Temporal–compositional trends over short and long time-scales in basalts of the Big Pine Volcanic Field, California

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Abstract

Primitive basaltic single eruptions in the Big Pine Volcanic Field (BPVF) of Owens Valley, California show systematic temporal–compositional variation that cannot be described by simple models of fractional crystallization, partial melting of a single source, or crustal contamination. We targeted five monogenetic eruption sequences in the BPVF for detailed chemical and isotopic measurements and ⁴⁰Ar/³⁹Ar dating, focusing primarily on the Papoose Canyon sequence. The vent of the primitive (Mg# = 69) Papoose Canyon sequence (760.8±22.8 ka) produced magmas with systematically decreasing (up to a factor of two) incompatible element concentrations, at roughly constant MgO (9.8±0.3 (1σ) wt.%) and Na₂O. SiO₂ and compatible elements (Cr and Ni) show systematic increases, while ⁸⁷Sr/⁸⁶Sr systematically decreases (0.7063–0.7055) and εNd increases (−3.4 to −1.1). ¹⁸⁷Os/¹⁸⁸Os is highly radiogenic (0.20–0.31), but variations among four samples do not correlate with other chemical or isotopic indices, are not systematic with respect to eruption order, and thus the Os system appears to be decoupled from the dominant trends. The single eruption trends likely result from coupled melting and mixing of two isotopically distinct sources, either through melt–rock interaction or melting of a lithologically heterogeneous source. The other four sequences, Jalopy Cone (469.4±9.2 ka), Quarry Cone (90.5±17.6 ka), Volcanic Bomb Cone (61.6±23.4 ka), and Goodale Bee Cone (31.8±12.1 ka) show similar systematic temporal decreases in incompatible elements. Monogenetic volcanic fields are often used to decipher tectonic changes on the order of 10⁵–10⁶ yr through long-term changes in lava chemistry. However, the systematic variation found in Papoose Canyon (10⁰–10² yr) nearly spans that of the entire volcanic field, and straddles cutoffs for models of changing tectonic regime over much longer time-scales. Moreover, ten new ⁴⁰Ar/³⁹Ar ages combined with chemistry from all BPVF single eruption sequences show the long-term trend of BPVF evolution comprises the overlapping, temporal–compositional trends of the monogenetic vents. This suggests that the single eruption sequences contain the bulk of the systematic chemical variation, whereas their aggregate compositions define the long-term trend of volcanic field evolution.

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1. Introduction

As melting products of the mantle, basaltic magmas are useful to interpret source variations and a range of melting and melt migration processes. Such interpretations are typically made based on chemical variations, both spatial and temporal, revealing different processes depending on the scale examined. Studies of single basaltic eruptions from individual vents, but lacking temporal control, have shown ranges of variation nearly as great as in entire volcanoes or regions (Harpp, 1995; Rubin et al., 2001; Maclellan et al., 2003). Other studies of intraplate basaltic magmatism, from continental monogenetic vents to hot spot volcanoes, have sampled with sufficiently high resolution to elucidate temporal–compositional variation within single eruption sequences. In some cases these variations are clearly related to shallow-level differentiation. But where they are not, temporal single eruption variation may be important to decipher
certain types of mantle processes and source variations in relatively primitive basalts, such as melt-rock reaction during melt migration, pervasive lithologic heterogeneity (e.g., meter or decimeter-scale veins), or melt-melt mixing, because these may be most evident in erupted products at this \(10^5-10^7\) yr timescale. In general, these sequences show temporal–compositional trends in several major and trace elements (Francis and Ludden, 1990; Glazner et al., 1991; Carracedo et al., 1992; Reiners and Nelson, 1998; Sigmansson et al., 1998; Garcia et al., 2000; Reiners, 2002). Reiners (2002) noted that these cases have several common features, including systematic decreases in incompatible major and trace elements (by up to a factor of 2–4) through the eruption sequence, accompanied by increases in SiO\(_2\) and Al\(_2\)O\(_3\), and comparatively small changes in compatible elements. Systematic changes in Sr and Nd isotopic compositions also are present in several of the sequences, though the senses and magnitudes of isotopic change are not consistent among different sites. Though studies of historic volcanic eruptions have the greatest temporal resolution (e.g. Carracedo et al., 1992; Garcia et al., 2000), determining the boundaries of single eruption sequences, at multiple points in time over a \(10^5-10^7\) yr history, can be difficult on large volcanoes. In monogenetic volcanic fields, however, this \(10^5-10^7\) yr concentrated eruption history is spread out into discrete cones, each representing an isolated \(10^5-10^7\) yr eruption, which can be used to compare temporal monogenetic vent variation to larger scale volcanic field and regional variation.

Here we focus on compositional variations within single eruption sequences of primitive, basaltic magmas (defined here as those with whole-rock Mg\#>0.68) and compare these to longer-term regional variations. A single eruption sequence is a series of erupted magmatic units produced from small, isolated volcanic vents that appear to be monogenetic, in a single eruption. Such vents, for example by analyzing stacked sequential flows of an eruption.

