PRIMITIVE MAGMAS AT FIVE CASCADE VOLCANIC FIELDS: MELTS FROM HOT, HETEROGENEOUS SUB-ARC MANTLE

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ABSTRACT

Major and trace element concentrations, including REE by isotope dilution, and Sr, Nd, Pb, and O isotope ratios have been determined for 38 mafic lavas from the Mount Adams, Crater Lake, Mount Shasta, Medicine Lake, and Lassen volcanic fields, in the Cascade arc, northwestern part of the United States. Many of the samples have a high Mg# [100Mg/(Mg + Fe2+)] > 60] and Ni content (>140 ppm) such that we consider them to be primitive. We recognize three end-member primitive magma groups in the Cascades, characterized mainly by their trace-element and alkali-metal abundances: (1) High-alumina olivine tholeiite (HAOT) has trace element abundances similar to N-MORB, except for slightly elevated LILE, and has Eu/Eu* > 1. (2) Arc basalt and basaltic andesite have notably higher LILE contents, generally have higher SiO2 contents, are more oxidized, and have higher Cr for a given Ni abundance than HAOT. These lavas show relative depletion in HFSE, have lower HREE and higher LREE than HAOT, and have smaller Eu/Eu* (0.94–1.06). (3) Alkali basalt from the Simcoe volcanic field east of Mount Adams represents the third end-member, which contributes an intraplate geochemical signature to magma compositions. Notable geochemical features among the volcanic fields are: (1) Mount Adams rocks are richest in Fe and most incompatible elements including I/FSE; (2) the most incompatible-element depleted lavas occur at Medicine Lake; (3) all centers have relatively primitive lavas with high LILE/HFSE ratios but only the Mount Adams, Lassen, and Medicine Lake volcanic fields also have relatively primitive rocks with an intraplate geochemical signature; (4) there is a tendency for increasing 87Sr/86Sr, 207Pb/204Pb, and 818O and decreasing 206Pb/204Pb and 143Nd/144Nd from north to south. The three end-member Cascade magma types reflect contributions from three mantle components: depleted sub-arc mantle modestly enriched in LILE during ancient subduction; a modern, hydrous subduction component; and OIB-source-like domains. Lavas with arc and intraplate (OIB) geochemical signatures were erupted close to HAOT, and many lavas are blends of two or more magma types. Pre-eruptive H2O contents of HAOT, coupled with phase-equilibrium studies, suggest that these magmas were relatively dry and last equilibrated in the mantle wedge at temperatures of ~1300°C and depths of ~40 km, virtually at the base of the crust. Arc basalt and basaltic andesite represent greater extents of melting than HAOT, presumably in the same general thermal regime but at somewhat lower mantle separation temperatures, of domains of sub-arc mantle that have been enriched by a hydrous subduction component derived from the young, relatively hot Juan de Fuca plate. The primitive magmas originated by partial melting in response to adiabatic upwelling within the mantle wedge. Tectonic extension in this part of the Cascade arc, one characterized by slow oblique convergence, contributes to mantle upwelling and facilitates eruption of primitive magmas.

Keywords: arc magmatism, primitive basalt, geochemistry, isotopes, trace elements, Cascades, northwestern United States.

SOMMAIRE

Nous avons déterminé la concentration des éléments majeurs et des éléments traces, y compris les terres rares, par dilution d'isotopes, ainsi que les rapports des isotopes de Sr, Nd, Pb et O, de 38 échantillons de laves mafiques des suites volcaniques de Mount Adams, Crater Lake, Mount Shasta, Medicine Lake, et Lassen, dans l’arc des Cascades, dans le nord-ouest des États-Unis. Plusieurs des échantillons ont une valeur élevée de Mg# [100Mg/(Mg + Fe2+)] > 60] et une teneur élevée en Ni (>140 ppm), de sorte que nous leurs attribuons un caractère primitif. Nous préconisons l’existence de trois pôles de magmas primitifs dans les Cascades, que distinguent les concentrations en éléments traces et en alcalins. (1) Les tholéites à olivine riches en Al (HAOT) possèdent des concentrations en éléments traces semblables à celles des basaltes normaux des rides océaniques (N-MORB), sauf pour un léger enrichissement en éléments lithophiles à large rayon (LILE), et montrent un rapport Eu/Eu* supérieur à 1. (2) Les basaltes d’arc et les andésites basaltiques possèdent une concentration nettement plus élevée en LILE, et sont en général plus riches en éléments traces et en terres rares, de sorte que leur teneur en Ni et Cr sont plus élevées que HAOT, et un rapport Eu/Eu* plus faible (0.94–1.06). (3) Le basaltic alcalin de la suite de Simcoe, à l’est de Mount Adams, un troisième pôle, contribue une signature géochimique “intraplaque” aux compositions de magmas. Parmi les caractéristiques géochimiques notables de ces suites volcaniques, signalons que (1) les roches de Mount Adams sont les plus riches en Fe et en la plupart des éléments incompatibles, y compris les HFSE, (2) les laves les plus appauvries en éléments incompatibles se trouvent à Medicine Lake, (3) tous les centres contiennent des laves relativement primitives, ayant

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INTRODUCTION

The major goal of this study is to “see through” effects of differentiation and contamination in order to establish mantle characteristics and melting processes beneath the Cascades (Fig. 1) by selecting phenocryst-poor samples of chemically primitive lava that approximate liquid compositions. We consider rocks primitive if they are rich in Mg relative to Fe, have high concentrations of compatible trace elements, and low contents of phenocrysts (generally <5%). In extreme cases, primitive lavas may approach compositions of primary magmas, in which ferromagnesian phenocrysts have mantle-compatible compositions, but in most of our examples, the designation primitive merely indicates that a sample is one of a particular eruptive unit that has been least modified since the magmas left the mantle. Primitive lavas have equilibrium assemblages of phenocrysts and commonly have olivine or olivine + chromian spinel as their only phenocrysts. Olivine is typically Fo86-88 in tholeiitic (see below) and Fo86-90 in calc-alkaline lavas. The chromian spinel is present in a wide range of compositions that correlate with rock chemistry (Clynne & Borg 1997). Plagioclase phenocrysts (An70-90) occur in some lavas, and clinopyroxene (typically diopside with 0.5–1.07% Cr2O3) also may be present, especially in basaltic andesite. Most samples in our data-set are comparatively rich in compatible trace elements (Fig. 2; e.g., >140 ppm Ni, >200 ppm Cr), have high Mg contents (8–10.5 wt.% MgO), and a high Mg# [= 100Mg/(Mg + Fe2+)] (i.e., >60). A few evolved samples were deliberately included in order to assess fractionation and contamination. Because primitive lavas are not common among the many monogenetic vents and shield volcanoes of any given center, detection of systematic across-arc compositional variation is hampered by the small number of samples; exploring larger data-sets of less primitive lavas is beyond the scope of this study (cf. Borg et al. 1997).

Many of the analyzed samples are poor in incompatible elements and belong to the group variously termed high-alumina basalt [HAB: Gerlach & Grove (1982); see Donnelly-Nolan et al. (1991, p. 21,856) for history of HAB terminology], high-alumina olivine tholeite [HAOT: Hart et al. (1984), Bacon (1990), Barnes (1992)], or low-K olivine tholeite (LKOT: Bullen & Clynne 1989); we will refer to these as HAOT. Other lavas are designated arc basalt (SiO2 ≤ 52 wt.%), and basaltic andesite (SiO2 > 52 wt.%); a sample of magnesian andesite with 58 wt.% SiO2 is included with basaltic andesite for simplicity). One sample in our set is an alkali basalt from the Simcoe volcanic field, east of Mount Adams in Washington; it represents a melt of intraplate-type mantle.

