The Caldera

The caldera clearly exists as a 7 × 12 km topographic depression in the top of the volcano, but the location of the rim is poorly constrained except by alignments of vents. No faulting associated with caldera collapse has been identified. *Anderson* [1941] suggested that the caldera formed by collapse following extrusion of large volumes of andesite erupted from vents at the caldera rim. However, the distribution of late Pleistocene vents, mostly concentrated along the caldera rim, suggests that ring faults already existed along which the andesite traveled to the surface. No single large eruption can be related to formation of the caldera; the only eruption known to have resulted in ash-flow tuff occurred in late Pleistocene time and was not accompanied by caldera faulting [*Donnelly-Nolan and Nolan*, 1986]. Much of the volcano, however, is covered by relatively young lavas, and an early caldera-forming event cannot be discounted. The most likely explanation for the existence of the caldera is a variation on Anderson's 1941 idea. In this revised model the caldera formed early in the history of the volcano after collapse of the top. Collapse followed extrusion of fluid lava that moved downslope away from the center in a manner similar to the formation of Kilauea caldera, Hawaii. The caldera has persisted through time by the same mechanism and is not related to any one or more large explosive events. The volcano consists mostly of fluid lavas, and once the ring faults were established, they may have served to localize vents and allow net movement of lava aw from the central focus of the volcano, thus maintaining a depression at the top by repeated downsagging of the caldera floor.

Primitive basalt has not erupted in the caldera in late Pleistocene or Holocene time despite numerous eruptions outside it. Eruptions outside the caldera are strongly controlled by the regional tectonic stress field as indicated by alignments of vents typically within 30 degrees of north. More easterly directions are present southwest of the caldera at Giant Crater where one set of vents is oriented N55°E and in the Paint Pot Crater area where two different basalt flows erupted from vents oriented N40°E. These vent orientations may reflect the strong ENE locus of volcanic activity that forms a highland extending from Mount Shasta. This ENE trend may reflect some aspect of the regional stress pattern.

Dikes and Tectonic Control

According to *Bacon* [1985], large magma bodies affect the stress regime in roof rocks so that precaldera leaks occur in nontectonic patterns. He further suggests that silicic vents that form linear arrays in areas of focused silicic volcanism may lead to small calderas; linear arrays of coeval silicic vents whose orientation is a consequence of the regional tectonic stress regime of the upper crust may be fed from small or deep reservoirs incapable of catastrophic eruption. Linear arrays of silicic vents at Medicine Lake volcano indicate that one of the latter possibilities is most likely. The 7.5-km-long dike eruption of LGM shows no evidence of curvature and is interpreted by *Fink and Pollard* [1983] to be vertical. Similarly, the 5-km-long dike that fed GM appears to consist of shorter, straight, en echelon segments with no evidence of curvature toward the caldera.

Small Silicic Chamber

Heiken [1978] suggested that a small deep magma chamber exists under Medicine Lake volcano and that this body fed the Glass Mountain, Little Glass Mountain, and Crater Glass flows via cone sheets. The body (Figure 3) is inferred to lie 7 km below the caldera and to be 3 km across at its widest point; no bottom is shown. This hypothesized body is similar to that modeled by J. R. Evans (written communication, 1986), although the latter model suggests a much shallower body. In the Heiken model the cone sheets dip 45°–60° and the required distance of travel to the surface is 8–12 km. The shallower depth of the body as modeled by Evans would require shallower dips of about 25°–35° and shorter distances of travel of 7.5–8.5 km or more complicated indirect pathways to the surface. If a single body such as that envisioned by Heiken or Evans fed eruptions of the GM and LGM dikes, then the rhyolite magma must have traveled a minimum of 7.5 km from the magma body to the surface and erupted over lengths of 5 km in the case of GM and 7.5 km for the LGM event. In both cases the magma must bypass the ring faults of the caldera and the more direct path straight up to the caldera floor and erupt at the surface along straight alignments rather than the curved ones that might be expected from cone sheets erupting at the surface.