Because it has been well studied at the volcanic field scale and in the context of western US evolution, the Big Pine Volcanic Field (BPVF), provides a good location to target and contrast single eruption trends, and thus differentiate between small-scale magmatic and larger scale tectonic processes. The BPVF is located in the Owens Valley of California, east of the Sierra Nevada and on the far western edge of the western Great Basin (WGB). Basalts of the WGB straddle the \(^{87}\text{Sr}/^{86}\text{Sr}\) isotopic 0.7060 boundary (Kistler and Peterman, 1973) of the western U.S. and are highly variable in composition. Alkali-rich basaltic rocks range in \(^{87}\text{Sr}/^{86}\text{Sr}\) from 0.7040 to 0.7078, \(\varepsilon_{\text{Nd}}\) from –10.5 to 5.1, and SiO\(_2\) from 46 to 53 wt.% in samples with MgO>4 wt.% (Rogers et al., 1995). The BPVF comprises 1 silicic and ~24 basaltic monogenetic volcanic vents covering ~500 km\(^2\) and ranging in age from 1.2 to 0.032 Ma (Gillespie et al., 1983; Turrin and Gillespie, 1986; Kempton et al., 1991; Connor and Conway, 2000). Mafic lavas range from basanites to alkaline and sub-alkaline basalts. Most lavas, many of which are primitive, are largely aphanitic and contain a variety of xenoliths (Darrow, 1972, 1974; Moore and Dodge, 1980). Whole-rock \(^{87}\text{Sr}/^{86}\text{Sr}\) ratios range from 0.70534 to 0.70648, \(\varepsilon_{\text{Nd}}\) ranges from ~6.0 to 0, SiO\(_2\) concentrations vary from 44.1 to 53.0 wt.%., and MgO from 5.5 to 13.0 wt.% (Darrow, 1972; Ormerod, 1988; Ormerod et al., 1988, 1991; Beard and Glazner, 1995; Rogers et al., 1995; Waits, 1995; Reid and Ramos, 1996; Beard and Johnson, 1997; DePaolo and Daley, 2000; Wang et al., 2002). Previous studies of the BPVF and the WGB have attributed compositional variation to a variety of processes occurring over \(10^7–10^7\) yr time-scales including contributions from heterogeneous melt-metasomatized lithospheric mantle (Menzies et al., 1983; Beard and Glazner, 1995; Leeman, 1995), lithospheric foundering and subsequent increased asthenospheric input (Ducea and Saleeby, 1998; Lee et al., 2001; Elkins-Tanton and Grove, 2003), or variable degrees of partial melting of a homogenous lithospheric mantle (Ormerod et al., 1991).

Xenoliths not only provide possible source region analogues but also may constrain some of the wall rock material during BPVF magma transport. BPVF xenoliths are dominantly ultramafic, and include dunites, harzburgites, lherzolites, websterites, orthopyroxenites, clinopyroxenites, hornblendetes, hornblende diorites, gabbro, and granodiorites similar to the Eastern Sierran batholith (Ducea and Saleeby, 1996). Garnet is absent in Big Pine xenoliths (Darrow, 1972; Ducea and Saleeby, 1996), as it is in most mantle xenoliths of the western United States (Wilshire et al., 1988). Thermobarometry of mantle xenoliths in Owens Valley, including the BPVF, show some peridotites equilibrated as shallowly as 35 km, but at high temperatures (1180–1250 °C) and following an adiabat, suggesting that the uppermost mantle here is asthenospheric up to the base of the crust (Ducea and Saleeby, 1996). Clinopyroxene thermobarometry of the BPVF melts yield an average depth of 45 km and higher equilibration temperatures of 1240–1356 °C (Mordick and Glazner, 2006). Regional magnetotelluric studies beneath Owens valley and electrical conductivity work on BPVF xenoliths give conductivity values consistent with an interconnected, conductive fluid in the uppermost mantle, likely partial melt (Park and Ducea, 2003). Whole rock and clinopyroxene separates of spinel lherzolites have \(\varepsilon_{\text{Nd}}\) values ranging from ~3.7 to +14.1 and \(^{87}\text{Sr}/^{86}\text{Sr}\) from 0.70218–0.70652 (Beard and Glazner, 1995). Sr and Nd isotopic compositions of the mantle xenoliths extend to much more isotopically depleted values than the lavas and cluster bimodally either in enriched or depleted isotopic space.

2. Samples and methods

2.1. Field work and sample collection

We chemically analyzed and dated basalts from five different monogenetic single eruption sequences as well as samples from cones with no easily identifiable sequences. We applied new names, in quotes, to five previously unnamed (or inconsistently named) single eruption sequences in the BPVF (Fig. 1). The
Fig. 1. Map of the Big Pine Volcanic Field. Landsat Orthoimagery Mosaic (RGB=432). Green stars indicate single eruption sequences with $^{40}\text{Ar}/^{39}\text{Ar}$ and chemical analyses. Blue stars indicate sample locations with $^{40}\text{Ar}/^{39}\text{Ar}$ and chemical analyses. Yellow points indicate sample locations with chemistry only. $^{40}\text{Ar}/^{39}\text{Ar}$ ages are given in the grey text boxes. Top inset is a USGS shaded relief map of California with a white box representing the BPVF. Owens Valley is the N–S trending graben containing the BPVF directly east of the Eastern Sierra. The bottom inset shows the thin, stacked flows of latter (upper) part of the Papoose Canyon single eruption sequence (samples 03MB07–03MB19). Earlier, thicker flows are to the left of the image. The author, in a red shirt, is at the base of the sequence for scale.
largest sequence, with the greatest number of distinguishable flows and chemical variation, is "Papoose Canyon." This vertical section of stacked flows derives from the easternmost of three cinder cones to the east of the Tinemaha Reservoir. Two other cones, the northern "Quarry Cone" and the western "Jalopy Cone," also contain visible and sampled stacked sequences. On the western side of the BPVF, "Goodale Bee," south of Goodale Creek, has a sequence of stacked flows, and "Volcanic Bomb Cone," between Goodale and Taboose Creeks, has three flows whose order we determined by flow contacts. We also sampled the southern and easternmost flows of Oak Creek for chemistry and ⁴⁰Ar/³⁹Ar dating. Flow thicknesses in all vents range from a few centimeters to ~30 m, the entire range found in the Papoose Canyon sequence. Except in the thinnest flows, we sampled at the flow centers. In all but Volcanic Bomb Cone, not every identifiable flow was sampled, especially where multiple stacked thin flows were present. Precise sample locations are given in Table 1 for the Papoose Canyon sequence and in Table A1 of the online supplementary material for all five sequences.

