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# Segmentation of the Cascades Arc as indicated by Sr and Nd isotopic variation among diverse primitive basalts

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**Segmentation of the Cascades Arc as indicated by Sr and Nd isotopic variation among diverse primitive basalts**

**Abstract**

In the central Oregon Cascades, extension of the arc has promoted eruption of primitive basalts that are of three types, calcalkaline (CAB), low-K tholeiitic (LKT) and rare absarokitic (ABS) in the forearc. Based on a comparison with the distribution of primitive magma types and their $^{87}Sr/^{86}Sr$ and $^{143}Nd/^{144}Nd$ isotopic signature in the Cascades, we divide the arc into four segments that correspond to distinct tectonic settings and reflect mantle domains and melting regimes at depth. The segments are: 1) the North Segment from Mt. Meager to Glacier Peak; 2) the Columbia Segment from Mt. Rainier to Mt. Jefferson; 3) the Central Segment from the Three Sisters to Medicine Lake, and 4) the South Segment from Mt. Shasta to Lassen Peak.

Calcalkaline basalts (CABs) are found all along the arc axis and are produced by fluxing of variable mantle domains by subduction-derived fluid. In the South Segment, the degree of fluxing and melting is greatest as indicated by high $^{87}Sr/^{86}Sr$ and Ba/Ce of CABs relative to other types of ambient basalt and is consistent with the greater abundance of high-Mg basaltic andesite, relative to other segments. High flux and abundant melt is enhanced by the presence of a slab window and subduction of the altered and deformed Gorda Plate. In the northern part of the arc, small degrees of flux melting are coupled with the presence of an enriched mantle component to yield abundant high-field strength element–enriched (HFSE-rich) basalts. Extension and higher heat flow favors the production of abundant low potassium tholeiites LKT in the Central Segment. A distinct shift in $^{87}Sr/^{86}Sr$ of low LKTs occurs between the Columbia and Central Segments (0.7028 vs 0.7034, respectively), which we interpret as juxtaposition of mantle of accreted oceanic terranes, including the enriched large igneous province Siletz Terrane, with encroaching mantle related to the adjacent Basin and Range Province. The latter, although depleted, carries an enrichment signature from an older subduction history. The segmentation presented here for the Cascades Arc provides a framework for testing the relative influences of the downgoing slab, mantle heterogeneity, and the tectonics and make up of the upper place.

## 1. Introduction

The systematic distribution of magma compositions in volcanic arcs has long been the ground truth on which models of subduction processes are built. Variation in magma composition along volcanic arcs has been correlated to crustal composition and thickness (e.g. Southern Andes; Hildreth and Moorbath, 1988), the depth to the Benioff Zone (e.g. Japan; Kuno, 1959; Dickinson, 1975), the age of the down going slab (e.g. Garibaldi Belt in the Cascade Range; Green and Harry, 1999) and slab fluid and sediment contributions (e.g. the Aleutian Arc; Jicha et al, 2004). Variation in compositions across arcs has been attributed to depth of melting (Mt. Shasta and Medicine Lake; Elkins Tanton et al, 2001), and variations in dip, age, or material contributions from the downgoing plate (e.g. Marianas; Stern et al, 1993). Varying tectonic regimes along arcs may also control asthenospheric upwelling and localization of magma in the crust.

Six physical segments of the Cascade Arc have been defined based on changes in the density and distribution of volcanic vents (Fig. 1a; Guffanti and Weaver, 1988; Hughes et al, 1993). The segment that includes most of the Oregon Cascades has produced anomalously abundant, diffusely distributed mafic volcanism erupted from aligned scoria cones (Hughes and Taylor, 1986; Sherrod and Smith, 1990). Elsewhere along the arc, volcanism is focused at major central volcanoes (Fig. 1a; Sherrod and Smith, 1990). This region of abundant mafic volcanism in Oregon broadly corresponds with extension within the arc, as indicated by discontinuous, north-striking graben faults (Hughes and Taylor, 1986). We therefore focus on the central Oregon Cascades to identify the variety of mantle-derived magmas that are contributing to arc volcanism and to provide a basis for comparing primitive magmas among other arc segments.

The striking physical segmentation of the Cascades Arc invites comparison of its distribution of primitive magma compositions with gross tectonic features along the arc. Tectonic features include the age and type of lithosphere under the arc, as well as the age, dip, and seismicity of the subducting plate. The Cascade Arc is built on crust that is a patchwork of accreted terranes that range from Paleozoic to Eocene (Fig. 1). The subducting crust is young and includes three microplates, the Explorer, Juan de Fuca, and

Gorda Plates that are 2-6 m.y., 4-28 m.y., and 10-26 m.y. at the trench, respectively (Wilson, 1988). Convergence rate of the microplates with North America is 40-45 mm/yr and varies from orthogonal in the British Columbia and Washington Cascades to northward-oblique in the southern arc (Fig. 1a; Wilson, 1988). We here compare compositional and isotopic variations among young basaltic volcanic rocks and how they are distributed along the arc.

Compositional variability among primitive basaltic volcanic rocks of the Cascades has been attributed to the existence of at least three mantle reservoirs for the different basalt types widely distributed beneath the arc (Bacon et al, 1997; Conrey et al, 1997; Green and Harry, 1999; Leeman et al, 1990; Leeman et al, 2005). The main compositional types include calcalkaline basalts (CABs), low K tholeiites (LKTs), and basalts that have light rare-earth element enrichments and high-field-strength element enrichments akin to ocean-island basalts. We refer to these as HFSE-enriched basalts. Two additional primitive compositions have been identified, high-Mg basaltic andesites from Mt. Shasta and Lassen Peak (Baker et al, 1994; Bullen and Clynne, 1990) as well as rare strongly alkalic absarokitic rocks (ABS; Conrey et al, 1997.

We focus on the $^{87}Sr/^{86}Sr$, $^{143}Nd/^{144}Nd$, and trace element compositions to indicate sources and melting histories for these primitive magma groups and to identify isotopic arc segments. Compiled isotopic data for Cascade Arc volcanoes, including new data from the Central Oregon Cascades were used to define four segments (Figure 1b). These are: 1) the North Segment from Mt. Meager to Glacier Peak; 2) the Columbia Segment from Mt. Rainier to Mt. Jefferson; 3) the Central Segment from the Three Sisters to Medicine Lake, and 4) the South Segment, which includes Mt. Shasta to Lassen Peak.

## 2. Tectonic Framework of the Cascades Arc

The youthfulness of the subducting crust along with ongoing extension and high heat flow within the central part of the Cascade arc has led to the characterization of Cascadia as a hot subduction zone. Slab seismicity occurs mainly in the northern and southern parts of the arc, tracking the depth of the down-going slab to ~100 km. In contrast, the slab under central and southern Oregon is largely aseismic (Weaver and

Baker, 1988; McCrory et al, 2004). The Nootka and Blanco Fracture Zones separate the subducting Explorer, Juan de Fuca, and Gorda microplates and provide pathways for seawater to serpentinize the oceanic crust (Melson and Thompson, 1971). The Mendocino triple junction defines the southern margin of the Cascadia convergent margin, where the Mendocino Fracture Zone is being subducted and a slab window may be contributing to mantle upwelling (Beaudoin et al, 1996). Motion along the Mendocino Fracture Zone and the southern Cascadia Subduction Zone has caused deformation of the Gorda Plate (Chaytor et al, 2004). The amount of sediment that is subducted has likely varied through time along the arc and presently varies from ~0% at Vancouver Island to ~50% in central Oregon (MacKay et al, 1992; Fleuh et al, 1998).

Although only 1300 km in length, the Cascades Arc features a wide range of tectonic environments within the upper plate (Fig. 1a). The northernmost Cascade volcanoes (Glacier Peak to Mt. Meager) are built on crust ~50 km thick (Miller et al, 1997) made of metamorphosed Paleozoic to Mesozoic oceanic rocks that were accreted to North America during the Middle Cretaceous (Brown, 1985; Whitney and McGroder, 1989). Volcanism in the northernmost Cascades is mainly restricted to the major centers (Guffanti and Weaver, 1988; Sherrod and Smith, 1990. At the northern margin, waning volcanic vigor has been correlated with the younging of the downgoing Explorer Plate to the north (Green and Harry, 1999; Green and Sinha, 2005).

A ~90 km gap separates Glacier Peak and the active arc in southern Washington (Fig. 1a), where the arc front shifts westward and the arc widens to ~150 km across to include forearc volcanism in the Portland Basin and backarc volcanism at the Simcoe Volcanic Field. The arc in southern Washington and northern Oregon is built on crust of the Columbia Embayment, which is defined by negative gravity anomalies (Couch and Riddihough, 1989) and is thought to consist of crust of oceanic affinity (Miller, 1989; Burchfiel, 1992). The largest block of the Columbia Embayment is the Early Paleogene Siletz Terrane, a fossil oceanic plateau that makes up much of the Oregon and Washington Coast Range and varies from 10-15 km thick in southern Washington to 30 km thick in Oregon (Stanley et al, 1990; Trehu et al, 1994; Parsons et al, 1999). The eastern margin of the Siletz Terrane is unresolved and may underlie the Quaternary arc (Trehu, personal communication). The geochemical influence of the Siletz Terrane has been recognized in the Pb isotopic ratios of sulfide ore deposits associated with Tertiary plutons, where $^{206}Pb/^{204}Pb$ is lower (less than 18.90) in the northern half of Oregon (45°21' to 44°12') compared to data from Washington and southern Oregon (18.90 to 19.05) (Church et al, 1985).

