JOURNAL OF GEOPHYSICAL RESEARCH, VOL. 93, NO. B5, PAGES 4412–4420, MAY 10, 1988

A Magmatic Model of Medicine Lake Volcano, California

JULIE M. DONNELLY-NOLAN

U.S. Geological Survey, Menlo Park, California

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.

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.

Paper number 7B7064.

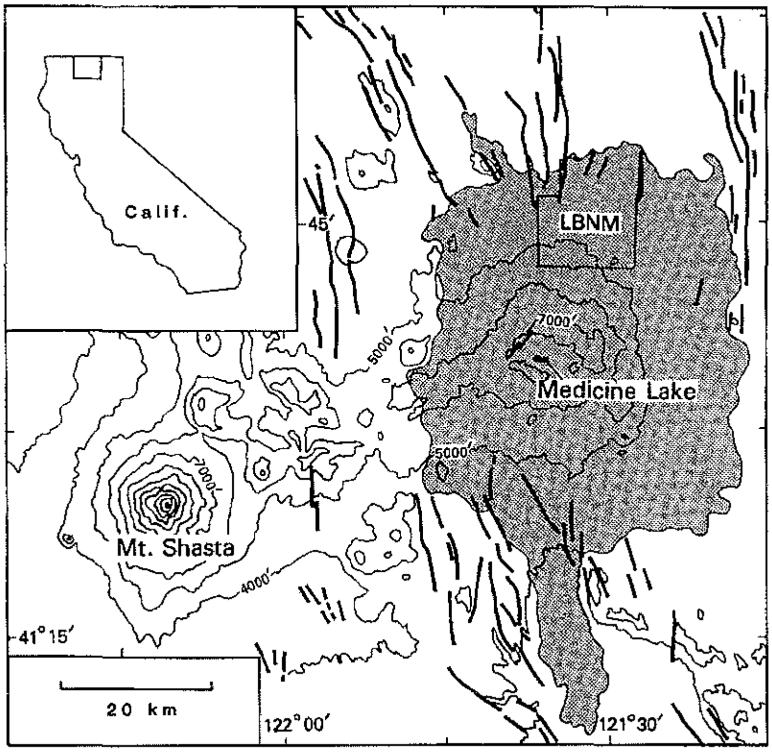

Fig. 1. Location map showing extent of lavas of Medicine Lake volcano in lined pattern. LBNM is Lava Beds National Monument. Contour interval is 1000 feet. Medicine Lake volcano is entirely below 8000 feet and mostly above 4000 feet. Heavy lines are faults [*Gay and Aune*, 1958].

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-

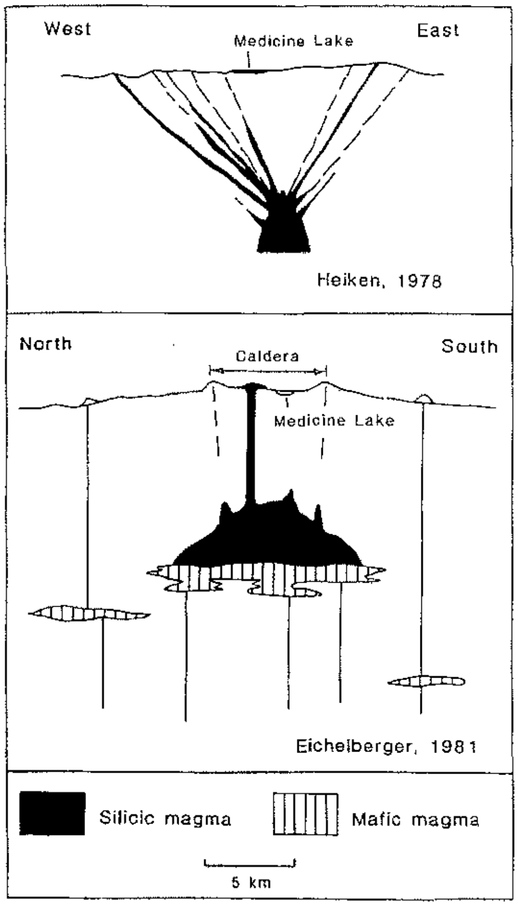

Fig. 3. Previously published models of Medicine lake magma system. Volume of *Heiken* [1978] magma reservoir as shown is approximately 10 km^3. Volume of *Eichelberger* [1981] silicic reservoir is approximately 140 km^3.

