Compositional variations within scoria cones

Mel Strong
John Wolff
Department of Geology, Washington State University, Pullman, Washington 99164, USA

ABSTRACT

Basaltic to andesitic monogenic scoria cones from the southern Cascades exhibit large chemical variations within the products of single eruptions. Two types of chemical variations occur within cones. First, there are several instances where the chemistry of the late-stage lava flow is significantly different from that of the scoria. The two magma types cannot be related to each other by fractional crystallization, and instead seem to be derived from different sources. Second, chemical variations occur within the scoria, most easily recognized in ratios of large ion lithophile elements to high field strength elements. Repeatedly, an ocean-island basalt–like component has erupted contemporaneously with the dominant calc-alkaline compositions, requiring two distinct mantle sources (one ocean-island basalt source and one mid-ocean-ridge basalt source) as well as the variable addition of slab-derived fluids. Such variations within the scoria suggest that either magma chambers do not exist and the melt migrates from the source through dike-like structures without homogenization, or that magma chambers are inefficient in their ability to mix liquids. Small volumes of basalt, which may normally be thermally challenged to reach the surface, might ascend through the crust through pathways recently traveled by previous melt batches, causing pairs of magmas to erupt at each vent.

Keywords: basalt, scoria, Cascades, transport, chemical evolution, magma.

INTRODUCTION

It is well known that products of individual large silicic eruptions often show chemical zonation, in which element concentrations and isotopic ratios in the magma vary over the course of the eruption. Much less documentation exists for chemical variations within basaltic systems over the duration of a single eruption or closely spaced eruptive events. In the waning stages of the Parícutin eruption, lavas and scoria became more enriched in silica and radiogenic Sr, a transition that occurred over a few months (McBirney et al., 1987). During the 1733–1736 Lanzarote eruption, the lavas changed from alkali basalts to olivine tholeiites over a period no longer than two weeks (Carracedo et al., 1992). For the preceding examples, chemical variations are attributed to assimilation–fractional crystallization (AFC) processes by the respective authors, although variable mantle sources have also been proposed (Reiners, 2002). Progressive mild depletion of incompatible elements during the course of the 1986–1992 Pu‘u O‘o eruption has been attributed to an increasing degree of partial melting driving the eruptive episodes (Garcia et al., 1996). Saal et al. (1998) reported Pb isotope variations in glass inclusions within olivine grains from single oceanic-island basalt (OIB) samples even though the host lavas are isotopically homogeneous, suggesting heterogeneities within a single source region or mixing of separate source regions.

In this paper we document compositional variations within individual late Quaternary basaltic to andesitic monogenetic scoria cones in the southern Cascade arc. Although the volumes of erupted material are small ($\sim$0.01 km^3), and eruption durations short (typically $<$1 yr, Wood, 1980), significant variations in major and trace element concentrations occur within products of single eruptions. These variations may be present in incremental amounts in the scoria, or may be reflected in major overall changes of chemistry between the scoria and late-stage lava flows. In most cases the chemical variations cannot be ascribed solely to fractional crystallization or AFC processes. We describe four cones that have systematic chemical variations between the scoria and lava, and four cones showing variations within the scoria. These variations may be due to changes in partial melting, source heterogeneities in fluid-mobile components, or simultaneous tapping of two distinctly different source regions.

SOUTHERN CASCADE VOLCANISM

The southernmost Cascades are at the western extent of the Basin and Range Province, east of the north-migrating Mendocino triple junction and above the subducting Gorda plate (Guffanti et al., 1990). Studies of the petrology and geochemistry of the Lassen Volcanic Center (Clynne, 1990; Borg et al., 1997, and references therein) have concluded that variations among primitive lavas are due to the variable addition of a slab-derived component to a mantle wedge enriched by a previous subduction regime, while associated rhyolites are the partial melts of these mafic lava equivalents intruded into the lower crust.