Most Quaternary Cascades Arc volcanism in Oregon lies within a discontinuous N-S graben structure (Fig. 1a; Hughes and Taylor, 1986). In addition to arc-typical andesites and dacites that erupted from central volcanoes (e.g. Mt. Jefferson), the Cascades volcanoes in the central part of Oregon have produced more mafic lavas than in other parts of the arc and mainly from monogenetic vents aligned parallel to the graben (Sherrod and Smith, 1990). Between 8 and 0 Ma, the occurrence of LKTs has progressed northward from the latitude of Three Sisters to Mt. Adams. This has been interpreted as the inception and northward propagation of an intra-arc rift (Conrey et al, 2004). Paleomagnetic and geodetic surveys suggest that the Siletz forearc block is presently rotating counter-clock-wise, contributing to the opening of the intra-arc rift in Oregon as well as to the compression, uplift, and thrust faulting in the Olympic Mountains and Yakima fold and thrust belt of Washington (Wells et al, 1998). The Brother's Fault Zone (Fig. 1a), a zone of distributed northwest-striking faults at the northwestern margin of the Basin and Range, intersects the Cascades Arc in a diffuse zone in the vicinity of the Three Sisters Volcanoes, where vent density is the greatest (Guffanti and Weaver, 1988) and the intra-arc graben is the widest (Conrey et al, 2004). Tertiary to Quaternary bimodal, basalt-rhyolite, volcanism of the High Lava Plains, with rhyolite centers that are successively younger to the west, broadly coincides with the Brother's Fault Zone (MacLead et al, 1975; Jordan et al, 2002).

In southern Oregon and northern California, the volcanic arc lies on accreted terranes of the Klamath Mountain region. The Klamath basement rocks include the Paleozoic Trinity ultramafic sheet and Paleozoic to Mesozoic marine arc-related volcanic and sedimentary rocks accreted to North America by the Late Triassic (Irvin, 1981; Snoke and Barnes, 2006).

## 3. Central Oregon Mafic Magmas and Analytical Techniques

Major element and isotopic data were obtained for primitive basalts from the Central Oregon Cascades in the vicinity of the Three Sisters Volcanic Complex (Table 1) (Rowe, 2006; Rowe et al, 2006). Of the basalt localities, only Cayuse Crater is peripheral to a composite volcano (Broken Top Volcano of the Three Sisters Volcanic Complex); the rest are from monogenetic volcanoes. The vent of the canyon-filling Foley Ridge lava flow (Rowe, 2006; Conrey et al, 2002) and Wizard Falls scoria cone (Table 1) are centered over N-S oriented graben faults that bound the Quaternary volcanic arc. The Wizard Falls scoria cone is ~40 km north of the other sample locations (Rowe, 2006) and has been grouped with Mt. Jefferson in Fig 1b. The Quartzville location is a small lava flow that erupted in the forearc and west of the High Cascades Graben (Conrey et al, 1997; Rowe, 2006).

Major element data (Table 1) were obtained by X-ray fluorescence analysis and trace element data were acquired by HP 4500 inductively coupled plasma source mass spectrometer at the GeoAnalytical Lab at Washington State University (Johnson et al, 1999). Sr and Nd data (Table 1) were acquired from whole rock basalt and basaltic andesite samples at the University of Colorado with a Finnegan-MAT mass spectrometer. Sr and Nd were separated using conventional techniques (Sr separated using SrSpec resin). $^{87}Sr/^{86}Sr$ ratios were analyzed using four-collector static mode measurements. Thirty measurements of SRM-987 during the study period yielded mean $^{87}Sr/^{86}Sr=0.71032\pm2$ ($2\sigma$). Measured $^{87}Sr/^{86}Sr$ were corrected to SRM-987= 0.71028. Measured $^{143}Nd/^{144}Nd$ were normalized to $^{146}Nd/^{144}Nd=0.7219$. Analyses were dynamic mode, three-collector measurements. Thirty-three measurements of the La Jolla Nd standard during the study period yielded a mean $^{143}Nd/^{144}Nd=0.511838\pm8$ ($2\sigma$).

The basalts are primitive with 8.6 to 10.0 wt% MgO and Mg # > 65 (Mg # = molar $MgO/(MgO+FeO^*)\times100$). The Foley Ridge and Cayuse Crater basalts are similar in composition (Table 1), but the Foley Ridge sample has lower $K_2O$ as well as low large ion lithophile elements (LILE) overall, making it akin to the depleted arc wide magma type LKT. Cayuse Crater has lower FeO*/MgO and higher $K_2O/TiO_2$, making it a calcalkaline basalt (CAB). The Quartzville basalt (Table 1) has unusually high LILEs (e.g. 2240 ppm Ba), P, and very steep REE (Ce/Yb of 173). The extreme enriched character of the Quartzville basalt distinguishes it as an absarokitic basalt (ABS). The basalts from Foley Ridge and Cayuse Crater fall within the narrow range of $^{87}Sr/^{86}Sr$ and $^{143}Nd/^{144}Nd$ for basalts at the latitude of Three Sisters (0.70354 - 0.70358 and 0.51292 - 0.51294, respectively; Fig. 1b). The Quartzville is distinct with higher $^{87}Sr/^{86}Sr$ (0.70382) and slightly lower $^{143}Nd/^{144}Nd$ (0.51290) than the primitive basalts within the High Cascades Graben. The northernmost sample from Wizard Falls scoria cone has low $K_2O$ (0.4 wt%) and low Ba/Nb relative to the other Central Oregon basalts, which led Rowe (2006) to call it an OIB or HFSE-rich basalt. But the Wizard Falls basalt also has lower FeO*/MgO and steeper rare earth element (REE) patterns than Foley Ridge, as well as low Nb concentrations, making it a CAB. Wizard Falls has lower $^{87}Sr/^{86}Sr$ (0.70317) and higher $^{143}Nd/^{144}Nd$ than primitive basalts just to the south and is isotopically more like Mt. Jefferson (Conrey et al, 2001) than other Three Sisters basalts (Fig 1b). We next compare the variety of primitive basalts in the central Oregon Cascades to elsewhere along the arc.

## 4. Variety of Primitive Magmas in the Arc

We compiled compositional and isotopic data for basalts to rhyolites from the length of the Cascades arc and immediate back arc (Electronic Appendix A). Available data are mainly for Quaternary volcanic rocks. Complete data sets that include Sr and Nd isotopic data plus major- and trace-element composition are few. The presentation here focuses on primitive volcanic rocks, which mainly erupted from small scoria cones and shields peripheral to, or parasitic to, the major central volcanoes that define the volcanic arc. For geographic convenience, we group the data with the nearest major arc volcano (Fig. 1). We focus on primitive volcanic rocks in order to screen for effects of fractional crystallization or crustal contamination (Table 2) on the geochemical imprint derived from the mantle. We group as primitive those rocks with MgO greater than 7 wt% and Mg # greater than 60. Most of the primitive rocks by these measures are basalts (range 46-52 wt% $SiO_2$), and some are basaltic andesite to andesite (52-58.2 wt% $SiO_2$; Electronic Appendix A).

Analyses of primitive volcanic rocks were grouped into four types of basalt and one basaltic andesite or andesite. These are low K tholeiite (LKT), calc-alkaline basalt

(CAB), HFSE-rich basalt, absarokitic basalt (ABS), and high-Mg basaltic andesite (Table 2). We have included some analyses with lower MgO and Mg # among the HFSE-type and the LKT-type where available data for a region or type were scant. The primitive magma types define a continuum of compositions, rather than neat data clusters (Figs 2,4,5). A few of these basalts have Mg#s in excess of 70.

Calc-alkaline basalts (CAB) are overall the most widely occurring basalt type. They have lower FeO*/MgO (Miyashiro, 1974) and higher CaO and alkali concentrations than tholeiitic basalts, such as LKTs (Table 2; Electronic Appendix A). CABs are also enriched in large ion lithophile element (LILEs; e.g. Sr, and Ba) and have negative high field strength element (HFSEs) anomalies when compared to midocean ridge basalts (MORBs). The composition of Cascades CABs, referred to as “arc basalts” by Bacon and others (Bacon et al, 1997), is like basalts typical of subduction zones and carry the integrated geochemical signals of processes that involve dehydration and (or) melting of the subducting plate (cf., Gill, 1981; Nye and Reid, 1986). The CAB group subsumes LILE-enriched primitive shoshonites and high-K CAB magma types (Conrey et al, 1997; Leeman et al, 2005). Extreme enrichment of incompatible elements (P, LILE, and LREE) is manifested in very rare Cascades absarokites (ABS; Ewart, 1982), such as Quartzville (Table 1) and one locality west of Mt. Hood, which occur as small-volume, forearc flows (Rowe, 2006).