2.2. Analytical methods

Major and trace element concentrations were determined for the samples described above using standard XRF and ICP-MS techniques at Washington State University. Sr and Nd isotopic analyses for fourteen whole-rock Papoose Canyon samples were performed on a VG Sector 54 multiple collector mass spectrometer at the University of Arizona. The filament loading and mass spectrometric analysis procedures were similar to the ones previously described by Ducea et al. (2003). The Sr isotopic ratios were normalized to ⁸⁶Sr/⁸⁸Sr=0.1194, whereas the Nd isotopic ratios were normalized to ¹⁴⁶Nd/¹⁴⁴Nd=0.7219. Estimated analytical ±2σ uncertainties are: ⁸⁷Sr/⁸⁶Sr=0.0011% and ¹⁴⁴Nd/¹⁴⁶Nd=0.0018%. Ten analyses of standard SRM 987 analyzed during the course of this study yielded mean ratios of ⁸⁶Sr/⁸⁸Sr=0.710265±7 and six analyses of Nd standard La Jolla Nd yielded a mean ratio of ¹⁴⁴Nd/¹⁴⁶Nd=0.511849±11. The grand means of isotopic ratios were corrected by an off-line manipulation program, which adjusts for the fractionation correction for each ratio. Os isotopic compositions and Re–Os concentrations were determined at the University of Arizona for four samples by NTIMS. Isotope dilution measurements of Re and Os were undertaken on samples collected and processed with special care to avoid metal contamination (for Os) and powdered using an alumina jaw crusher and shatter box. Powders were prepared by crushing for 5–10 min to ensure homogeneity and also to minimize the grain size to avoid the nugget effect. Sample dissolution, spike equilibration (¹⁸⁵Re and ¹⁹⁰Os), analytical methods, blanks and reproducibility are described in detail in Chesley et al. (2002) and Righter et al. (2008).

⁴⁰Ar/³⁹Ar ages were determined at the University of Wisconsin, Madison, following methods of Singer et al. (2004). Procedures involved crushing and sieving whole-rock samples to isolate the 180–250 micron fraction, isolating the magnetic groundmass with a hand magnet, separating remaining olivine using heavy liquids, and hand picking. The remaining groundmass was used for dating. Three to four packets of 10 samples, each ~100 mg, were wrapped in Cu foil and irradiated for 15 min at Oregon State University along with sanidine from the 1.194 Ma Alder Creek rhyolite (Renne et al., 1998). Corrections for undesirable nucleogenic reactions on ⁴⁰K and ⁴⁰Ca, based on previous measurements of Ca- and K-free salts (see Singer et al., 2004), are ⁴⁰Ar/³⁹ArK=0.00086; ⁴⁰Ar/³⁹ArCa=0.000264; ⁴⁰Ar/³⁹ArCa=0.000673. Incremental heating experiments of 12 to 16 steps between 500 and 1220 °C using a resistance furnace were done on each sample; additional experiments were done on three of these samples to minimize random errors and improve precision. Blanks were measured in 100 to 200 °C increments from 600 to 1200 °C before and after each sample and were about 2×10⁻¹⁸ mol of ³⁶Ar and 5×10⁻¹⁶ mol of ⁴⁰Ar in atmospheric proportions. These blanks are orders of magnitude smaller than the sample signals and, because of the large size of the samples, contribute less than 1% to the final uncertainty of the age calculation. Mass discrimination was monitored using an automated air pipette and was 1.0070±0.0003 to 1.0074±0.0003 per atomic mass unit during the analytical period. Age plateau and isochron criteria are those of Singer et al. (2004) with uncertainties reflecting analytical procedures estimated at the 2σ level. Because isochrons do not assume that the trapped component is atmospheric in composition, the isochron ages are preferred over the plateau ages.

3. Results

3.1. ⁴⁰Ar/³⁹Ar ages

⁴⁰Ar/³⁹Ar ages, ranging from 31.8±12.1 to 1273±119 ka, were determined for ten different locations in the BPVF (Figs. 1–3, Table 2). Details of the heating experiments can be found in the appendix (Table A2). All but one of the fourteen heating experiments for the ten locations yield nearly concordant spectra with >94% ³⁹Ar defining a plateau. The 63.1% ³⁹Ar released from intermediate steps define a plateau for the remaining sample, 05MB110. All experiments have atmospheric inverse isochron ³⁶Ar/³⁹Ar intercept ratios and thus no evidence for excess argon. At least for Papoose Canyon, our inference that different flows from a single vent represent a short-lived, single eruption is consistent with the ⁴⁰Ar/³⁹Ar ages. Two separate incremental heating experiments on an early flow of this sequence (Papoose Bottom) and the youngest flow suitable for ⁴⁰Ar/³⁹Ar dating (Papoose Mid) yield statistically indistinguishable inverse isochron ages of 747.6±31.1 and 776.2±33.6 ka, respectively. The combined Papoose Canyon inverse isochron age from these four experiments is 760.8±22.8 ka (Fig. 3c).

3.2. General description of the sequence and petrography

Systematic petrographic variations through the eruption sequence include an upsection decrease in flow thickness and xenolith abundance, an increase in vesicularity and alteration, and the presence of augite megacrysts in the earliest flows up to 03MB35. Olivine is the dominant phenocryst in most flows, but neither its abundance nor size changes systematically.

translated through the sequence. A few samples have ~5% clinopyroxene and plagioclase phenocrysts. Groundmass phases in all samples include plagioclase, olivine, orthopyroxene, clinopyroxene, magnetite, \( \pm \) albite \( \pm \) hematite \( \pm \) alkali feldspar \( \pm \) calcite \( \pm \) trace amounts of apatite. There is a bimodal distribution of Mg\# in the olivine phenocrysts. The "normal" olivines range from \( \text{Fo}_{79.4} - 89.7 \). Cores are generally more magnesian than the rims. The second group has highly unusual, extremely forsteritic (\( \text{Fo}_{97.2} \)) compositions, and abundant oxide and pyroxene inclusions. Rare occurrences of similar high magnesian olivines have been observed in other settings, and were interpreted as either forming under highly oxidized conditions (Sigurdsson and Brown, 1970) or as regenerated olivines from dehydrated serpentinites (Vance and Duncan, 1977). Because the presence or abundance of high Fo olivine in flows of the BPVF does not correspond to the systematic whole rock variation targeted in this paper, we do not further address these forsterites here. Xenoliths in Papoose Canyon include peridotites, wehrlites, spinel clinopyroxenites, and locally-derived crustal material. Reaction rims between xenoliths and the basaltic groundmass are evident although minor.

