

Hot, shallow mantle melting under the Cascades volcanic arc

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ABSTRACT

Melting occurs at progressively greater depths and higher temperatures from west to east across the Cascades volcanic arc in northern California, as demonstrated by compositional variations observed in high-alumina olivine tholeiites. The lavas studied erupted from seven vents defining a 75-km-long, east-west transect across the arc, from near Mount Shasta to east of Medicine Lake volcano. The increase in melting depth across the arc parallels modeled isotherms in the mantle wedge and does not parallel the inferred dip of the slab. The depth of mantle melting at which the high-alumina olivine tholeiites were created is ~36 km at the western end of the transect and 66 km at the eastern end. The very high temperatures of dry melting so close to the crust indicate a transitory condition of the mantle.

Keywords: Cascade Range, tholeiite, subduction zones, petrology, mantle, melting.

INTRODUCTION

Quaternary volcanism in the Cascades arc in northern California produced lavas with a wide compositional range. Modern Mount Shasta has been built of four major eruptive episodes, from 120 ka to ca. 2 ka, and includes both dry and wet magmas (Baker et al., 1994). Medicine Lake volcano has erupted throughout the past 500 k.y. (Donnelly-Nolan, 1988), producing both near-anhydrous, high-alumina olivine tholeiites and hydrous, subduction-related calc-alkaline basalts (Kinzler et al., 2000).

The lavas chosen for study are near-anhydrous, Quaternary high-alumina olivine tholeiites, all younger than 500 ka, and closely associated in time and space with Mount Shasta and Medicine Lake volcanoes. Lavas analyzed are from the following seven units, from west to east: basalts of Whaleback–Deer Mountain saddle, Tennant, Giant Crater, Yellowjacket Butte, Mammoth Crater, Tionesta, and Damons Butte. The seven vent areas are in a transect ~75 km long (Fig. 1). These vents each produced 2–5 km³ of magma during brief eruptions (~100 yr, Champion and Donnelly-Nolan, 1994). The lavas of the seven units are aphanitic to fine-grained (some are diktytaxitic) and equigranular to microporphyritic with <2% olivine and plagioclase microphenocrysts 0.3–0.5 mm in size, and likely represent liquid compositions.

The Mg#s of the lavas range to 71 (where Mg# = [mol% MgO / (mol% MgO + mol% FeO)]). The compositional range is wide even when the data set is confined to lavas with Mg#s higher than 60: FeO in these more primitive lavas ranges from 6.8 to 10.5 wt% (Fe₂O₃ was not measured separately), MgO is from 8.0 to 10.5 wt%, SiO₂ is from 47.2 to 50.5 wt%, CaO is from 9.5 to 12.5 wt%, K₂O is from 0.1 to 0.4, and Al₂O₃ is from 16.0 to 19.5 wt%. The Rb content varies from ~1 to 20 ppm, and Sr ranges from 150 to 450 ppm (Table 1).

The fractional crystallization and mantle melting models applied here require dry magmas. Preruptive water contents have been determined from melt inclusion studies and are generally <0.25 wt% (Sis-

son and Layne, 1993; Anderson, 1973). A few high-alumina olivine tholeiites, however, have Sr contents near the high end of the range for Cascades high-alumina olivine tholeiites. In these lavas K₂O and Rb are low while Sr is elevated relative to that of the other lavas. Crustal contamination will lead to lower Sr abundance (Baker et al., 1991) and higher K₂O and Rb abundances. At Medicine Lake, elevated Sr has been demonstrated to be a proxy for the presence of an H₂O-rich slab fluid component (see Kinzler et al., 2000, then Fig. 10) and suggestive of hydrous melting, not a proxy for crustal contamination.

For the purpose of calculating the conditions of formation, only the lava compositions with Mg#s > 60 are considered. Limiting the compositions to Mg# > 60 left between 7 and 60 analyses available for each unit (note that the higher SiO₂, lower Mg# samples are typically found at or near the vent, while the most primitive lavas are

