Investigating ocean island mantle source heterogeneity with boron isotopes in melt inclusions

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Abstract: The processes that drive magma formation beneath the Cascade arc and other warm-slab subduction zones have been debated because young oceanic crust is predicted to largely dehydrate beneath the forearc during subduction. In addition, geochemical variability along strike in the Cascades has led to contrasting interpretations about the role of volatiles in magma generation. Here, we focus on the Lassen segment of the Cascade arc, where previous work has demonstrated across-arc geochemical variations related to subduction enrichment, and H-isotope data suggest that H2O in basaltic magmas is derived from the final breakdown of chlorite in the mantle portion of the slab. We use naturally glassy, olivine-hosted melt inclusions from the tephra deposits of eight primitive (MgO > 7 wt%) basaltic cinder cones to quantify the pre-eruptive volatile contents of mantle-derived melts in this region. The melt inclusions have B concentrations and isotope ratios that are similar to mid-ocean ridge basalt (MORB), suggesting extensive dehydration of the downgoing plate prior to reaching sub-arc depths and little input of slab-derived B into the mantle wedge. However, correlations of volatile and trace element ratios (H2O/Ce, Cl/Nb, Sr/Nd) in the melt inclusions demonstrate that geochemical variability is the result of variable addition of a hydrous subduction component to the mantle wedge. Furthermore, correlations between subduction component tracers and radiogenic isotope ratios show that the subduction component has less radiogenic Sr and Pb than the Lassen sub-arc mantle, which can be explained by melting of subducted Gorda MORB beneath the arc. Agreement between pMELTS melting models and melt inclusion volatile, major, and trace element data suggests that hydrous slab melt addition to the mantle wedge can produce the range in primitive compositions erupted in the Lassen region. Our results provide further evidence that chlorite-derived fluids from the mantle portion of the slab (~7-9 km below the slab top) cause flux melting of the subducted oceanic crust, producing hydrous slab melts that migrate into the overlying mantle, where they react with peridotite to induce further melting.

Slab melting and magma formation beneath the southern Cascade Arc

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Abstract

The processes that drive magma formation beneath the Cascade arc and other warm-slab subduction zones have been debated because young oceanic crust is predicted to largely dehydrate beneath the forearc during subduction. In addition, geochemical variability along strike in the Cascades has led to contrasting interpretations about the role of volatiles in magma generation. Here, we focus on the Lassen segment of the Cascade arc, where previous work has demonstrated across-arc geochemical variations related to subduction enrichment, and H-isotope data suggest that H_2O in basaltic magmas is derived from the final breakdown of chlorite in the mantle portion of the slab. We use naturally glassy, olivine-hosted melt inclusions (MI) from the tephra deposits of eight primitive (MgO > 7 wt%) basaltic cinder cones to quantify the pre-eruptive volatile contents of mantle-derived melts in this region. The melt inclusions have B concentrations and isotope ratios that are similar to mid-ocean ridge basalt (MORB), suggesting extensive dehydration of the downgoing plate prior to reaching sub-arc depths and little input of slab-derived B into the mantle wedge. However, correlations of volatile and trace element ratios (H_2O/Ce, Cl/Nb, Sr/Nd) in the melt inclusions demonstrate that geochemical variability is the result of variable addition of a hydrous subduction component to the mantle wedge. Furthermore, correlations between subduction component tracers and radiogenic isotope ratios show that the subduction component has less radiogenic Sr and Pb than the Lassen sub-arc mantle, which can be explained by melting of subducted Gorda MORB beneath the arc. Agreement between pMELTS melting models and melt inclusion volatile, major, and trace element data suggests that hydrous slab melt addition to the mantle wedge can produce the range in primitive compositions erupted in the Lassen region. Our results provide further evidence that chlorite-derived fluids from the mantle portion of the slab (~7-9 km below the slab top) cause flux melting of the subducted oceanic crust, producing hydrous slab melts that migrate into the overlying mantle, where they react with peridotite to induce further melting.

1. Introduction

Dehydration of subducted oceanic lithosphere drives arc magmatism at convergent plate margins. However, the thermal structure of an individual subduction zone controls the depths at which key dehydration reactions occur (Schmidt and Poli, 1998; Van Keken et al., 2011). Thermal structure is commonly assessed using the thermal parameter (ϕ), which is a function of downgoing plate age, dip angle, and convergence rate (e.g., Syracuse et al., 2010). Variability in ϕ globally is predicted to cause a wide range of slab surface temperatures beneath arcs (675-950°C), as estimated from geodynamic models (e.g., Syracuse et al., 2010) and geochemical tools (e.g., Cooper et al., 2012). The results suggest a continuum of subduction zones between 'cold' (Tonga, Kamchatka) and 'warm' slabs (Cascades, Mexico). Fluids released from the subducting slab have been shown to become more solute-rich with increased temperature (Kessel et al., 2005a; Herman and Spandler, 2006; Cooper et al., 2012; Ruscitto et al., 2012), and there is geochemical evidence for melting of the oceanic crust beneath some warm-slab endmembers such Mexico (Cai et al., 2014), the Cascades (Walowski et al., 2015), and SW Japan (Kimura et al., 2014). In addition, there is widespread geochemical evidence for melting of subducted sediment beneath arcs (e.g., Plank et al., 2005). However, whether the oceanic crust begins to melt beneath most arcs has been debated, and a consensus is emerging that the oceanic crust dehydrates and contributes fluids to the mantle wedge in arcs with cold to intermediate slab temperatures (e.g., van Keken et al., 2011). To understand slab recycling and magma generation, it is imperative to differentiate the roles of different components in the subducted oceanic lithosphere (altered oceanic crust, sediment, serpentinized peridotite) and determine how these components are transferred to the overlying mantle wedge (as fluids, melts or a supercritical phase). The Cascade arc represents a global warm-slab endmember due to slow, shallow subduction of young oceanic crust (6-10 Ma at the trench; Wilson et al., 2002). Geodynamic models (Syracuse et al., 2010; Wada and Wang, 2009) and geochemical studies (Cooper et al., 2012; Ruscitto et al., 2012; Walowski et al., 2015) agree that slab surface temperatures beneath the arc axis are hotter, on average, than many other arcs globally. Previous work in the central Oregon Cascades has suggested that the mantle wedge beneath the arc receives a reduced flux of volatiles from the downgoing slab (Ruscitto et al., 2012), and H_2O concentrations in olivine-hosted melt inclusions (MI) from both the central and southern Cascades (~3.2 wt%; Ruscitto et al., 2010, 2011; LeVoyer et al., 2010) fall slightly below the global average (~3.9 wt%; Plank et al., 2013). Walowski et al. (2015) found that hydrogen isotope ratios of primitive magmas from the Lassen region of the southern Cascades are lighter than those for the Mariana arc. This is likely the result of waning dehydration of chlorite in the mantle portion of the downgoing slab (~7-9 km below the slab top) after the crustal portion of the slab has already dehydrated beneath the forearc. These results also provide evidence that flux-melting of the oceanic crust occurs when fluids released from the slab interior interact with oceanic crust that is above its wet solidus temperature (e.g., Spandler and Pirard, 2013).

We measured the volatile contents, major element, trace element, and B isotope compositions of olivine-hosted MI and the radiogenic isotopic compositions of bulk tephra from the eruptive centers in the Lassen region studied by Walowski et al. (2015). We use these data to quantify the chemical contributions from the subducting oceanic lithosphere and to better understand how subduction of warm oceanic crust affects the composition of mantle melts and the productivity of melting in the mantle wedge. We also test the hypothesis of Walowski et al. (2015) that magma production beneath the southern Cascades involves a multi-stage process that includes flux melting of the subducted oceanic crust and hydrous slab melt addition to the overlying mantle wedge.

2. Geologic Setting

The Lassen region is the southern terminus of the active Cascade arc (Guffanti et al., 1990). Volcanism is the result of oblique subduction of the Gorda micro-plate beneath the North American plate (Fig. 1; Wilson, 2002), producing dominantly calc-alkaline magmas (Clynne and Muffler, 2010). Westward expansion of the Basin and Range extensional province into the eastern flanks of the Cascade arc, including the Hat Creek and Lake Almanor Grabens, has produced many normal faults that provide pathways for mafic magmas to reach the surface (Guffanti et al., 1990; Clynne and Muffler, 2010). The Quaternary volcanics in the Lassen region sit above a broad platform of mafic to intermediate volcanoes and volcanic products 2-4 km thick (Berge and Stauber, 1987), which is underlain by Sierran and Klamath metamorphic/plutonic basement rocks (Berge and Stauber, 1987). Surrounding the Lassen Peak dacitic dome complex (Clynne and Muffler, 2010) is a large volcanic field containing over 500 cinder cones and small shield volcanoes erupted in the last

12 Ma (Guffanti et al., 1990). Previous work on the Quaternary mafic volcanoes has identified a range in compositions from low-K tholeiitic basalts (LKT; also called high-alumina olivine tholeiites, or HAOT) to calc-alkaline basalt, basaltic andesite, and andesite (Clynne, 1993; Borg et al., 1997). The most primitive calc-alkaline volcanic rocks show distinct across-arc geochemical variations that are interpreted to result from variable enrichment of the sub-arc mantle by a subduction component (Fig. 1; Borg et al., 1997, 2002). Figure 1 shows variations in both Sr/Nd and $^{87}Sr/^{86}Sr$ with increasing distance from the trench. Because there is no evidence for plagioclase fractionation in the primitive magmas, these ratios are robust indicators of subduction enrichment (Borg et al., 1997; see Supplementary Discussion and Fig. S2 for details). The pattern of variable Sr/Nd in the forearc and decreasing and consistently low values of Sr/Nd in the back-arc has been interpreted to indicate the waning addition of a subduction component with distance from the trench (Borg et al., 1997). The $^{87}Sr/^{86}Sr$ ratios display an opposite pattern and generally increase toward the back-arc, indicating that the subduction component has a less radiogenic Sr isotope signature than the sub-arc mantle, which is unusual for arc volcanoes (e.g., Turner and Langmuir, 2015). Variability in whole-rock Nb/Zr and mineral cheMItry (olivine and spinel) suggests that the Lassen sub-arc mantle is heterogeneous before any slab addition (Supplementary Fig. S1; Clynne, 1993; Borg et al., 1997; Walowski et al., 2015), but there is no systematic variation of Nb/Zr with distance from the trench. A full summary of geochemical variations can be found in the Supplementary Materials, and a detailed review is provided by Borg et al. (2002).