METHODS

Scoria cones selected for this study range from basalt (to 9.4% MgO) to andesite in composition and are within 2500 km^2 of the northeast of the Lassen volcanic center (Fig. 1). Recent quarrying exposed tens of meters of section per cone, providing a cross section of the erupted products, including dikes and late-stage lava flows. We sampled throughout the eruptive sequence for each cone, although the earliest erupted products, estimated as the first 25% of erupted volume, were never exposed. Scoria and lava samples were analyzed by X-ray fluorescence and inductively coupled plasma–mass spectroscopy facilities at Washington State University according to procedures described in Johnson et al. (1999) and Knaack et al. (1994). The Nd and Sr isotope analyses were done at the University of California, Los Angeles, as described by Ramos (1992).

GEOCHEMICAL DIFFERENCES BETWEEN SCORIA AND LAVA ERUPTED FROM THE SAME VENT

Brush Mountain

Brush Mountain erupted andesitic scoria (58.5% SiO_2, 4.7% MgO), rich in fluid-mobile elements (e.g., K, Rb, Ba) and with strong

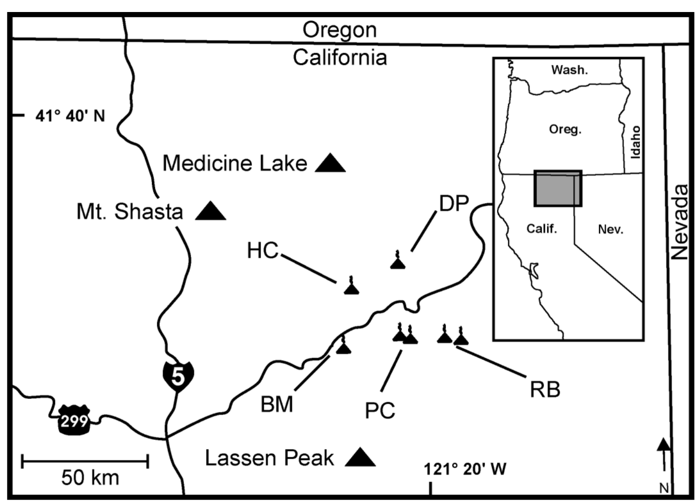

Figure 1. Locations of quarried scoria cones in southern Cascades referred to in this paper. HC—Horr's Corner; DP—Day Pit; RB—Round Barn; PC—Popcorn Cave; BM—Brush Mountain.