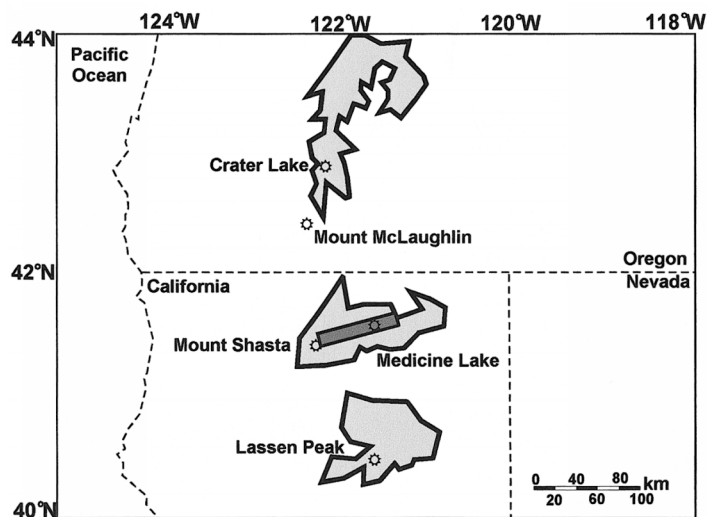


Figure 1. Study area. Areas in Cascades arc with vents younger than 2 Ma are shaded. Transect from this paper is marked with darker rectangle (after Blakely et al., 1997, Plate 2).

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TABLE 1. COMPOSITIONAL DATA FROM EACH BASALT UNIT

Basalt Unit	Sample	Mg#	SiO ₂	Al ₂ O ₃	FeO	MgO	CaO	Na ₂ O	K ₂ O	TiO ₂	P ₂ O ₅	MnO	Rb	Sr	Y	Zr	Nb	Ba	Ni	Cu	Zn	Cr	
Whaleback-Deer Mountain	83-43	70.1	50.70	17.70	7.06	9.30	10.72	3.06	0.28	1.06	0.11	0.00											
Tennant	1634	64.3	48.31	18.76	9.02	9.13	10.89	2.61	0.13	0.89	0.10	0.16	9	354	29	74	5	121	136	65	65	185	
Giant Crater	82-72f	69.6	47.69	18.54	8.20	10.52	12.02	2.16	0.07	0.59	0.06	0.15	1	180	17	48	2	29	245	135	44	180	
Mammoth Crater	840M	66.4	48.65	18.02	8.65	9.61	11.21	2.66	0.16	0.77	0.10	0.16	2	268	20	69	2	79	159	95	53	225	
Yellowjacket Butte	1788M	65.3	50.39	18.48	7.81	8.23	10.60	2.83	0.43	0.89	0.18	0.15	9	390	20	92	8	250	110	84	54	220	
Tionesta	1629	67.0	48.16	18.26	8.71	9.92	11.44	2.47	0.10	0.72	0.06	0.15	0	217	18	58	0	80	212	97	58	177	
Damons Butte	1630	62.4	47.83	17.89	9.68	8.99	11.25	2.76	0.22	1.07	0.14	0.17	0	304	24	85	7	115	147	114	67	164	

Note: Units are listed from west to east. Analysis of whole rocks was done at the U.S. Geological Survey laboratories at Lakewood, Colorado, and Menlo Park, California. Oxides are recalculated to 100 wt%; elements are in ppm.

typically erupted late and tube fed to distal locations; it is interesting that there is a general trend from higher Mg#s in the west to lower Mg#s in the east).

DEPTHS OF FRACTIONAL CRYSTALLIZATION

The effects of fractional crystallization and crustal assimilation must be removed from even the most primitive lava composition to reconstruct a model primary mantle melt from which pressure and temperature of formation can be calculated. Our selection of seven units with primitive lavas yielded lava compositions that underwent fractional crystallization of only olivine and plagioclase. This relatively simple fractional crystallization history is used to infer a model primary magma.

Using the technique of Yang et al. (1996), we calculated the positions of the boundaries defining the olivine, plagioclase, and clinopyroxene primary phase volumes in the olivine-plagioclase-clinopyroxene pseudoternary. Compositions from all the vents plot along their predicted olivine and plagioclase saturation boundaries, indicating olivine plus plagioclase fractionation under near-anhydrous conditions (e.g., Fig. 2).

Grove et al. (1992) demonstrated that pressure variation has little effect on the position of the olivine + plagioclase saturation boundary. The major effect of increasing pressure is to move the olivine + plagioclase + clinopyroxene boundary down toward the olivine + pla-

gioclase join at nearly constant proportions of olivine to plagioclase. We infer a maximum pressure for fractional crystallization by calculating olivine + plagioclase + clinopyroxene saturation points for each composition at a range of pressures, and finding the location of the lavas with respect to these multiple saturation points.