The basalts with the lowest overall concentration of incompatible elements (Table 2) are the low K tholeiites (LKTs), which are also called high alumina olivine tholeiite, HAOT by some workers (e.g. Bacon et al, 1997; Grove et al, 2002; Hart et al, 55). The LKTs have high concentrations of alumina (greater than 16% $Al_2O_3$ at 8% MgO) and high FeO* and $TiO_2$ (Hart et al, 1984). In spite of the depleted character of primitive LKTs, they share with CABs enrichment in large ion lithophile element (LILEs; e.g. Ba, Sr, Pb) relative to midocean ridge basalts (MORBs). LKTs also have near-flat chondrite-normalized rare earth element (REE) patterns with no, or modest 2- to 3-fold light rare earth element (REE; La, Ce) enrichment relative to MORB. These compositional characteristics suggest that LKTs are dry, decompression-induced melts of a subduction fluid-modified, depleted mantle (Bacon et al, 1997; Conrey et al, 1997), such as has been identified in other arcs, including the Indonesian (Sisson and Bronto, 1998) and Central American Arcs (Cameron et al, 2002).

Uniformly enriched HFSE-rich basalts, called ocean island basalts OIBs by other workers (Bacon et al, 1997; Conrey et al, 1997), lack the depletion in HFSEs that is typical of most arc magmas (Bacon et al, 1997; Conrey et al, 1997; Leeman et al, 2005) and have high concentrations of Nb (>20 ppm) and low $Al_2O_3/TiO_2$ (Table 2). At the latitude of the Simcoe Volcanic Field, HFSE-rich basalts are common, but are rarely primitive and contain less than 6.5 % MgO (Bacon et al, 1997; Leeman et al, 1990). We nevertheless include HFSE-rich basalts with the primitive compositions because numerous workers judged that they reflect distinct "primitive" basalt type (Bacon et al, 1997; Conrey et al, 1997; Leeman et al, 2005). The rare, yet significant occurrence of HFSE-rich basalts has also been identified in other arcs, including the Banda-Sunda (Elburg et al, 2004) and Marianas (Stern et al, 1993).

Mg-rich (MgO>7.5%) basaltic andesite and andesite (Table 2; Baker et al, 1994) were also included in this survey. High-Mg basaltic andesites and andesites are calc-alkaline and span a wide range of compositions (Table 1). For example, Sr concentrations of Mg-rich basaltic andesites range from 275 to 1270 ppm. In the Cascades, high-Mg basaltic andesites and andesites have been interpreted to be primary hydrous mantle melts (Baker et al, 1994; Grove et al, 2002), but they may also result from mixing primitive basalt with dacite magma plus ultramafic debris from the crust (Streck et al, 2007).

Basaltic andesites (52-57% $SiO_2$), most of which are not primitive, are more abundant than basalts along the Cascades Arc (Sherrod and Smith, 1990), reflecting the overprint of magmatic differentiation in the crust. Cascades basaltic andesites are diverse, ranging from low to high $K_2O$ (as high as 2.2 wt%) as well as Sr concentrations up to 1650 ppm (Bacon et al, 1997; Bacon, 1990). Among andesites and dacites, it becomes increasingly difficult to distinguish arc-wide magma types, but their Sr and Nd isotopic compositions are generally similar to those of ambient basalts (Fig. 3).

**5. Arc Segments and Diversity of Primitive Magma Types**

Variations in the occurrence of primitive magma types along the Cascades Arc (Fig 1b) along with $^{87}Sr/^{86}Sr$ and $^{143}Nd/^{144}Nd$, define four arc segments (Fig. 1, 4). These are: 1) the North Segment from Mt. Meager to Glacier Peak; 2) the Columbia Segment from Mt. Rainier to Mt. Jefferson; 3) the Central Segment from the Three Sisters to Medicine Lake, and 4) the South Segment, which includes Mt. Shasta and Lassen Peak. These segments generally coincide with physiographic segments defined by Guffanti and Weaver (1988). We have reduced the number of segments and changed the boundaries based on compositional groupings, particularly based on clustering among the lowest $^{87}Sr/^{86}Sr$ values for LKTs along the arc (Fig. 1). The three main changes to the segmentation presented by Guffanti and Weaver (1988) are that we include Mt. Jefferson and Mt. Hood with the southern Washington Cascades volcanoes, we also combine their segments 4 and 5 into one South Segment, and we define a Central Segment that includes Medicine Lake and Newberry Volcano. These two volcanoes are similar to each other and distinct from other Cascades volcanoes in that they both lie immediately behind the arc on the margin of the extensional Basin and Range Province and are large caldera-bearing, shield volcanoes with a bimodal assemblage of high-silica rhyolite and basalt. Medicine Lake volcanohas primarily produced LKTs, while Newberry Volcano has produced a more diverse assemblage of LKTs and CABs, including some CABs with higher HFSE than found on the Central Segment arc axis (Carlson, personal comm.; Rowe personal comm.). We do not include the High Lava Plains, the volcanic plateau associated with the Brothers Fault Zone (Fig. 1), with the arc (Guffanti and Weaver (1988) segment 6) because the High Lava Plains extend several hundred km eastward. The basalts characteristic of the High Lava Plains, however, are like the LKTs, which are common in the Central Segment of the arc (Table 2; Jordan et al, 2002; Jordan, 2002).

In the North Segment, volcanism is strongly focused at central volcanoes, the subduction direction is orthogonal, and the arc axis lies about 400 km from the trench. Basaltic volcanism is predominantly of CAB type with minor occurrence of LKT south of Glacier Peak (Taylor, 2001) and HFSE-rich basalt near Garibaldi (Green and Harry, 1999; Green and Sinha, 2005). The North Segment is compositionally similar to the Columbia Segment except that it has a more restricted range in trace element and isotope ratios (Figs 1, 2, 4, 5).

The Columbia Segment lies on the crust of the Columbia Embayment. The arc axis is displaced about 100 km closer to the trench than in the North Segment. The Columbia Segment is distinguished by the abundance of HFSE-like basalts, which are particularly common at Simcoe Volcanic Field (Fig. 1; Bacon et al, 1997; Leeman et al, 1990). $^{87}Sr/^{86}Sr$ reaches the lowest values in the Columbia Segment and CABs have generally more elevated values than HFSE and LKT basalts. The North and Columbia Segments differ from the Central and South Segments by the presence of the HFSE basalt and by higher concentrations of light REEs, and lower Ba/Ce and Ba/Nb, regardless of basalt type (Figs 2 and 5).

The Quaternary arc crest of the Central Segment, including the Three Sisters, Crater Lake and Mt. McLaughlin occurs within a graben structure (Hughes and Taylor, 1986). Abundant and widely distributed, monogenetic mafic volcanoes occur around and between the major arc volcanoes (Sherrod and Smith, 1990). Medicine Lake and Newberry Volcano sit in extensional backarc settings and are also included in the Central Segment. In this segment, LKTs dominate and CABs are only slightly enriched in incompatible elements relative to LKTs (Fig. 2, 5). A few high-Mg basaltic andesites occur in the southern part of the segment and absarokitic basalt (ABS) occurs at the latitude of Three Sisters in the forearc. The Central Segment has the most restricted Sr isotopic range and the lower limit of $^{87}Sr/^{86}Sr$ of LKTs (0.7035) is higher than along the rest of the arc (Fig. 1b).

The South Segment lies inboard of the Gorda Plate. This segment is distinguished by the occurrence of high-Mg basaltic andesite and andesite, particularly associated with Mt Shasta, in addition to LKT and CAB types. Mt. Shasta is the largest volcano of the Cascades and has high $H_2O$ concentration in its primitive magmas, with values as great as 6.5 wt% in glassy melt inclusions within olivine (Anderson, 1973) and based on mineral equilibria hygrometers (Grove et al, 2002). Primitive magmas from the South Segment encompass the greatest range in $^{87}Sr/^{86}Sr$ and the fluid component indicators Ba/Nb and Ba/Ce (Fig 2).

**6. Relationships among magmas**

By looking at the full suite of primitive magmas from the Cascades Arc, we can address questions about their origins. To what degree are variations in isotopic ratios and trace elements of the diverse primitive magmas the result of heterogeneities in the mantle source? And to what degree do they reflect mantle melting processes? We propose that both mantle heterogeneity and variations in process are responsible and are linked to regional tectonic setting.

High values of Ba/Ce (or Ba/La, Fig. 2) and Ba/Nb are indicators of involvement of a subducting slab-derived fluid, which when coupled with indicators of increasing degree of melting (e.g. decreasing Ce/Yb or Nb), yield hyperbolic variation patterns that have been elegantly modeled as fluid- fluxed melting (Cameron et al, 2002; Elliot et al, 1997; Reiners et al, 2000). In fluid flux melting, the dilution of incompatible elements with increased melting is linked to enrichment of the melt in components carried in the fluxing fluid. Such a model accounts for the variation among HFSE-rich basalts mainly as variable and small degrees of melting, with CABs reflecting divergence to high concentrations of fluid component as degree of melting increases (Fig. 2). Olivine-hosted melt inclusions from the Wizard Falls CAB at the southernmost part of the Columbia Segment have characteristics, such as 17-28 ppm Nb that are similar to HFSE-rich basalts (Rowe, 2006). This likely reflects their origin as higher degree fluid flux melt of an enriched source. CABs occur everywhere in the arc and are evidence that flux melting is active the length of the Cascades. High flux melting is particularly prevalent in the South Segment where Ba/Ce is high at given Ce/Yb and where values range to higher values than typical elsewhere in the arc (Figs 2). The contribution of a slab melt (Defant and Drummond, 1990) is unlikely because Ce/Yb ratios of CABs are not especially high and are similar to those of primitive magmas.