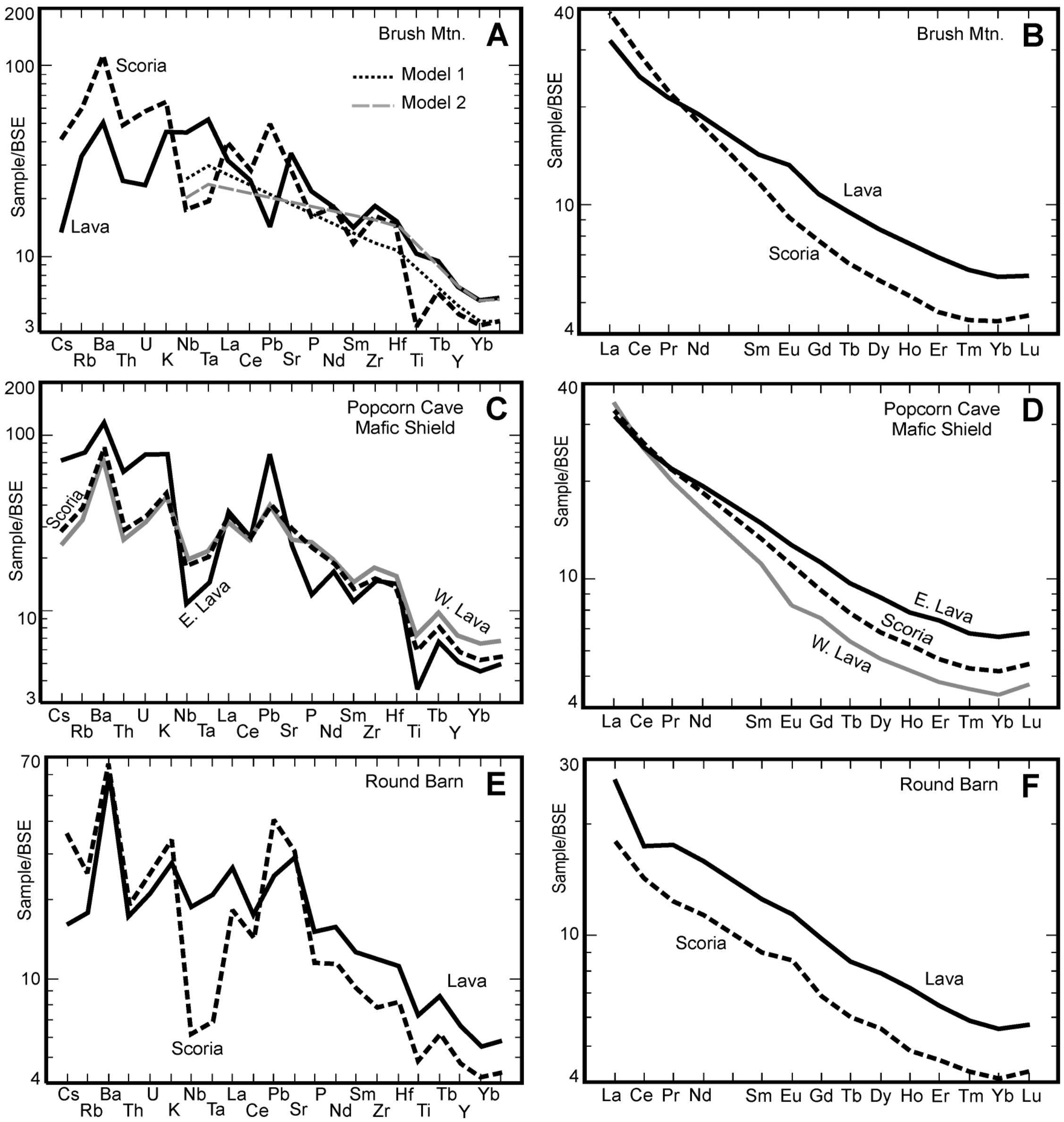

Figure 2. Comparisons of four scoria cone compositions and their lava flows. Mantle-normalized incompatible trace element diagrams (A, C, E) and rare earth element (REE) plots (B, D, F) for Brush Mountain, Popcorn Cave, and Round Barn vents. Normalizing values are from McDonough and Sun (1995) for bulk silicate earth (BSE). A: Included on this diagram are two fractional mantle partial melting models. Model 1—best fit for heavy REEs—simulates alkali basalt as 3% fractional melt and scoria as 5% partial melt. Model 2—best match for high field strength elements—simulates alkali basalt and is modeled as 2% bulk melt and scoria as 5% bulk melt. It is impossible to derive scoria and lava flow from same source by simple melting models.

Nb-Ta depletion[1] (Fig. 2A). This was followed by an alkali basaltic lava flow (50.0% SiO_2, 5.8% MgO), which contained elevated high field strength elements (HFSE), lower large ion lithophile elements (LILE), and lower heavy rare earth elements (REE) compared to the scoria (Figs. 2A, 2B). The scorias have radiogenic isotope values that plot near the enriched end of the Cascade array, while the lava flow plots near local low-potassium olivine tholeiite (LKOT) fields (Fig. 3A).

Popcorn Cave Mafic Shield

The Popcorn Cave mafic shield is built mostly of LKOT lava flows, but is spotted with scoria cones of calc-alkaline composition. Two such cones are located ~0.5 km from each other on the southeast flank of the shield. Both are composed of basaltic andesite (54.5% SiO_2, 5.3% MgO) scoria and are chemically identical. The late lava flow from each cone deviates from the scoria composition. In the west cone, the lava is more primitive (53.1% SiO_2, 5.5% MgO) than the scoria, has elevated HFSEs and heavy REEs, and has a more primitive isotopic signature (Fig. 3A). In the east cone, the lava is more evolved (60.2% SiO_2, 3.9% MgO) with lower HFSEs and heavy REEs (Figs. 2C, 2D). There is little variation in LILEs between the scoria and the more primitive western flow, but the evolved eastern flow has considerably higher LILEs.