Table 1

<table>
<thead>
<tr>
<th>Locations, major elements, trace elements, and isotopes for the Papoose Canyon single eruption sequence</th>
</tr>
</thead>
<tbody>
<tr>
<td>Papoose samples, oldest to youngest</td>
</tr>
<tr>
<td>29</td>
</tr>
<tr>
<td>N</td>
</tr>
<tr>
<td>W</td>
</tr>
<tr>
<td>SiO2</td>
</tr>
<tr>
<td>SiO2 (ppt)</td>
</tr>
<tr>
<td>Zr/Ba</td>
</tr>
<tr>
<td>Zn</td>
</tr>
<tr>
<td>⁴⁴Nd/⁴⁰Nd</td>
</tr>
<tr>
<td>Os (ppt)</td>
</tr>
<tr>
<td>Sm/Yb</td>
</tr>
<tr>
<td>Zr/Th</td>
</tr>
</tbody>
</table>

Major element oxides are normalized on an anhydrous basis to 100%. 2\( \sigma \) error estimates are 5% for the REE, < 10% for the other trace elements, and < 2 wt.% for the major element oxides. Unnormalized and normalized data for all five single eruption sequences, individual basalt flows and xenoliths are found in the Supplementary Material Table 1A.
3.3. Geochemistry and description of trends

Using whole rock geochemical and isotopic data (Table 1), we distinguish five types of temporal element, oxide, or isotopic trends in the Papoose Canyon eruption sequence. As shown in Fig. 4, these are: 1) decreasing throughout the sequence, 2) constant then decreasing, 3) increasing, 4) a middle peak (increasing then decreasing), and 5) no systematic variation. Most of the highly incompatible species show simple systematic decreases in concentration throughout the eruptive sequence by as much as a factor of two (e.g. La from 68 to 34 ppm; Sr from 1900 to 990 ppm; Ba from 1400 to 700 ppm; K<sub>2</sub>O from 2.2 to 1.2 wt.%) (Fig. 4a). Some major elements, FeO<sub>total</sub>, TiO<sub>2</sub>, and CaO show less pronounced decreases throughout the eruption sequence. Nb and Ta concentrations normally behave as highly incompatible elements but in this case they remain constant until the middle of the sequence (at approximately sample MB41) and then begin to decrease (Fig. 4b). Compatible trace elements such as Ni (150–210 ppm) and Cr (190–380 ppm) show systematic increases in concentration through the eruption sequence (Fig. 4c). Al<sub>2</sub>O<sub>3</sub> and SiO<sub>2</sub> also increase by more than...
2 wt.% (45–48 wt.%) (Fig. 4c). The HREE, including Er, Tb, Yb, and Lu, have peak concentrations in the middle of the eruption sequence, specifically at sample MB41 (Fig. 4d). In Er, Tb, and Yb, there is evidence of a slight decrease in concentration during the beginning of the eruption, then an increase and peak at sample MB41, followed by a decrease. However, the magnitude of variation in the HREEs (~10%) is much smaller than the LREEs, (~50%). MgO (9.8±0.3 (1σ) wt.%), Na2O (3.6±0.4 (1σ) wt.%), and MnO do not show any systematic variation over time (Fig. 4e). Sr and Nd isotope ratios also show clear trends through the eruption sequence. 87Sr/86Sr decreases from 0.7063 to 0.7055 with time, and εNd increases from −3.4 to −1.1 (Fig. 4f). 187Os/188Os ratios of four samples are highly radiogenic (0.20–0.31) and do not change systematically through the sequence (Fig. 4f).

The other BPVF single eruption sequences we examined show more restricted chemical variation but some of the same temporal–compositional trends, especially for those elements that have the greatest magnitude variation in the Papoose sequence. The common trend, associated with all five monogenetic vents, is the decrease in the incompatible elements, including Sr and La (Fig. 5). Lanthanum concentrations in Jalopy Cone decrease from 53 to 45 ppm, in Quarry Cone from 40 to 32 ppm, and in Goodale Bee from 47 to 35 ppm. The three flows of Volcanic Bomb Cone have La concentrations that change from 50 to 28 to 48 ppm. Only Goodale Bee Cone, like Papoose Canyon, has primitive MgO contents that do not vary systematically during the eruption sequence (10±0.2 (1σ) wt.%; Mg# =70). Both Jalopy and Quarry cones show decreases in MgO with stratigraphic height (7.55 to 6.04 and 7.83 to 6.89 wt.%, respectively). Volcanic Bomb cone has MgO contents that change from 9.45, 7.49, and 9.42 wt.% with time. The lower MgO contents of some of these lavas are likely the result of shallow level olivine fractionation.

3.4. Comparison to the WGB and the western US

Trace element and isotopic compositions of Papoose Canyon lavas fall within the range of the BPVF and the greater WGB (Fig. 6) (Beard and Glazner, 1995; Beard and Johnson, 1997; DePaolo and Daley, 2000, and references therein; Hughes, 1986; Glazner et al., 1991; Ormerod et al., 1991; Rogers et al., 1995; Reid and Ramos, 1996), but the isotopic variation within the Papoose Canyon sequence spans nearly that of all the BPVF basalts. As seen in the broader BPVF, the basalts have a significantly more restricted range of isotopic compositions than the peridotite xenoliths (Beard and Glazner, 1995).