Our study addresses questions of mantle composition, influence of subduction, melting processes, and thermal structure in the mantle beneath the arc. Variation in the composition of the crust complicates interpretation of geochemical data, even for primitive lavas, as will be seen below. Nevertheless, by considering our new results, unpublished data, and the few published results of complete analyses of primitive rocks from elsewhere in the Cascades, we are able to suggest answers to these questions.

We used our knowledge of the eruptive histories and compositional variety of five volcanic centers that we have mapped in detail to guide us in choosing representative primitive lavas for analysis. It is important to appreciate that each of the five centers is a volcanic field with many vents, even though it may bear the name of a single large volcano (e.g., Christiansen et al. 1977, Donnelly-Nolan 1988, Bacon 1990, Clynne 1990, Hildreth & Lanphere 1994). Although we attempted to characterize the primitive rocks of each center at the time this study was initiated, the entire
range of primitive compositions cannot be represented by a small number of samples, and our coverage of some centers is not comprehensive. In order to partially compensate for this inadequate coverage, our interpretations also consider published data and unpublished results of analyses in our files. Here, we report a new

Fig. 1. Location map showing major Cascade volcanoes (dots), the Cascade volcanic front (short dashes), and plate tectonic features (modified after Muffler & Tananyu 1995). Depth contours on the top of the slab (km) dashed where known. The number of the marine magnetic anomalies is shown for oceanic plates (age of anomaly 8 - 11 Ma). The small, young Juan de Fuca and Gorda plates converge slowly with the North American Plate. Plate convergence is normal to the Cascade arc in northern Washington and British Columbia, oblique in southern Washington – northern California. The volcanic zone is ≥100 km wide at Mount Adams, Mount Shasta – Medicine Lake, and Lassen, ~30 km wide at Crater Lake. Volcanoes not part of this study: M, Meager Mountain; C, Mount Cayley; G, Mount Garibaldi; B, Mount Baker; GP, Glacier Peak; R, Mount Rainier; SH, Mount St. Helens; H, Mount Hood; J, Mount Jefferson; TS, Three Sisters; N, Newberry.
TABLE 1. CHEMICAL AND ISOTOPIC ANALYSES OF PRIMIVITELY LAVAS

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|-type & data set that is internally consistent, precise (e.g., concentrations of the rare-earth elements, REE, by isotope dilution), and reasonably complete in terms of the elements and isotopes of interest to geochemists.

Geological Setting

The Cascade volcanic arc extends from northern California to southern British Columbia (Fig. 1). Arc volcanism is associated here with subduction of the...
TABLE 1. CHEMICAL AND ISOTOPIC ANALYSES OF PRIMITIVE LAVAS

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**Note:** The table includes chemical and isotopic analyses of primitive lavas, with data for various elements and isotopes. The data are presented in weight percent and parts per million. The chemical composition includes major elements such as Silicon Dioxide (SiO₂), Aluminum Oxide (Al₂O₃), Iron Oxide (Fe₂O₃), and Magnesium Oxide (MgO), among others. The isotopic data include ratios such as ⁸⁷Sr/⁸⁶Sr. The table is part of a study on primitive magmas at five Cascade volcanic fields.

Young Juan de Fuca and Gorda plates. From Glacier Peak northward, convergence is normal to the axis of the arc, and volcanism is restricted to comparatively isolated composite volcanoes and dome clusters (Rogers 1985, Guffanti & Weaver 1988). Between Mount Adams and the Lassen volcanic center, subduction is oblique, and the arc consists of widely spaced major composite volcanoes and abundant monogenetic volcanoes ranging from cinder cones to shields. There is no consensus as to whether features such as the Medicine Lake shield volcano, which lies behind the main axis of the arc, should be considered “Cascade” volcanoes. We include them in the scope of this paper in order to obtain a complete picture of magmatism in the Cascade arc.
Chemically primitive lavas are present throughout most of the arc in the zone of oblique convergence. These typically issued from monogenetic cinder cones, shields, or fissure vents.

From the Three Sisters to Lassen, the Basin and Range province impinges upon the arc, so that NW–SE to N–S normal faults are common at least as far west as the arc axis. Normal faults in the Cascade continue as far north as the Columbia River (Walker & MacLeod 1991), but do not occur in southern Washington. Pre-

Cenozoic crystalline basement of the sub-arc crust is widely exposed north of a point approximately midway between Mounts Adams and Rainier. From Mount Shasta to the south, Mesozoic and Paleozoic oceanic and immature continental terranes are exposed adjacent to the arc. The intervening region, however, lacks basement exposures, and the modern arc is constructed on Mesozoic and Paleozoic basement rocks in the north, and locally as far south as central Oregon. There may be no pre-Tertiary basement rocks in the north of a point approximately midway between Mounts Adams and Rainier. From Mount Shasta to the south, Mesozoic and Paleozoic oceanic and immature continental terranes are exposed adjacent to the arc. The intervening region, however, lacks basement exposures, and the modern arc is constructed on Mesozoic and Paleozoic basement rocks in the north, and locally as far south as central Oregon. There may be no pre-Tertiary basement rocks in the north, and locally as far south as central Oregon. There may be no pre-Tertiary
The continental crust is ~40 km thick beneath the Mount Adams volcanic field (Mooney & Weaver 1989). A reversed seismic refraction profile ~30 km west-southwest of Crater Lake defined a crustal thickness of 44 km (Leaver et al. 1984), although it is uncertain if this is the case under the volcanic field. Extensive

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The continental crust is ~40 km thick beneath the Mount Adams volcanic field (Mooney & Weaver 1989). A reversed seismic refraction profile ~30 km west-southwest of Crater Lake defined a crustal thickness of 44 km (Leaver et al. 1984), although it is uncertain if this is the case under the volcanic field. Extensive
seismic refraction surveys of the Mount Shasta – Medicine Lake area delineate crustal structure but not total thickness (Fuis et al. 1987), which Mooney & Weaver suggested is 38–40 km. Crustal thickness beneath the Lassen region is 38 ± 4 km (Mooney & Weaver 1989).

**METHODS**

**Samples**

Samples were selected from collections made during geological mapping of Mount Adams (Hildreth & Fierstein 1995), Mount Mazama and Crater Lake calderas (Bacon, unpubl. map, 1995), Mount Shasta (Christiansen, unpubl. map, 1995), the Medicine Lake volcano (Donnelly-Nolan, unpubl. map, 1995), and the Lassen volcanic center (Clynne & Muffler, unpubl. map, 1995). Powders were ground in an alumina shatterbox. Although many samples had been analyzed previously, the entire set was re-analyzed as a group (except for isotopic compositions and some REE abundances) in order to improve precision.

**Major elements**

Major elements were determined by wavelength-dispersion X-ray fluorescence (XRF) on fused glass disks in Lakewood, Colorado. The Na$_2$O and K$_2$O values given in Table 1 were determined by flame photometry. Ferrous iron, H$_2$O, and CO$_2$ contents were determined by standard wet-chemical methods.