LKT trace element compositions can also be reconciled with a flux melting model where the degree of melting is high (promoted by warm mantle for example) and where the fluid component input is low, either owing to low flux or low concentration in the fluid. Most LKTs have lower $^{87}Sr/^{86}Sr$ and Sr compared to ambient HFSE-rich basalts, which is at odds with simply being part of progressive fluid flux melting by a high $^{87}Sr/^{86}Sr$, Sr-rich fluid (Figs. 1, 5). A fluid with MORB-like low $^{87}Sr/^{86}Sr$ (c.f. Class et al, 2000) would also have to be Sr- and LILE-poor in order to generate low $^{87}Sr/^{86}Sr$ LKT instead of CAB from the same mantle that generates HFSE-rich basalts. Experiments by on LKT from Medicine Lake volcano(Bartels et al, 1991) indicate that LKTs equilibrated with the mantle at shallow pressure (~11 kbar). Calculated pressure and temperature conditions for the generation of LKTs increase from Mt. Shasta to Medicine Lake volcano(Elkins Tanton et al, 2001), indicating that Medicine Lake volcanocould tap a separate, deeper mantle behind the arc that is restricted in $^{87}Sr/^{86}Sr$ and depleted in Ce/Yb (2.2-4.1 at Medicine Lake vs. 4.4-8.4 at Mt. Shasta). These interpretations agree with arguments for a decompression-dominated melting origin of a MORB-like mantle (Hart et al, 1984) for similar, Neogene LKT's of the High Lava Plains (Table 2). Elevated Sr, Pb, and Ba in LKTs is consistent with origin from a mantle source carrying an older subduction contamination signature, as has been argued for Lassen Peak lavas (Borg et al, 1997, 2002). Indeed, Borg et al (2002) argue for existence of a depleted mantle source and another depleted mantle source carrying an old subduction-derived enrichment both of which encounter a modern subduction fluid to account for the compositional and isotopic variability at Lassen Peak.

The Central Segment data closely cluster in both Sr and Nd isotopes and in Sr concentration (Figs. 4 and 5), but CABs have slightly higher $^{87}Sr/^{86}Sr$ and Sr, and lower $^{143}Nd/^{144}Nd$ than LKTs, consistent with only modest fluid flux input to derive CABs from the same source as LKTs. LKTs from the Columbia Segment have distinctly lower $^{87}Sr/^{86}Sr$ than those of the Central Segment, indicating existence of a separate more depleted mantle source. On the other hand, HFSE-rich basalts from the Columbia Segment mainly have higher $^{87}Sr/^{86}Sr$ and lower $^{143}Nd/^{144}Nd$ than nearby LKTs, consistent with HFSE-rich basalts being derived from a separate, more enriched mantle domain that is also high in Ce/Yb (Leeman et al, 1990).

A plot of Sr isotopic ratio versus Sr concentration (Fig. 5a) can support a fluid flux melting model to derive CAB from LKT. LKT have low concentrations of Sr (Table 2), but their $^{87}Sr/^{86}Sr$ varies along the arc, while CAB form trends away from ambient LKTs toward higher Sr and higher $^{87}Sr/^{86}Sr$ for each arc segment, with some exceptions in the South Segment. This trend is particularly well defined in the isotopically and compositionally restricted Central Segment where LKT and CAB form a narrow array of increasing $^{87}Sr/^{86}Sr$ and Sr concentration (Fig. 5a).

Decreasing ratios of fluid mobile to immobile elements from the fore- to backarc, indicating a waning influence of the subducted slab fluid have been identified at various locations along the arc. In southern Washington, B/Nb and Li/Y decrease across the arc and are correlated with decreasing $\delta^{11}B$ (Leeman et al, 2004). In Central Oregon, Cl/Ti in olivine-hosted melt inclusion have been found to decrease across the arc (Rowe, 2006). At Mt. Shasta and Medicine Lake, $K_2O/TiO_2$ decreases from fore- to backarc (Bacon et al, 1997; Baker et al, 1994; Grove et al, 2002), as does Sr/P at Lassen Peak (Borg et al, 1997).

The rare alkali-enriched absarokite (ABS) primitive magma is restricted to the forearc, and very enriched in light REE (Ce/Yb ~178, Fig. 2), Sr, and P, but with Ba/Ce comparable to CAB. The unusual characteristics of the ABS appear to be the result of low degree partial melting of a fluid-fluxed and strongly depleted mantle (Conrey et al, 1997; Rowe et al, 2006). The Sr of the ABS from the Central Segment is more radiogenic than other primitive basalts and may indicate that ABS melts came from an old, metasomatized source region, perhaps within the lithospheric mantle.

High-Mg basaltic andesites are found in all segments of the Cascades Arc, but high-Mg basaltic andesites and andesites are only common in the South Segment where they encompass a broad range of $^{87}Sr/^{86}Sr$ (Fig. 1b). Mt. Shasta and Mt Lassen high-Mg basaltic andesite and andesites are hugely variable and reach $^{87}Sr/^{86}Sr$ values as low as, or lower than, the most primitive LKT (Grove et al, 2002; Borg et al, 1997). This more primitive $^{87}Sr/^{86}Sr$ may reflect partial melting of a depleted, low $^{87}Sr/^{86}Sr$-mantle source, contamination by ultramafic material from the crust (Streck et al, 2007), or contamination by a low-$^{87}Sr/^{86}Sr$, high-Sr fluid from the dewatering of subducted MORB (Grove et al, 2002) as has been suggested for the Aleutian Arc (Class et al, 2000). Although high $H_2O$ in the Mt. Shasta high-Mg basaltic andesites and andesites may indicate a high degree of hydrous melt (Grove et al, 2002), not all high-Mg basaltic andesites in the Cascades Arc are necessarily primary mantle melts. Evidence of magma mixing such as mineral resorption textures is common in some of these basaltic andesites (Leeman et al, 2004). Also, the isotopic ratios Sr and Nd of these basaltic andesites are not as systematic as they are for primitive basalts (Fig. 1b and 5).

The Sr isotopic range of more evolved volcanic rocks is essentially that of the primitive lavas in each segment (Fig. 3), indicating that all of the mantle-derived magma types may be parental to the arc suite. For example, the wide isotopic range defined by the petrologically diverse primitive compositions of the South Segment is mirrored in the diversity amongst dacites and rhyodacites. There does not appear to be a pervasive zone of isotopic homogenization in the crust at the scale of the arc segment. In contrast, the $^{87}Sr/^{86}Sr$ of the Columbia Segment is low overall, but around 52 wt% $SiO_2$, the variability of $^{87}Sr/^{86}Sr$ is greatest. Damping of the variability at greater $SiO_2$ likely reflects a crustal influence of mixing among magmas and (or) contamination. The Central Segment has higher and more restricted $^{87}Sr/^{86}Sr$ than the North and Columbia Segments regardless of $SiO_2$. This suggests that the crust has been homogenized to mantle-like isotopic compositions through abundant recharge from the mantle (Schmidt, 2005).

**7. Tectonic segmentation**

Changes in the tectonic regime along the Cascadia margin are reflected in the erupted magma in the arc. The isotopic segments agree reasonably well with segments defined by vent distributions (Guffanti and Weaver, 1988) although the segment boundaries have been shifted. Segmentation of Cascadia based on episodic tremor and slip recurrence intervals in the forearc (Brudzinski and Allen, 2007) also agree with geochemcial variations we see along the arc front. The depth of the slab is well-resolved to subarc depths in the North and South Segments (Weaver and Baker, 1988; McCrory et al, 2004; Wells et al, 1998). The lack of slab seismicity (Weaver and Baker, 1988; McCrorey et al, 2004) and the dominance of drier LKT and HFSE-rich basalts in the Central and Columbia Segments have been linked to high heat flow and mantle upwelling related to intra-arc extension.

In the North Segment, subduction is more shallow and orthogonal and CABs erupted at central volcanoes are dominant. The degree of flux melting is small in the North Segment and decreases progressively to the north (Green and Harry, 1999; Green and Sinha, 2005). To the south, convergence is increasingly oblique, erupted primitive magma types are more diverse and LKTs are more abundant. Previous workers have recognized a general increase in $^{87}Sr/^{86}Sr$ from north to south along the arc (Bacon et al, 1997), which in large part reflects increased fluid fluxing to the south. However, new Central Oregon data (Table 2) resolve a distinct shift in $^{87}Sr/^{86}Sr$ among LKT and in abundance of HFSE-rich basalt. This shift between the Columbia and Central Segments occurs at the intersection of two crustal terranes, the southern margin of the young, oceanic Siletz Terrane of the Columbia Embayment and Klamath-Sierra crustal block, and also coincides with the intersection of the Brother's Fault Zone with the volcanic arc (Fig. 1b). The trace element signature of the subducted slab, such as Ba/Ce (Fig. 2) or Ba/Nb, is obscured in the Columbia and North Segments, where primitive magmas have particularly high light REE and HFSE. HFSE-rich basalts have higher $^{87}Sr/^{86}Sr$ and lower $^{143}Nd/^{144}Nd$ (Fig. 4a) than LKT in the Columbia Segment indicating that LKT cannot be derived by high degree fluid flux melting of the same source. The lower range in $^{87}Sr/^{86}Sr$ and presence of HFSE-rich basalts in the Columbia Segment suggests that the arc taps an accreted, enriched (possibly lithospheric; Leeman et al, 2005) Siletz Terrane mantle. Alkaline intrusions (36-32 Ma) with HFSE-rich affinities (high HFSE and HREE) in the Oregon Coast Range (Oxford, 2006) further indicate the presence of an accreted, enriched mantle beneath the Siletz Terrane. The Central Segment, in contrast produces drier, higher degree melts from an isotopically restricted mantle that is widespread under the northwest Basin and Range Province (Hart, 1984).