3. Sample Descriptions and Analytical Methods

Samples were collected from the tephra deposits of Quaternary monogenetic vents spanning ~80 km from the forearc to the back-arc (Fig. 1). Vents that erupted primitive basalt or basaltic andesite (MgO > 7 wt%) identified from bulk rock analyses (Clynne, 1993; Borg et al., 1997) were targeted because they are close in composition to primary mantle melts. Coarse ash was collected to minimize the potential for syn-eruptive diffusive H loss (e.g., Lloyd, 2013) or crystallization of melt inclusions. Loose olivine crystals (250 μm to 1 mm) were hand-picked from sieved tephra, treated in HBF_4 to remove adhering glass, and examined in immersion oil to locate MI. Olivine crystals hosting fully enclosed, glassy MI were mounted in acetone-soluble resin on glass slides and prepared as doubly polished wafers. H_2O and CO_2 concentrations of the MI were measured at the University of Oregon using a Thermo-Nicolet Nexus 670 FTIR spectrometer interfaced with a Continuum IR microscope. Concentrations were calculated from IR peak absorbances using the Beer–Lambert law and compositionally appropriate absorption coefficients (see Johnson et al., 2008). MI and host olivine were analyzed for major elements (plus S and Cl for inclusions) on the Cameca SX-100 electron microprobe at the University of Oregon (see Ruscitto et al., 2010, for details). MI were subsequently analyzed for a suite of trace elements on the Photon Machines Analyte G2 135 nm ArF "fast"Excimer Laser system at Oregon State University, using 50 μm spot size with a 5 Hz pulse rate. Measured trace element concentrations were determined by reference to GSE-1G glass as a calibration standard and using 43Ca as an internal standard (see Loewen and Kent, 2012). BHVO-2G, BCR-2G, and GSD-1G glasses were also analyzed to monitor accuracy and precision, and the analyzed values were within 10% of accepted values (see Supplementary Table S5).

A subset of the MI that were analyzed for H isotopes and trace elements by Walowski et al. (2015) were also analyzed for B isotope ratios using the Cameca IMS 1280 at Woods Hole Oceanographic Institution, with O^- primary beam, 30 nA primary current, 10,000 V secondary voltage, and a 20 μm spot size. More detailed methods are described in Marschall and Monteleone (2014) and Supplementary Table S3. Some of the MI were too small to allow a new SIMS spot adjacent to an existing NanoSIMS spot (20x20 rastered area, ~5 μm deep). In these cases, the SIMS spot was placed within the pre-existing NanoSIMS spot. Tests comparing measurements within pre-existing spots to those on a clean surface from a single MI revealed no systematic differences.

The Sr, Nd, Hf, and Pb isotope ratios of bulk tephra samples were measured at the Pacific Centre for Isotopic and Geochemical Research at the University of British Columbia. Pb, Nd, and Hf isotope ratios were measured by MC-ICP-MS (Nu Instruments Ltd., Nu Plasma II NP 214), and Sr isotope ratios were measured by Thermo Finnigan Triton TIMS using procedures described in Weis et al. (2006, 2007). Additional details regarding sample preparation and analytical techniques are given by Mullen and Weis (2015). Analytical reproducibility and correction methods for radiogenic isotope data are described in Supplementary Table S2. Tephra from sample CC was excluded from isotopic analyses because of clear evidence for crustal contamination (abundant quartz xenocrysts, partially melted granitic xenoliths).

4. Results

4.1 MI major and trace element compositions

The olivine host crystals vary from Fo_{83} to Fo_{90} (Supplementary Table S1 and S7). For each cinder cone, 11-17 MI were analyzed. The major element compositions of the inclusions were corrected for post-entrapment crystallization (PEC) and Fe-loss using Petrolog 3.1.1.3 (Danyushevsky and Plechov, 2011), using models for olivine-melt equilibria from Ford et al. (1983) and oxidation state from Borisov and Shapkin (1990). Concentrations of volatiles and trace elements that are incompatible in the olivine hosts were corrected using the Petrolog results for the major elements. Initial Fe contents were chosen based either on the FeO^T of the bulk tephra or the highest value of FeO^T for MI from a particular cone. An average oxygen fugacity of ΔQFM+1, determined using the partitioning of V between the MI and host olivine using methods of Mallmann and O'Neill (2009), was used in the Petrolog calculations. Calculated values of PEC vary from 0 to 14%. Corrected MI compositions overlap with the most primitive lavas previously analyzed in the Lassen region (Fig. 2) and have MgO concentrations of 7.4-9.8 wt% (Supplementary Table S1). To estimate a primary melt composition for each cone, we added equilibrium olivine (in 0.1 wt% increments) to the average MI composition from each cone until the melt composition was in equilibrium with Fo_{90} olivine (Table 1; Ruscitto et al., 2010). The calculated primary melt compositions required 1-20%

olivine addition (Table 1). Although variability in mantle olivine compositions likely exists beneath the Lassen region (Clynne, 1993; Borg et al., 1997), we assume Fo_{90} for simplicity and because there is little evidence for more refractory mantle compositions, unlike the Mt. Shasta region to the north, where some lavas and tephra have olivine up to Fo_{94} (Ruscitto et al., 2011).

The MI are dominantly medium-K CAB, with some that fall into the low-K field (Fig. 2a), and compositionally similar to the bulk tephra compositions (Walowski et al., 2015; Supplementary Fig. S2). Previous work in the Lassen region has suggested that LKT and CAB magmas have different source regions (Clynne, 1993; Bacon et al., 1997). However, the low-K samples used in this study do not display the lower LREE/HREE and LILE/HFSE values typical of the endmember LKT volcanic rocks in this region (Fig. 2; see also Bacon et al., 1997). All samples used in this study display trace element patterns similar to the regional CABs (Fig. 2), suggesting that despite variability in major and trace element compositions, they were enriched by a component derived from the downgoing slab.

4.2 Magmatic volatile contents

Dissolved H_2O contents of the MI, after correction for PEC and Fe loss, are 0.6-3.5wt%. At individual cinder cones, a range in H_2O concentrations is observed and is likely due to differences in extent of pre-entrapment degassing (e.g., Johnson et al., 2009) and/or post-entrapment hydrogen loss (Lloyd et al., 2013; Bucholz et al., 2013). We do not observe correlations between relative MI size and H_2O contents. Because these processes decrease H_2O, the maximum measured H_2O/K_2O ratio for each cone was used to estimate the initial H_2O content (H_2O_{max}) of the magma erupted at that cone. In the Lassen region, H_2O_{max} ranges from 1.3-3.4 wt%. The H_2O_{max} values were used to estimate the H_2O concentrations in primary mantle-derived melts using the olivine addition method described above, yielding values of 1.1-3.4 wt% (Table 1). These values overlap with calculated primary melt H_2O concentrations for basaltic and basaltic andesite melts from central Oregon (1.4-3.0 wt%; Ruscitto et al., 2010). In contrast to H_2O, Cl is not affected by either pre-entrapment degassing (except at very low pressures) or post-entrapment diffusive effects. Concentrations of Cl in calculated primary melts range from 100-600 ppm, except at BRM, where Cl values are as high as 2500 ppm (Supplementary Table S1).

Similar to H_2O, CO_2 concentrations are variable at individual cones and reflect a combination of pre-entrapment degassing and post-entrapment loss. We report the highest PEC-corrected CO_2 contents from individual cinder cones, and these range from 599-1493 ppm (Supplementary Table S1; Fo_{90} corrected primary melts = 521-1435 ppm; Table 1). It is important to note that these CO_2 values underestimate the initial CO_2 concentration of the melt. Most MI analyzed in this study contain a vapor bubble (presence /absence of vapor bubble noted in Supplementary Table S1), and such bubbles typically contain a substantial fraction (40-90%) of the CO_2 that was initially dissolved in the trapped melt (Wallace et al., 2015; Moore et al., 2015). As a result, the CO_2 contents of the MI are underestimates of the magmatic CO_2 content. Sulfur contents of PEC corrected MI range from 380-2140 ppm (Supplementary Table S4; Fo_{90} corrected primary melts = 900-1600 ppm; Table 1). Samples BRVB, BPB, and BBL each have one MI that contains a small (<5 μm sphere) coexisting sulfide phase. Because post-entrapment Fe-loss can cause sulfide saturation and decreasing sulfur in the residual melt (Danyushevsky et al., 2002), these few individual MI may have lost some S after entrapment. However, there is no evidence to suggest this process had an effect on most MI, such as highly variable S contents from an individual MI suite.

4.3 Isotopic Compositions

The average $\delta^{11}B$ ratios of MI from individual cones in the Lassen region range from -9.9‰ to -2.4‰ (Fig. 3; Supplementary Table S3). These values overlap with those measured for bulk rock samples from the southern Washington Cascades (-9‰ to -0.4‰; Leeman et al., 2004) and MI from the Mt. Shasta region (Fig. 3; Rose et al., 2001; LeVoyer et al., 2010). MI from the Cascades have lower B concentrations and more negative $\delta^{11}B$ than those measured in other arcs, such as Kamchatka and Mariana, where older oceanic crust subducts (Fig. 3; Ishikawa et al., 2001; Ishikawa and Tera, 1999).

The Sr, Nd, Hf, and Pb isotope ratios for bulk tephra samples overlap with those previously determined for volcanic rocks in the Lassen Region (Fig. 4; Table 2).

5. Discussion

5.1 The source of volatiles in Lassen Region primitive magmas

Boron is a fluid mobile element that is present in higher concentrations in subducted materials than the mantle, making it an excellent tracer of fluids from subducting slabs (e.g., Tonarini et al., 2001). In addition, subducted materials such as sediment, oceanic crust, and serpentinitized mantle have $\delta^{11}B$ that is distinct from the mantle wedge (e.g., Ishikawa and Nakamura, 1993). However, the Lassen region MI have MORB-like to slightly elevated B isotopic compositions and low B concentrations, which suggests that the sub-arc mantle receives little B from the subducting slab (Fig. 3). This is probably the result of extensive dehydration of the slab before it reaches sub-arc depths (Leeman et al., 2004; Manea et al., 2014). However, geodynamic modeling and calculated metamorphic phase equilibria suggest that, unlike B, H_2O can be carried to sub-arc depths beneath the Lassen region by chlorite in the hydrated mantle portion of the slab (van Keken et al., 2011; Walowski et al., 2015). Because nearly all B is released from hydrated peridotite beneath the forearc during antigorite breakdown, chlorite-derived fluids contribute little B to the subduction component (Spandler et al., 2014). This explains how the slab beneath the Cascades can release a hydrous component that contains very little B, such that primitive magmas formed in the wedge have B isotope ratios and concentrations only slightly elevated compared to MORB.

Despite low B concentrations, H_2O and Cl are high compared to MORB, which requires that these volatiles are retained in the slab to greater depths than B. Furthermore, strong correlations of H_2O_{max}/Ce and Cl/Nb with Sr/Nd clearly demonstrate that volatile and trace element enrichments are coupled and therefore derived from the same process (Fig. 5). This observation is consistent correlations globally and at other warm-slab subduction zones (Ruscitto et al., 2012). To quantify this, we calculated the compositions of partial melts from two mantle endmembers to which variable amounts of subduction component were added. Figure 5 shows good agreement between the model curves and the MI data, which indicates that volatile and trace element variability between vents is the result of different amounts of a subduction component added to a heterogeneous mantle wedge. However, MI from cone BRM have lower H_2O/Ce than predicted by the melting model. This could be caused by variability in the H_2O and trace element ratios of the hydrous subduction component, or it could be that MI from this cone were strongly affected by pre-entrapment degassing or post-entrapment H loss. Cl/Nb provides a more robust indication of initial volatile concentration because Cl is not affected by diffusive loss and only degasses at very low pressure. Good agreement between data and melting models for Cl/Nb vs. Sr/Nd provides support for the interpretation that initial H_2O concentrations are related to the amount of a subduction component added to the mantle wedge beneath the arc and that the slab component has ratios of H_2O and Cl to LILE that are not highly variable (Fig. 5b, c). This suggests that BRM, the sample with the highest Sr/Nd and therefore largest amount of a subduction component, has very low H_2O/Ce as a result of extensive degassing or post-entrapment diffusive loss.