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

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

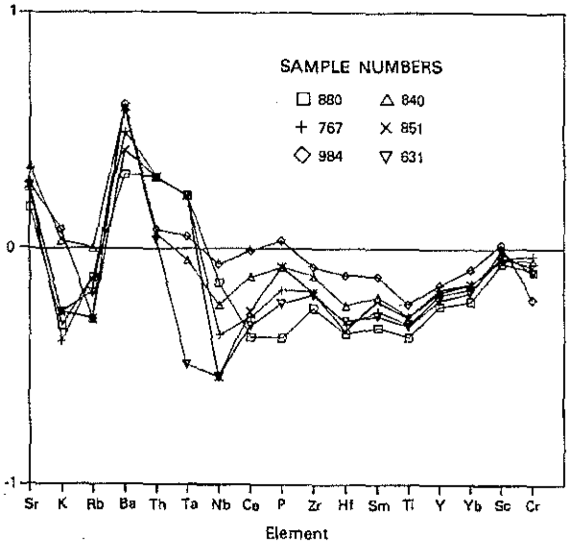

Fig. 4. Spider diagram of Medicine Lake high-alumina basalts. Sample number 880 is early Holocene basalt of Giant Crater. Samples 767 and 840 are latest Pleistocene in age. Samples 984, 851, and 631 represent early basalts of the volcano, mid-Pleistocene in age. Note that there is no difference between 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.

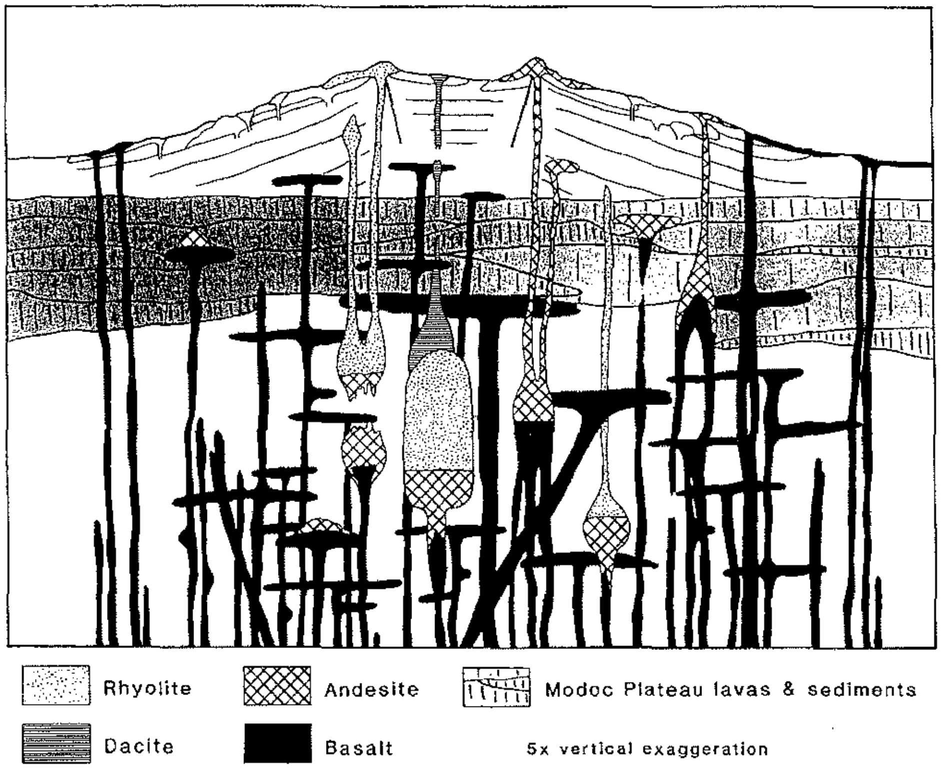

Fig. 5. Cartoon of Medicine Lake magma system. The field of view is approximately 40 km wide by 5 km high, with 5 × vertical exaggeration. The width of conduits is greatly exaggerated. Underlying the Modoc Plateau lavas and sediments is an arc terrane similar to the Sierra Nevada [*Zucca et al.*, 1986;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

Acknowledgments. I thank J. R. Evans, T. L. Grove, D. E. Champion, C. R. Bacon, and J. H. Fink for stimulating discussions on this and related topics. M. A. Clynne, N. S. MacLeod, Grant Heiken, and S. A. Mertzman provided helpful reviews.

REFERENCES

Anderson, C. A., Volcanic history of Glass Mountain, northern California, *Am. J. Sci.*, *26*, 485–506, 1933.

Anderson, C. A., Volcanoes of the Medicine Lake Highland, California, *Univ. Calif. Publ. Bull. Dep. Geol. Sci.*, *25*, 347–422, 1941.

Arculus, R. J., and R. W. Johnson, Island-arc magma sources: A geochemical assessment of the roles of slab-derived components and crustal contamination, *Geochem. J.*, *15*, 109–133, 1981.

Bacon, C. R., Eruptive history of Mount Mazama and Crater Lake caldera, Cascade Range, U.S.A., *J. Volcanol. Geotherm. Res.*, *18*, 57–115, 1983.