Because the olivine + plagioclase + clinopyroxene multiple saturation point is pressure sensitive, and the lavas have undergone only olivine + plagioclase fractionation, a maximum fractionation pressure can be estimated, but fractional crystallization at lower pressures cannot be excluded. The maximum possible fractionation pressure is given by the lava composition and the multiple saturation point that have the highest clinopyroxene content (between 8 and 10 kbar in Fig. 2 for all seven units). If the pressure at which fractional crystallization occurred were any higher, the lava compositions would cluster at the multiple saturation point and show compositional variability that indicated olivine + plagioclase + clinopyroxene crystallization. Because the compositional variations in the lava suites indicate olivine + plagioclase fractionation, fractional crystallization must have occurred at a pressure below that where clinopyroxene was a stable phase with liquid + olivine + plagioclase. Fractional crystallization of olivine + plagioclase thus could have occurred at any pressure lower than the maximum estimated pressure.

Using this method, we calculated the highest pressure at which fractional crystallization of olivine + plagioclase could have occurred for each of the vents. The compositions from all seven units show that fractional crystallization could not have begun any deeper than 12 kbar, or ~36 km depth, which corresponds to the base of the crust in this area (Fuis et al., 1987; Zucca et al., 1986). Fractional crystallization of olivine + plagioclase could have occurred at shallower depths, but at no greater depth than the base of the crust.

PRESSURES AND TEMPERATURES OF MANTLE MELTING

To estimate the pressures and temperatures of mantle melting we first calculate a model primary magma, the progenitor of the high-alumina olivine tholeiites from each vent. Using the most primitive composition from each unit (Table 1), we added equilibrium olivine and plagioclase to the lava composition in the proportion necessary to keep the liquid on the olivine + plagioclase cosaturation boundary. These proportions are predicted in the Yang et al. (1996) model. For all the vents, the predicted ratio (Yang et al., 1996) was close to 71 wt% plagioclase and 29 wt% olivine. The olivine and plagioclase are added in 2% increments at the 71:29 ratio, recalculating the equilibrium composition after each increment, until the resulting magma is in equilibrium with mantle olivine having a forsterite component of 89 mol%, approximately that of the mantle. This is the model primary magma. The compositions required addition of from 4 to 35 wt% olivine + plagioclase to bring them into equilibrium with mantle olivine.

The assumption that these liquids were saturated with only olivine + plagioclase is based on three lines of reasoning. (1) All of the high-alumina olivine tholeiites that have been examined show compositional and petrographic evidence for olivine + plagioclase saturation. (2) We

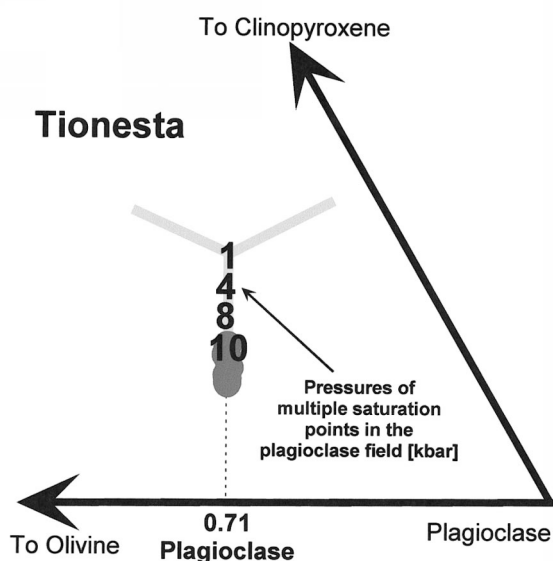


Figure 2. Magnified corner of pseudo-ternary diagram of olivine-plagioclase-clinopyroxene, with data from Tionesta. Three cosaturation boundaries are shown, with locations for points of multiple saturation at 1 atm, 4, 8, and 10 kbar. These lavas co-crystallized olivine and plagioclase no deeper than 10 kbar, or ~33 km.