Round Barn Cones

Two closely spaced scoria cones (<1 km) are present within the vicinity of the Round Barn pit. The northeast cone erupted basaltic scoria (54% SiO_2, 4.5% MgO) with a strong depletion in Nb and Ta. The lava flow is more mafic (51.2% SiO_2, 5.6% MgO) than the scoria, lacks Nb-Ta depletion, and is elevated in all REEs (Figs. 2E, 2F). This lava flow composition is nearly identical to deposits from the neighboring southwest cone.

GEOCHEMICAL VARIATIONS WITHIN SCORIA

In addition to the chemical differences that occur between scoria and lava, we also find chemical variations that occur within the scoria. The scoria erupted at Day Pit shows progressive increase in the LILEs during the eruption (Fig. 3B). The lava flow has the same composition as the last scoria and spatter erupted from the vent, with no compositional gap between the scoria and lava. The scoria from the Round

[1]GSA Data Repository item 2003012, Table DR1, Detailed geochemistry, is available from Documents Secretary, GSA, P.O. Box 9140, Boulder, CO 80301-9140, editing@geosociety.org, or at www.geosociety.org/pubs/ft2003.htm.

Barn pit also shows an upward increase in LILE/HFSE ratios. The andesitic scoria from Brush Mountain also has variable LILE/HFSE ratios, but shows no correlation with eruptive stratigraphy. Several individual scoria clasts sampled from a single 10-cm-thick interval within the cone span the compositional range. The Horr's Corner cone, one of several LKOT cones that feed a mafic shield, also displays systematic compositional variations. As the eruption progressed, the light REE/heavy REE ratios increase, rotating the REE patterns clockwise (Fig. 3C).

POTENTIAL CAUSES FOR CHEMICAL VARIABILITY

Arguments Against Fractional Crystallization

Fractional crystallization cannot account for the compositional variations. In the case of Brush Mountain, a positive correlation between incompatible elements and Mg# prohibits fractional crystallization. With the Round Barn and Popcorn Cave cones, the only possible Ti-bearing phase capable of preferentially removing HFSEs from the parent magma is titanomagnetite, which is absent from the phenocryst assemblage, while simulations using the MELTS software (Ghiorso and Sack, 1995) yield titanomagnetite only under unrealistic oxidizing conditions (hematite-magnetite fo_2 buffer). Fractional crystallization also appears to only play a minor role in the chemical variations noted among the scoria of Day Pit and Horr's Corner cones. In each cone, changes in the Ba/Nb ratio cannot be produced by the fractionation of olivine, pyroxene, or plagioclase. At Day Pit, the variation in LILEs is not correlated with any variation in compatible elements. Likewise, the clockwise rotation of the light REEs in the Horr's Corner scoria is not accompanied by any change in the compatible elements. Although fractional crystallization may have occurred within the magmatic systems at each of these cones, its effects did not contribute significantly toward the chemical variations.

Variable Slab-Derived Components and Partial Melting

Borg et al. (1997) concluded that the diversity of primitive magmas observed at the Lassen Volcanic Center is due to variability in the amount and composition of slab-derived fluid added to the mantle wedge source. The cones in this study may be the product of melting of a similarly variably metasomatized source. Higher amounts of fluid-mobile components produce higher degrees of partial melting and lower HFSE concentrations (Gill, 1981; Reiners et al., 2000), resulting in the observed negative correlation between the LILEs and HFSEs. Increasing light REE/heavy REE ratios with progressive eruptive activity at Horr's Corner cone are suggestive of a decreasing degree of partial melting. In this case, the HFSE concentrations increase but are not accompanied by any changes in LILEs. Variable Nb/Zr ratios from the other cones (Fig. 3B) also suggest differential partial melting.

Role for Contamination?

Brush Mountain serves as a case example of how contamination is not a viable process for producing the different magma types erupting at the same vent. In a contamination scenario, the plausible parent is the alkaline basalt flow, while the andesitic scoria would be the product of assimilation of a silicic crustal component similar to the xenoliths in Lassen lavas (Borg and Clynne, 1998). A major problem with assimilation models is that the andesite has higher Mg#, Ni, and Cr, and more primitive olivine than the basalt flow, the opposite of what is expected from contamination by a silicic component.