Bacon, C. R., Implications of silicic vent patterns for the presence of large crustal magma chambers, *J. Geophys. Res.*, *90*, 11,243–11,272, 1985.

Barsky, C. K., Geochemistry of basalts and andesites from the Medicine Lake Highland, California, Ph.D. Dissertation, 373 pp., Washington Univ., St. Louis, Mo., 1975.

Berge, P. A., P. B. Dawson, and J. R. Evans, Active seismic imaging experiment (abstract), *Eos Trans. AGU*, *66*, 603–604, 1985.

Christiansen, R. L. Volcanic hazard potential in the California Cascades, *Calif. Div. Mines Geol. Spec. Publ.*, *63*, 41–59, 1982.

Ciancanelli, E. V., Geology of Medicine Lake volcano, *Trans. Geotherm. Resour. Counc.*, *7*, 135–140, 1983.

Condie, K. C., and D. L. Hayslip, Young bimodal volcanism at Medicine Lake volcanic center, northern California, *Geochim. Cosmochim. Acta*, *39*, 1165–1178, 1975.

Donnelly-Nolan, J. M., Two ash-flow tuffs and the stratigraphy of Medicine Lake volcano, northern California Cascades, *Geol. Soc. Am. Abstr. Programs*, *15*, 330, 1983.

Donnelly-Nolan, J. M., and D. E. Champion, Geologic map of Lava Beds National Monument, northern California, *Map I-1804*, scale 1:24,000, U.S. Geol. Surv., Reston, Va., 1987.

Donnelly-Nolan, J. M., and K. M. Nolan, Catastrophic flooding and eruption of ash-flow tuff at Medicine Lake volcano, California, *Geology*, *14*, 875–878, 1986.

Dzurisin, D., R. Y. Koyanagi, and T. T. English, Magma supply and storage at Kilauea volcano, Hawaii, 1956–1983, *J. Volcanol. Geotherm. Res.*, *21*, 177–206, 1984.

Eichelberger, J. C., Origin of andesite and dacite: Evidence of mixing at Glass Mountain in California and at other circum-Pacific volcanoes, *Geol. Soc. Am. Bull.*, *86*, 1381–1391, 1975.

Eichelberger, J. C., Vesiculation of mafic magma during replenishment of silicic magma reservoirs, *Nature*, *288*, 446–450, 1980.

Eichelberger, J. C., Mechanism of magma mixing at Glass Mountain, Medicine Lake Highland volcano, California, Guides to Some Volcanic Terranes in Washington, Idaho, Oregon, and Northern California, edited by D. A. Johnston and J. M. Donnelly-Nolan, *U.S. Geol. Surv. Circ.*, *838*, 183–189, 1981.

Evans, J. R., Compressional-wave velocity structure of the Medicine Lake volcano and vicinity from teleseismic relative travel-time residuals, paper presented at the 52nd Annual International Meeting, Soc. of Explor. Geophys., Dallas, Tex., 1982.

Evans, J. R., D. A. Stauber, and P. B. Dawson, Prospecting for shallow magma chambers in the Cascade Range using seismic topography, *U.S. Geol. Surv. Circ.*, *974*, 15–16, 1986.

Fink, J. H., and D. D. Pollard, Structural evidence for dikes beneath silicic domes, Medicine Lake Highland volcano, California, *Geology*, *11*, 458–461, 1983.

Finn, C., and D. L. Williams, Gravity evidence for a shallow intrusion under Medicine Lake volcano, California, *Geology*, *10*, 503–507, 1982.

Fuis, G. S., J. J. Zucca, W. D. Mooney, and B. Milkereit, A geologic interpretation of seismic-refraction results in northeastern California, *Geol. Soc. Am. Bull.*, *98*, 53–65, 1987.

Gay, T. E., Jr., and Q. A. Aune, Alturas sheet, Geologic map of California, scale 1:250,000, Calif. Div. of Mines and Geol., Sacramento, 1958.

Gerlach, D. C., and T. L. Grove, Petrology of Medicine Lake Highland volcanics, characterization of endmembers of magma mixing, *Contrib. Mineral. Petrol.*, *80*, 147–159, 1982.

Grove, T. L., and M. B. Baker, Phase equilibrium controls on the tholeiitic versus calc-alkaline differentiation trends, *J. Geophys. Res.*, *89*, 3253–3274, 1984.

Grove, T. L., and J. M. Donnelly-Nolan, The evolution of young silicic lavas at Medicine Lake volcano, California, implications for the origin of compositional gaps in calc-alkaline series lavas, *Contrib. Mineral. Petrol.*, *92*, 281–302, 1986.

Grove, T. L., and R. J. Kinzler, Petrogenesis of andesites, *Annu. Rev. Earth Planet. Sci.*, *14*, 417–454, 1986.