**Trace elements**

Lead and REE concentrations were measured by isotope-dilution mass spectrometry. Energy-dispersion XRF was used for Rb, Sr, Y, Zr, Ba, Ni, and Cu concentrations. Concentrations of Nb and V were determined by inductively coupled plasma – atomic emission spectrometry (ICP–AES) following quantitative chemical separation. Although the Nb values are precise, there is some question as to their accuracy at the lowest concentrations reported because of poor knowledge of concentrations in standards. The concentrations of the remaining elements reported in Table 1 (Cs, Sc, Cr, Co, Zn, Hf, Ta, Th, and U) were measured by instrumental neutron-activation analysis (INAA) in Reston, Virginia. In a few samples, some of these elements are present at concentrations below detection limits. A special effort was made to obtain data for Cs by INAA by counting after approximately one year in order to allow interfering nuclides to decay to low levels.

**Isotopes**

Isotopic compositions of Sr, Nd, Pb, and O (Table 1) were determined for all 38 samples of this study. Analyses (Sr, Nd, Pb) were performed with a Finnigan MAT 262 variable multicolonlector mass spectrometer. Measured $^{87}$Sr/$^{86}$Sr ratios were normalized to a value of 0.1194, and $^{146}$Nd/$^{144}$Nd ratios, to a value of 0.7219. Empirical thermal mass-fractionation corrections of 0.11% per mass unit were applied to Pb isotope measurements. Oxygen was extracted with ClF$_3$, converted to CO$_2$, and analyzed using a modified Nier-type, 6-inch dual-collecting mass spectrometer. Reported whole-rock $\delta^{18}$O values are calibrated to a $\delta^{18}$O value of +9.6‰ for NBS–28 quartz relative to the SMOW standard. Further details of analytical procedures for isotopic compositions are given in Bacon et al. (1994).

**PRIMITIVE MAGMA-TYPES**

We recognize three end-member primitive magma-groups in the Cascades, characterized mainly by their trace-element and alkali-metal abundances: high-alumina olivine tholeiite, arc basalt and basaltic andesite, and intraplate basalt. Names of these end-members reflect historical precedent, the subduction-related geochemistry of "arc" basalt and basaltic andesite, and the fact that tholeitic and intraplate basalts are not limited in occurrence to the arc itself. We emphasize that a continuum of compositions seems to exist between these end-members, although examples intermediate between extreme-arc and intraplate varieties are scarce, and that assignment of some lavas with intermediate characteristics to any one group is somewhat arbitrary.

A fundamental observation is that approximately coeval lavas of different types have erupted from nearby vents. A corollary is that Quaternary across-arc compositional variation, present where the volcanic arc is wide, is manifested only in the broadest terms by occurrence of extreme subduction-component-enriched magmas in the fore-arc and more alkaline, intraplate types in the back-arc region (e.g., Lassen area; Borg et al. 1997).

**High-alumina olivine tholeiite (HAOT)**

Primitive HAOT occurs locally throughout the Cascades from southern Washington to northern California. The field occurrence of HAOT reflects the low viscosity of these normally phenocryst-poor to aphyric magmas. Vents are marked by low shield summits, pit craters, small spatter cones, or spatter ramparts along eruptive fissures. Pahoehoe flow surfaces are common in complex sequences of many related flows, each of which may be as little as 0.5 m thick, but in their entirety may total many tens of meters in intracanyon settings or topographic depressions. Tube-fed HAOT flow fields, such as the Giant Crater flows at Medicine Lake (Donnelly-Nolan et al. 1991), extend as much as 45 km from their vents. Diktytaxitic texture and subophitic groundmass augite are common in HAOT.

The major-element compositions of HAOT samples are similar to those of mid-ocean ridge basalt, MORB,
Fig. 2. Selected variation diagrams (major-element oxides recalculated to sum to 100 wt.% volatile-free and with all Fe as FeO*, Ni and Cr in ppm). Bold italic letters identify samples of HAOT, including differentiated and contaminated sample from Medicine Lake. Note log scale for K$_2$O in order to show variation in HAOT. Non-italic letters identify arc basalt and basaltic andesite, which have higher SiO$_2$, K$_2$O, and Cr, generally lower Al$_2$O$_3$ and CaO contents than HAOT; MgO and Mg$^o$ [100MgO/(MgO + FeO*)], molar] can be comparable. SM is mantle-xenolith-bearing alkali basalt from the Simcoe Mountains volcanic field. High Ni content and Mg$^o$ of most samples, including basaltic andesites, imply that they are primitive. Representative basalts in this and other figures plotted for reference: IAB is Okmok basalt sample ID-16 of Nye & Reid (1986), KIL is Kilauea basalt standard BHVO (Abbey 1983), and MORB is a FAMOUS area mid-ocean ridge basalt (Langmuir et al. 1977).
but are distinguished by higher Al contents, commonly >17% Al₂O₃ (Fig. 2). In comparison to other primitive Cascade lavas, HAOTs have high Ca (most >11% CaO; Fig. 2) and low Na (<2.5% versus ≥3% Na₂O). Incompatible elements are present at concentrations nearly as low as, or similar to, those in MORB, as exemplified by K (commonly <0.10% K₂O; Fig. 2). Measurements of dissolved H₂O in melt inclusions in olivine from Medicine Lake suggest that HAOT magmas had pre-eruptive H₂O contents of ≤0.3% (Sisson & Layne 1993). Concentrations of Ba, Cs, Rb, Th, Sr, and Pb, however, are typically higher in HAOT than in N-MORB. Some HOAT samples have Cs/Rb and Cs/K ratios notably higher than values typical of OIB, ocean-island basalt, or MORB, and they plot along the arc trend in Figure 3c. Likewise, HAOT samples have high

Fig. 3. Characteristic trace-element ratios and concentrations. In this and subsequent diagrams, N-MORB, E-MORB, and OIB are from Sun & McDonough (1989). a) Chondrite-normalized (Sun & McDonough 1989) La/Sm versus Eu/Eu². b) Nb versus Ba concentrations (ppm). Trend “To Simcoe Mountains” refers to sample labeled SM in other figures (672 ppm Ba, 57 ppm Nb). Most samples plot along the arc trend, but those from the Mount Adams and four from the Lassen volcanic fields are richer in Nb at comparable Ba contents. Average upper and lower crust (Avg U Crust, Avg L Crust) are from Taylor & McLennan (1995). c) Cs-Rb-K relations. Coupled Cs/Rb and Cs/K ratios higher than in oceanic basalts reflect modern subduction-derived component in arc basalt and basaltic andesite, ancient (?) in HAOT-source. “Upper crustal contamination” refers to Giant Crater lavas, shown by Baker et al. (1991) to have assimilated hypabyssal granite (three Medicine Lake samples with high Cs/K ratios). Avg Granite is the average of 8 granitic xenoliths in the Burnt Lava flow at Medicine Lake (Grove et al. 1988). d) La/Nb versus Ba/Nb ratios showing lines of equal Ba/La ratio. Higher Ba/Nb ratios than N-MORB at La/Nb > 1 for all samples except three from Mount Adams and the Simcoe Mountains alkali basalt reflect presence of a subduction-derived component. The low Ba/La value of Mount Adams samples is in keeping with a relatively strong intraplate geochemical signature there. Field for lavas from Crater Lake area with >6% MgO from Bruggman et al. (1989) and C.R. Bacon (unpubl. data, 1995).
Fig. 4. Concentrations of Nb and Ta, FeO–FeO* relations, and element-ratio discrimination diagrams. a) Nb versus Ta (ppm), showing lines of equal Nb/Ta ratio. Most samples have Nb/Ta ratios lower than oceanic basalts. Precision is poor at low abundances, so Nb/Ta ratios for samples with Nb < 2 ppm are imprecise. Two Medicine Lake samples with Nb/Ta = 9 are HAOT fractionates contaminated with hypabyssal granite represented by Avg Granite, the average composition of 8 xenoliths in the Burnt Lava flow at Medicine Lake (Grove et al. 1988). b) Analyzed FeO contents versus total Fe as FeO* showing lines of equal FeO/FeO* ratio. Arc basalts and basaltic andesites typically are more oxidized than samples of HAOT. c) Nb/Zr versus Ba/Zr ratios (after Leeman et al. 1990, Figure 7b). This diagram separates intraplate (high Nb/Zr) from subduction-related (high Ba/Zr) magmas. Evidence for an intraplate component in the present data-set exists for Lassen and Mount Adams volcanic fields (compare with Fig. 4d). Dotted field encloses compositions of 85 lavas from the Crater Lake area with ≥6% MgO (Bruggman et al. 1989; C.R. Bacon, unpubl. data, 1995). Average upper crust (Avg U Crust) is from Taylor & McLennan (1995), and probably has higher Nb/Zr and Ta/Yb than Cascade arc crust. Pelagic sediment composition (To Sed) is from Hole et al. (1984). d) Ta/Yb versus Th/Yb ratios. Expanded data-sets for all but the Shasta area show presence of a high-(Ta/Yb) intraplate component at Mount Adams, Lassen, and Medicine Lake volcanic fields, but not at Crater Lake. Field for lavas from Crater Lake area as in Figure 4c. Fields for Mount Adams, Lassen, and Medicine Lake volcanic fields from unpublished data of W. Hildreth, M.A. Clynne, and J.M. Donnelly-Nolan, respectively (1995). MORB in this figure represents both N-MORB and E-MORB of Sun & McDonough (1989).