4. Discussion/interpretations

4.1. Olivine correction

To compare trace element contents of all the single eruption sequences, we corrected bulk compositions for olivine
fractionation for those samples in the remaining four sequences with less than 10 wt.% MgO. For major elements this was done by iteratively adding small mass fractions ($1 \times 10^{-6}$) of olivine in equilibrium with the basalt, assuming a $K_D$ (the distribution coefficient describing the partitioning of Mg and Fe between olivine and liquid (Roeder and Emslie, 1970)) of 0.3 until the MgO content of the basalt was 10 wt.%. We then used the calculated degree of crystallization, $X$ (Table A1), for each sample to correct trace element concentrations for fractionation using partition coefficients for each element in olivine (McKenzie and O’Nions, 1991). Fig. 5 shows fractionation-corrected Sr concentrations in the five single eruption sequences with compiled BPVF data and $^{40}$Ar/$^{39}$Ar ages from this study. In addition to the short-term individual trends, all the data combined gives a long-term pattern of incompatible element depletion with the same direction of variation.

4.2. Implausibility of fractional crystallization or single source melting

Some of the most commonly invoked mechanisms for explaining chemical variation in basalts are fractional crystallization and varying degrees of partial melting of a single source, but these simple mechanisms cannot produce the trends in the Papoose Canyon sequence. Partial melting of a single source is not possible simply because of the temporally variable isotopic composition, which requires multiple sources.

Fractional crystallization alone can be ruled out because the approximately two-fold variation in highly incompatible elements in the Papoose Canyon sequence would require roughly 50% fractional crystallization, whereas the range of Ni contents in the lavas restricts the maximum extent to less than 5−10%. Fractional crystallization would also be expected to generate
Table 2

Ar/Ar experiments for 10 locations in the BPVF

<table>
<thead>
<tr>
<th>Sample Location</th>
<th>Latitude</th>
<th>Longitude</th>
<th>Age spectrum</th>
<th>N</th>
<th>Isochron analysis</th>
</tr>
</thead>
<tbody>
<tr>
<td>Experiment wt. K/Ca total</td>
<td>Total fusion Age (ka)±2σ</td>
<td>Increments used (°C)</td>
<td>39Ar (%)</td>
<td>Age (ka)±2σ MSWD</td>
<td>MSWD 40Ar/36Ar±2σ</td>
</tr>
<tr>
<td>05-MB-76 Goodale Bee</td>
<td>N 36°58.168′ W 118°17.900′</td>
<td>37.9±12</td>
<td>540–1150</td>
<td>100</td>
<td>35.4±7.4</td>
</tr>
<tr>
<td>05-MB-113 Bomb Cone</td>
<td>N 36°59.567′ W 118°17.975′</td>
<td>91.9±14.2</td>
<td>540–1150</td>
<td>100</td>
<td>87.0±11.7</td>
</tr>
<tr>
<td>05-MB-107 Quarry Cone</td>
<td>N 37°00.909′ W 118°10.056′</td>
<td>85.7±9.9</td>
<td>520–1150</td>
<td>100</td>
<td>89.8±9.3</td>
</tr>
<tr>
<td>05-MB-109 Oak Creek, GB</td>
<td>N 36°50.564′ W 118°18.775′</td>
<td>230.1±27.5</td>
<td>560–1220</td>
<td>98.2</td>
<td>215.1±18.9</td>
</tr>
<tr>
<td>05-MB-94 Jalopy Cone</td>
<td>N 37°00.765′ W 118°11.525′</td>
<td>471.5±7.1</td>
<td>540–1150</td>
<td>100</td>
<td>469.5±5.3</td>
</tr>
<tr>
<td>05-MB-106 Papoose Bot.</td>
<td>N 37°00.912′ W 118°09.807′</td>
<td>757.5±26.0</td>
<td>520–1180</td>
<td>98.8</td>
<td>757.0±20.5</td>
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<tr>
<td>05-MB-108 Papoose Mid</td>
<td>N 37°00.918′ W 118°10.230′</td>
<td>758.0±22.4</td>
<td>520–1200</td>
<td>100</td>
<td>751.2±19.3</td>
</tr>
<tr>
<td>05-MB-105 Papoose Dike</td>
<td>N 37°00.894′ W 118°09.739′</td>
<td>782.1±13.0</td>
<td>540–1150</td>
<td>100</td>
<td>783.7±10.6</td>
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<tr>
<td>05-MB-111 Oak Creek, GA</td>
<td>N 36°50.804′ W 118°17.301′</td>
<td>1221±16</td>
<td>520–1200</td>
<td>100</td>
<td>1221±15</td>
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<tr>
<td>05-MB-110 Oak Creek, GC</td>
<td>N 36°50.299′ W 118°18.747′</td>
<td>1198±15</td>
<td>630–880</td>
<td>61.3</td>
<td>1240±15</td>
</tr>
</tbody>
</table>

Bold ages are either the only or the weighted average age of multiple experiments.
lower MgO concentrations in samples with high incompatible element concentrations, but all of the lavas have high (~10 wt.%) and nearly constant MgO concentrations, and the Mg# is near equilibrium with Fo 89 olivine.

4.3. Multiple sources

4.3.1. Depleted and enriched end-members

Sr and Nd isotopic compositions of Papoose Canyon magmas require a source with a (long-term) relatively incompatible-element depleted (low $^{87}$Sr/$^{86}$Sr, high $\varepsilon_{Nd}$) composition, and a relatively enriched (incompatible-element enriched, high $^{87}$Sr/$^{86}$Sr, low $\varepsilon_{Nd}$) one (Figs. 5 and 6). Assuming binary mixing, asymptotic relationships of isotopic compositions as a function of trace element ratios (Albarède, 1995) suggest that the enriched component would have $^{87}$Sr/$^{86}$Sr of approximately 0.7065 and $\varepsilon_{Nd}$ of −3.75. This is near the most enriched basalt and peridotite xenolith compositions in the BPVF (Fig. 6), which falls within the OIB field on the mantle array, and the isotopic composition of much of the proximal Sierran Batholith (Kistler and Peterman, 1973).