The complex tectonic setting of the South Segment is reflected in the compositional and isotopic diversity of the primitive magmas. The South Segment differs greatly from other parts of the Cascades Arc in having magmas with high water contents, abundant high MgO volcanic rocks (Baker et al, 1994; Grove et al, 2002), and the most variable Sr and Nd isotopic ratios among primitive rocks (Grove et al, 2002; Borg et al, 1997). The $^{87}Sr/^{86}Sr$ of LKT from the South Segment span nearly the full range of Cascades Arc (Figs 1b, 4). This diversity relates to influences from at least two mantle sources, one like that of the Central Segment with a modest enrichment by ancient subduction fluids (Borg et al, 1997, 2002) and a depleted sub-arc mantle. Primitive CAB from the Lassen Peak area are related to nearby LKT, but diverge to both high $^{87}Sr/^{86}Sr$ and low $^{87}Sr/^{86}Sr$ with increasing Sr concentration (Fig 5a). This supports the contributions of two high Sr fluids with contrasting $^{87}Sr/^{86}Sr$ (Fig. 5b) in the South

Segment (Grove et al, 2002). These fluids may reflect both the modern dewatering of the Gorda Plate and older Sr that was inherited during prior subduction (Borg et al, 1997, 2002). Involvement of abundant fluid in magmatism in the southernmost Cascades may be via the serpentinized fracture zones associated with the deformed, downgoing Gorda Plate (Chaytor et al, 2004) and (or) from previously hydrated accreted crust of the Klamath-Sierra Nevada block (Streck et al, 2007).

**9. Conclusions**

The compositional diversity and Sr and Nd isotopic data for primitive volcanic rocks of the Cascades Arc correlate with distinct tectonic arc segments. These are: 1) the North Segment from Mt. Meager to Glacier Peak; 2) the Columbia Segment from Mt. Rainier to Mt. Jefferson; 3) the Central Segment from the Three Sisters to Medicine Lake, and 4) the South Segment, which includes Mt. Shasta and Lassen Peak.

We propose a general model of a subarc mantle that is heterogeneous along strike and that is also undergoing flux melting. The addition of a high-$^{87}Sr/^{86}Sr$ and fluid mobile element-enriched fluid to a heterogeneous mantle generates CABs. CABs are found along the entire arc and are the dominant type in the North Segment, where convergence is orthogonal, and in the South Segment, where high $H_2O$ contents (Bullen and Clynne, 1990; Grove et al, 2002; Borg et al, 1997) and Ba/Ce indicate that fluid fluxing is high. Larger degrees of fluid-poor melting occur in the central and southern arc where transtension extends the arc in an oblique convergence environment, favoring the formation of LKTs with affinity to the neighboring northwest Basin and Range Province. An accreted mantle domain with higher HFSE and LREE, and lower $^{87}Sr/^{86}Sr$ underlies the Columbia and North Segments, where HFSE-rich basalts are produced

No single primitive magma type is parental to the rest of the arc suite (as per Bacon et al, 1997; Conrey et al, 1997). Complete data sets with full isotopic and elemental compositions are scarce, in spite of the accessibility of the Cascades. This segmentation scheme for the Cascades Arc provides a framework for testing hypotheses for the relative influences of the down-going plate and the tectonics and composition of the upper plate.

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**Figure Captions**

**Figure 1a**. Map of the Cascadia subduction zone with important terranes and tectonic provinces (Couch and Riddihough, 1989; Trehu et al, 1994). Contours for the depths of the slab are in km (Weaver and Baker, 1988) and dashed lines on oceanic plates are magnetic anomalies (Wilson, 1988). The Mendocino Triple Junction (TJ) marks the southern extent of Cascadia subduction. Numbered hysical segmentation of the Cascade Arc is based on the distribution of volcanic vents (Guffanti and Weaver, 1988) and differs slightly from the isotopic segmentation defined here and shown with bold lines and lettering. Major central volcanoes are illustrated as triangles. Abbreviations of central volcanoes correlate with centers listed in 1b, except MM Mt. Meager, MC Mt. Cayley, and MG Mt. Garibaldi. **b.** $^{87}Sr/^{86}Sr$ histogram of volcanic rocks clustered with closest central volcano along the Cascade Arc, compiled from the literature and characterized according to Table 1 (Bacon et al, 1994, 1997, Bacon and Druitt, 1988; Baker et al, 1991, 1994; Borg et al, 1997, 2000; Bruggman et al, 1989, 1993; Bullen and Clynne, 1990; Conrey et al, 2001; DeBari, unpublished data; Donnelly-Nolan, unpublished data; Goles and Lambert, 1990; Green and Harry, 1999; Green and Sinha, 2005; Grove et al, 1988, 2002; Leeman et al, 1990, 2004, 2005; Magna et al, 2006; Mertzman and Gooding, 1988; Mertzman and Savin, 1985; Schmidt, 2005; Wagner et al, 1995). Ranges are given for basaltic andesites (ba), andesites (and), and dacites and rhyodacites (dac, rd) with the number of analyses shown in parentheses and median $^{87}Sr/^{86}Sr$ values indicated by ‘x’. Ranges are also given for primitive basalts from Mt. Hood (Gunn et al, 1996) and Newberry Volcano (Carlson, written communication. Olivine cumulate basalts from Crater Lake (Bacon et al, 1994) have greater than 15% MgO and are not considered to be primary melts and are not discussed further. Thick black lines mark the lower limit for LKT for each isotopic segment. Range in $^{87}Sr/^{86}Sr$ of MORB is shown for reference (Cohen and O’Nions, 1982).

**Figure 2.** Ba/Ce versus Ce/Yb for primitive Cascade Arc basalts (Bacon et al, 1994, 1997, Bacon and Druitt, 1988; Baker et al, 1991, 1994; Borg et al, 1997, 2000; Bruggman et al, 1989, 1993; Bullen and Clynne, 1990; Conrey et al, 2001; DeBari, unpublished

data; Goles and Lambert, 1990; Green and Harry, 1999; Green and Sinha, 2005; Grove et al, 1988, 2002; Leeman et al, 1990, 2004, 2005; Magna et al, 2006; Mertzman and Gooding, 1988; Mertzman and Savin, 1985; Schmidt, 2005; Wagner et al, 1995) with fields for isotopic segments indicated.

**Figure 3.** $^{87}Sr/^{86}Sr$ vs. $SiO_2$ for the compilation of isotopic data from the Cascade Arc (Bacon et al, 1994, 1997, Bacon and Druitt, 1988; Baker et al, 1991, 1994; Borg et al, 1997, 2000; Bruggman et al, 1989, 1993; Bullen and Clynne, 1990; Conrey et al, 2001; DeBari, unpublished data; Donnelly-Nolan, unpublished data; Goles and Lambert, 1990; Green and Harry, 1999; Green and Sinha, 2005; Grove et al, 1988, 2002; Leeman et al, 1990, 2004, 2005; Magna et al, 2006; Mertzman and Gooding, 1988; Mertzman and Savin, 1985; Schmidt, 2005; Wagner et al, 1995). Symbols represent isotopic segments. The relative scarcity of higher $SiO_2$ data reflects the density isotopic data from literature, not the lack of evolved volcanic rocks in the Cascades. For example, dacites are common in the North, but their isotopic compositions have not been examined and (or) published. High $SiO_2$ data are dominated by volcanic centers where abundant isotopic work has been done, including Lassen Peak, Mt. Shasta, Crater Lake, and Mt. Jefferson

**Figure 4.** $^{144}Nd/^{143}Nd$ vs. $^{87}Sr/^{86}Sr$ for primitive basalts in the Cascade Range (Bacon et al, 1994, 1997; Baker et al, 1991, 1994; Borg et al, 1997, 2000; Bullen and Clynne, 1990; Conrey et al, 2001; DeBari, unpublished data; Green and Harry, 1999; Green and Sinha, 2005; Grove et al, 2002; Leeman et al, 1990, 2004, 2005; Magna et al, 2006). Points are colored according to isotopic segment. The range in $^{87}Sr/^{86}Sr$ for the segments taken from Figure 1. **a)** LKT and HFSE-rich basalts with gray CAB field. Ranges for each segment are for $^{87}Sr/^{86}Sr$ of LKT and HFSE. **b)** CAB points with gray LKT field.