Volatile and trace element ratios for the central Oregon Cascades can also be explained using the calculated melting curves, but require a more enriched mantle source than Lassen magmas (Fig. 5a; Ruscitto et al., 2010). Interestingly, MI with the highest values of Sr/Nd in both the Lassen region (BRM) and the Mt. Shasta region do not have the highest values of H_2O/Ce, but they do have the highest Cl/Nb and also have Cl concentrations significantly higher than other cones throughout the Cascades (Ruscitto et al., 2012). As suggested above, these magmas likely experienced extensive degassing of H_2O in the crust before MI entrapment (evidenced by very low CO_2 in many MI), and/or were affected by post-entrapment H loss. However, if the BRM and Shasta magmas had pre-degassing compositions that fit the model curves in Figure 5a, they would have had initial H_2O concentrations as high as 8-10 wt% H_2O, in agreement with experimental phase equilibria (Krawczynski et al., 2012). The Blanco Fracture zone, which separates the Juan de Fuca and Gorda plates, may provide a pathway for deep serpentinization of the upper mantle in the downgoing slab offshore of the Cascades, and has been proposed as a source for the volatile-rich component beneath Mt. Shasta (Grove et al., 2002; Manea et al., 2014). However, plate reconstructions suggest the Blanco Fracture zone is not old enough to project beneath the arc (Wilson, 2002), and thus, the causes of geochemical differences between the Mt. Shasta and Lassen regions (Fig. 5) remain enigmatic.

5.2 The Lassen sub-arc mantle

Previous workers using trace elements and radiogenic isotopes in the Lassen region found negative correlations between LILE/LREE ratios and $^{87}Sr/^{86}Sr$. This requires that the modern subduction component is less radiogenic than the sub-arc mantle and that the latter has anomalously high Pb and Sr isotope ratios (Borg et al., 1997, 2002; Fig. 4). This observation by Borg et al. (1997) led to the conclusion that the sub-arc mantle had been previously enriched by a sediment component, but they suggested the enrichment must have occurred during an earlier, possibly Mesozoic, subduction event because the Pb isotope ratios of young Pacific sediments were too low to explain the values. Subsequent research on sediments from the Cascadia Basin (Fig. 4a; Carpentier et al., 2014; Mullen and Weis, 2015) has shown that the sediments have radiogenic Pb isotopic ratios. Addition of such a bulk sediment to depleted MORB mantle (DMM) could explain the anomalously radiogenic Pb and Sr isotope ratios and trace element enrichments inferred for the Lassen sub-arc mantle (Fig. 4a). However, it does not resolve the questions of when or how the bulk sediment component was added, nor does it solve the puzzle evident in Figs. 1c, d, and 4a that modern subduction seems to involve addition of a less radiogenic slab component to an already isotopically enriched mantle wedge. Addition of bulk sediment rather than sediment melt could be explained by mélange diapirs that rise from the top of the subducted plate (e.g., Behn et al., 2011; Gerya et al., 2003). Interestingly, the enriched mantle signature is restricted to the southernmost Cascades, and may best be explained by either the addition of bulk sediment to the mantle wedge during the accretionary events which produced the Klamath Mountains terranes from 130-260 Ma (Irwin and Wooden, 1999) or during subduction related to Sierra Nevada magmatism. Although the cause of the mantle enrichment in the Lassen (and Shasta) region is unclear, the data suggests that this component is distinct from the modern subduction component (Fig. 4). Therefore, in subsequent models and interpretations, we consider the enriched mantle as a single component and focus on the modern, volatile-rich and unradiogenic subduction component that is evident in the Lassen-region mafic magmas.

5.3 Evidence for slab melting

In the North Cascades, basaltic magma compositions can be explained by three component mixing between DMM, sediment melts, and oceanic crust melts (Fig. 4a; Mullen and Weis, 2015). However, the low Sr/Nd magmas in the Lassen region cannot be explained by mixing of the same components, and the strong negative correlation of the Lassen data (Fig. 4a) suggests the magmas are dominated by two components – enriched sub-arc mantle and subducted MORB crust – with a lesser role for sediment melt (Fig. 4b). These observations suggest that low-Sr/Nd magmas in the Lassen region reflect their derivation from a sub-arc mantle with an isotopically-enriched character, as explained in the previous section. New radiogenic isotope data from this study overlap with previously published data (Fig. 4). Because elevated H_2O/Ce, Cl/Nb, and Sr/Nd ratios are related to subduction component addition, our data confirm that the subduction component has a MORB-like isotopic composition, with less radiogenic Sr and Pb than the Lassen sub-arc mantle. In its isotopic characteristics, the subduction component is similar to offshore Gorda Ridge MORB (Davis et al., 2008).

Melting of subducted MORB crust was discounted by Borg et al. (1997) because melting of dry eclogitized oceanic lithosphere requires higher temperatures than expected for the slab top at sub-arc depths. Grove et al. (2002) discounted slab melting beneath Shasta, where similar isotopic relationships are observed (Fig. 4), because models of hydrous peridotite melting could reproduce the observed major element compositions of primitive volcanic rocks in that region. Recent work by Walowski et al. (2015) interpreted the light D/H values of MI from the Lassen region as resulting from final dehydration of chlorite in the hydrated upper mantle portion of the downgoing slab. This provides a mechanism to deliver H_2O to the basaltic slab top and drive wet slab melting beneath the arc, as proposed by Till et al. (2013), Kimura et al. (2014), and Spandler and Pirard (2014).

To test this hypothesis, we calculated mixing and partial melting models involving sub-arc mantle and a partial melt of Gorda MORB (Fig 4b, c). Because temperatures of the plate top are at or above the wet MORB and wet sediment solidi (Schmidt and Poli, 1998; Herman and Spandler, 2006), we assume the subduction components are partial melts rather than aqueous fluids (Cooper et al., 2012; Ruscitto et al., 2012; Kimura et al., 2014; Walowski et al., 2015). Our use of unaltered Gorda MORB as the dominant slab component requires that the most altered part of the slab (which contain seawater-derived Sr) loses much of its Sr during dehydration beneath the forearc during transition to eclogite (Walowski et al., 2015). Because Sr/Nd is an indicator of subduction enrichment, primitive basalts with the lowest Sr/Nd values should be most representative of the Lassen sub-arc mantle. These samples exhibit a small range of Sr, Nd, and Pb isotope ratios which is probably indicative of mantle heterogeneity beneath the arc (Borg et al., 1997; 2002). We thus use a range in sub-arc mantle compositions (Fig. 4; $^{87}Sr/^{86}Sr$ = 0.7039 – 0.7043 and $^{208}Pb/^{204}Pb$ = 38.512 – 38.782). Figure 4b and c show curves that represent melts of sub-arc mantle after addition of variable amounts of Gorda MORB melt, the results of which suggest 1-10 wt% addition of the slab melt.

Our proposed mechanism for slab melting relies on breakdown of chlorite in the lithospheric mantle of the downgoing plate. However, in the model shown in Figure 4b and c, the chemical composition of this chlorite-derived fluid component has been neglected. Fluids from the breakdown of chlorite at sub-arc depths have some distinct trace element characteristics (e.g., elevated LREE/HREE) but, overall, are solute poor (Spandler et al., 2014). As a result, chlorite-derived fluids will have little effect on the trace element composition of the magmas formed by flux melting of the upper oceanic crust. We therefore conclude that fluids derived from chlorite breakdown in the hydrated mantle portion of the slab dominantly contribute H_2O to the system but do not impart a distinctive trace element signature.

5.4 The role of sediment melts and crustal assimilation

Although the model results in Figures 4b and 4c can explain a majority of the compositions, some values of Sr and Pb isotopes are above the model predictions. There are three possible explanations for these small offsets: 1) contributions from zones of altered MORB in the downgoing plate that partially retained their altered isotopic signature after complete dehydration, 2) involvement of small proportions of a sediment melt component (Borg et al., 1997; 2002), and/or 3) contamination by crustal material. To further distinguish sediment and slab melt contributions, we use Th/La as a discriminant because of the high Th concentrations in sediments relative to MORB and sub-arc mantle (Fig. 4d; Plank et al., 2005). The mixing model in Figure 4d shows that Th/La variations in primitive Lassen magmas can result from addition of <10% of a subduction component made up of variable proportions of sediment and MORB melts. At all but two cinder cones, MI trace element compositions suggest that the slab component is dominated by melts of basaltic oceanic crust and contains <30% sediment melt. Two cinder cones (BPB and CC) have larger apparent contributions from sediment melts. Cinder Cone, in particular, contains the highest Th/La values from our dataset. However, the bulk lava and tephra at this cone contain abundant quartz xenocrysts and variably melted granitic xenoliths, which are clear indications of crustal contamination. This sample was therefore excluded from radiogenic isotope analyses. We also note that MI from the Lassen region samples have lower Th/La values on average than many of the published bulk rock analyses from this area (Fig. 4d; Borg et al., 1997, 2002). This could be because MI are trapped at depth, before even minor crustal contamination occurs. Previous workers in the Lassen region interpreted unradiogenic Os isotopic compositions in the most primitive basalts and basaltic andesites as evidence for minimal contamination by continental crust (Borg et al., 1997, 2000). However, very high Th concentrations in the granitic basement rocks (Cecil et al., 2012) make it possible for small amounts of contamination to increase Th/La ratios to make it difficult to differentiate between sediment melt and contamination.

5.5 Modeling slab melt addition and the Sr/Y adakite signature

The studied Lassen magmas have basaltic major element compositions and are not high-Mg andesites as might be expected for magmas derived by slab melting (Kelemen et al., 2003). To test whether the major and trace element compositions of these magmas can be reproduced by slab melt addition to the mantle wedge, we used pMELTS (Ghiorso et al., 2002) to compare the effects of fluid vs. hydrous melt addition (Eiler et al., 2000) to the wedge at temperatures and pressures expected for the Lassen sub-arc mantle. We created the starting bulk compositions by adding various amounts of either a dacitic slab melt (Klimm et al., 2008) or pure H_2O to a primitive mantle composition (MM3; Baker and Stolper, 1994). The pMELTS program was used to determine the phase equilibria of the bulk mixture from 900-1400°C at a pressure of 1.5 GPa. These values are based on temperatures from geodynamic model results for the Lassen region (Walowski et al., 2015), beginning at the slab-wedge interface to ~100°C hotter than peak temperatures expected in the wedge. See Supplementary Discussion S3 for further details.

Melt fractions for both the hydrous-melt-fluxed and fluid-fluxed peridotite cases are nearly indistinguishable (Supplementary Fig. S3). This suggests that for a given mantle composition, the amount of H_2O supplied to the mantle controls the degree of melting irrespective of whether the H_2O is added as melt or fluid, consistent with experiments of Mallik et al. (2015). Figure 6 shows the major element compositions of partial melts resulting from various amounts of slab melt and aqueous fluid addition to the mantle wedge. For small amounts of slab melt addition (1-3 wt%), the major element compositions of resulting basaltic melts are similar to those of the aqueous fluid addition case. This indicates that equilibrium between partial melt and residual mantle largely controls the major element composition of the final melt. Primary magma compositions calculated from the MI data overlap with the pMELTS model results (Fig. 6), demonstrating that hydrous-melt-fluxed melting of the mantle wedge is a viable explanation for the production of these magmas.