Granitic Inclusions

The GM and LGM events and Medicine dacite brought rare partially melted granitic inclusions to the surface. Such inclusions, although usually more melted, are also present in several basalts and basaltic andesites. They may represent both slowly cooled rhyolitic equivalents and bedrock fragments derived from the arc-type bedrock inferred by seismic refraction work [*Zucca et al.*, 1986; *Fuis et al.*, 1987]. Short residence times are indicated for the granitic fragments in the host melts, particularly for mafic host magmas which would quickly melt such inclusions. Fast travel times to the surface or shallow depth of origin or both are indicated.

CONTROLS ON THE MEDICINE LAKE MAGMA SYSTEM

Tectonic Setting

Medicine Lake volcano is located at the western edge of the Modoc Plateau where north-south trending normal faults with up to a few hundred meters of displacement project toward the volcano and are buried beneath it. These faults decrease in number to the west and are not present at Mount Shasta. The faulted region around Medicine Lake volcano is evidently a transition zone between the Cascade volcanic arc and the Basin and Range province to the east. Intersecting with the N-S structural trend is a strong ENE trending lineament that crosses the Cascades from Mount Shasta to Medicine Lake. A concentration of volcanic vents forms a highland that connects the two volcanoes. An older structural trend of NW trending normal faults also projects under Medicine Lake volcano. Thus the location of the volcano is likely to be a result of the intersection of structural trends forming a locus of weakness within the crust. *Heiken* [1978] pointed out that Medicine Lake volcano lies at the intersection of several fault systems, an additional similarity with Newberry volcano.

Open ground cracks are common on and around Medicine Lake volcano. Cracks that are associated with the late Holocene LGM event have been described by *Fink and Pollard* [1983], who use the geometry of the cracks to argue for a dike eruption of the rhyolite. Sawtooth edges of the cracks can be shown to fit back together in an east-west direction, consistent with the extension direction indicated by the regional normal faults (Figure 1). The structural evidence indicates that Medicine Lake volcano lies in a region of east-west extension. This back-arc, strongly extensional environment [*McKee et al.*, 1983; *Hart et al.*, 1984] provides the necessary tectonic setting for some primitive basalt to reach the surface after traversing 35–40 km [*Hill*, 1978; *Zucca et al.*, 1986] of crust without evidence of contamination. Many basalt magmas may travel upward from the mantle along pathways previously traveled by similar basalt, thus decreasing the possibility of crustal contamination.

High-Alumina Basalt

Primitive high-alumina basalt has erupted around the flanks of Medicine Lake volcano throughout its history. Lavas erupted at Giant Crater on the south flank of the volcano in early Holocene time are as primitive as any erupted early in the volcano's history (Figure 4). Basaltic lavas with K_2O contents of 0.1% and less are relatively common; their major and trace element signatures, hand specimens, and thin sections are nearly indistinguishable. Based on the long span of time during which it has erupted, its consistent chemistry and areal distribution, and petrological experiments and modeling, high-alumina basalt magma is here and elsewhere [*Grove et al.*, 1982; *Grove and Baker*, 1984; *Grove and Kinzler*, 1986] interpreted to be parental to the higher silica lavas of the volcano, in part by fractional crystallization and in part by other processes including contamination and mixing of magmas.

The total volume of high-alumina basalt erupted to the surface at Medicine Lake volcano during its history is unknown. During Holocene time an estimated 5 km^3 erupted, nearly all of that at vents for the basalt of Giant Crater (Figure 2) over a time span estimated from paleomagnetic