Grove, T. L., D. C. Gerlach, and T. W. Sando, Origin of calc-alkaline series lavas at Medicine Lake volcano by fractionation, assimilation and mixing, *Contrib. Mineral. Petrol.*, *80*, 160–182, 1982.

Hart, S. R., K. Rb, Cs, Sr and Ba contents and Sr isotope ratios of ocean floor basalts, *Philos. Trans. R. Soc. London, Ser. A*, *268*, 573–587, 1971.

Hart, W. K., J. L. Aronson, and S. A. Mertzman, Areal distribution and age of low-K, high-alumina olivine tholeiite magmatism in the northwestern Great Basin, *Geol. Soc. Am. Bull.*, *95*, 186–195, *Suppl. Data*, *84-3*, 1984.

Heiken, G., Plinian-type eruptions in the Medicine Lake Highland, California, and the nature of the underlying magma, *J. Volcanol. Geotherm. Res.*, *4*, 375–402, 1978.

Hill, D. P., Seismic evidence for the structure and Cenozoic tectonics of the Pacific Coast states, Cenozoic Tectonics and Regional Geophysics of the Western Cordillera, edited by R. B. Smith and G. P. Eaton, *Mem. Geol. Soc. Am.*, *152*, 145–174, 1978.

Iyer, H. M., Geophysical evidence for the locations, shapes and sizes, and internal structures of magma chambers beneath regions of Quaternary volcanism, *Philos. Trans. R. Soc. London, Ser. A.*, *310*, 473–510, 1984.

LaFehr, T. R., Gravity, isostasy and crustal structure in the southern Cascade Range, *J. Geophys. Res.*, *70*, 5581–5597, 1965.

Luedke, R. G., and M. A. Lanphere, K-Ar ages of upper Cenozoic volcanic rocks, northern California, *Isochron/West*, *28*, 7–8, 1980.

McKee, E. H., W. A. Duffield, and R. J. Stern, Late Miocene and early Pliocene basaltic rocks and their implications for crustal structure, northeastern California and south-central Oregon, *Geol. Soc. Am. Bull.*, *94*, 292–304, 1983.

Mertzman, S. A., Jr., The petrology and geochemistry of the Medicine Lake volcano, California, *Contrib. Mineral. Petrol.*, *62*, 221–247, 1977*a*.

Mertzman, S. A., Jr., Recent volcanism at Schonchin and Cinder buttes, northern California, *Contrib. Mineral. Petrol.*, *61*, 231–243, 1977*b*.

Mertzman, S. A., K-Ar results for silicic volcanics from the Medicine Lake Highland, northeastern California—A summary, *Isochron/West*, *34*, 3–7, 1982.

Mertzman, S. A., An addendum to "K-Ar results for silicic volcanics from the Medicine Lake Highland, northeastern California—A summary," *Isochron/West*, *38*, 3–5, 1983.

Mertzman, S. A., and R. J. Williams, Genesis of Recent silicic magmatism in the Medicine Lake Highland, California, evidence from cognate inclusions found at Little Glass Mountain, *Geochim. Cosmochim. Acta*, *45*, 1463–1478, 1981.

Peacock, M. A., The Modoc lava field, northern California, *Geogr. Rev.*, *21*, 259–275, 1931.

Pearce, J. A., Role of the sub-continental lithosphere in magma genesis at active continental margins, in *Continental Basalts and Mantle Xenoliths* edited by C. M. Hawkesworth and M. J. Norry, pp. 230–249, Shiva Publishing, Nantwich, Cheshire, United Kingdom, 1983.

Philpotts, J. A., W. Martin, and C. C. Schnetzler, Geochemical aspects of some Japanese lavas, *Earth Planet. Sci. Lett.*, *12*, 89–96, 1971.

Powers, H. A., The lavas of the Modoc Lava-Bed quadrangle, California, *Am. Mineral.*, *17*, 253–295, 1932.

Stanley, W. D., A regional magnetotelluric survey of the Cascade Mountains region, *U.S Geol. Surv. Open File Rep.*, *82-126*, 1982.

Waters, A. C., Basalt magma types and their tectonic associations: Pacific Northwest of the United States, in *The Crust of the Pacific Basin*, *Geophys. Monogr. Ser.*, vol. 6, edited by G. A. MacDonald and H. Kuno, pp. 158-170, AGU, Washington, D. C., 1962.

Zucca, J. J., G. S. Fuis, B. Milkereit, W. D. Mooney, and R. D. Catchings, Crustal structure of northeastern California, *J. Geophys. Res.*, *91*, 7359–7382, 1986.

J. M. Donnelly-Nolan, U.S. Geological Survey, M.S. 910, 345 Middlefield Road, Menlo Park, CA 94025.

(Received May 7, 1987;
revised November 24, 1987;
accepted December 22, 1987.)