**Figure 5. a)** $^{87}Sr/^{86}Sr$ vs. Sr concentration with fields corresponding to isotopic segments of the Cascades (Bacon et al, 1994, 1997; Baker et al, 1991, 1994; Borg et al, 1997, 2000; Bullen and Clynne, 1990; Conrey et al, 2001; DeBari, unpublished data; Green and Harry, 1999; Green and Sinha, 2005; Grove et al, 2002; Leeman et al, 1990, 2004, 2005; Magna et al, 2006) Fields encircle the isotopic segments. **b)** $^{87}Sr/^{86}Sr$ vs. Ba/Ce.

**Table 1. Central Oregon primitive basalt elemental and isotopic data**

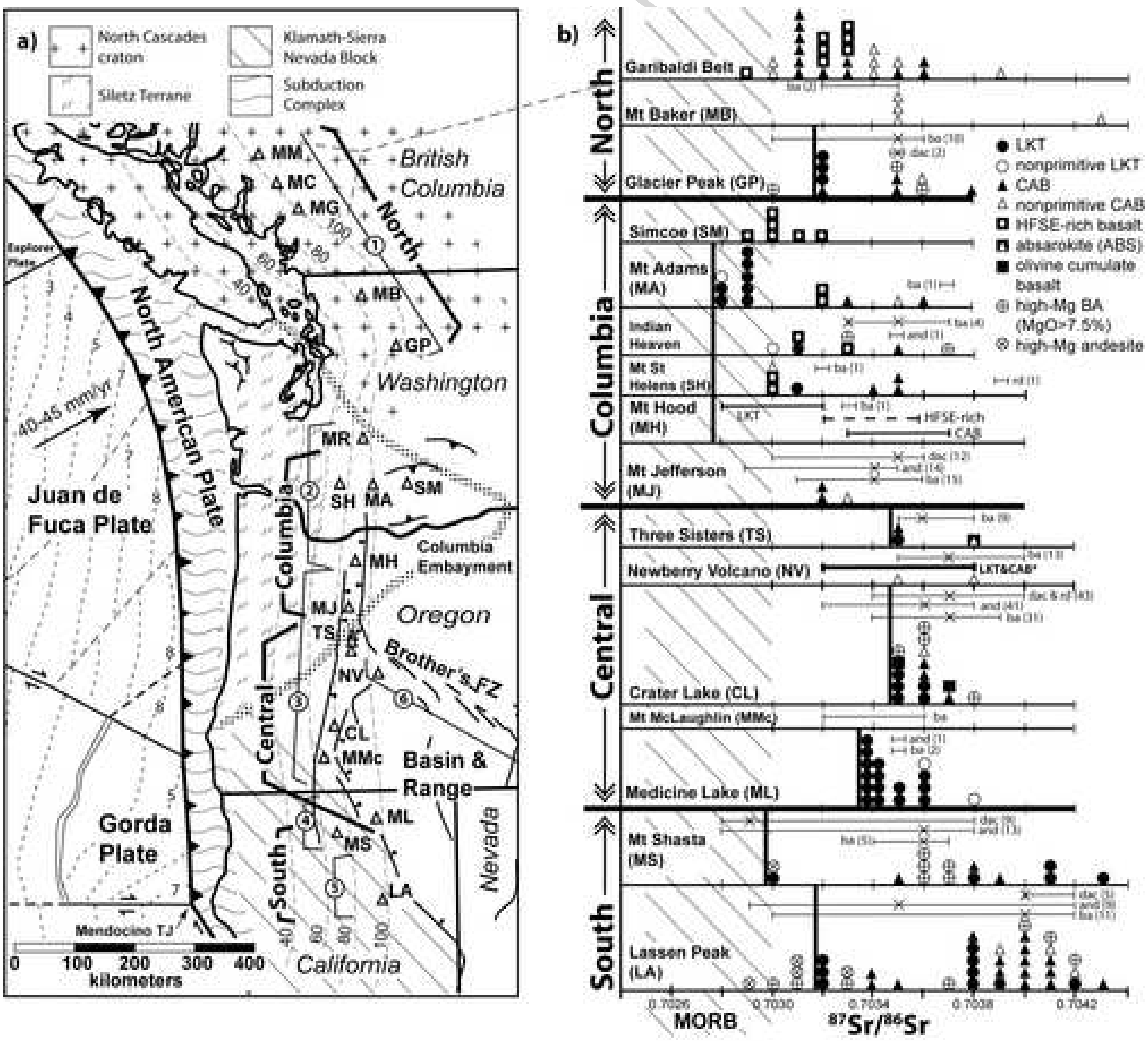
| Sample # | CC 02 1[1] | FLR 03 1 | QV 03 1[2] | WF 02 1 |
|---|---|---|---|---|
| Location | CayuseCrater | Foley Ridge | Quartzville | WizardFalls |
| Lat/long | 44.06°/-121.71° | 44.17°/-122.11° | 44.60°/-122.34° | 44.52°/-122.63° |
| Magma type | CAB | LKT | ABS | CAB |
| wt%: | | | | |
| $SiO_2$ | 51.94 | 49.08 | 50.06 | 49.09 |
| $Al_2O_3$ | 16.53 | 16.94 | 13.64 | 15.91 |
| $TiO_2$ | 1.053 | 1.510 | 1.581 | 1.588 |
| FeO*[3] | 7.85 | 9.57 | 6.53 | 9.78 |
| MnO | 0.150 | 0.175 | 0.105 | 0.179 |
| CaO | 9.15 | 9.83 | 10.14 | 9.44 |
| MgO | 8.62 | 9.03 | 9.86 | 10.00 |
| $K_2O$ | 0.65 | 0.40 | 3.11 | 0.39 |
| $Na_2O$ | 3.13 | 3.07 | 2.88 | 2.91 |
| $P_2O_5$ | 0.221 | 0.332 | 1.173 | 0.436 |
| ppm: | | | | |
| Ni | 153 | 176 | 256 | 235 |
| Cr | 411 | 359 | 436 | 349 |
| V | 185 | 229 | 140 | 184 |
| Ba | 224 | 231 | 2242 | 222 |
| Th | 1.27 | 0.98 | 7.97 | 1.23 |
| Nb | 6.67 | 7.39 | 7.23 | 10.04 |
| Y | 20.49 | 27.82 | 20.60 | 27.49 |
| Hf | 2.41 | 3.00 | 8.31 | 3.69 |
| Ta | 0.42 | 0.51 | 0.37 | 0.63 |
| U | 0.44 | 0.23 | 2.18 | 0.33 |
| Pb | 2.76 | 2.27 | 13.63 | 2.06 |
| Rb | 10.9 | 4.3 | 26.9 | 2.3 |
| Cs | 0.39 | 0.20 | 0.20 | 0.07 |
| Sr | 431 | 398 | 3124 | 701 |
| Sc | 31.3 | 35.7 | 23.5 | 35.4 |
| Zr | 93 | 116 | 336 | 156 |
| La | 10.01 | 11.77 | 83.94 | 17.39 |
| Ce | 21.31 | 25.95 | 184.60 | 39.03 |
| Pr | 2.76 | 3.58 | 24.35 | 5.13 |
| Nd | 12.48 | 16.37 | 100.09 | 22.54 |
| Sm | 3.39 | 4.58 | 17.49 | 5.41 |
| Eu | 1.23 | 1.64 | 4.59 | 1.84 |
| Gd | 3.66 | 4.95 | 10.35 | 5.37 |
| Tb | 0.61 | 0.82 | 1.11 | 0.85 |
| Dy | 3.77 | 5.18 | 4.85 | 5.22 |
| Ho | 0.78 | 1.05 | 0.74 | 1.03 |
| Er | 2.10 | 2.88 | 1.64 | 2.78 |
| Tm | 0.30 | 0.40 | 0.20 | 0.40 |
| Yb | 1.84 | 2.56 | 1.07 | 2.47 |
| $^{87}Sr/^{86}Sr$ | 0.70354 | 0.70358 | 0.70382 | 0.70317 |
| $^{143}Nd/^{144}Nd$ | 0.51294 | 0.51292 | 0.51290 | 0.51296 |

Major element data for the Cayuse Crater sample[1] (Rowe et al, 2007) and major and trace element data for the Quartzville sample[2] (Rowe, 2006) have been published elsewhere. [3] Total Fe is expressed as FeO*.

