

## High-magnesian andesite from Mount Shasta: A product of magma mixing and contamination, not a primitive melt: COMMENT AND REPLY

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Streck et al. (2007) concluded that the high-magnesian andesite (HMA) from Mt. Shasta represents a mix of dacite, basalt, and underlying Trinity ophiolite. The authors present two mixing models calculated to reproduce the major element composition of the HMA (average of samples 85–41a-d; Baker et al., 1994). The two models mix a Mt. Shasta dacite (sample 83–58; Grove et al., 2005); a theoretical harzburgite, thought to come from the Trinity ophiolite; and a Mt. Shasta basalt, either a high-alumina olivine tholeiite (HAOT; sample 85–38; Baker et al., 1994) for model 1 or a calc-alkaline basalt (CAB; sample 85–1a; Baker et al., 1994) for model 2. These models led the authors to conclude that HMAs are not mantle-derived melts, that the HMA of Mt. Shasta is produced because of the availability of ultramafic material (Trinity ophiolite; Quick, 1981) underlying the volcano, and that the “primitive” and “adakitic” signatures of HMAs may be decoupled on a local scale (adakitic signature coming from the dacite, and the primitive signature coming from the entrained ultramafic debris). However, data available in work cited by Streck et al. (e.g., Baker et al., 1994; Grove et al., 2002, 2003, 2005; Quick, 1981; Anderson, 1973) are inconsistent with their conclusions and were overlooked in the development of the mixing models.

### Primitive Olivine Not From the Trinity Ophiolite

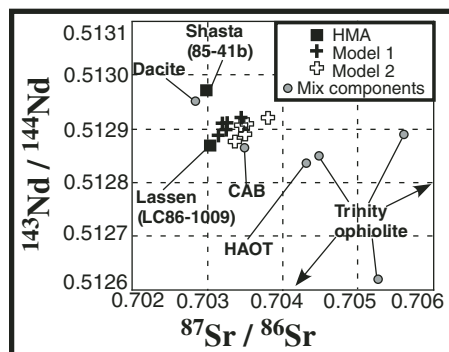
Olivines ( $Fo_{90-94}$ ) found in the HMA are interpreted by the authors as xenocrysts from the Trinity ophiolite. Abundant spinel from these olivines have chromium numbers from 70 to 80 (where chromium number is molar  $[Cr/Cr+Al]$ ; Baker et al., 1994). Spinel from the Trinity ophiolite, in contrast, have chromium numbers from 40 to 60, and the most primitive olivines reported are  $Fo_{92.6}$  (Quick, 1981). Further, melt inclusions in HMA olivines described by Anderson (1973) show compositions similar to that of the host HMA. These pieces of evidence indicate a magmatic, phenocrystic origin for the primitive olivine found in the HMA, not a xenocrystic origin from the Trinity ophiolite.

### Mixing Models Fail for Trace Elements

Mixing models must produce the target composition for both major and trace elements and isotopes. Results of the mixing models of Streck et al. for Sr and Nd isotopes indicate that their models do not reproduce the HMA even with the large variation in the Trinity ophiolite samples (Fig. 1). Mass balance calculations show that mixing the dacite and basalts in the two models produce an overabundance of many trace elements, including Sr, Ba, Dy, Lu, Y, Yb, Pb, and Zr. This illustrates the inability of the mixing models to produce the HMA with any third component, Trinity ophiolite or otherwise.

### Mt. Lassen HMA

The assertion by the authors that the HMA of Mt. Shasta was the only HMA magma in the Cascades is incorrect. The studies of Clynne and Borg (1997) and Borg et al. (1997) describe HMAs for the Mt. Lassen region. That region has no underlying ultramafic body but the HMAs still contain primitive olivine phenocrysts ( $Fo_{89-91}$ ) with abundant euhedral Cr-spinel inclusions (Cr#s 71–77; Clynne and Borg, 1997). Based on a comprehensive study of the primitive magmas in the region, the study of Clynne and Borg (1997) determined that the Mt. Lassen HMAs were produced by higher extents of melting of less fertile mantle, with a greater slab-derived component, than those of the HAOTs



**Figure 1. Predicted isotopic composition of the Mt. Shasta high-magnesian andesite (HMA), using the mixing models of Streck et al. (2007), are shown as Model 1 and Model 2. Trinity ophiolite samples (including two that plot outside of the region shown—indicated by arrows) from Jacobsen et al. (1984) and Gruau et al. (1995). Dacite (83–58), HAOT (85–38), CAB (85–1a), and HMA (85–41b) samples are all from Grove et al. (2002). Mt. Lassen HMA (LC86–1009) is from Borg et al. (1997). CAB—calc-alkaline basalt; HAOT—high-alumina olivine tholeiite.**

and CABs of the region. This is also the model proposed by Grove et al. (2002) for the production of the Mt. Shasta HMA.