Ba/Nb, Ba/La, and La/Nb ratios (many have La/Nb > 2), except for those from the Mount Adams volcanic field (Fig. 3d). This subduction-related signature also is present in HAOT from east of the Cascades (Hart et al. 1984; W.K. Hart, unpubl. data, 1995), suggesting that enrichment of the large-ion lithophile elements, LILE, in HAOT is not related to modern subduction and the present Cascade arc, but is an older subduction-related feature that is characteristic of the HAOT source over a larger region.
The lavas from Medicine Lake are the most incompatible-element-depleted in this study. They include primitive through moderately differentiated and contaminated lavas, in part from the Giant Crater lava field (Donnelly-Nolan et al. 1991). The distinct trend of the Medicine Lake samples toward high Cs/K (Fig. 3c) reflects assimilation of granite, as documented in the Burnt Lava (Grove et al. 1988), the Giant Crater flows (Baker et al. 1991), and Lake Basalt (Wagner et al. 1995).

Chondrite-normalized REE patterns for HAOT are LREE-depleted to slightly LREE-enriched. Heavy REE concentrations are generally \( \geq 10 \times \) chondrites, considerably higher than in most primitive arc lavas and basaltic andesites of the Cascades. Positive Eu anomalies (Eu/Eu* up to \( \sim 1.2 \)) are negatively correlated with La/Sr (Fig. 3a).

The Nb/Ta ratio varies significantly among our HAOT samples (Fig. 4a). Most have Nb/Ta ratios of \( \sim 12-16 \), significantly lower than MORB, OIB, or chondritic values of 17-18 given by Sun & McDonough (1989). There is a tendency for increasing Nb/Ta with increasing abundances of these elements in the Cascade lavas, although this is somewhat equivocal because of potential systematic error at low concentrations. These observations are not readily explained by a single-stage partial melting process because the ratio of crystal/melt partition coefficients, \( D_{Nb}/D_{Ta} \), is generally \( \leq 1 \) for virtually all phases that have been studied experimentally (Green 1995). Plank & White (1995) suggested that the cause of sub-chondritic Nb/Ta values they measured for low-(Nb,Ta) arc basalts and MORB may be source depletion by prior extraction of low-degree, relatively high-(Nb,Ta) partial melt. Judging from the compositions of granitic xenoliths presented by Grove et al. (1988), the two Medicine Lake samples with Nb/Ta ratios of \( \sim 9 \) have these low values, and relatively high Nb and Ta concentrations, because of assimilation of granite, as described by Baker et al. (1991).

Compatible trace-element abundances are somewhat diagnostic of magma type. Although both HAOT and arc lavas have Ni concentrations up to \( \sim 200 \) ppm, Cr values in HAOT lavas do not exceed \( \sim 400 \) ppm (Fig. 2). HAOT lavas typically have higher Co and Sc concentrations (most \( >40 \) and \( >30 \) ppm, respectively) than the arc lavas.

**Arc basalt and basaltic andesite**

Arc ("calc-alkaline") basalt and basaltic andesite lavas are abundant near the axis of the Quaternary Cascades as far north as southern Washington. They commonly have more abundant olivine and plagioclase phenocrysts than HAOT, and may also contain clinopyroxene; some lack plagioclase phenocrysts. Higher SiO\(_2\) content and probable lower temperatures of eruption translate to higher viscosities and a different mode of occurrence. These magmas erupted from vents marked by cinder cones or form cone-capped shields. The flows themselves are thicker and, where preserved, have blocky or aa surfaces.

Primitive arc basalts and magmas of basaltic andesite have higher SiO\(_2\) contents and comparable or even higher Mg\# than found in HAOT (Fig. 2). Most do not reach the extreme CaO and MgO contents of HAOT [Fig. 2; note, however, that some compositions given in Clyne (1993) and Baker et al. (1994) have MgO as high as in HAOT]. Arc basalt and basaltic andesite are characterized by the LILE (Cs, Rb, K, Ba, Sr, Pb, Th, U) enrichment relative to the HFSE (Nb, Ta, Zr, Hf, Ti) typical of arc magmas, and greater than that in HAOT as seen, for example, in a plot of Nb versus Ba (Fig. 3b). Cs/K and Cs/Rb ratios (Fig. 3c) are higher than MORB or OIB values (Morris & Hart 1983, Ben Othman et al. 1989), as noted above for some HAOT samples, and trend toward primitive Aleutian arc basalt (Nye & Reid 1986).

Light REE enrichment relative to HREE and HFSE is typical of Cascade primitive arc basalt and basaltic andesite. In these rocks, La/Nb ratios range from 1.5 to 4, far higher than in MORB or OIB (Fig. 3d), and comparable to island-arc basalt. There is a corresponding relative enrichment in Ba, as indicated by high Ba/Nb and Ba/La ratios. The arc basalts and basaltic andesites have comparatively small Eu anomalies, which may be either positive or negative (Fig. 3a), and low HREE contents (most \( <10 \times \) chondrites).

Values of Nb/Ta are \( \sim 13-17 \) for the arc basalts and basaltic andesites in the present study (Fig. 4a). As in HAOT, many of these ratios are sub-chondritic. Low Nb/Ta ratios are not unique to the Cascade arc, as Plank & White (1995) reported Nb/Ta ratios down to 6 in ICP–MS characterization of arc basalts. The low ratios may reflect prior extraction of melt from the source (Plank & White 1995) and preferential retention of Nb relative to Ta in rutile during dehydration of a subducting slab, resulting in lowering of Nb/Ta in the overlying mantle wedge (Green 1995). The latter suggestion is based on rutile – aqueous fluid partition coefficients, where \( D_{Nb}/D_{Ta} \) is nominally \( >1 \) in results of many, but not all, experiments reported by Brennan et al. (1994); note, however, that \( D_{Nb}/D_{Ta} \) is generally indistinguishable from 1 if published analytical uncertainty is considered.