One hallmark of slab melt is high Sr/Y caused by the presence of garnet, which makes up a large proportion of eclogitized MORB in the subducted plate

(Defant and Drummond, 1990). Most Lassen magmas, however, do not have high Sr/Y values compared with the global array of adakites (Fig 7). Using the mixed mantle compositions and melt fractions from the pMELTS models, melting curves in Figure 8b show that for small amounts of slab melt addition (1-10%), the Sr/Y ratio is dampened due to addition of Y from the spinel peridotite mantle component. This yields values that overlap with values measured in MI from all but one sample (BRM) from the Lassen region (Fig. 8b). The results are consistent with calculations by Kelemen (1993) showing that peridotite-melt reaction produces melts with lower LREE/HREE than the initial slab melts. Our model results suggest that high Sr/Y adakitic signatures are only retained in arc magmas if slab melt addition is >10 wt%. Larger proportions of slab melt addition are thus required to explain the high Sr/Y value of sample BRM, consistent with estimates of ~10% slab melt addition inferred from radiogenic isotopes (Fig. 4). The high-Mg andesites from the Lassen (M. Clynne, unpub. data) and Shasta regions that have higher values of Sr/Y (~150; Ruscitto et al., 2011) could therefore be produced by larger amounts of hydrous slab melt addition to the mantle wedge.

Although most primitive Cascade arc magmas do not have particularly high Sr/Y compared to adakites, they do have other characteristics that indicate melting in the presence of garnet when compared to the global array of basaltic arc magmas. For example, primitive magmas from warm-slab subduction zones (Cascades, Mexico) display elevated LREE/HREE and MREE/HREE (e.g. La/Yb and Dy/Yb; Walowski et al., 2015 and Turner et al., 2015, respectively) and coupled high $^{176}Hf/^{177}Hf$ and $^{143}Nd/^{144}Nd$ with lower values of Lu/Hf (Cai et al., 2014) when compared to arcs associated with older oceanic crust. These relationships demonstrate that partial melts of subducted oceanic crust play an increasingly important role in the formation of magmas in arcs associated with young oceanic crust.

6. Model for magma generation beneath the southern Cascade arc

Our results suggest that southern Cascade magmas are produced by a multi-stage process involving fluid-flux melting of the basaltic slab top (±lesser sediment) and ascent of this hydrous melt into the mantle wedge. Figure 8 shows a schematic interpretation of this process based on the thermo-petrologic model results of Walowski et al. (2015), the shear wave velocity model from Liu et al. (2012), and the magnetotelluric data from Wannamaker et al. (2014). In our model, H_2O is retained in the hydrated upper mantle portion of the downgoing slab to greater depths than those at which H_2O is lost from the slab top (Fig. 9). Final chlorite breakdown occurs in the slab interior when the slab top reaches ~75-80 km. At this depth, the upper portions of the slab are above the MORB+H_2O solidus, and thus should melt when fluxed by rising chlorite-derived fluids (e.g., Spandler and Pirard, 2013). The resulting hydrous dacitic melts (Klimm et al., 2008) then rise into the overlying mantle wedge and react with the surrounding mantle to produce hydrous, calc-alkaline, basaltic to basaltic andesite melts (Fig. 7).

As a further test of this model, we determined whether breakdown of chlorite can supply enough H_2O to balance the flux of H_2O from Cascade arc magmatism. Previous work in Nicaragua (Ranero et al., 2003) and other arcs has provided evidence for hydration of the deep slab and the importance of fluids released from the deep slab in the production of arc magmas (e.g., Spandler and Pirard, 2013). For the Juan de Fuca plate, higher temperatures at Moho depths caused by the younger slab age may limit the extent of serpentinization (Nedimovic et al., 2009), but no data are available for the Gorda plate to assess upper mantle hydration. Due to this uncertainty, Walowski et al. (2015) conservatively assumed 2 km of hydration below the Moho of the downgoing plate and a bulk H_2O concentration of 2 wt% for the hydrated peridotite. Using these model parameters, the H_2O flux contributed by chlorite breakdown in the slab interior is estimated to be ~1-2 x 10^6 kg/km arc length/yr. For the magmatic flux of H_2O from the Cascades, we use the estimate from Ruscitto et al. (2012). This method, which includes extrusive and intrusive magma fluxes and utilizes volatile contents from the central Oregon Cascades (which overlap with those from the Lassen region), yields a maximum H_2O flux of 1.93 x 10^6 kg/km/yr. This estimate agrees very well with the flux from the thermo-petrologic model, demonstrating that fluids derived from the breakdown of chlorite in the hydrated upper mantle portion of the slab may be sufficient to produce observed volatile fluxes in the Cascade arc.

The thermo-petrologic model results of Walowski et al. (2015) predict two main pulses of fluid from the downgoing slab associated with 1) the final breakdown of hydrous phases during eclogitization of the oceanic crust, and 2) the final breakdown of chlorite in the hydrated mantle portion of the slab (Fig. 9). The first, more shallow pulse of fluid release correlates well with the location of a low-resistivity anomaly beneath the forearc (Wannamaker et al., 2014), and likely reflects a region of serpentinization of the cold nose of the mantle wedge. The second, which causes flux melting of the slab top, agrees well with regions of low shear wave velocity beneath the Lassen region (Liu et al., 2012). The shape of the low shear wave velocity region is consistent with models of fluid migration into the mantle wedge that suggest that for most values of wedge permeability, slab dip, and convergence velocity there is a net migration of fluids and melts away from the trench (Cagnioncle et al., 2007). This implies that arc magmas will inherit a slab signature from a region of the slab that is slightly up-dip of the region that lies directly beneath the arc. Therefore, patterns of decreasing amounts of a subduction component towards the rear-arc, as observed in the geochemical data (Clynne, 1993; Borg et al., 1997; 2002), are consistent with the model in Figure 9.

7. Conclusions

The process of melt generation in warm-slab suduction zones, such as Cascadia, has been debated due to the high slab surface temperatures and extensive slab dehydration predicted by geodynamic and geochemical models. Our results provide strong evidence that magma production in the southern Cascade arc is driven by hydrous slab melt addition to the mantle wedge. Low B concentrations and MORB-like B isotope ratios indicate that extensive dehydration of the plate occurs before it reaches sub-arc depths. However, volatile concentrations and correlations of volatile and trace element ratios (H_2O/Ce, Cl/Nb, Sr/Nd) show that Lassen magmas have been enriched by variable amounts of addition of a hydrous subduction component. Correlation of fluid mobile trace elements and radiogenic isotopes demonstrates that the modern subduction component in the southern Cascades is less radiogenic than the sub-arc mantle wedge and must be dominantly derived from a partial melt of subducting Gorda MORB, with a minor contribution from subducted sediment melts. The pMELTS model results show that hydrous melt-fluxed melting of the mantle wedge can produce basaltic magmas with similar major element compositions to those measured in Lassen MI. Our results provide further evidence that chlorite-derived fluids from the deep slab interior can flux-melt the oceanic crust, producing hydrous slab melts that migrate into the overlying mantle, where they react with peridotite to induce further melting. The combined observations provide new insight on element recycling at subduction zones and demonstrate that partial melts of subducted oceanic crust play an important role in arcs associated with the subduction of young oceanic crust.

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Figure Captions

Figure 1: a) Regional map of the Northwestern United States showing major tectonic boundaries. The Cascade volcanic arc is defined by the major peaks (black triangles). Lassen Peak is highlighted with a red triangle. Black arrows show convergence direction and are labeled with the convergence rate relative to North America. b) Larger scale map of the Lassen region with locations of vents sampled in this study (BRVB: Basalt of Round Valley Butte; BPB: Basalt of Poison Butte; BRM: Basalt of Red Mountain; BBL: Basalt of Big Lake; BAS-44: Basalt of Hwy 44; BPPC: Basalt of Paine Parasitic Cone; BORG: Basalt of Old Railroad Grade; CC: Cinder Cone; see Table 1 for details) and previously sampled by Clynne (1993) and Borg (1995; gray diamonds). Lassen Peak (large white triangle), outcropping basement rocks (shaded pink areas), major highways (thin black lines), and large lakes (shaded blue regions), are also highlighted. Distance from the trench vs. c) Sr/Nd and d) $^{87}Sr/^{86}Sr$ for samples in this study (colored symbols) and Borg et al. (1997; gray diamonds). Symbols and colors for individual cinder cones are consistent throughout the manuscript.

Figure 2: a) Average MI trace element composition for each cone normalized to normal-MORB (N-MORB; Sun and McDonough, 1989). Shown for comparison are endmember compositions (CAB, Borg et al., 1997; HAOT, Bacon et al. 1997). b) K_2O and SiO_2 contents of individual MI (corrected to equilibrium with host olivine and,

normalized on a volatile-free basis) compared with bulk rock analyses from Clynne (1993; gray diamonds).

Figure 3: Boron isotope compositions of Lassen MI. Each data point (symbols as in Fig. 1) represents an average of 4-8 individual MI from a given cone. Symbol size represents ≥1 SE (Table 2). Shown for comparison are data from the southern Washington Cascades (Leeman et al., 2004; filled squares, whole-rock analyses) Mt. Shasta (Rose et al., 2001, open circles; individual MI; LeVoyer et al., 2010, filled circles, MI), the Marianas (Ishikawa, 2001), and Kamchatka (Ishikawa and Tera, 1999). Dashed black curve represents basaltic magmas formed by flux melting of depleted MORB mantle by hydrous slab fluid (Marschall, 2007).