Tapping Different Mantle Sources

The striking differences between the lava and scoria compositions from the Brush Mountain and Popcorn Cave cones seem to require that different magma batches were tapped for the scoria and subsequent lava flow. The differences in HFSEs, REEs, and radiogenic isotopes suggest that these different magma batches had very different origins.

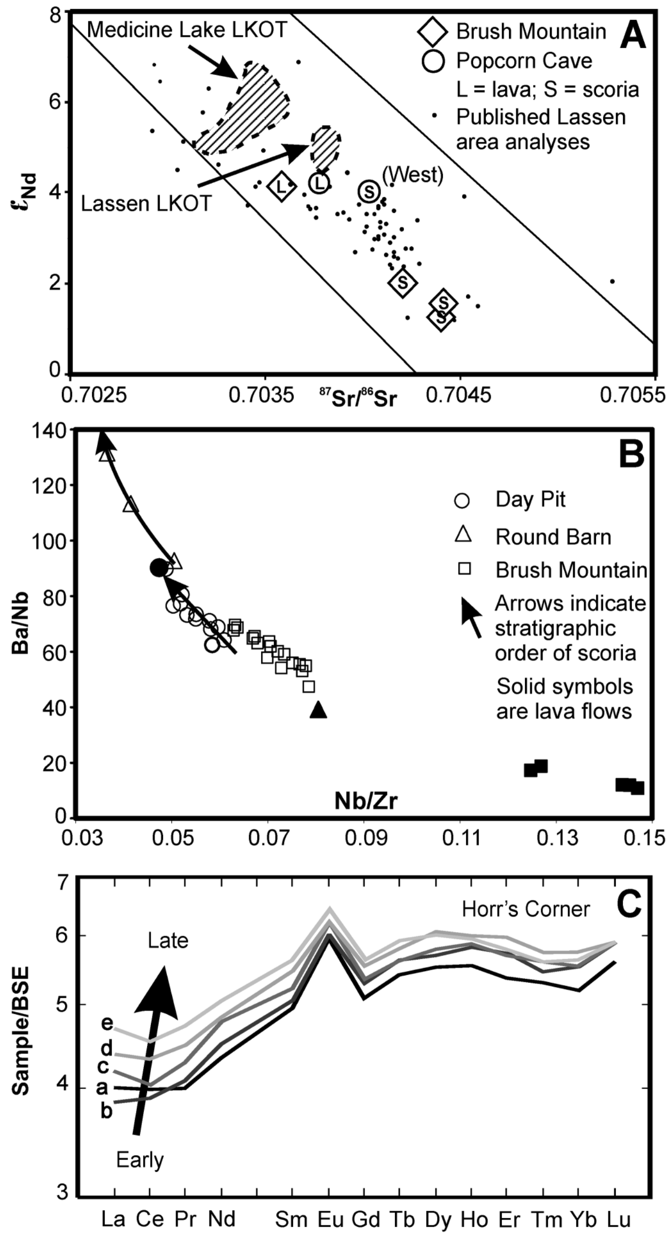

Figure 3. A: Radiogenic isotopes from two cones compared to regional Quaternary volcanic rocks. LKOT is low-potassium olivine tholeiite. B: Variations of large ion lithophile/high field strength element (LILE/HFSE) ratios within scoria and between scoria and lava. Day Pit and Round Barn scoria become progressively enriched in LILE/HFSE ratios upsection. There is no such pattern in Brush Mountain scoria. C: Horr's Corner scoria becomes progressively enriched in light rare earth elements upsection (a = base; e = top of section). BSE—bulk silicate earth.