The arc lavas are relatively oxidized, as found elsewhere by others (e.g., Gill 1981). Values of FeO/FeO* range from 0.9 for the most primitive samples of HAOT to 0.6 for some of the arc rocks (Fig. 4b). Presumably, the arc signature is correlated with an increase in pre-eruptive H\(_2\)O content (e.g., Sisson & Layne 1993, Stolper & Newman 1994). The more oxidized nature of the arc rocks probably reflects relative pre-eruptive oxidation state and is unlikely to be related to degassing of the more hydrous magmas (Carmichael 1991). Water transported to the mantle wedge by subduction probably is responsible for oxidation of the source region of arc magmas (Brandon & Draper 1996).
Intraplate basalt

Basalt with a strong intraplate chemical signature of LILE enrichment in the absence of Nb-Ta depletion is limited in our data set to the sample from the Simcoe Mountains volcanic field (SM in figures). However, primitive lavas from the Lassen and Mount Adams volcanic fields contain hints of an intraplate component (Fig. 3b; Bullen & Clynne 1989, Leeman et al. 1990). The Simcoe Mountains sample is from an ejecta ring that contains mantle xenoliths. Although few lavas are as strongly alkaline as the Simcoe units, Quaternary
alkali basalt vents are not restricted to the back arc, but occur in a 150 km east–west belt across the Cascade arc in southern Washington.

**Mantle Components Implied by End-Member Magmas**

Compositions of primitive Cascade lavas suggest blending of melts from, or mixing of, end-member geochemical domains in their mantle sources. Consideration of data for moderately evolved lavas along with the set of primitive rocks analyzed here strengthens the case for a minimum of three end-member primitive liquids that reflect components of the mantle beneath the Cascades: depleted sub-arc mantle, a subduction component, and intraplate mantle.

**Trace-element ratios**

Following Leeman et al. (1990), we have plotted Nb/Zr versus Ba/Zr (Fig. 4c) to illustrate some of the effects of mixing of three end-member magma types or mantle components. A large number of high-quality analyses for Nb in specimens from the Crater Lake area suggest that there is no intraplate mantle present there, as all data trend directly from primitive HAOT toward IAB and pelagic sediment at nearly constant Nb/Zr. Note that all samples from the Mount Adams and a few from the Lassen volcanic fields are displaced to slightly higher Nb/Zr values, relative to the Crater Lake trend, and the Simcoe Mountains sample lies at higher Nb/Zr than Kilauea basalt.

The number of data points available for plotting increases considerably when INAA results are used in a plot of Ta/Yb versus Tb/Yb (Fig. 4d). The large numbers of data points for Medicine Lake, Crater Lake, Lassen, and Mount Adams volcanic suites define fields that show the same trends as in Figure 4c. The INAA data confirm the lack of an intraplate (high Ta/Yb) signature at Crater Lake, suggest that one is weakly present at Medicine Lake, and add a few samples to the Lassen and Mount Adams fields that reflect mixing of all three end-members. Alternatively, crustal contamination could result in values intermediate between arc and intraplate trends, because the Ta/Yb ratio of average crust is higher than in arc lavas (Taylor & McLennan 1995). However, the slopes of the lower field boundaries for the three centers are remarkably consistent in Figure 4d and cannot be explained by addition of crustal material.

**Isotopic composition**

The primitive lavas of the present study plot within or very close to the conservatively drawn mantle array (after Leeman et al. 1990) on the Sr/Sr versus Nd/Nd diagram (Fig. 5a). Regional differences in isotopic composition (discussed below) and the limited number of primitive samples analyzed from each center preclude definitive statements about isotopic compositions of end-member mantle components. The lowest Sr/Sr and highest Nd/Nd ratios were measured for samples of HAOT from the Mount Adams field, but most have values comparable to those for arc basalt and basaltic andesite. Lavas with particularly high Sr/Sr and low Nd/Nd ratios may be contaminated. Borg et al. (1997) suggested that lavas from the Lassen area that plot below the mantle array (e.g., magnesian basaltic andesite LC86–1009, Fig. 5a) contain a large fraction of fluid-transported Sr, but not Nd, derived from metabasalt of the subducted slab; this sample also has MORB-like Pb isotopic ratios. Note, however, that the alkali basalt from the Simcoe Mountains has a similar isotopic composition of Sr, Nd, and Pb (Figs. 5a, b), as though such features also may be intrinsic to intraplate mantle.

The isotopic composition of Pb is sensitive to crustal contamination, particularly in HAOT, where the base-level concentration is <1 ppm. Nearly all samples have higher Pb/Pb/Pb ratios than the northern hemisphere regression line and Pacific MORB on a Pb/Pb/Pb versus Pb/Pb/Pb diagram (Fig. 5b). The Pb-isotopic trend toward fields for northeast Pacific sediments and Cascade ores may reflect crustal contamination or Pb derived from (not necessarily recently) subducted sediment. A modern sedimentary component should produce a positive correlation between the Pb isotope ratios. Miller et al. (1994) reported a strong negative correlation between Pb/Pb/Pb and Ce/Pb ratios for Umnak in the Aleutians, and interpreted this as evidence for fluid-transported mantle Pb. Our Cascade data have the low Ce/Pb ratios typical of arcs, but possess only a weak negative correlation overall between Pb/Pb/Pb and Ce/Pb ratios.

Oxygen isotope ratios show a good correlation with geological setting, as δ18O values ≥ +6.5‰ are limited to the Lassen and Shasta areas, where Klamath – Sierra Nevada basement is known to be present. That values between +5.6‰ and +6.1‰ also occur at Lassen, along with the negative correlation between δ18O and εNd (Fig. 5c) in the data set as a whole, suggests that the high δ18O and low εNd values may be due to assimilation of crust. Implications of regional isotopic variation are discussed further below.

**Chemical Characteristics of the Five Centers: Element-Abundance Diagrams**

Element-abundance diagrams (Fig. 6) highlight chemical similarities and differences among the centers. These plots also provide for comparison with examples of primitive lava compositions from ocean ridge, island arc, and intraplate settings (Fig. 6f, N–MORB, E–MORB, IAB, OIB) that aid in identification of geochemical signatures of mantle components. Also evident are effects
Fig. 6. Element-abundance diagrams for the five volcanic fields of this study and representative N-MORB, E-MORB, IAB, and OIB (sources of data as in other figures). Normalization values from Sun & McDonough (1989). Filled symbols are HAOT, and open symbols represent arc basalt and basaltic andesite, and alkali basalt. SiO$_2$ contents indicated for Cascade lavas (recalculated to sum to 100 wt.% volatile-free and with all Fe as FeO*). The effects of fractionation of HAOT and contamination with granite in the upper crust are shown by four samples from the Giant Crater lava field at Medicine Lake (differentiated and contaminated HAOT plotted with open symbols). Base-level HAOT has N-MORB-like abundances of most incompatible elements, but is enriched in LILE, as are samples of HAOT at the other centers. Crater Lake, Shasta, and Lassen samples form a continuum of compositions from HAOT to arc basaltic andesite. Magnesian basaltic andesite from Lassen (LC86-1009; dashed pattern), an extreme example of the arc signature, is strongly depleted in elements at the right of the diagram. Alkali basalt from the Simcoe Mountains has an OIB-like (intraplate) pattern. Arc basalt from Mount Adams and a basalt from Lassen also have steep patterns and comparatively small Nb-Ta “wells” suggestive of an intraplate component.
of processes such as assimilation of rocks derived from the upper crust.