The temporal control on the eruption sequence requires that a mixing scenario must produce higher proportions of the isotopically and incompatible element enriched component in the early erupting melts and increasing proportions of the depleted component, projecting toward MORB and the depleted BPVF xenoliths, in later melts (Fig. 6). BPVF mantle xenoliths show a much broader range of isotopic variation than the BPVF basalts and their bimodal distribution could represent parent end-members (Fig. 6).

Fig. 4. Geochemical trends of the Papoose Canyon primitive single eruption sequence. a–e) Five types of trends are evident in the Papoose Canyon single eruption sequence. In all graphs increasing stratigraphic height is to the right. C/C$_{\text{max}}$ is the concentration of the denoted species in a particular hand sample normalized to its maximum concentration in the entire sequence (see Table 1 for concentrations). Note the expanded scale on the secondary y-axis for SiO$_2$ and Al$_2$O$_3$. f) Sr, Nd, and Os isotopic compositions throughout the eruption sequence. Axes for both $\varepsilon_{Nd}$ and $^{187}$Os/$^{188}$Os are on the right hand side of the figure. $^{87}$Sr/$^{86}$Sr systematically decreases while $\varepsilon_{Nd}$ systematically increases through the Papoose Canyon eruption sequence. Os isotopic ratios show no consistent trend, but are highly radiogenic.
4.3.2. Crustal contamination

The highly radiogenic Os found in the lavas is suggestive of crustal input. However, several features of the data are inconsistent with any simple scenario of crustal contamination as the dominant control of the geochemical and isotopic trends in the Papoose Canyon lavas. The lavas are primitive, with high and relatively uniform MgO. Abundant mantle xenoliths, such as are found in the Papoose Canyon sequence, are typically interpreted to require a very short residence time in the crust, though this also could be explained by a rapidly convecting magma chamber or re-entrainment by a later melt. The inverse correlation between incompatible elements and SiO$_2$ is opposite

Fig. 5. Short-term vs. long-term trends. Decreasing incompatible element concentrations with time are evident in both single eruptions (10$^5$–10$^7$ yr time-scale) and over the history (10$^3$–10$^5$ yr time-scale) of the BPVF. Each string of data is one single eruption sequence. The x-axis represents increasing relative time to the right. The trace elements for sequences with less than 10 wt.% MgO are corrected for olivine fractionation as described in Section 4.1. The stated age is the age for all flows in each single eruption sequence. The three data points on the far left are from the Oak Creek region, which consists of multiple eruptions of different ages (Table 2) and includes the oldest flows in the BPVF. The black boxes are Sr concentrations of basalts from the same vents published in earlier studies (Ormerod, 1988; Waits, 1995).

![Graph showing short-term vs. long-term trends](image)

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Fig. 6. Sr–Nd isotope plots for Papoose Canyon, the BPVF, the greater Western Great Basin, and other areas of the western U.S. for comparison. The Papoose Canyon sequence (blue squares/field) trends to higher $\varepsilon_{Nd}$ and lower $^{87}$Sr/$^{86}$Sr with time. The Papoose Canyon sequence nearly spans the isotopic field of the entire BPVF (yellow field). The BPVF basalts fall at one end-member of the BPVF peridotite xenolith compositions (grey field). Western Great Basin basalts are shown in the green field. The white field with the black outline represents chemical analyses from other locations in the Basin & Range and Colorado Plateau (Beard and Johnson, 1997; DePaolo and Daley, 2000, and references therein; Kempton et al., 1991; Reid and Ramos, 1996). The vertical dotted line is the maximum $^{87}$Sr/$^{86}$Sr calculated for the enriched component from Section 4.3.1. The horizontal dotted line is the minimum $\varepsilon_{Nd}$ calculated for the enriched component.

![Sr–Nd isotope plots for Papoose Canyon, the BPVF, and other areas](image)
of expectations for contamination by silicic crust, and carbonate contamination would be expected to decouple the Sr and Nd isotopic systems. Os isotopic compositions do not correlate with Sr and Nd isotopic systems or any of the major and trace element trends. This suggests primary variation within the mantle was overprinted by mixing of the mantle melt with mafic lower crustal material leading to a decoupling of the Os from the other isotopic and chemical systems.