Figure 4: Bulk tephra isotopic compositions and average trace element compositions from MI (Table 2; filled symbols as in Figure 3;) and bulk tephra (open symbols; Walowski et al., 2015; no bulk tephra data available for BRM [purple]). a) $^{87}Sr/^{86}Sr$ vs. Sr/Nd; the North Cascades (pink shaded region in panel a; Mullen and Weis, 2015), and Mt. Adams (red shaded region in panel a; Jicha et al., 2009) are shown for comparison. Dashed lines connect the three components most likely to contribute to magma formation, as described in previous work (Mullen and Weis, 2015), but are not mixing models. Compositional similarity of bulk tephra and MI is described in Supplementary Discussion S2 and Fig. S2, which provides support for plotting MI compositions with bulk tephra radiogenic isotopes. Isotopic composition of BRM is from Borg et al. (1997), not this study. CC was omitted due to evidence for crustal

contamination (see text). Bulk lava analyses from the Lassen and Shasta regions (Borg et al., 1997; Grove et al., 2002, respectively). b) Again, $^{87}Sr/^{86}Sr$ vs. Sr/Nd; symbols as in a), now with North Cascade sediment (yellow shaded region; Carpentier et al., 2013, 2014) and northern Sierran granites (gray shaded region; Cecil et al., 2012) highlighted to show components that may contribute to trace element and radiogenic isotope variability of samples. Melting models (dashed lines) calculated using the batch melting equation for a range in mantle sources (calculated for the Lassen sub-arc mantle; see Discussion section 5.2 for details) mixed with 2, 5, and 10 wt.% (labeled on modeled curves) of a slab melt derived by 5% partial melting of Gorda MORB (Davis et al., 2008; partition coefficients [4 GPa, 1000°C] from Kessel et al., 2005a; Supplementary Table S6). Bulk partition coefficients for mantle melting were calculated for a spinel peridotite assemblage 53/30/12/5-Ol/Opx/Cpx/Sp (Ruscitto et al., 2010) using partition coefficients of Eiler et al. (2005) for Sr and Nd (Supplementary Table S6). Melt fractions were derived from pMELTS model results (for a given temperature and amount of slab melt addition; Fig. 6). c) $^{208}Pb/^{204}Pb$ vs. Sr/Nd; symbols and shaded regions as in a,b), and mixing/melting model as in b). d) MI data only (from this study), and Lassen bulk lava compositions from Borg et al. (1997). Curves represent partial melting models for the Lassen sub-arc mantle (composition inferred from bulk rock samples with smallest amount of apparent subduction component; see Discussion section 5.2) mixed with either sediment partial melts (upper curves) or partial melts from the basaltic slab (lower curves). The sediment partial melts were assumed to be generated by either 5% partial melting (large filled gray diamond) or 20% partial melting (small filled gray diamond) of N. Cascade sediment (partition coefficients from Kessel et al., 2005a; Supplementary Table S6). The basaltic slab partial melts likewise were assumed to be generated by either 5% partial melting (large filled black diamond) or 20% partial melting (small filled black diamond) of Gorda MORB (partition coefficients from Kessel et al., 2005a; Supplementary Table S6). The gray shaded regions show the range of melt compositions created in the mantle by addition of <10 wt% total of these subduction components (made with various proportions of MORB vs. sediment melts) to the mantle wedge. The lines with tick marks (in 10% increments) connecting the mixing curves are labeled with the proportion of the subduction component derived from sediment partial melt, with the remainder of the subduction component derived from the slab melt.

Figure 5: a) H_2O/Ce vs. Sr/Nd in MI. Data points are shown for MI that contain H_2O concentrations within 0.5 wt% of the H_2O_{max} value for each cone, as these values represent the least degassed compositions. b) Cl/Nb vs. Sr/Nd (all MI; corrected) and c) Cl/Nb vs. Sr/Nd (average MI values for each cone; y-axis is extended to higher values than in panel b). In a and c, data from central Oregon (Ruscitto et al., 2010; solid blue circles enclosed in light blue shaded field] and Mt. Shasta (Ruscitto et al., 2008; primitive basaltic andesite (PBA): solid gray triangles enclosed in gray shaded field; high-Mg andesites (HMA): open gray triangles enclosed in a gray shaded field) are shown for comparison. Black lines represent 10% partial melts of two endmember mantle compositions (DMM; Workman and Hart, 2005; and average central Oregon mantle; Ruscitto et al., 2010) mixed with variable amounts of a

hydrous subduction component (gray diamond in a; calculated using methods of Portnyagin et al., 2007, based on primary magma composition of sample BORG; Table 1). The gray bar represents the range in sub-arc mantle compositions determined by Walowski et al. (2015). MI that experienced degassing before entrapment or post-entrapment H loss will deviate from the melting curves as indicated by the black arrow in panel a.

Figure 6: pMELTS model results compared with calculated primary magma compositions from each cone (Table 1). a) H_2O, b) $K_2O + Na_2O$, c) CaO and d) Al_2O_3 wt% vs. SiO_2 (all major elements are normalized volatile free). Phase equilibria were calculated using pMELTS with a starting bulk composition of a mantle source (MM3; Baker and Stolper, 1994) mixed with 1, 2, 5, or 10% of either pure H_2O (dashed curves) or a hydrous dacite melt (solid curves; dacite melt from Klimm et al., 2008) at 1.5 GPa. Each curve represents melting model results from 900-1400°C, with major element compositions normalized volatile free. See Supplementary Discussion S3 and Supplementary Table S6 for model parameters and further details.

Figure 7: Average values of Sr/Y and Y for each cone (Table 2) compared to global range of adakite compositions (GEOROC database) and experimental partial melts of eclogite (Klimm et al., 2008). Solid and dashed curves represent modeled mantle melt compositions for various amounts of slab melt addition from 900-1350°C at 1.5 GPa. Modeled Sr and Y were calculated using the batch melting equation for a

mantle source (calculated for the Lassen sub-arc mantle) mixed with 2, 5, and 10% (labeled on model curves) of a partial melt of Gorda MORB (as in Fig. 4d; Supplementary Table S6). Bulk partition coefficients were calculated for a spinel peridotite assemblage 35/30/12/5-Ol/Opx/Cpx/Sp using mineral partition coefficients of Eiler et al. (2005) for Sr and Eiler et al. (2001) for Y (Supplementary Table S6). Melt fractions were derived from pMELTS model results (for a given temperature and amount of slab melt addition; Fig. S3).

Figure 8: Schematic diagram depicting the petrogenesis of Lassen region magmas. Chlorite-derived fluids from the deep slab interior beneath the forearc vents (small blue arrows) drive flux-melting of the oceanic crust (red colored area), producing hydrous slab melts that migrate into the overlying mantle (red arrows), where they react with peridotite to induce further melting. The location of hydrous phase stability in the downgoing slab (dark blue shaded region) and main pulses of fluid release from the slab (small light blue arrows) are based on the thermo-petrologic model results of Walowski et al. (2015). Area of low-velocity (dark and light orange shaded regions for latitudes 41° and 40.6° of the 2D models, respectively) based on shear wave velocity model of Lui et al. (2012). Green shaded region shows the location of low resistivity from Wannamaker et al. (2014).

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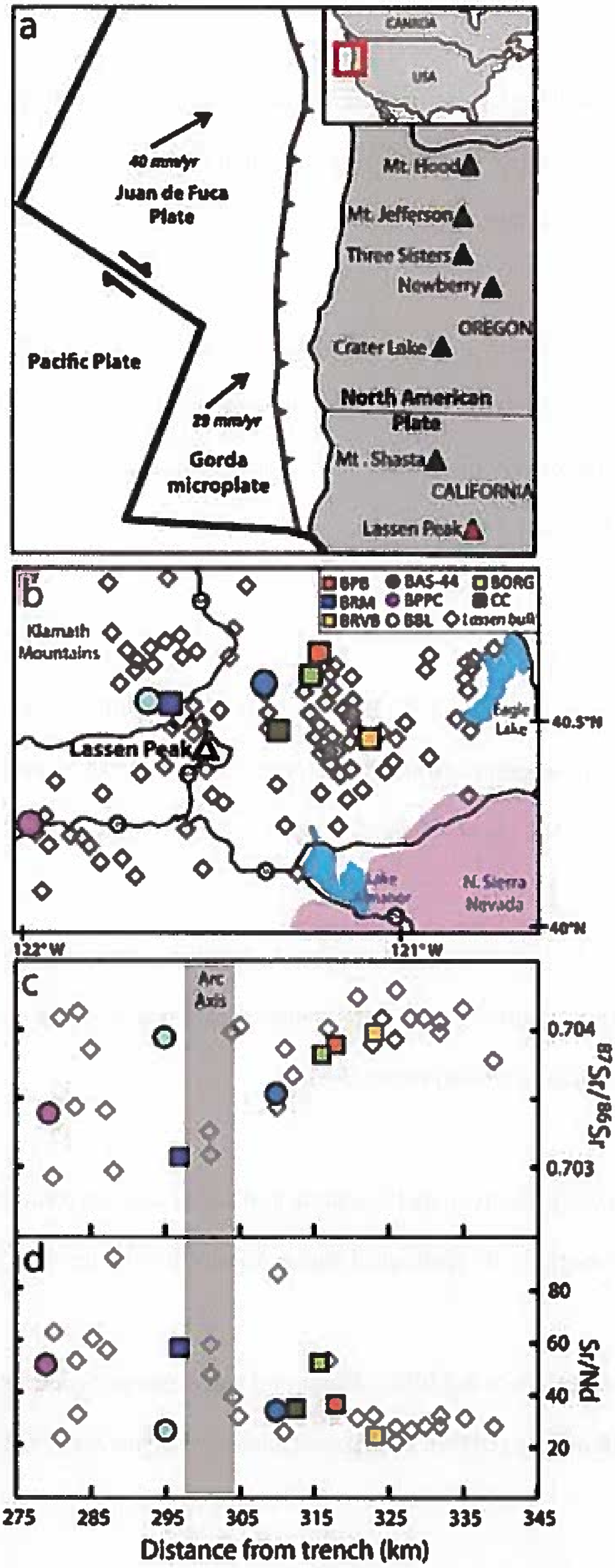

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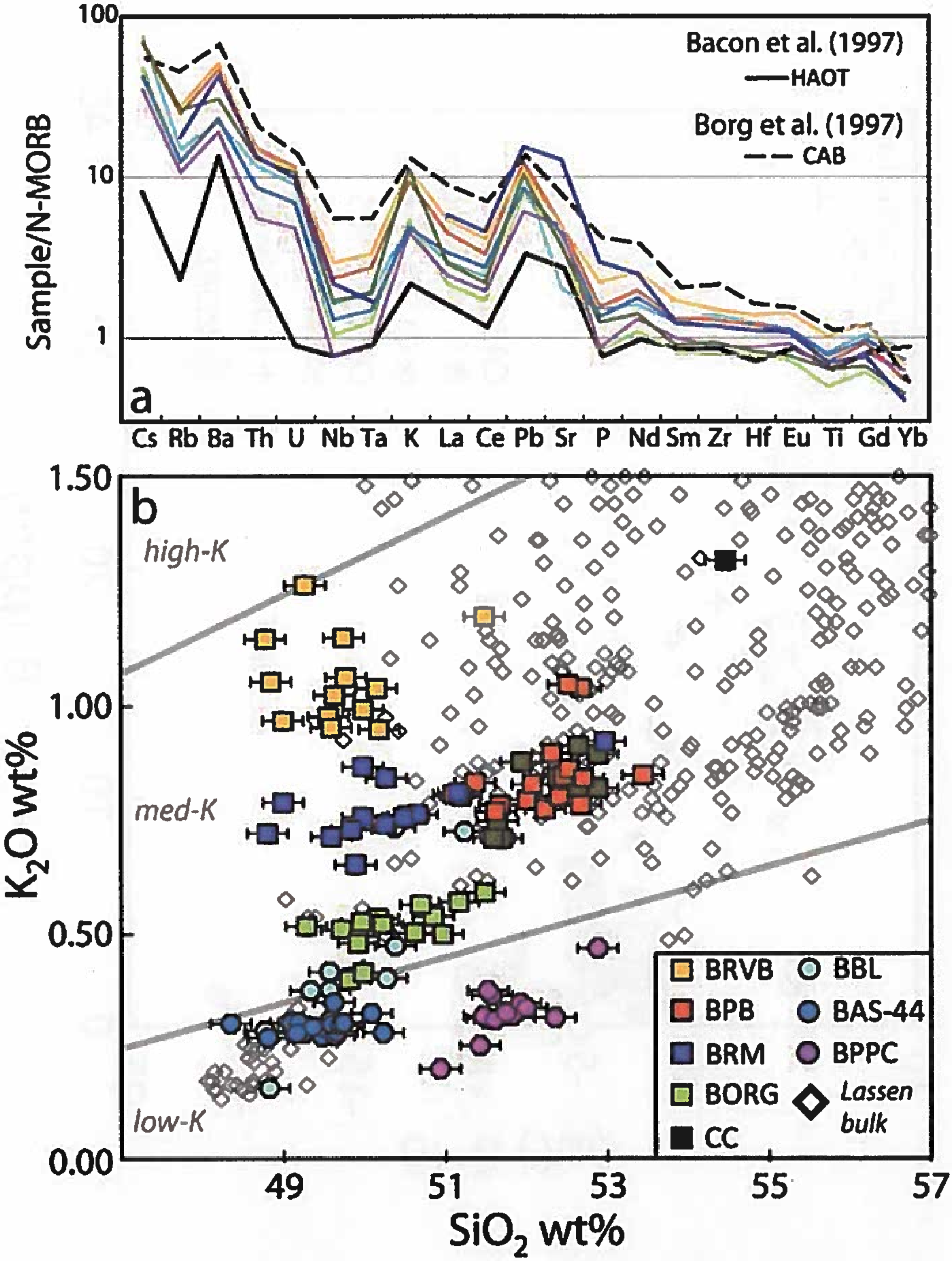