**Medicine Lake volcano**

Four representative samples from the Giant Crater lava field of the Medicine Lake volcano (Fig. 6a) illustrate the effects of fractionation and crustal assimilation on the trace-element pattern of primitive HAOT (Donnelly-Nolan et al. 1991, Baker et al. 1991). The least differentiated rock (82–72–f, studied by Bartels et al. 1991) has HFSE and HREE abundances ~0.5× the Sun & McDonough (1989) N-MORB values, and is the most incompatible-element-depleted sample in our data set. Even this primitive rock, however, has elevated concentrations of some LILE relative to the other incompatible elements. The other three samples display a systematic increase in incompatible elements, except for Sr. Baker et al. (1991) described how the variation in composition of the Giant Crater lavas is due to fractionation of HAOT plus assimilation of granite in the upper crust. This scenario is consistent with the patterns in Figure 6a, where increases in Sr, Eu, and Ti are suppressed. Note also that the HREE and most elements on the right side of the diagram increase in an approximately parallel fashion, and that Ba is not enriched relative to Th and Rb in the two most-evolved samples (cf. IAB in Figure 6f).

**Crater Lake**

The four samples from the Crater Lake area illustrate the effect of blending TAGT and arc magmas or their source components (Bacon 1990, Bacon et al. 1994) in the absence of an intraplate component or contamination with felsic material (Fig. 6b). The most primitive HAOT has HFSE and REE abundances comparable to N-MORB, except that Nb is lower in the Crater Lake rock. Other than K, the concentrations of the LILE are elevated, as at Medicine Lake. The other samples, which range from differentiated HAOT to magnesian basaltic andesite, display a systematic enrichment in all elements to the left of Ti and a concomitant decrease in HREE and Y; i.e., as the lavas become richer in incompatible elements, the arc signature becomes more pronounced, and concentrations of the moderately incompatible elements decrease. This observation applies in a general way to Crater Lake, Shasta, and Lassen.

**Mount Shasta area**

The three samples from the Mount Shasta area plotted in Figure 6c can be interpreted in the same way as those from Crater Lake. The HAOT is more differentiated than the most primitive rocks from Medicine Lake or Crater Lake, but still has the relatively flat P–Yb pattern. The two samples of basaltic andesite show enhancement of the arc signature, including relative depletion in HREE and Y. Note the high Pb/Sr ratios of the Shasta area lavas. Samples of HAOT and magnesian basaltic andesite from the Shasta region described by Baker et al. (1994) have similar N–MORB-normalized patterns to those in Figure 6c.

**Mount Adams volcanic field**

All three components are present in the Mount Adams volcanic field samples (Fig. 6d), as also found by Leeman et al. (1990) for the southern Washington Cascades taken as a whole. The Simcoe Mountains sample has a clear intraplate signature, as stated previously. The high Nb and Ta concentrations in the sample of HAOT plotted may result from presence of intraplate-type mantle in its source. Arc basalt shows a moderate Nb-Ta “well”, overall low concentrations of the HFSE, comparatively high Pb/Sr ratio, and HREE depletion typical of other samples rich in a subduction component.

**Lassen volcanic field**

The Lassen volcanic center and surrounding region contain many vents and a great variety of mafic lavas (Bullen & Clyne 1989, Clyne 1993, Borg et al. 1997). The three components are present at Lassen as in southern Washington. Primitive HAOT is much like that at Crater Lake but for its higher Pb/Sr ratio and slight K enrichment. True alkali basalt does not occur at Lassen, but intraplate mantle is clearly represented (Fig. 4d), and may be responsible for the relatively shallow Nb-Ta “well” and high Ti of sample LM87–1384 (Fig. 6e). There is no question of a strong arc signature in many of the Lassen volcanic field lavas. It is most striking in magnesian basaltic andesite (dotted line), which has a pattern very much like that of primitive IAB (Fig. 6f), yet contains 58% SiO₂ at an Mg# of 71.

**Chemical Characteristics of the Five Centers: REE Patterns**

Isotope-dilution analyses for the REE are sufficiently precise that subtleties of chondrite-normalized patterns are meaningful and can be interpreted in terms of processes and mantle sources. Patterns are presented in Figure 7 for the same samples as are plotted in Figure 6.

**Medicine Lake volcano**

The convex-upward pattern of the most primitive HAOT from Giant Crater (Fig. 7a) is similar to that of N–MORB (Fig. 7f), although REE concentrations are lower overall in the Medicine Lake rock. The positive Eu anomaly is pronounced. With fractionation of basaltic magma and assimilation of granite, the REE abundances increase, the LREE become fractionated, the
Fig. 7. Isotope-dilution REE data for samples plotted in Figure 6 normalized to the C-1 chondrite values of Sun & McDonough (1989). Symbols and SiO₂ contents as in Figure 6. Four samples from the Giant Crater Lava field, Medicine Lake, have decreasing Eu/Eu*, increasing LREE fractionation, and uniform increases in HREE with differentiation and contamination with granite. Negative Ce anomalies, as in 1085M, are present in other Medicine Lake lavas. REE patterns of Crater Lake samples change systematically from LREE-depleted HAOT with positive Eu anomaly to sigmoidal patterns in basaltic andesites. Similar patterns are found at Lassen and Shasta. Low abundances of the HREE in the arc basalt and basaltic andesite patterns suggest generally higher degrees of melting than for samples of HAOT. The sigmoidal shape of the REE pattern, which suggests an eclogitic residue, apparently is inherited from a subduction-derived component, possibly transported to the mantle wedge by a partial melt of the slab. Although the HAOT pattern at Mount Adams is like those elsewhere, arc basalt is similar to alkali basalt from the Simcoe Mountains.
HREE show a parallel rise, and the Eu anomaly decreases, becoming negative in the most evolved sample. Fractionation and contamination of the Giant Crater lavas thus result in HREE behavior unlike that in arc basalts and basaltic andesites of the other volcanic fields. In fact, lavas at the Medicine Lake volcano (and Mount Adams volcanic field) have relatively high abundances of the HREE overall: of 168 INAA determinations of REE concentrations in Medicine Lake samples with $\geq 6\%$ MgO, only two have Yb$_N$ less than 10 (J.M. Donnelly-Nolan, unpubl. data, 1995). This expanded data-set contains a few examples of "sigmoidal" REE patterns (see below), but with lower LREE and higher HREE than at Crater Lake. Patterns with monotonic slopes, as are common in lavas from Mount Adams, are rare and have comparatively gentle slopes ($30 < \text{La}_N < 50$).

The precision of the isotope-dilution analyses for the REE and replication by INAA indicate that the negative Ce anomaly in sample 1085M (and 1376M, Table 1) is real. The INAA data-set for Medicine Lake contains many samples with a negative Ce anomaly. The only other samples in this study with a negative Eu anomaly are two specimens of HAOT from Lassen. The presence of a negative Ce anomaly in island-arc lavas has been attributed to subduction of pelagic sediment (White & Patchett 1984, Hole et al. 1984). It may be that the negative Ce anomaly results from comparatively ancient (Mesozoic?) sediment subduction that locally affected the HAOT source, and that is not evident in arc basalt and basaltic andesite because of an overwhelming contribution from modern subduction, in which pelagic sediment is not well represented.