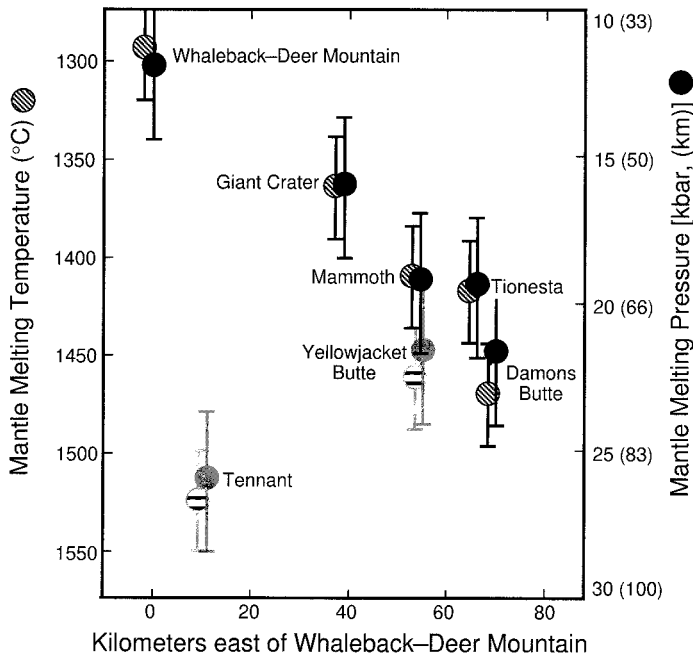


Figure 3. Temperatures and pressures of mantle melting for seven basalt units, shown with west on left. Tennant and Yellowjacket Butte are gray because we believe their results are anomalous due to addition of slab fluid. Temperature is shown with hatched symbols; pressure and depth are shown with solid symbols. Kinzler and Grove (1992) demonstrated that these algorithms have pressure error of ± 2.5 kbar and temperature error of ± 25 °C, as shown by error bars.

explored models that assume that the primitive magmas had just reached olivine + plagioclase saturation, and prior crystallization involved only olivine. When olivine alone is added to produce a liquid that is in equilibrium with Fo₈₉ mantle olivine, the model primary liquid compositions yield pressure estimates at crustal, not mantle, depths, and their compositions are not similar to the primary magma compositions predicted by the Kinzler and Grove (1992) model. (3) The addition of the phases that are present in the primitive lavas (olivine + plagioclase) is sufficient to bring the liquid to a composition in equilibrium with a mantle peridotite residue.

Using the algorithm of Kinzler and Grove (1992) for spinel-lherzolite melting and the compositions of the model primary magmas, we calculated pressures and temperatures of mantle melting. There is an increase in maximum calculated pressure from west to east across the arc corresponding to nearly a doubling in depth of the origin of the magma, from 12 kbar (~36 km depth) in the west to 22 kbar (~66 km depth) in the east. Temperatures likewise increase across the arc, from 1300 °C in the west to 1450 °C in the east (Fig. 3). Bartels et al. (1991) found, through phase equilibrium experiments, that a high-alumina olivine basalt from Giant Crater is in equilibrium with spinel lherzolite at 1290 °C and 11 kbar, in agreement with our results (see also Bacon et al., 1997).

The Kinzler and Grove (1992) model is calibrated for dry melting. While we chose the most primitive, driest magmas, results for two of the samples, the basalts of Tennant and Yellowjacket Butte, indicated the influence of fluid as the analysis proceeded. The parental magmas from these lava flows that were used for the model primary melt calculation have elevated Sr values of ~350 ppm. These elevated Sr values strongly suggest a slab fluid component. The Kinzler and Grove (1992) temperature algorithm returns anomalously high temperatures for the model primary magmas of these slightly hydrous compositions.

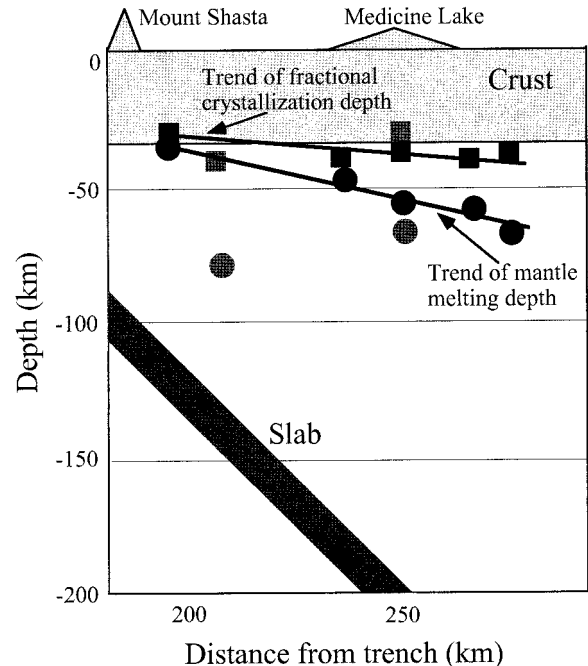


Figure 4. Cross section across arc. Position of slab is from Harris et al. (1991) and thickness of crust is from Zucca et al. (1986). Tennant and Yellowjacket Butte are gray because we believe their results are anomalous due to addition of slab fluid. Squares show maximum depth of fractionation of olivine and plagioclase, and solid circles show mantle melting depth.