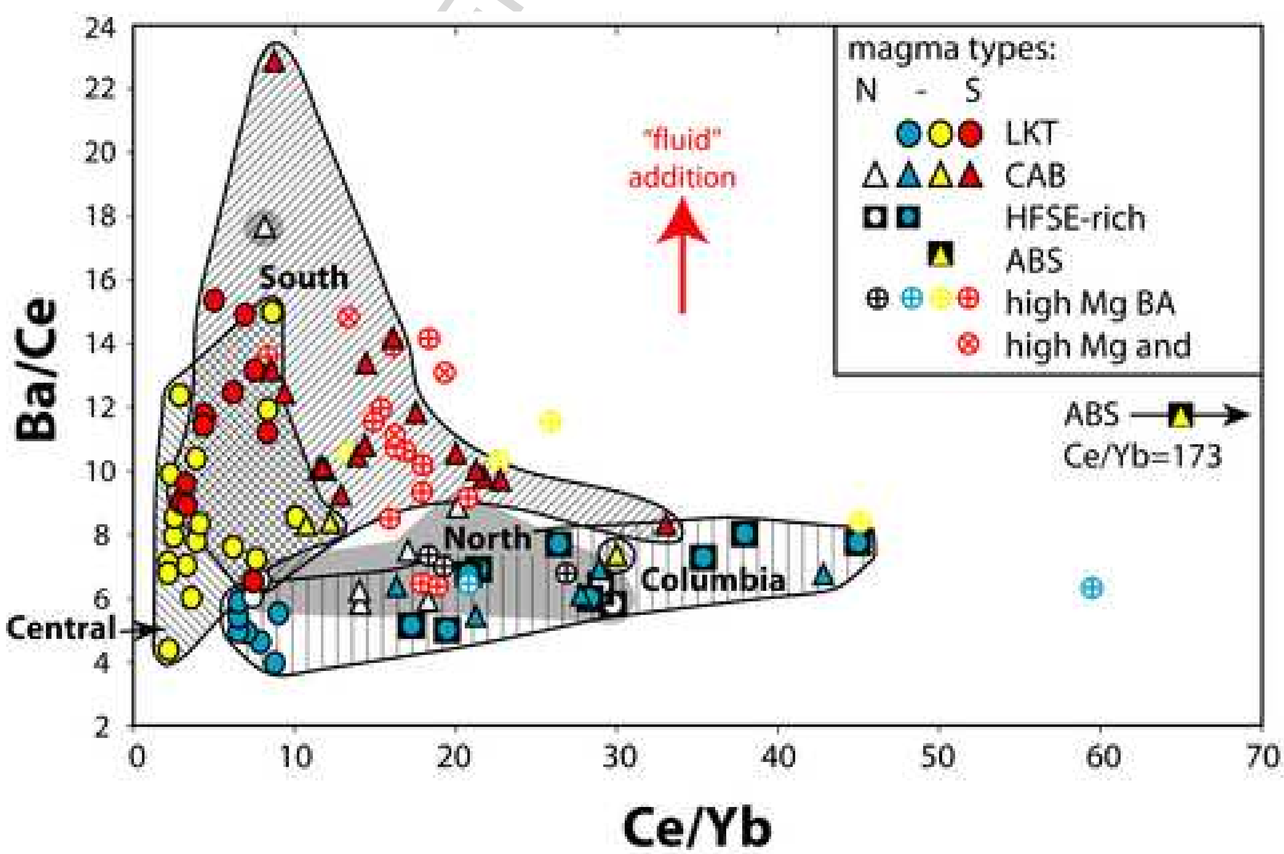
**Table 2. Primitive magma characterization scheme**

| | MgO | Mg#[1] | $Al_2O_3$/ $TiO_2$ | $K_2O$ | Sr | P | Nb | Ce | Ce/Sm | Ce/Yb |
|---|---|---|---|---|---|---|---|---|---|---|
| | wt% | | | wt% | ppm | ppm | ppm | Ppm | | |
| <52% $SiO_2$: | | | | | | | | | | |
| **CAB** | 7- 12 | 53-73 | 8-26 | 0.4 – 2.2 | 290-1330 | 520-2270 | 2-19 | 9-81 | 4.5-10 | 5-43 |
| **ABS** | >8.0 | 73 | 9 | 3.1 | 3120 | 5120 | 7 | 185 | 12 | 173 |
| **LKT** | 7 - 12 | 50-72 | 11-32 | <0.6 | 190 - 500 | 215-1450 | 1-10 | 4-26 | 2.5-7.5 | 2–10.5 |
| **HFSE-rich**[2] | 5.5-10.0 | 48-65 | 4-11 | 0.6 – 2.3 | 410 - 1000 | 1520-3320 | >20 | 35–79 | 6.0-10.5 | 17–45 |
| >52% $SiO_2$: | | | | | | | | | | |
| **High-Mg BA**[3] | >7.5 | 60-72 | | 0.3-1.2 | 270-1270 | 480-2270 | 2-18 | 10-57 | 4.5-12 | 4.5-94 |

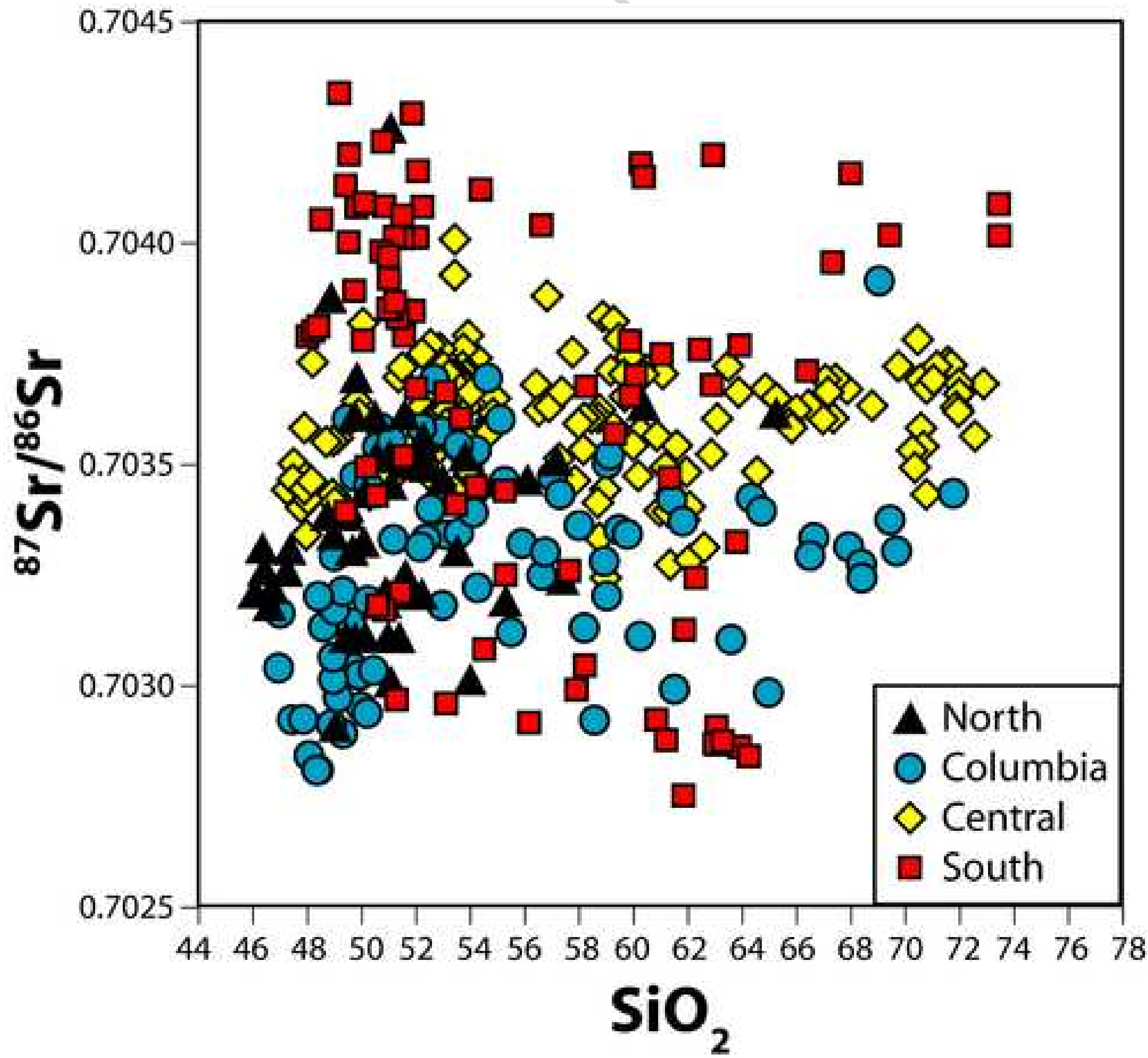
Abbreviations are LKT low K tholeiite, CAB calc-alkaline basalt, HFSE-rich high field strength element enriched basalts, and ABS absarokite. [1]Mg# is the atomic ratio of 100Mg/(MgO+$FeO^{Total}$). [2]HFSE-rich basalts lack a Nb anomaly, $(K/Nb)_N$ 0.5 to 0.2 (C1 chondrite-normalized ratio (MacDonough and Sun, 1995). [3]High-Mg BA (basaltic andesites) have greater than 52 wt% $SiO_2$ and high MgO concentrations.