**Crater Lake**

The REE patterns for the four samples in Figure 7b from the Crater Lake area rotate about a point near Tb, as noted previously for HAOT and calc-alkaline basaltic andesites (Bacon 1990). Primitive HAOT has an N-MORB-like pattern and also the strongly positive Eu anomaly typical of end-member HAOT. Differentiated HAOT (84C1143) has higher REE abundances overall and, although still convex upward, is slightly LREE-enriched. Arc basalt and magnesian basaltic andesite show a progressive increase in LREE and decrease in HREE while retaining a small positive Eu anomaly. These samples have a sigmoidal pattern: convex-upward LREE and concave-upward HREE. The larger Crater Lake data-set of 76 samples with MgO $\geq 6\%$ analyzed by INAA (Bruggman et al. 1989, C.R. Bacon, unpubl. data 1995) contains 18 examples having Yb$_N$ < 10 and several with a sigmoidal pattern.

**Mount Shasta area**

The one sample of HAOT from the Mount Shasta area has a flat REE pattern with small positive Eu anomaly at a little more than 10X chondrites (Fig. 7c). The basaltic andesites have lower levels of the HREE than the HAOT, a small positive Eu anomaly, and slight to moderate LREE enrichment. Sample 75SV-3 has a sigmoidal pattern like magnesian basaltic andesite from Crater Lake, but with less pronounced LREE enrichment.

**Mount Adams volcanic field**

The REE pattern for HAOT from the Mount Adams volcanic field (Fig. 7d) is similar to that of HAOT from the other centers. Alkali basalt from the Simcoe Mountains volcanic field has a steep, straight pattern. Surprisingly, arc basalt has a nearly identical pattern, including Yb at $\sim 10X$ chondrite, and lacking upward concavity in the HREE pattern as found in lavas with arc signature at the other centers. A search of 48 INAA results of rocks with MgO $\geq 6\%$ (W. Hildreth & J. Fierstein, unpubl. data, 1995) found three with sigmoidal patterns, and only one with Yb$_N < 10$.

**Lassen volcanic field**

As expected on the basis of element-abundance patterns, the four representative samples from the Lassen volcanic field in Figure 7e show a wide range of REE patterns. HAOT is similar to its relatives at the other centers. Sample LC88-1398 is arc basalt on the basis of chemical composition, but it has HAOT-like compositions of the phenocrysts (Clynne 1993). It has similar HREE, but notably higher LREE concentrations, than primitive HAOT. This sample also has high LILE (except Sr) concentrations, high $^{87}$Sr/$^{86}$Sr, $^{207}$Pb/$^{206}$Pb, $^{81}$O, and low $^{143}$Nd/$^{144}$Nd values. Arc basalt has a sigmoidal pattern similar to magnesian basaltic andesite from Crater Lake. The magnesian basaltic andesite from the Lassen field, although characterized by a similarly shaped pattern, has much lower abundances of the REE, in keeping with its incompatible-element-poor overall composition. Positive Eu anomalies are small or lacking in the Lassen area samples. In the examples in Figure 7e, and in a larger data-set of 42 compositions of rocks with MgO $\geq 6\%$ (Clynne 1993), there is no sample with the straight, fractionated pattern shown by alkali basalt from the Simcoe Mountains, as might be anticipated to be found on the basis of the other trace-element evidence for an intraplate component (Fig. 4d). As at Crater Lake, some samples from the Lassen area have relatively low HREE contents (10 of 42 have Yb$_N < 10$).

**Regional Differences in the Composition of Primitive Lavas**

Description of the compositions of primitive lavas from the five centers has touched upon systematic regional variations in abundances of the incompatible...
Fig. 8. TiO₂ contents and selected isotope ratios versus latitude. Shaded fields indicate ranges of literature data [isotopic data for Mount Adams from Leeman et al. (1990), Crater Lake from Bacon et al. (1994), Lassen from Bullen & Clynne (1990) and unpublished data, 1995; TiO₂ contents from Baker et al. (1994) and sources listed for Fig. 4d]. Note increase in minimum TiO₂ content from south to north, and regional differences in median values (dots) of isotope ratios for data of this study (letters).
elements and isotopic compositions. Here, we plot and discuss selected geochemical parameters as functions of latitude in order to focus on the more significant features of regional variation.

Variations in TiO₂ content and various isotopic ratios are plotted versus latitude in Figure 8. Also shown are fields defined by our own unpublished data and literature values for the Mount Adams, Crater Lake, and Lassen areas. Available isotopic data for Shasta and Medicine Lake are insufficient for meaningful definition of ranges of values. Of the others, Crater Lake has the narrowest range of isotopic compositions.

**HFSE and Fe**

There are the most data for Ti among the HFSE. Minimum TiO₂ contents at MgO ≥ 6% increase by a factor of two from south to north (Fig. 8a). Crater Lake has the most restricted range of concentrations, in keeping with the lack of an observed HFSE-rich intraplate contribution. Maximum TiO₂ values at Medicine Lake (1.9%), Lassen (1.8%), and Mount Adams (2.5%) are similar to those of intraplate basalts. Mount Adams also has higher concentrations of other HFSE and Fe than the centers to the south. The relatively high HFSE contents of basalts from the Mount St. Helens, Indian Heaven, and Mount Adams volcanic fields were noted by Leeman et al. (1990).

**REE**

All five centers have HAOT with LREE-depleted to slightly LREE-enriched chondrite-normalized patterns, with a positive Eu anomaly. A negative Ce anomaly is present in some samples of HAOT, and is particularly common at Medicine Lake. "Sigmoidal" LREE-enriched patterns with convex-upward LREE, concave-upward HREE, and Ybₙ < 10 are common at Crater Lake, Shasta, and Lassen. Patterns with monotonic steep negative slopes and Ybₙ ~10 are common only at Mount Adams.

**Sr, Pb, Nd, and O isotopes**

The range in Sr isotopic composition is well defined by the expanded data-sets for the Mount Adams, Crater Lake, and Lassen volcanic fields, which include results published elsewhere. Of these, Lassen shows the greatest variation. Note that the fields for ⁸⁷Sr/⁸⁶Sr in Figure 8b contain a few samples of andesite with <6% MgO and low ⁸⁷Sr/⁸⁶Sr ratios; these samples are believed to have had a low-⁸⁷Sr/⁸⁶Sr basaltic parent not represented among erupted lavas (e.g., Bacon et al. 1994). The primitive lavas analyzed in the present study have median ⁸⁷Sr/⁸⁶Sr ratios that tend to decrease from south to north.

Lead isotopic compositions show broad overlap among the Cascade centers. However, values for the primitive lavas of this study again suggest regional differences. In this case, ²⁰⁷Pb/²⁰⁶Pb tends to be higher and ²⁰⁸Pb/²⁰⁴Pb lower in the south (Figs. 8c, d). This crude anti-correlation between Pb isotope ratios may reflect crustal contamination of lavas erupted in California, or it may be an artifact of inadequate coverage in the present data-set. Lower crust would be expected to have low ²³⁵U/²⁰⁴Pb, and hence comparatively low ²⁰⁸Pb/²⁰⁶Pb (as seen at Lassen) if sufficiently old.

Minimum ε Nd values show a general increase from south to north (Fig. 8e), with Medicine Lake being restricted to relatively high values, perhaps because of the limited coverage in this data set. The trend is defined by relatively low ε⁶⁸⁰ of the Lassen and Shasta samples.