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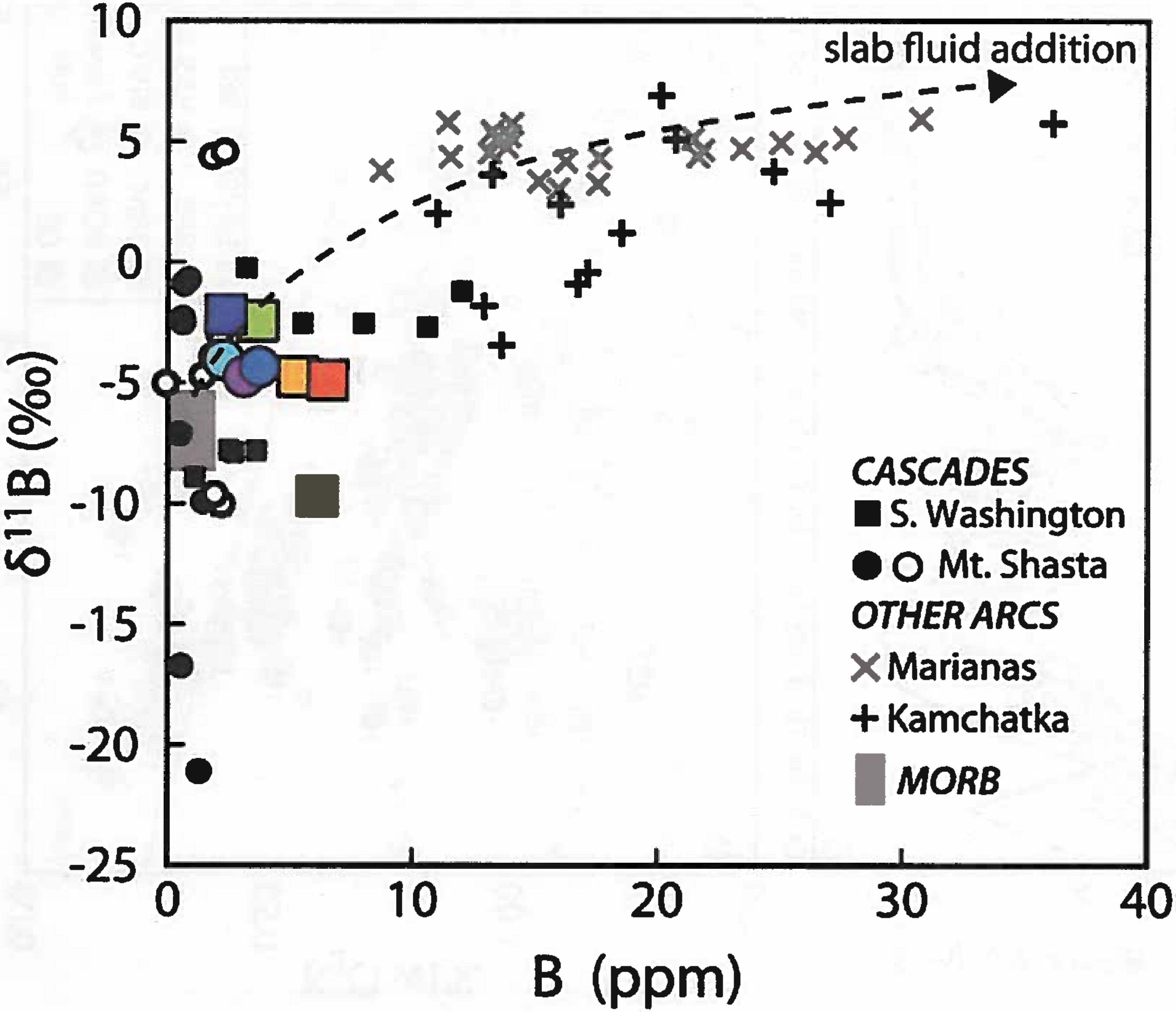
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CASCADES
S. Washington
Mt. Shasta
OTHER ARCS
Marianas
Kamchatka
MORB

Figure
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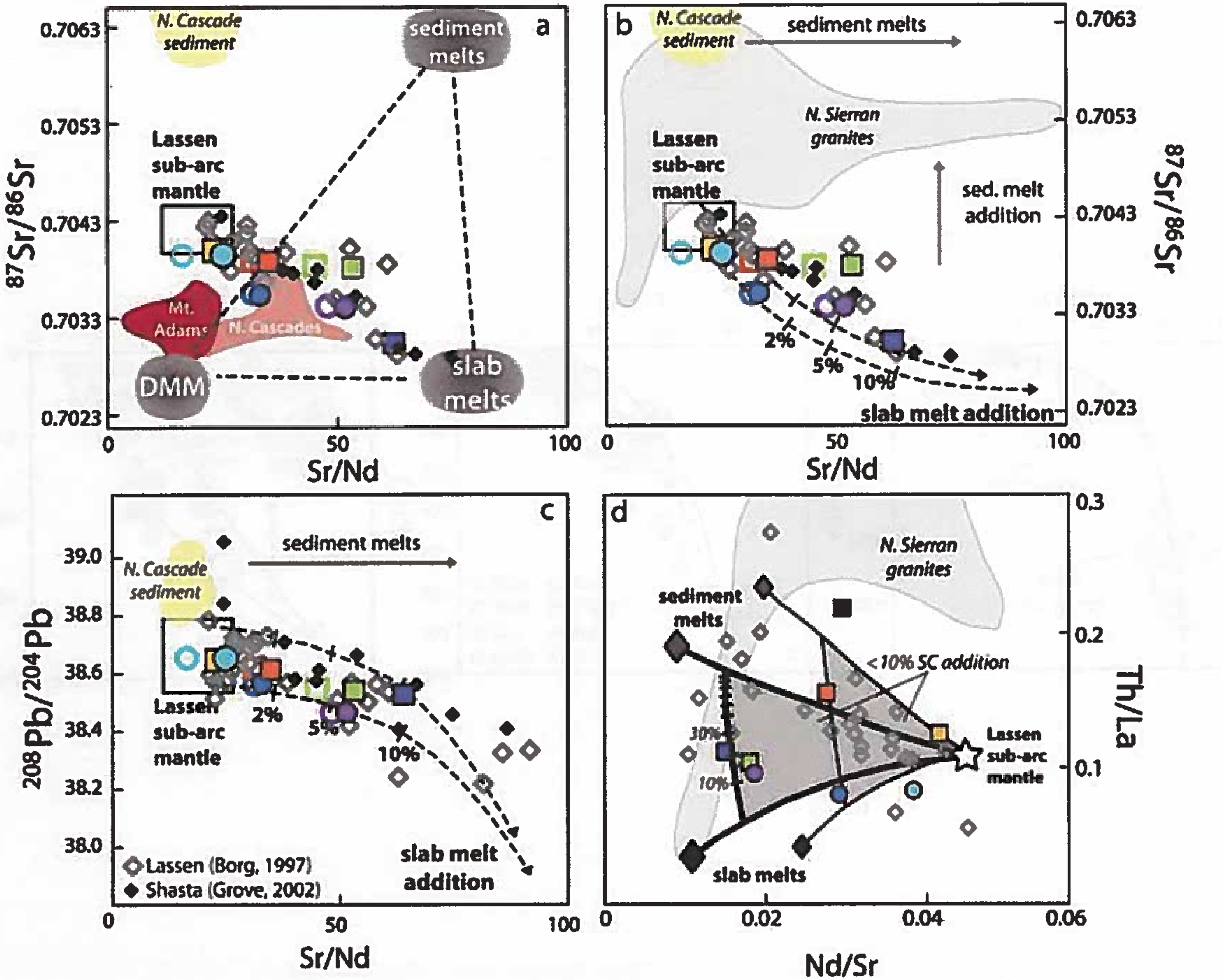

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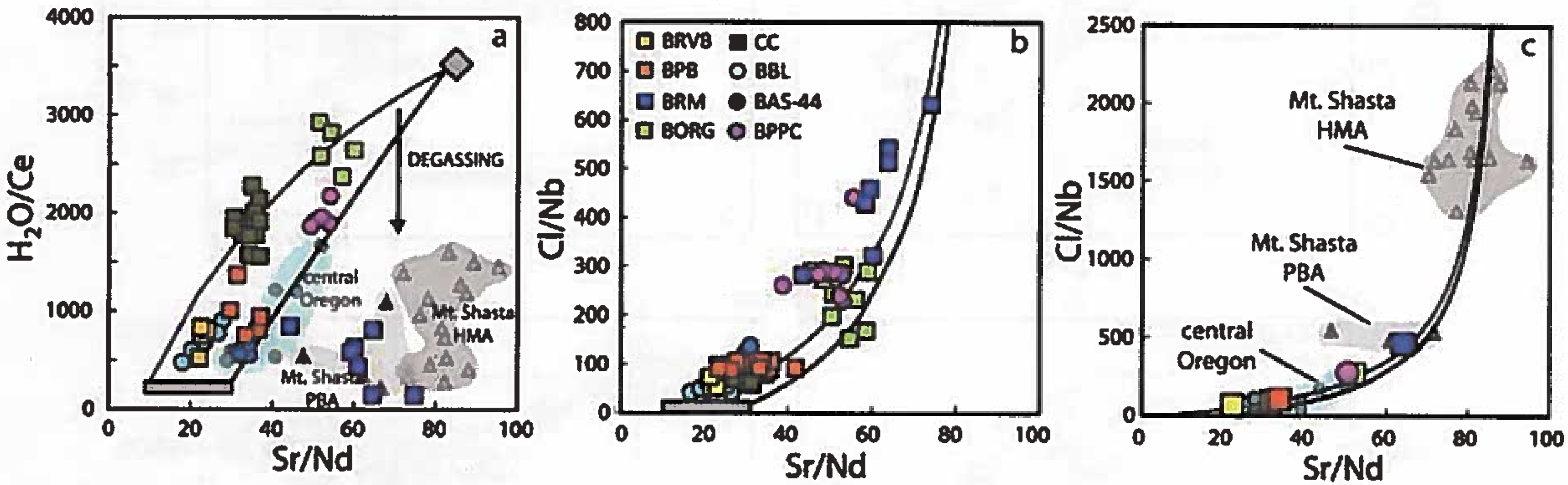