The $^{187}\text{Os}/^{188}\text{Os}$ in peridotite and unmodified basalts rarely have values $>0.135$, in part due to the low Re/Os ratios and high Os concentrations in the upper mantle (Shirey and Walker, 1998; Chesley et al., 2004). Assimilation and fractional crystallization (AFC) or binary mixing of a mafic assimilant into a basalt are the two most reasonable scenarios that would result in elevated $^{187}\text{Os}/^{188}\text{Os}$ up to levels of 0.31 without significantly changing the Sr, Nd or trace element signatures in the Papoose Canyon lavas. Assuming the contaminant has higher $^{87}\text{Sr}/^{86}\text{Sr}$ than the initial melt, it is possible to fit an AFC model in $^{87}\text{Sr}/^{86}\text{Sr}$ vs. [Sr] space to the Papoose Canyon data in which the melt in a conduit becomes progressively immune to contamination effects during an eruption. However, this implies significant amounts of olivine fractionation from the earliest erupting melts, which is not supported by the invariant and relatively high MgO without invoking contamination by a highly incompatible-element enriched but high-MgO source. For example, with an initial melt with $^{87}\text{Sr}/^{86}\text{Sr}=0.7035$ and [Sr]=400, and an isotopically enriched assimilant with $^{87}\text{Sr}/^{86}\text{Sr}=0.7070$ and [Sr]=200, $D=0.001$, and $r_f=0.98$, about 13% crystallization is required to match the $^{87}\text{Sr}/^{86}\text{Sr}$ and [Sr] of the earliest Papoose Canyon melt, and this would decrease the MgO of the first Papoose Canyon melt from 10 to 5 wt.%. Binary mixing between a basalt ([Os]=15 ppt, $^{187}\text{Os}/^{188}\text{Os}=0.13$) and a mafic assimilant ([Os]=20 ppt, $^{187}\text{Os}/^{188}\text{Os}=1$) would require incorporation of up to 15% of the mafic material to reach $^{187}\text{Os}/^{188}\text{Os}$ of 0.31. However, if 15% mafic lower crust were incorporated, it must have MgO, $^{87}\text{Sr}/^{86}\text{Sr}$, and $\varepsilon_{\text{Nd}}$ similar to the original melt, which could reflect mixing with older underplated basalt as a mechanism of the Os decoupling. If the contaminant had higher [Os] or $^{187}\text{Os}/^{188}\text{Os}$, then only a few percent of it would be required to change a peridotite-derived melt to $^{187}\text{Os}/^{188}\text{Os}$ of 0.31, which could have negligible effects on the other systems. Although crustal contamination likely affected certain elements and isotopes, particularly Os, it is difficult to reconcile with the large magnitude and systematic trends for most elements and isotopes.

4.3.3. Coupled mixing and melting

Here we examine qualitative mixing and melting scenarios that may generate the single eruption trends, so that in the next section we can compare variation resulting from short-term single eruption processes to long-term tectonic variation. We can infer from the geochemical trends that simple binary melt mixing is not possible. Whereas a linear mixing model can be supported by the systematically decreasing LREE and other highly incompatible elements, more complicated time-series trends for some elements (such as the HREE; Fig. 4) show that either more than two sources are required or that some other process, such as coupling between degrees of melting and mixing of the two sources, is required. In the absence of isotopic evidence for more than two sources, we favor an interpretation involving a coupled melting and mixing model.

Asthenspheric and continental lithospheric mantle are often invoked as potential sources of isotopically depleted and enriched magmas, respectively. Certain regions of the lithosphere have been enriched over time by ascending melts and fluids from subducting slabs leaving these areas very highly enriched compared to the asthenosphere (Menzies et al., 1983). Hot, depleted asthenospheric melts may rise and heat the base of the lithosphere, inducing melting of enriched domains. If these chemically evolving melts are preferentially sampled in early-erupting melt but then are overwhelmed by the ascending asthenospheric melts, this could generate temporal–compositional trends at least qualitatively similar to those observed. If there was no existing mantle lithosphere beneath the BPVF at the time of eruption, as suggested in Ducea and Saleeby (1996), then the isotopically enriched end-member may be delaminated lithosphere that had become convectively entrained and heated in the asthenosphere, consistent with the hot, enriched xenoliths found in the BPVF.

Another way to generate enriched and depleted melts that could potentially serve as end-members in the Papoose Canyon sequence is through lithologic heterogeneity in the mantle source region. Mafic heterogeneities (e.g., pyroxenites), for example, would be expected to have both compositions and melt productivities different from those of ambient peridotite matrix. These heterogeneities could be derived from old subducted material or incompletely extracted melts that have not been completely mixed back into the asthenosphere (Lassiter and Hauri, 1998; Lassiter et al., 2000; Kogiso et al., 2004). Reiners (2002) proposed that, because pyroxenites may begin melting deeper and melt to larger degrees than ambient peridotite in upwelling mantle (Hirschmann and Stolper, 1996), temporal–compositional trends could reflect sequential top-down eruption of small-degree peridotite melts overlying high-degree pyroxenite melts. This mechanism assumes that a high degree of melting of pyroxenite exerts a larger control on the incompatible element concentration of its melt than the initial source composition, which would probably be enriched relative to peridotite matrix. In contrast, the isotopic composition of the pyroxenitic source may be isotopically depleted, relative to peridotite (e.g., Hirschmann and Stolper, 1996). Recent studies (Tuff et al., 2005; Sobolev et al., 2007) show a Ni increase with an increased pyroxenite source component, which in our study would indicate an increasing pyroxenite component during the course of a single eruption.

Another potential source of the chemical variation is melt-mantle interaction. Spiegelman and Kelemen (2003) showed that reactive porous melt channels in the mantle (e.g. Kelemen et al., 1995) can produce extreme small-scale chemical variation from a homogenous source. In the context of these single eruption trends, decreasing concentrations of incompatible elements in sequentially erupted melts could, at least qualitatively, be produced by sequentially tapping high porosity channel centers (tapping deep small-degree melts), outward to the
depleted low porosity channel edges. The systematic isotopic variation observed in the Papoose Canyon sequence, however, requires at least two compositionally distinct sources, which could indicate different isotopic compositions of the migrating melt (and its original source) and mantle wall rock. Other mechanisms of melt-rock interaction that could theoretically produce temporal–compositional trends include linked fractional crystallization and wall rock interaction processes (e.g. DePaolo, 1981), or the chromatographic effects of melt reaction with a porous mantle during extraction (Navon and Stolper, 1987; Godard et al., 1995; Reiners, 1998). Variation generated by chromatographic processes alone, however, is inconsistent with the good correlations among many elements with strongly varying distribution coefficients, so that substantial dispersion or mineralogical reaction would be necessary in the model.