These two vents are shown with gray symbols in Figures 3 and 4 to differentiate them from the other, near-anhydrous compositions.

IMPLICATIONS FOR MANTLE CORNER FLOW

Although the pressures of mantle melting increase across the arc from west to east, they do not conform to the dip of the slab as inferred tomographically by Harris et al. (1991). The descending slab is ~100 km beneath Mount Shasta and 200 km beneath Medicine Lake volcano, and so falls 100 km deeper over the distance of the transect. The depth of mantle melting at which the high-alumina olivine tholeiites were created, by comparison, is ~36 km at the western edge of the transect and 66 km at the eastern edge, and so has descended only 30 km across the transect.

The increase in the pressure of mantle melting parallels the corner flow lines in the mantle wedge calculated by Furukawa (1993). The temperatures of mantle melting, however, are anomalously high for their proximity to the crust (Figs. 3 and 4). These results imply that magma between 1300 and 1450 °C is entering the lower crust, and that mantle material at these temperatures is passing beneath it.

If mantle at this temperature remained in steady-state contact with the lithosphere at 36 km, then within 1 m.y. the bottom of the crust would have melted upward ~6 km, depending on composition (e.g., Mareschal and Bergantz, 1990). Mantle above 1300 °C and 36 km should, moreover, be partially melted. The predicted crustal melt volumes indicated (6–7 km³/km² on the surface) are not seen on the surface, nor inferred from seismic data (Zucca et al., 1986). We are forced to conclude, therefore, that the high-temperature mantle is in transient contact with the crust.

Baker et al. (1991) showed that more than 50% of the Giant Crater series lavas were produced by a combination of processes whereby mantle melts intrude the shallow crust, assimilate crustal material, and mix with previous injections in variable amounts. The Giant Crater

lava field preserves six distinctive eruptive episodes, and each successive eruption contains less crustal contamination. The last eruptive phase is a near-pristine near-primary mantle melt that does not contain a crustal component. The Giant Crater lavas were erupted ~10 k.y. ago over a time span of ~30 yr (Champion and Donnelly-Nolan, 1994). The eruptive flux was sustained over a time that allowed crustally contaminated melts to be cleared out from the magma plumbing system and primitive high-alumina olivine tholeiites to be delivered to the surface. After the Giant Crater eruption, there was a 6 k.y. gap in Medicine Lake volcano magmatic activity (Donnelly-Nolan, 1988). Although we do not have a precise time chronology for all seven eruptive units, it is likely that they also represent short-lived events separated by long time intervals. Therefore, magma supply to the Mount Shasta–Medicine Lake region has been episodic, and the persistence of hot mantle near the base of the crust should be viewed as a transitory phenomenon punctuated by long periods of quiescence accompanied by cooling of shallow mantle.

CONCLUSIONS

Analysis of the most primitive, near-anhydrous, high-alumina olivine tholeiites erupted along a transect across the Cascades volcanic arc, northern California, shows that the magmas underwent fractional crystallization of olivine + plagioclase no deeper than the base of the crust, and originated from mantle melts at 36–66 km depth and 1300–1450 °C, increasing from west to east across the arc. Although the depths of segregation of mantle melts increase from west to east across the arc, and temperatures of origin also rise commensurably, the increase in depth does not parallel the slab dip. Rather, the increase in depth of origin parallels modeled mantle corner flow lines. To match eruptive cycles and avoid creation of questionably high volumes of crustal melt, these high temperatures must be transitory at the base of the crust.