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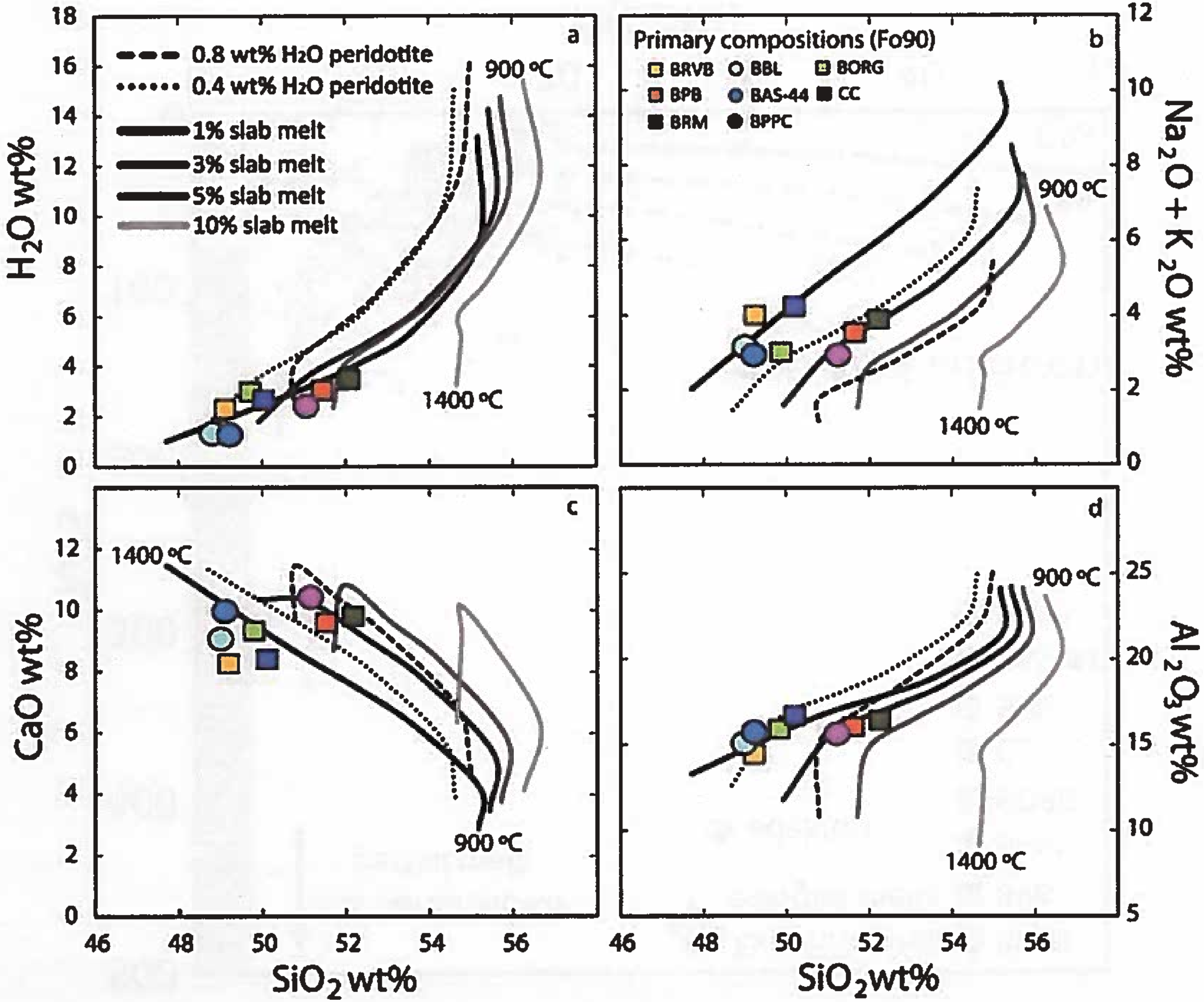

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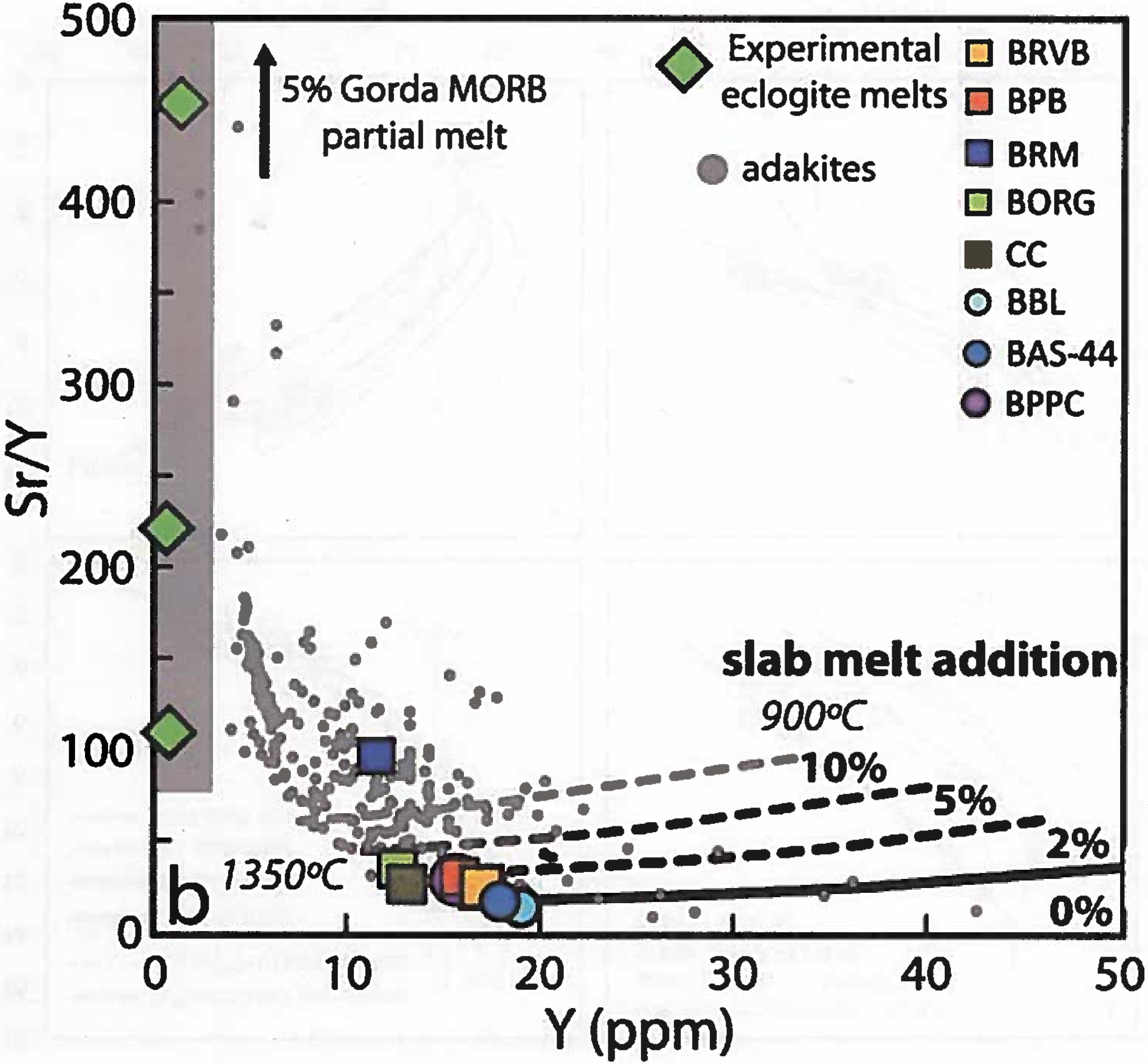
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slab melt addition
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10%
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b

Figure
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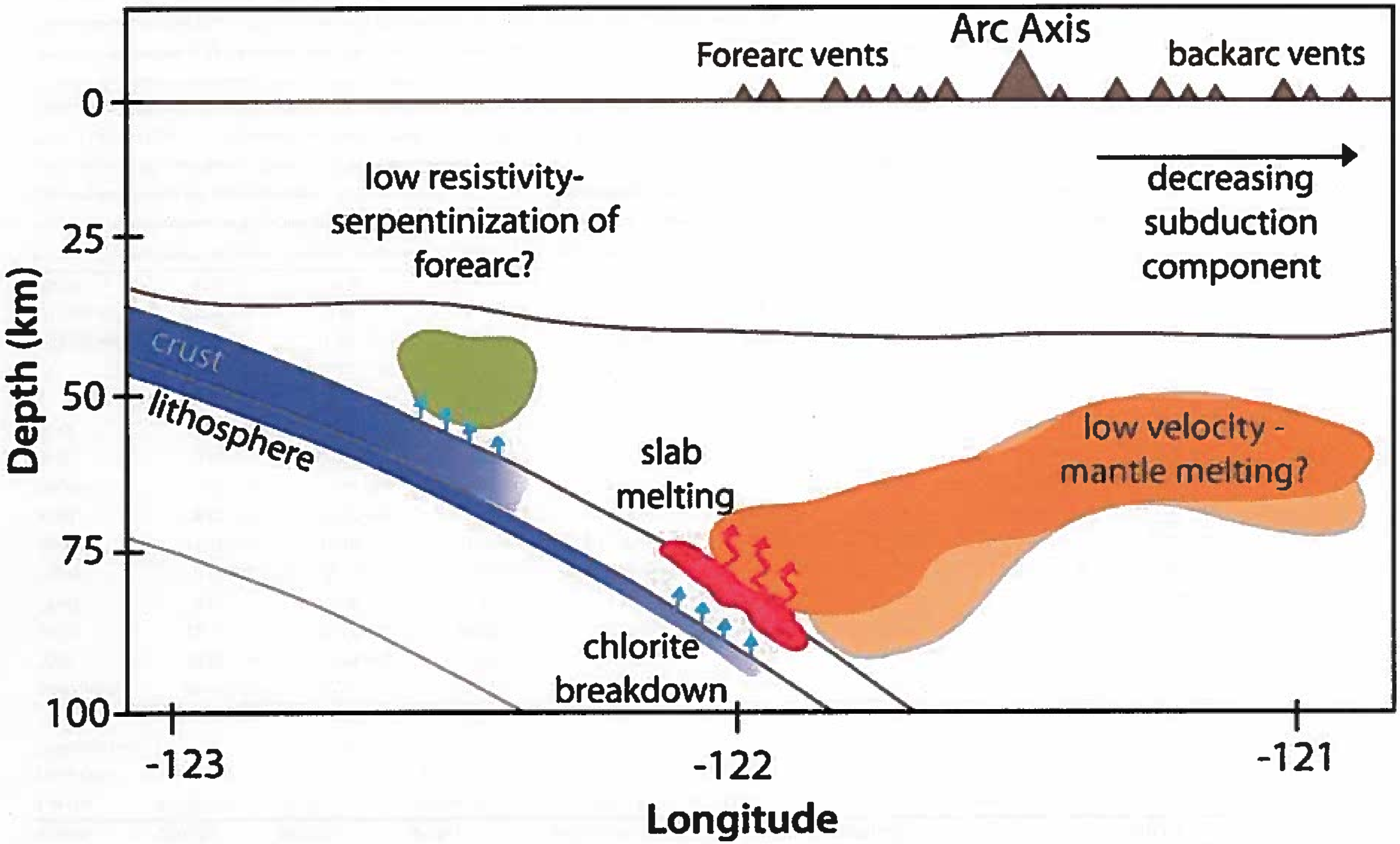