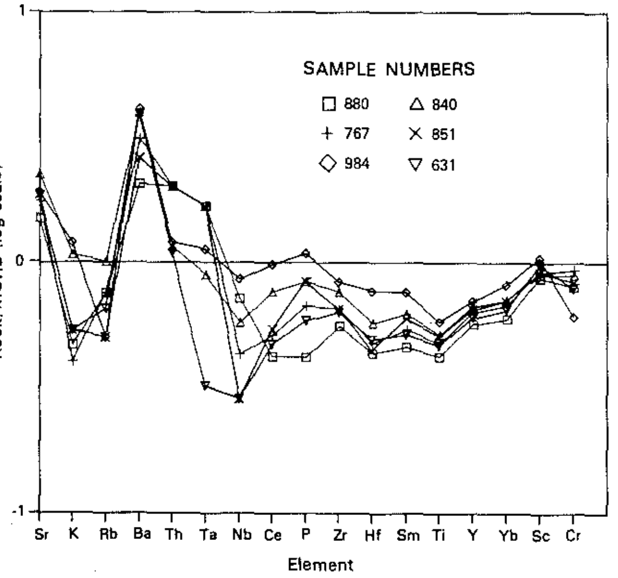

Fig. 4. Spider diagram of Medicine Lake high-alumina basalts. Sample number 880 is early Holocene basalt of Giant Crater. Samples 767 and 840 are latest Pleistocene in age. Samples 984, 851, and 631 represent early basalts of the volcano, mid-Pleistocene in age. Note that there is no difference between young and old basalts. Note also the unusual K and Rb depletions and the Sr and Ba enrichments, the latter typical of island arc basalts.

data (D. E. Champion, oral communication, 1986) to be less than 100 yr. The initial part of the Giant Crater material has a higher silica content and contains granitic inclusions, but this contaminated lava represents only a relatively small part of the total volume. High-alumina basalt accounts for about 60% of the volume of all material erupted at Medicine Lake volcano in Holocene time. Because most of the Holocene high-alumina basalt erupted in a single episode, the volume erupted in Holocene time may not be an accurate predictor of total volume. Other large-volume high-alumina basalt eruptions occurred in late Pleistocene time, e.g., the Mammoth Crater event on the north flank of the volcano during which about 5 km^3 of basaltic lava erupted. Lack of stratigraphic exposure limits the accuracy of volume estimates for lavas in pre–late Pleistocene time. The volcano is surrounded by a broad apron of high-alumina basalt, mostly of unknown age and from unknown vents. The very fluid nature of this basalt may account for its relative scarcity in outcrop on the main edifice of the volcano when compared with the abundant derivative lavas of higher viscosity.

An estimate can be made of the magma supply rate. Assuming that two times as much magma is intruded as extruded, as is the case in Hawaii [*Dzurisin et al.*, 1984], then the calculated rate of supply to Medicine Lake volcano in Holocene time is 0.002 km^3/yr. Assuming that the volume of all products of Medicine Lake volcano is 600 km^3 and that the oldest lavas are 1 m.y. old, the calculated long-term rate is the same, 0.002 km^3/yr. The ratio of intruded to extruded magma at Medicine Lake is probably higher than that in Hawaii in order to account for the much larger volume of high-silica derivative magmas, but even assuming 10 times as much intruded as extruded, the calculated magma supply rate of 0.01 km^3/yr is still only a tenth of the rate of Hawaii. During a particular episode of basaltic volcanism at Medicine Lake such as that of Giant Crater, the rate is about the same as at Kilauea.

The high-alumina basalt at Medicine Lake volcano has been compared to mid-ocean ridge basalt by *Hart* [1971], *Philpotts et al.* [1971], *McKee et al.* [1983], and *Hart et al.* [1984]. Its primitive nature can be seen in Figure 4, which shows it to be depleted in many elements including K_2O compared to the mid-ocean ridge basalt (MORB) of *Pearce* [1983]. However, enrichments in Ba and Sr are typical of primitive island-arc basalts [*Arculus and Johnson*, 1981]. Behind the Cascade arc, high-alumina basalt is a common rock type, particularly in Oregon, northern California, southwestern Idaho, and northwestern Nevada [*Waters*, 1962; *McKee et al.*, 1983; *Hart et al.*, 1984].

Origin of Derivative Magmas

Grove and his students [*Grove et al.*, 1982; *Gerlach and Grove*, 1982; *Grove and Baker*, 1984] have convincingly demonstrated that the calc-alkaline andesite of Medicine Lake volcano can be derived from high-alumina basalt by a combination of processes including fractional crystallization, assimilation of crustal material, and magma mixing. *Grove and Donnelly-Nolan* [1986] showed that rhyolitic magmas can be produced by fractional crystallization of andesite. Inclusion suites in Holocene silicic lavas include granite and other plutonic fragments, chilled mafic melts, and cumulate gabbros. The granitic fragments provide physical evidence of contamination, and the cumulates represent material removed from the andesite parent during fractional crystallization.