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REFERENCES CITED

- Anderson, A.T., Jr., 1973, The before-eruption water content of some high-alumina magmas: *Bulletin of Volcanology*, v. 37, p. 530–552.
- Bacon, C.R., Bruggman, P.E., Christiansen, R.L., Clynne, M.A., Donnelly-Nolan, J.M., and Hildreth, W., 1997, Primitive magmas at five Cascades volcanic fields: Melts from hot, heterogeneous sub-arc mantle: *Canadian Mineralogist*, v. 35, p. 397–423.
- Baker, M.B., Grove, T.L., Kinzler, R.J., Donnelly-Nolan, J.M., and Wandless, G.A., 1991, Origin of compositional zonation (high-alumina basalt to basaltic andesite) in the Giant Crater lava field, Medicine Lake volcano, northern California: *Journal of Geophysical Research*, v. 96, p. 21 819–21 842.
- Baker, M.B., Grove, T.L., and Price, R., 1994, Primitive basalts and andesites from the Mt. Shasta region, N. California: Products of varying melt fraction and water content: *Contributions to Mineralogy and Petrology*, v. 118, p. 111–129.
- Bartels, K.S., Kinzler, R.J., and Grove, T.L., 1991, High pressure phase relations of primitive high-alumina basalts from Medicine Lake volcano, northern California: *Contributions to Mineralogy and Petrology*, v. 108, p. 253–270.
- Blakely, R.J., Christiansen, R.L., Guffanti, M., Wells, R.E., Donnelly-Nolan, J.M., Patrick Muffler, L.J., Clynne, M.A., and Smith, J.G., 1997, Gravity anomalies, Quaternary vents, and Quaternary faults in the southern Cascade Range, Oregon and California: Implications for arc and backarc evolution: *Journal of Geophysical Research*, v. 102, p. 22 513–22 527.
- Champion, D.E., and Donnelly-Nolan, J.M., 1994, Duration of eruption at the Giant Crater lava field, Medicine Lake volcano, California, based on paleomagnetic secular variation: *Journal of Geophysical Research*, v. 99, p. 15 595–15 604.
- Donnelly-Nolan, J.M., 1988, A magmatic model of Medicine Lake volcano, California: *Journal of Geophysical Research*, v. 93, p. 4412–4420.
- Furukawa, Y., 1993, Magmatic processes under arcs and formation of the volcanic front: *Journal of Geophysical Research*, v. 98, p. 8309–8319.
- Fuis, G.S., Zucca, J.J., Mooney, W.D., and Milkereit, B., 1987, A geologic interpretation of seismic-refraction results in northeastern California: *Geological Society of America Bulletin*, v. 98, p. 53–65.
- Grove, T.L., Kinzler, R.J., and Bryan, W.B., 1992, Fractionation of mid-ocean ridge basalt (MORB), in Morgan, J.P., et al., eds., *Mantle flow and melt generation at mid-ocean ridges*: American Geophysical Union Geophysical Monograph 71, p. 281–310.
- Harris, R.A., Iyer, H.M., and Dawson, P.B., 1991, Imaging the Juan de Fuca plate beneath southern Oregon using teleseismic P-wave residuals: *Journal of Geophysical Research*, v. 96, p. 19 879–19 889.
- Kinzler, R.J., and Grove, T.L., 1992, Primary magmas of mid-ocean ridge basalts I. Experiments and methods: *Journal of Geophysical Research*, v. 97, p. 6885–6906.
- Kinzler, R.J., Donnelly-Nolan, J.M., and Grove, T.L., 2000, Late Holocene hydrous mafic magmatism at the Paint Pot Crater and Callahan flows, Medicine Lake volcano, N. California and the influence of H₂O in the generation of silicic magmas: *Contributions to Mineralogy and Petrology*, v. 138, p. 1–16.
- Mareschal, J.-C., and Bergantz, G., 1990, Constraints on thermal models of the Basin and Range province: *Tectonophysics*, v. 174, p. 137–146.
- Sisson, T.W., and Layne, G.D., 1993, H₂O in basalt and basaltic andesite glass inclusions from four subduction-related volcanoes: *Earth and Planetary Science Letters*, v. 117, p. 619–635.
- Yang, H.-J., Kinzler, R.J., and Grove, T.L., 1996, Experiments and models of anhydrous, basaltic olivine-plagioclase-augite saturated melts from 0.001 to 10 kbar: *Contributions to Mineralogy and Petrology*, v. 124, p. 1–18.
- Zucca, J.J., Fuis, G.S., Milkereit, B., Mooney, W.D., and Catchings, R.D., 1986, Crustal structure of northeastern California: *Journal of Geophysical Research*, v. 9, p. 7359–7382.

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