Table

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Table 1: Primary melt compositions (Major and Volatile)

Sample	BBL-05	BORG-1	BPB-1	BAS-44-02	BPPC-01	BRVB-01	CC-1	BRM-1
Lat (N)	40°34'33.72"	40°39'15.63"	40°40'40.80"	40°37'50.64"	40°19'34.22"	40°31'48.78"	40°32'24.50"	40°34'13.17"
Long (W)	121°37'1.32"	121°13'29.07"	121°12'51.00"	121°20'40.14"	121°54'38.64"	121° 4'34.32"	121°18'37.00"	121°35'31.59"
[a]Distance (km)	295	316	318	310	279	323	312	297
	n = 11 *1 s.d.*	n = 15	n = 16	n = 17	n = 14	n = 14	n = 13	n = 15
SiO_2 *(wt%)*	48.94 *0.22*	49.95 *0.14*	51.52 *0.26*	49.42 *0.33*	51.16 *0.12*	48.96 *0.20*	52.54 *0.15*	49.85 *0.11*
TiO_2	0.92 *0.04*	0.70 *0.01*	0.84 *0.01*	0.93 *0.07*	0.76 *0.02*	1.22 *0.01*	0.86 *0.02*	0.77 *0.00*
Al_2O_3	14.72 *0.15*	16.14 *0.16*	15.98 *0.33*	16.23 *0.29*	15.69 *0.11*	13.98 *0.12*	17.15 *0.25*	16.25 *0.11*
[b]FeO^T	9.10	8.18	7.23	8.22	7.38	9.24	5.93	8.06
MnO	0.12 *0.007*	0.10 *0.005*	0.11 *0.005*	0.12 *0.002*	0.12 *0.005*	0.11 *0.002*	0.09 *0.004*	0.09 *0.002*
MgO	14.01 *0.28*	12.40 *0.13*	11.00 *0.27*	11.50 *0.09*	11.18 *0.07*	14.30 *0.09*	8.85 *0.27*	12.41 *0.07*
CaO	8.82 *0.15*	9.33 *0.05*	9.53 *0.18*	10.28 *0.14*	10.51 *0.07*	7.96 *0.17*	10.31 *0.18*	8.12 *0.04*
Na_2O	2.72 *0.08*	2.50 *0.04*	2.67 *0.07*	2.68 *0.06*	2.60 *0.04*	2.91 *0.06*	3.15 *0.07*	3.40 *0.08*
P_2O_5	0.16 *0.05*	0.09 *0.02*	0.23 *0.02*	0.15 *0.05*	0.18 *0.02*	0.27 *0.04*	0.16 *0.01*	0.26 *0.00*
K_2O	0.36 *0.016*	0.47 *0.003*	0.78 *0.007*	0.28 *0.016*	0.30 *0.004*	0.93 *0.002*	0.85 *0.004*	0.68 *0.002*
S	0.09 *0.003*	0.11 *0.004*	0.09 *0.010*	0.11 *0.016*	0.11 *0.004*	0.13 *0.003*	0.09 *0.007*	0.16 *0.002*
Cl	0.02 *0.002*	0.05 *0.001*	0.05 *0.005*	0.03 *0.002*	0.04 *0.001*	0.04 *0.000*	0.04 *0.002*	0.20 *0.001*
[c]CO_2 *(ppm)*	884 *52*	1384 *111*	1436 *47*	754 *56*	1209 *72*	622 *118*	1436 *58*	521 *44*
[d]H_2O *(wt%)*	1.29 *0.08*	3.02 *0.15*	2.94 *0.22*	1.21 *0.22*	2.29 *0.14*	2.28 *0.10*	3.45 *0.10*	2.58 *0.03*
[e]% Ol	17.0	7.9	8.8	4.0	7.5	20.1	1.0	14.8

Primary melt compositions refer to the average MI composition calculated to be in equilibrium with Fo_{90} olivine for each cone (further explanation in Methods).

Major element uncertainty calculated as one standard deviation of the population used to calculate the average MI composition from each cone (including analytical uncertainty)

The complete corrected and uncorrected dataset of MI compositions can be found in Supplementary Tables S1 and S4. Sample names are abbreviations based on Clynne and Muffler (2010):

BBL = Basalt of Big Lake; BORG = Basalt of Old Railroad Grade 3; BPB = Basalt of Poison Butte 3; BAS-44 = Basalt of Highway 44; and unpublished locations:

BPPC = Basalt of Paynes Creek Parasitic Cone; BRVB = Basalt of Round Valley Butte; BRM = Basalt of Red Mountain. Locations are based on NAD27 datum used in Clynne and Muffler (2010).

Major and trace element compositions of bulk tephra can be found in Walowski et al. (2015). Additional data can be found in Clynne et al. (2008); Borg et al. (1997, 2002, 2000); Clynne (1993)

[a] Distance refers to estimated distance from the offshore trench in kilometers

[b] Initial Fe contents used in the calculations were chosen based either on the FeO^T of the bulk tephra or the highest value of FeO^T for MI from a particular cone

[c] CO_2 values represent the highest from each cone after PEC correction and recalculation for melt in equilibrium with Fo_{90} olivine

[d] H_2O values represent the highest from each cone after PEC correction and recalculation for melt in equilibrium with Fo_{90} olivine

[e] Refers to the percent olivine required for equilibrium with Fo_{90} olivine

Table
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Table 2: Primary Melt Compositions (Trace Element and Isotopic)

Sample	BBL-05	1 s.d.	BORG-1		BPB-1		BAS-44-02		BPPC-01		BRVB-01		CC-1		BRM-1	
Li	7.2	0.4	7.0	0.8	7.4	0.8	5.4	1.2	6.2	0.3	11.5	1.8	10.4	0.4	7.3	0.6
B	1.8	0.4	3.7	1.0	8.3	0.2	2.6	10.1	3.0	0.3	8.0	0.6	5.3	0.3	3.2	0.3
Sc	38	1.1	38	1.5	34	0.7	41	1.8	35	0.7	32	0.7	27	1.1	23	1.4
V	225	5	277	9	205	7	218	16	210	2	252	4	186	10	193	5
Rb	5.49	0.67	5.44	0.64	14.24	0.54	4.79	1.29	5.07	0.30	21.56	1.46	15.39	0.37	10.43	0.20
Sr	270	10	438	8	476	41	408	12	450	11	454	5	342	25	1197	6
Y	21.2	0.7	12.6	0.4	15.8	0.2	18.6	1.5	15.7	0.4	18.3	0.3	13.1	0.4	11.4	0.2
Zr	79	6	52	2	93	2	78	9	59	2	105	2	71	2	90	1
Nb	3.0	0.4	2.1	0.1	5.6	0.3	2.7	0.5	1.4	0.1	7.0	0.1	4.0	0.1	5.2	0.1
Ba	157	20	141	9	296	8	117	18	109	5	378	10	203	12	277	5
La	6.2	0.8	5.6	0.3	11.3	0.3	7.4	0.9	5.6	0.2	14.2	0.2	7.5	0.3	15.0	0.1
Ce	15.9	1.8	12.8	1.0	24.0	0.7	19.6	1.8	13.0	0.5	34.9	0.3	16.9	0.6	35.5	0.3
Pr	2.20	0.24	1.70	0.10	3.30	0.06	2.68	0.30	1.80	0.06	4.37	0.05	2.31	0.08	4.36	0.02
Nd	10.80	0.94	8.25	0.54	13.67	0.33	12.38	1.42	8.73	0.26	19.66	0.48	10.52	0.36	18.77	0.14
Sm	2.77	0.18	2.24	0.14	3.12	0.09	2.91	0.28	2.23	0.14	4.25	0.05	2.41	0.08	3.30	0.06
Eu	1.04	0.05	0.84	0.02	1.05	0.03	1.01	0.06	0.85	0.03	1.35	0.04	0.80	0.03	1.12	0.02
Gd	3.50	0.15	2.43	0.15	3.13	0.05	3.19	0.29	2.77	0.14	3.96	0.08	2.47	0.11	2.86	0.03
Dy	3.80	0.12	2.43	0.09	2.88	0.08	3.01	0.23	2.67	0.07	3.66	0.06	2.55	0.10	2.11	0.23
Er	2.51	0.09	1.40	0.12	1.80	0.07	2.21	0.15	1.81	0.09	1.97	0.11	1.39	0.06	1.24	0.03
Yb	2.47	0.08	1.37	0.08	1.73	0.08	2.11	0.16	1.73	0.04	1.92	0.05	1.39	0.06	1.27	0.04
Hf	1.78	0.14	1.35	0.15	2.22	0.09	1.99	0.18	1.71	0.07	2.54	0.17	1.73	0.05	2.33	0.03
Ta	0.17	0.03	0.11	0.02	0.34	0.01	0.15	0.03	0.08	0.01	0.35	0.02	0.26	0.01	0.23	0.00
Pb	1.85	0.25	2.26	0.20	4.01	0.14	1.54	0.28	1.62	0.10	4.14	0.41	3.22	0.21	4.81	0.06
Th	0.52	0.07	0.58	0.10	1.75	0.06	0.59	0.09	0.54	0.03	1.77	0.09	1.63	0.06	1.68	0.01
U	0.18	0.03	0.29	0.02	0.49	0.02	0.21	0.04	0.18	0.02	0.61	0.04	0.52	0.03	0.49	0.01
† $^{87}Sr/^{86}Sr$	0.703939		0.703813		0.703877		0.703529		0.703396		0.703985		N/A		0.703080	
† $^{208}Pb/^{204}Pb$	38.650		38.539		38.612		38.564		38.464		38.646		N/A		38.562	
† $^{177}Hf/^{176}Hf$	0.283057		0.283055		0.283059		0.283094		0.283052		0.283035		N/A		N/A	
† $^{143}Nd/^{144}Nd$	0.512859		0.512864		0.512827		0.512948		0.512926		0.512833		N/A		0.512901	
* $\delta^{11}B$‰ (±1SE)	-4.2(0.9)		-2.6(1.0)		-5.0(0.8)		-4.5(0.8)		-4.9(0.3)		-5.0(0.2)		-10.0(1.0)		-2.4(0.7)	
# $\delta D_{initial}$ ‰	-85		-90		-80		-70		-75		-75		-95		N/A	

Primary melt trace element compositions refer to the average MI composition calculated to be in equilibrium with Fo_{90} olivine for each cone.

Trace element uncertainty calculated as 1 standard deviation of the population used to calculate the average MI composition from each cone (including analytical uncertainty)

Sample names are abbreviations based on Clynne and Muffler (2010), as described in Table 1. Radiogenic isotope analyses are bulk tephra analyses as described discussion section 3

† Errors for individual radiogenic isotope compositions can be found in Supplementary Table S2

* $\delta^{11}B$ values represent an average from 4-8 MI from an individual vent. See Supplementary Table S3 for details.

δD values from Walowski et al. (2015), measured on the same MI that were analyzed for $\delta^{11}B$.