The chilled mafic melt inclusions are of variable composition even within a single host rhyolite or dacite, varyin from 49.5 to 57.5% SiO_2 in Glass Mountain and its associated domes and from 52.2 to 61.8% SiO_2 in the Little Glass Mountain–Crater Glass rhyolite. *Grove and Donnelly-Nolan* [1986] successfully modeled the production of a similar rhyolite using two of the andesitic inclusions as starting points. The range of inclusion compositions suggests that the eruption process may have tapped underlying compositionally zoned mafic magma.

GM and LGM rhyolitic lavas have essentially identical major and trace element compositions and were erupted within a very short time span [*Heiken*, 1978] on opposite sides of the volcano in late Holocene time. This fact led Heiken to suggest that both lavas were fed by cone sheets from a single small magma body. There are some differences between the GM and LGM magmas, e.g., the slightly different inclusion suites, the porphyritic nature of LGM rhyolite versus the aphyric GM rhyolite, and the initial eruption of mixed lava at GM. Such differences may be accounted for by variations in the process of transport of the magma to the surface, or perhaps by tapping of different parts of the magma reservoir. Alternatively, the magmas may have developed simultaneously on opposite sides of the caldera by fractionation of andesites of very similar composition. Very similar late Pleistocene andesite lavas are present in both areas.

POSSIBLE MAGMATIC MODELS

The lack of geophysical evidence for a large silicic magma body together with tectonic control of vent alignments and th dominance of mafic eruptions throughout the history of the volcano suggests that no such body exists. A large silicic magma body may have existed in the past based on the presence of older high-silica rhyolites, although no other evidence such as ash flow tuffs or large Plinian ashfall deposits has been found.

A single small silicic reservoir such as that envisioned by *Heiken* [1978] is a viable model, particularly in light of the discovery by J. R. Evans (written communication, 1986) of an apparent small low-velocity body under the caldera. Such a body also explains the essentially identical compositions of GM and LGM rhyolites on opposite sides of the caldera if tapped by dipping cone sheets. The model does not explain why the 5- and 7.5-km dikes that fed GM and LGM erupted outside the caldera, the magma bypassing both the direct vertical path to the surface and the ring faults of the caldera as conduits.

One possible explanation for the lack of basaltic vents in the caldera is that there is not enough pressure in the system for primitive basalt to erupt at the top of the volcano and instead it erupts on the flanks. This situation occurs frequently in Hawaii where magma intrudes into the rift zones of Kilauea rather than erupting in its caldera. Or the caldera may contain unconsolidated sedimentary fill or hydrothermally altered material that does not sustain fracturing. Such material could inhibit propagation of cracks to the caldera floor and thus promote subjacent intrusion and ponding. If something is interfering with the passage of the basalt to the surface, anoth possibility is that numerous small pockets of derivativ magma too small to be seen by geophysical techniques have formed and are forming under the central part of the volcano. Numerous small magma bodies and liquid-filled cracks may inhibit the flow of basalt to the surface and promote ponding