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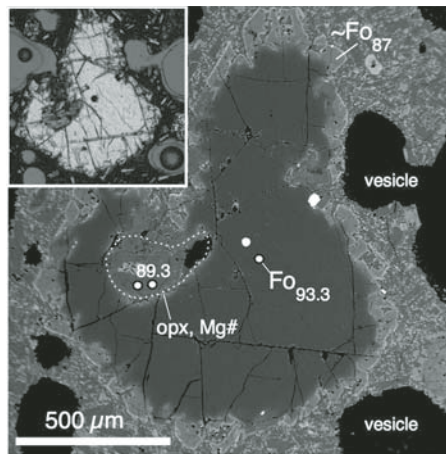
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We welcome the opportunity to reply to comments regarding our work on high-magnesian andesites (HMAs) from the Mt. Shasta area. Our interpretations are based foremost on petrographic observations that the HMA contains heterogeneous and strongly zoned crystals of diverse origin and cannot represent a primitive mantle-derived liquid. Barr et al. (2007) imply that our interpretations were driven by mixing models (the reverse is true), that the models fail to reproduce trace element and Sr-Nd isotopic data for the HMA (also incorrect), and that Fo-rich olivines in these rocks are primary liquidus phases precipitated from an actual magma of HMA-like composition rather than xenocrysts. They also point out that HMAs occur elsewhere in the Cascades.

Highly forsteritic olivine (mostly Fo<sub>93</sub>) in Mt. Shasta HMA is considered xenocrystic based on (1) the distinctly large size (> 1mm) of single crystals, combined with clearly anhedral shape, reacted margins, and sparse occurrence (Fig. 1); and (2) the association of these crystals with xenolithic peridotite fragments in the same hand sample. Although highly magnesian olivine (Fo ≥ 93) is reported from peridotitic xenoliths from cratonic depleted mantle, some low-Ca boninites, and some metamorphic rocks, it is rare in arc lavas. So, such forsteritic olivine is rare in arc lavas.

Also, compositions of melt inclusions described by Anderson (1973, his Table 9) are distinct from that of erupted bulk HMA. Most are hosted by Fo<sub>89-83</sub> olivines similar to those crystallized from the hybrid melt shortly before eruption (as stated in our paper). The one inclusion hosted by Fo<sub>94</sub> olivine has a composition (normalized to 100%) that differs from bulk HMA (all in wt%): CaO = 13.2 (versus 8.2 in HMA); MgO = 5.5 (versus 8.5); FeO\* = 3.97 (versus 5.6), and SiO<sub>2</sub> = 57 (versus 58.3).

Moreover, Grove et al. (2005, p. 549) state that “Rare cm-sized inclusions of peridotite have been found in all eruptive phases [at Mt. Shasta], in addition to orthopyroxenite inclusions that appear to record progressive meta-



**Figure 1. Backscattered electron and transmitted light (inset) images of a Fo<sub>93</sub> olivine in Shasta high-magnesian andesite (HMA). Note inclusion of disequilibrium orthopyroxene, embayed rim of original Fo<sub>93</sub> grain, and euhedral/skeletal overgrowth of Fo<sub>87</sub> olivine.**

morphism of serpentinite. These xenoliths are assumed to come from the underlying Trinity ultramafic complex.” The forsteritic xenocrysts could be derived from back-reacted serpentinite during metamorphism proximal to Shasta magma reservoirs.

Our models tested whether mixing of variants of the locally erupted basaltic and dacitic magmas coupled with contamination by ultramafic crystal debris could produce bulk composition of Mt. Shasta HMA. Trace element and isotopic compositions were not discussed as these models are sensitive to the choice of end members (e.g., Sr contents in Mt. Shasta dacites [63–64 wt% SiO<sub>2</sub>; 3–4 wt% MgO] range between ~1100 and 500 ppm; Grove et al., 2005). Using our original end members, mixing models for incompatible trace elements approximate the observed Shasta HMA (Table 1), except for Th and Sr that depend strongly on end-member dacite composition.

Barr et al.’s comments regarding Sr-Nd isotopic data are specious because ultramafic additives will have negligible influence on the isotopic composition of the mixture owing to their low Sr and Nd contents. Moreover, Barr et al. plotted isotopic data for a variety of rocks including amphibolites, gabbros, etc. that are irrelevant to our postulated mixing model.

Other high-Mg andesites in the Cascades are also unlikely to be derived directly from the upper mantle. For example, at Mt. Lassen primitive mafic and andesitic lavas have high δ<sup>18</sup>O and radiogenic <sup>187</sup>Os/<sup>188</sup>Os (Borg et al., 2000; Hart et al., 2002) that correlate inversely

TABLE 1. TRACE ELEMENTS IN HMA

ppm	HMA <sup>1</sup>	HMA <sup>2</sup>	HMA	HMA
	MS 1604	85–41b	Model 1	Model 2
Rb	14.6	17	16.3	14.6
Ba	190	189	212	200
Sr	765	812	883	842
Y	12.4	12	14.3	12
La	10.5	10.7	9.6	8.5
Ce	22.3	24.2	21	19
Sm	2.5	2.6	2.6	2.3
Dy	2.1	1.94	2.4	2.0
Yb	1.02	1.05	1.42	1.16
Zr	96	92	95	84
Th	1.9	1.69	1.27	1.11
Nb	2.5	3.6	3.1	2.6

Note: HMA—high magnesian andesite. Data: 1—this study, 2—Grove et al. (2002). Model 1 & 2 after this study. Trace elements for HAO (T #85-38), CAB basalt (#85-1a), and dacite (#83-58) are from Grove et al. (2002). Concentrations for harzburgite are set to zero (perfect dilutant) except for REE which are those of Trinity Iherzolite (Gruau et al., 1995).

with Os, MgO, Ni, and Cr concentrations—indicative that the lavas are products of fractionation and assimilation.

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