4.4. Petrotectonic associations

The new $^{40}$Ar/$^{39}$Ar ages combined with single eruption chemistry from five different vents show that there is both a short-term (single eruption) and long-term (volcanic field) temporal trend of decreasing incompatible elements (Fig. 5). Both short and long-term trends show the same direction of variation, consistent with common source materials. These data reveal the importance of interpreting basaltic geochemical signatures in the context of chemical variation over different time-scales. For example, the geochemical and isotopic variation in the Papoose Canyon single eruption sequence is nearly as great as the entire BPVF, but this variation occurs on a much shorter time-scale ($10^5–10^7$ yr) than could be reasonably expected for a large-scale tectonic control ($10^5–10^7$ yr). The fact that long-term and short-term data sets show similar chemical patterns and range of variation over time underscores the possibility that short-term (i.e., single-eruption) variation could obscure, distort, or even cause aliasing of long-term signals sampled narrowly in time or space. Thus before large time-scale interpretations (e.g., based on tectonic processes) are made, it is important to characterize and distinguish the short-term variation.

Two examples involving BPVF data illustrate similarity of short and long-term geochemical trends, and potential problems with inferring large-scale petrotectonic processes when the scale of variation may not be fully understood. Ormerod et al. (1988) interpreted Zr/Ba and $^{87}$Sr/$^{86}$Sr changes in WGB basalts erupted over ~1 Myr as reflecting an increasing asthenospheric component in their mantle source due to melts forming behind the tailing edge of the subducting plate beneath the region. These authors defined a cut-off point in these indices, whereby lavas with Zr/Ba $\geq 20$ and $^{87}$Sr/$^{86}$Sr $< 0.7060$ had an OIB signature indicating a large asthenospheric component, and lavas with the opposite characteristics were derived primarily from subcontinental lithospheric mantle affected by past subduction events. The Papoose Canyon single eruption sequence lavas span this cut-off, covering nearly the entire BPVF range. All other BPVF sequences except Jalopy Cone straddle the Zr/Ba cut-off as well. Attributing chemical variation of the same direction and magnitude, but expressed at such different time-scales, to the same large-scale tectonic process is problematic.

DePaolo and Daley (2000) used a similar approach with Nd isotopes to interpret the onset of lithospheric thinning. In this model, the melting region of the youngest lavas, including the BPVF, includes both the lithosphere and the asthenosphere, as they have defined them.

As another example, Wang et al. (2002) used an empirical SiO$_2$ barometer (along with other pressure-sensitive indices) to estimate pressure of melting for basalts in the WGB and Basin and Range. Their results show pressures of melting generally increasing to the east from the WGB to the Basin and Range, from roughly 1 to 4 GPa. The BPVF basalts compiled in the paper (Ormerod et al., 1988; Ormerod et al., 1991; Rogers et al., 1995) show the wide range in chemical variation typically seen in the BPVF. While it is reasonable to expect that the SiO$_2$ variation found in the entire volcanic field would represent a wide range of melting depths over the ~1.2 Myr history of the field, within basalts from the Papoose Canyon single eruption sequence itself, SiO$_2$ ranges from 45.0 to 47.6 wt.% Using the Wang et al. (2002) parameterization, this would require melting pressures in a single eruption ranging from ~2.2 to 5.6 GPa (73 to 184 km). Given highly conflicting constraints on melt ascent rates in various tectonic settings (Richardson et al., 1996; Kelley and Wartho, 2000; Turner et al., 2001), it is difficult to definitively rule out this range of melting depths for a single eruption, but we find this unlikely for such a short-lived event.

These examples highlight the possibility that chemical variation on short time-scales could be interpreted as long-term variations with large-scale (e.g., tectonic) origins. Larger-scale chemical trends reflecting long-term tectonic changes almost certainly exist, but distinguishing between different scales of variation is necessary before moving on to such interpretations. It is possible that both the long- and short-term trends in BPVF lavas have related underlying origins, especially because the single eruption data mimic volcanic field data in both range and form of variation with respect to time (Fig. 5). In a lithospheric thinning or slab rollback model, long-term chemical changes could be caused by increasing extents or proportions of asthenospheric melting. The single eruption variation, however, is caused by coupled mixing and melting of two sources, whose end-members are defined by the regional mantle composition. Because the long-term trend of single eruption variation decreases in a similar manner to the short-term trends (Fig. 5), one could consider long-term variation as a moving window of aggregate single eruption trends. In fact, if the explicit cause of the short-term trends can be determined, it may provide a more detailed basis to describe large-scale variation caused by changing tectonic environment.

5. Conclusions

Detailed chemistry of five primitive single eruption sequences from the BPVF show distinctive systematic temporal–compositional trends that are not consistent with fractional crystallization or partial melting of a single source. Crustal contamination is evident through highly radiogenic Os, but as this system is decoupled from the other isotopic or chemical trends, it may be
caused by contamination by minor mafic material with similar MgO, 87Sr/86Sr, and εNd. Systematic variation in isotopic data and non-linear mixing relationships in the LREEs and HREEs are consistent with an origin involving coupled mixing and melting of two isotopically distinct mantle sources.

Sampling at the time- and length-scale of a single eruption may be necessary in order to geochemically observe time-dependent mixing or melt extraction processes and can also shed light on regional petrotectonic associations. 40Ar/39Ar ages determined for ten locations, ranging from 31.8±12.1 to 1273±119 ka, provide new constraints on the timing of volcanism in the BPVF. Combining these ages and compilations of BPVF data, it appears that each of the five BPVF single eruption trends we examined shows the same temporal–compositional trends as the long-term geochemical trend of volcanic field evolution. Further, the systematic geochemical and isotopic variation found in the Papoose Canyon single eruption spans nearly that of the entire volcanic field, and straddles cut-offs for models of changing tectonic regime. That the magnitude and direction of variation for short time-scales (10^4–10^5 yr) and long time-scales (10^5–10^6 yr) are nearly the same suggests three conclusions: 1) while short-term and long-term trends must be a function of two different processes, they may involve the same parent or end-member compositions; 2) long-term variation may obscure valuable systematic short-term variation; 3) it is the short-term, single eruption trends that likely represent a coupled mixing and melting process, while the long-term trends may represent a moving aggregation of the short-term trends caused by systematic source changes.

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Appendix A. Supplementary data


References