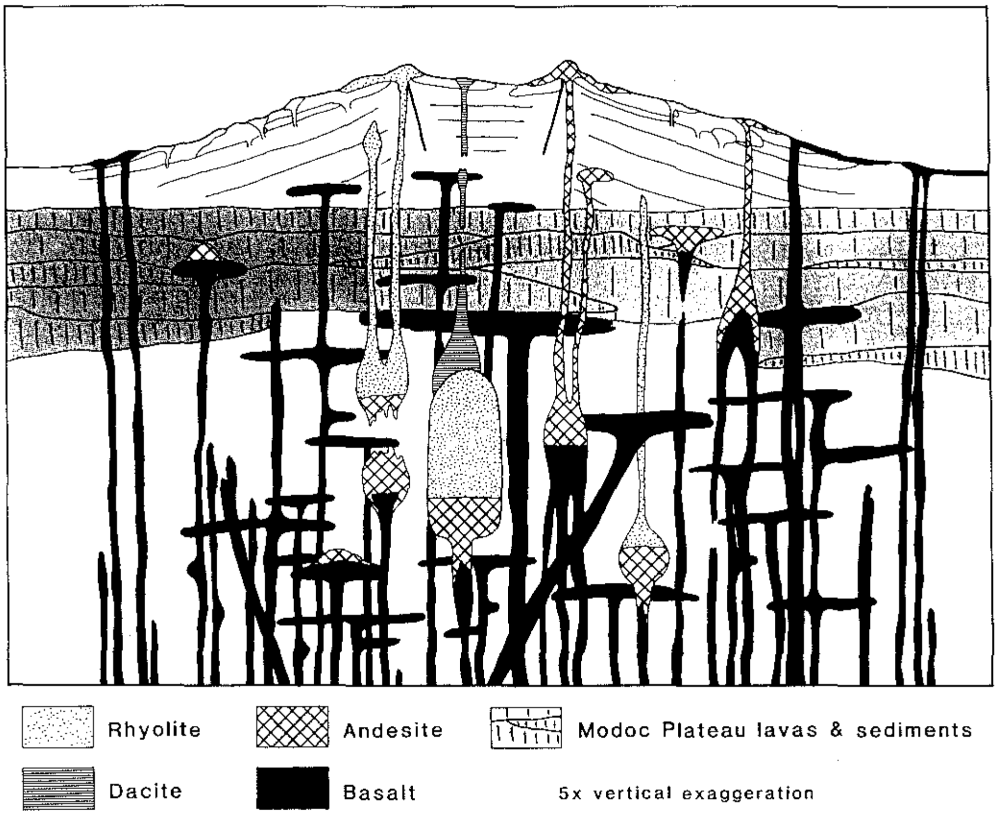

Fig. 5. Cartoon of Medicine Lake magma system. The field of view is approximately 40 km wide by 5 km high, with 5 × vertical exaggeration. The width of conduits is greatly exaggerated. Underlying the Modoc Plateau lavas and sediments is an arc terrane similar to the Sierra Nevada [*Zucca et al.*, 1986; *Fuis et al.*, 1987].

as sills and dikes. The presence of lower-density magma beneath the caldera could prevent the ascent of higher-density primitive basalt to the surface by ponding or mixing with the more silicic magma. Thus ultimately more heat and raw material are provided for still more derivative magmas to form, most commonly andesite and basaltic andesite, but also occasionally dacite and rhyolite. More time is probably required to form dacite and rhyolite, and the process may be interrupted by extensional episodes with consequent eruption before high-silica magma has been formed.

The numerous small lava flows and their vents, the dominance of mafic over silicic eruptions in both number and volume, and the alignments of both mafic and silicic vents indicating tectonic control on the system all combine to suggest a system with one or perhaps more small differentiated magma bodies. The models of *Heiken* [1978] and J. R. Evans (written communication, 1986) of a single small silicic magma body may be too simplified. Figure 5 is a more complicated possible model showing a silicic reservoir corresponding to Evans' model plus several smaller bodies of varying compositions together with numerous dikes and sills mostly of basalt.

CONCLUSIONS

Medicine Lake volcano is fundamentally basaltic and lacks a large silicic magma chamber. High-alumina basalt is probably the single most abundant rock type erupted from the volcano and is almost certainly the most abundant intruded rock type. Primitive basalt is parental to the other lavas by fractional crystallization, contamination, and mixing. If silicic lavas are produced by partial melting of crustal rocks, intruded basalt provides the heat. The common occurrence of open ground cracks on and around the volcano, typically oriented NNW to NNE, attests to the E-W extension that allows large volumes of low-K_2O, high-Al basalt to reach the surface. The dominant N-S fabric of vent alignments and fault orientations intersects the strong ENE trending lineament along which volcanism is focused between Medicine Lake and Mount Shasta. These two structural trends intersect at Medicine Lake volcano. Thus the tectonic setting influences both the location and style of volcanism.

The inability of geophysical techniques to identify a large magma body is most likely due to the absence of such a body. Geologic evidence exists to support this idea. Located in an extensional environment behind the Cascade volcanic arc, Medicine Lake volcano experiences episodes of extension at frequent intervals and lavas erupt to the surface along tectonically controlled alignments. As a consequence, large magma bodies are unlikely to form. In this tectonic environment, the most likely magma system is one of numerous dikes, sills, and small bodies of magma.

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