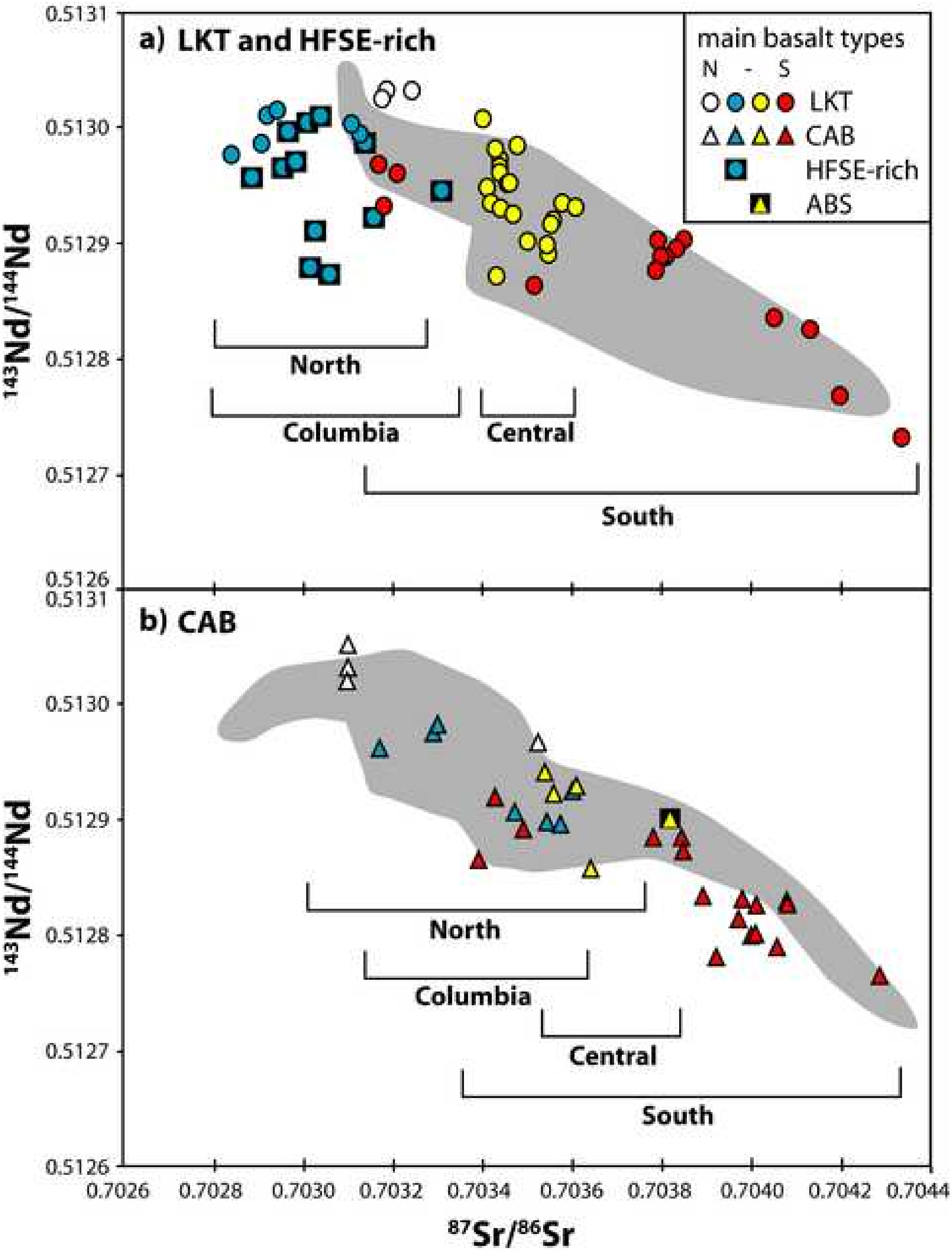
a)
North Cascades craton
Siletz Terrane
Klamath-Sierra Nevada Block
Subduction Complex
British Columbia
Washington
Oregon
California
Nevada
Juan de Fuca Plate
North American Plate
Gorda Plate
Explorer Plate
40-45 mm/yr
Columbia Embayment
Brother's FZ
Basin & Range
North
Columbia
Central
South
MM
MC
MG
MB
GP
MR
SH
MA
SM
MH
MJ
TS
NV
CL
MMc
ML
MS
LA
Mendocino TJ
0 100 200 300 400
kilometers
b)
Garibaldi Belt
Mt Baker (MB)
Glacier Peak (GP)
Simcoe (SM)
Mt Adams (MA)
Indian Heaven
Mt St Helens (SH)
Mt Hood (MH)
Mt Jefferson (MJ)
Three Sisters (TS)
Newberry Volcano (NV)
Crater Lake (CL)
Mt McLaughlin (MMc)
Medicine Lake (ML)
Mt Shasta (MS)
Lassen Peak (LA)
LKT
nonprimitive LKT
CAB
nonprimitive CAB
HFSE-rich basalt
absarokite (ABS)
olivine cumulate basalt
high-Mg BA (MgO>7.5%)
high-Mg andesite
LKT&CAB
HFSE-rich
0.7026
0.7030
0.7034
0.7038
0.7042
MORB
87Sr/86Sr

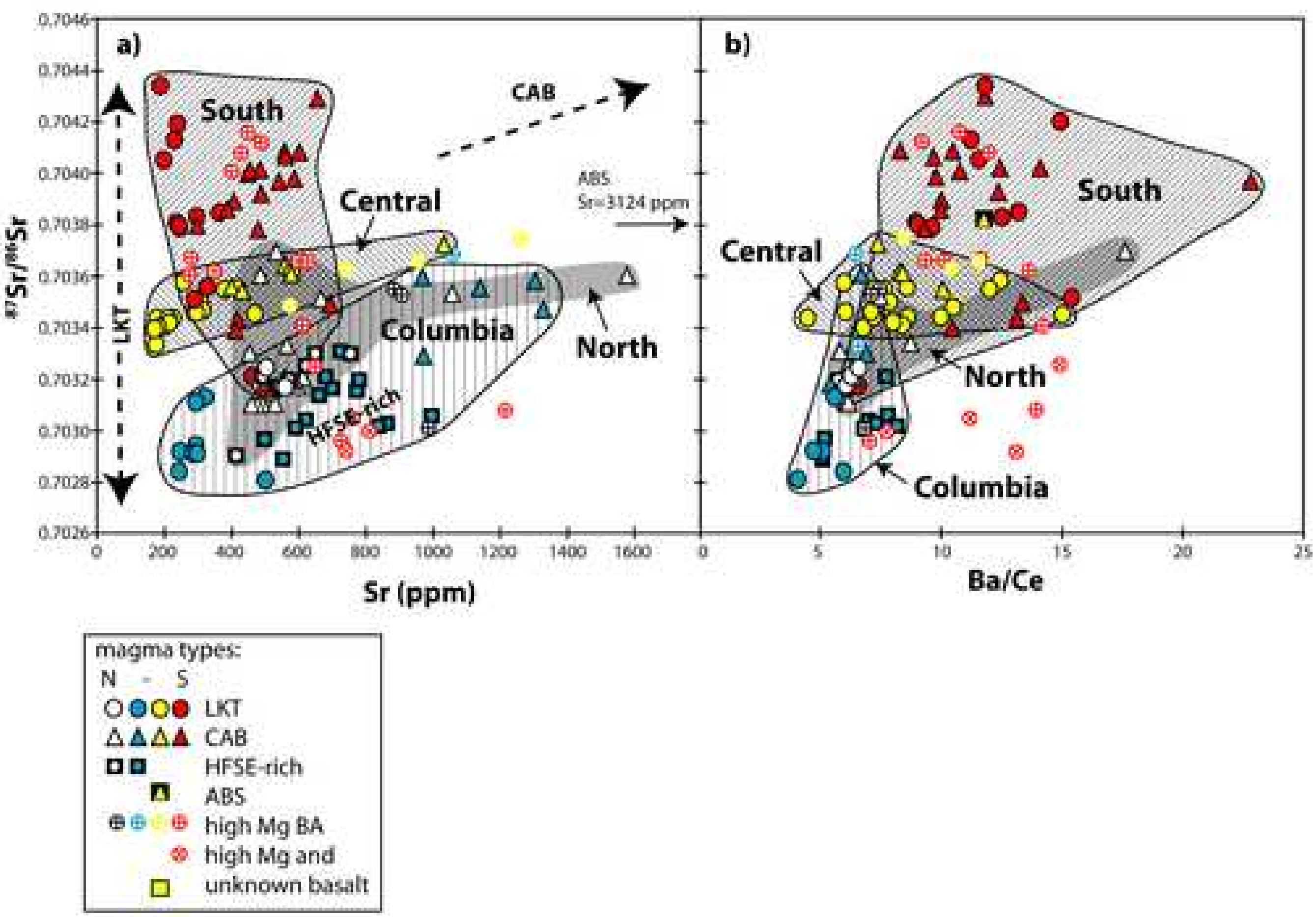


magma types:
N - S
LKT
CAB
HFSE-rich
ABS
high Mg BA
high Mg and
"fluid" addition
South
North
Columbia
Central
ABS
Ce/Yb=173
Ba/Ce
Ce/Yb



0.7045
0.7040
0.7035
0.7030
0.7025
$^{87}Sr/^{86}Sr$
44 46 48 50 52 54 56 58 60 62 64 66 68 70 72 74 76 78
$SiO_2$
North
Columbia
Central
South


a) LKT and HFSE-rich
main basalt types
N - S
LKT
CAB
HFSE-rich
ABS
North
Columbia
Central
South
b) CAB
North
Columbia
Central
South
143Nd/144Nd
87Sr/86Sr
0.5126
0.5127
0.5128
0.5129
0.5130
0.5131
0.7026
0.7028
0.7030
0.7032
0.7034
0.7036
0.7038
0.7040
0.7042
0.7044



a)
b)
South
Central
Columbia
North
HFSE-rich
CAB
LKT
ABS
Sr=3124 ppm
$^{87}$Sr/$^{86}$Sr
Sr (ppm)
Ba/Ce
magma types:
N - S
LKT
CAB
HFSE-rich
ABS
high Mg BA
high Mg and
unknown basalt