In each cone the HFSE/heavy REE ratio variability of the two magma types makes it difficult to derive both compositions from a similar mantle. Using clinopyroxene/melt partition coefficients (Hart and Dunn, 1993), a mantle composition capable of producing the alkali basalt lava cannot generate the scoria's low HFSE/heavy REE ratios at any degree of partial melting. Using Brush Mountain rocks for illustration, one model that approximates the heavy REEs and a second model that approximates the HFSEs are plotted in Figure 2A. It appears that two mantle compositions, one with low HFSE/heavy REE ratios (similar to the normal mid-ocean-ridge basalt [N-MORB] source), and the other with higher HFSE (similar to an OIB source), are required to explain the variations of HFSE/heavy REE ratios. In addition to the

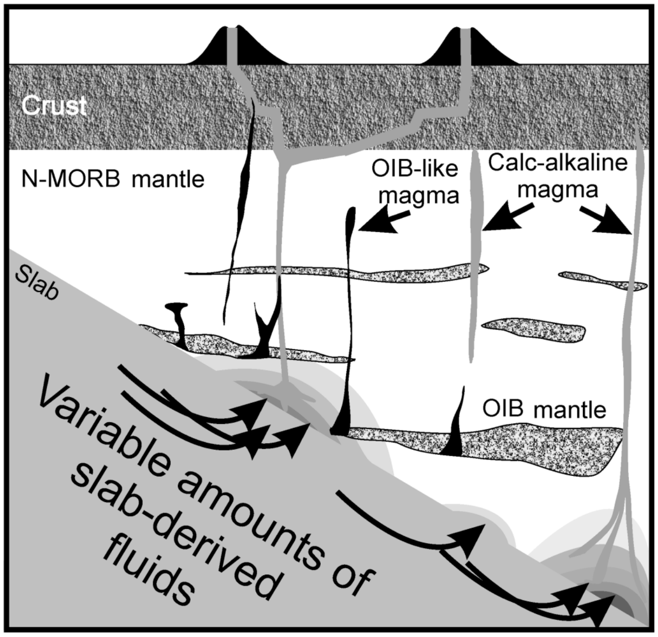

Figure 4. Proposed model for generation of observed chemical variations. Varying amounts of fluid fluxing from subducting slab generates low-volume batches of both calc-alkaline and oceanic-island basalt–like (OIB) magmas from heterogeneous mantle. Although many of these magma batches may freeze at depth, others may follow recently heated paths from previous magma ascents. As result, single eruption may lead to effusion of more than one magma batch. N-MORB—normal mid-ocean-ridge basalt.

two mantle components, a third component rich in fluid-mobile elements is required to explain the compositional variety. For the OIB-like magmas, there is a range of LILE enrichment, from the Brush Mountain lava (Ba/Nb ratio ~11) to the relatively enriched lava from the west Popcorn Cave cone (Ba/Nb ratio ~38). For this reason, we conclude that both OIB-source and N-MORB-source components in the mantle must be overprinted with variable amounts of slab-derived components.

IMPLICATIONS FOR SMALL-VOLUME BASALT GENERATION

Our observations raise questions as to the efficiency or even the existence of magma chambers for small-volume basaltic systems. Variations inherited from the mantle source could be preserved if the magmas were extracted and erupted immediately after generation. Rather than being stored in a homogeneous batch until a future ascent through the crust, magmas may rise through dike-like structures as a diffuse entity that never has the chance to homogenize (Fig. 4). If so, this implies that either the time scale for partial melting is very short, or it occurs over such a spatial scale that the melts do not have the chance to aggregate and mix. Work by Turner et al. (2001) suggests that melt-movement rates between generation and eruption in arc settings may be on the order of kilometers per year, consistent with a time scale needed to prevent homogenization of the melt batch. Small volumes of basaltic magma are thermally challenged in their ascent to the surface and may not complete the journey before crystallizing; perhaps they only reach the surface when they can follow the preheated path of a recent melt ascent. Alkaline melts due to small degrees of melting, such as the lava flow at Brush Mountain, are relatively rare in the Cascades. A heated pathway to the surface may be a prerequisite for the eruption of these magmas.

Most significantly, our results are consistent with findings from similarly detailed studies of small mafic eruptions and with recent reports of large isotopic variations in basalts at the phenocryst and melt inclusion scale (Saal et al., 1998; Rose et al., 2001). Regardless of the origins of these variations, we suggest that heterogeneity of basaltic melt batches should now be regarded as the rule rather than the exception.

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