A clear regional trend is shown by maximum δ¹⁸O values (Fig. 8f). The highest δ¹⁸O values in primitive rocks occur in the south, and median values generally decrease to the north. All centers except Shasta, where data are limited to four samples, have some values in the normal mantle range of +5.5 ± 0.4‰ (Mattey et al. 1994) and at or below the base-level of +5.9 to +6.2‰ for arc basalts suggested by Harmon & Hoefs (1995). Mattey et al. (1994) suggested that at the lowest solidus temperatures considered likely for peridotite, allowing for the largest mineral–melt fractionations, the maximum δ¹⁸O values of basaltic liquids in equilibrium with peridotitic mantle would be in the range +6.0 – +6.5‰. Causes of ¹⁸O enrichment are suggested below.

**REGIONAL DIFFERENCES IN BASEMENT ROCKS AND CRUSTAL CONTAMINATION**

Regional differences in geochemical parameters that are sensitive to contamination suggest that many primitive lavas record some degree of crustal interaction (e.g., Bacon et al. 1994). The most compelling evidence for this interaction in the data gathered for this study is the commonly high ¹⁸O values of samples from the Shasta and Lassen areas. The high ¹⁸O values might result from surface processes, although this seems unlikely given the restriction of ¹⁸O values ≥ +6.5‰ to the Lassen and Shasta volcanic fields and the large proportion of ¹⁸O-rich samples there (11 of 15). Chemically primitive lavas with ⁸⁷Sr/⁸⁶Sr ratios ≥ 0.704, only present at Lassen and Shasta, also have ¹⁸O ≥ +6.7‰. These samples commonly have high ²⁰⁷Pb/²⁰⁶Pb values, coupled with low ²⁰⁸Pb/²⁰⁴Pb and ε⁶⁸⁰ values (e.g., LC88–1998), which are consistent with contamination with lower crust characterized by ancient depletion in U. Potential assimilants or reactive wallrocks would have to be altered mafic or ultramafic rocks with comparatively high ¹⁸O values (+8 – +12‰), as may be present in the Klamath Mountains basement [see summary in Bacon et al. (1994, p. 1550)], in order to produce the required shift in ¹⁸O without notably
decreasing Mg# or concentrations of compatible trace-elements in the resulting magmas.

Regional geophysical surveys suggest a cause for the elevated \(^{818}O\) values for the Shasta and Lassen area volcanic rocks. Isostatic residual gravity highs immediately west of the Shasta and Lassen volcanic fields (Blakely et al. 1985, Blakely & Jachens 1990) approximately coincide with high P-wave velocities in the crust (Benz et al. 1992) and imply that thick sequences of mafic or ultramafic (ophiolitic) rocks (or both) project beneath Mount Shasta and probably also Lassen. North of Mount Shasta, where increases in \(^{818}O\) of primitive lavas relative to presumed mantle values are smaller (Fig. 8; Bacon et al. 1994), the continuation of the belt of gravity highs is west of the Cascades and merges with the Oregon Coast Ranges (Blakely & Jachens 1990), where the rocks responsible for it would have no effect on the modern arc. Results of seismic refraction surveys (Fuis et al. 1987, Fig. 11) indicate that the Ordovician Trinity ultramafic sheet is present in the upper crust as deep as ~10 km beneath Mount Shasta and that a 7.0 km/s layer, possibly consisting of ophiolitic rocks, begins ~7 km beneath the surface. To the east, beneath Medicine Lake, where high-\(^{18}O\) primitive lavas have not been reported, Fuis et al. (1987) did not identify the Trinity ultramafic sheet and found that a 7.0 km/s layer is not reached until a depth of ~27 km.

It has been suggested that the subduction component is the carrier of excess \(^{18}O\) in some arc lavas (e.g., Ito & Stern 1985/86, Woodhead et al. 1987). Borg et al. (1997) propose that the high \(^{18}O\) values for lavas from the Lassen area reflect their mantle source, which was modified by a high-\(^{18}O\) subduction component. Laser-fluorination \(^{18}O\)-isotopic analyses of mantle minerals strongly suggest that the mantle is quite uniform in its \(^{18}O\)-isotopic composition, regardless of the presence of hydrous phases, casting doubt on subduction-related increases in the \(^{18}O\) value of the mantle wedge (Mattey et al. 1994). The Sr/Nd ratio, which is likely to be lower in continental and oceanic crustal rocks than in arc magmas (Rudnick 1995), can be used to test the hypothesis that the subduction component is responsible for high-\(^{18}O\) lavas of the Shasta and Lassen areas. Were the subduction component responsible for elevated \(^{18}O\) values, samples with high \(^{18}O\) would have high Sr/Nd ratios. Because there is no correlation between \(^{18}O\) and Sr/Nd [or Sr/P, used as an index by Borg et al. (1997)], and because many of the high-\(^{18}O\) lavas also have Sr/Nd ratios of nearly anhydrous HADOT (Grove et al. 1988, Baker et al. 1991) that probably is Cenozoic in age. The most contaminated and differentiated of these Giant Crater samples (1161M) has a \(^{18}O\) value of +5.9\(^{\circ}\), whereas one sample of basalt (881M) has an anomalously low \(^{18}O\) value of +5.2\(^{\circ}\). Definitive O-isotopic evidence for a basement-contamination effect is lacking in southern Washington, even though Mount Adams is only ~40 km south of exposures of pre-Tertiary rocks. One sample from the Mount Adams area (MA-953) has a \(^{18}O\) value of only +5.1\(^{\circ}\). Contamination with a small amount of low-\(^{18}O\) rock from the upper crust may explain the \(^{18}O\) values of these samples. Alternatively, the low-\(^{18}O\) samples may simply reflect variation within the mantle, because these values are within the range defined by mantle peridotites (Mattey et al. 1994).

Although we have presented isotopic data that are readily interpreted in terms of crustal contamination, geochemical evidence for contamination is not always separable from the effects of subduction in the Cascade province. This is a direct result of the fact that the basement rocks consist of accreted oceanic and arc terranes stitched together by tonalite–granodiorite plutons, all of which have suffered the effects of Late Cenozoic magmatism and associated hydrothermal activity that have added to and re-processed the crust. Thus, the age of a subduction component identified in the geochemistry of primitive lavas can be somewhat ambiguous, at least in the HADOT source, as discussed below.

**Source Characteristics**

Many authors have pointed out that HADOT and arc lavas cannot be related by any reasonable combination of fractionation, assimilation, or melting of a common source (e.g., Hughes & Taylor 1986, Bacon 1990, Baker et al. 1994). The compositional spectrum results from variation in extent of melting of mantle sources that are variably enriched in a subduction component and have a range in capacity to produce basaltic melt (i.e., fertility).

**Temperature, depth, and water content**

The origin of HADOT liquids is relatively straightforward. Bartels et al. (1991) conducted phase-equilibrium experiments on primitive HADOT from Medicine Lake, including sample 82–72–f. They found that nominally anhydrous HADOT is in equilibrium with a spinel lherzolite assemblage at ~1290°C at 11 kbar, presumably the point of separation of HADOT magma from the mantle [recall that Sisson & Layne (1993) reported ≤0.3% dissolved H\(_2\)O in melt inclusions in olivine phenocrysts]. These pressure conditions correspond to a depth near the base of the crust (Mooney &
Weaver 1989). Baker et al. (1994) concluded that HAOT at Shasta (their high-alumina basalt) represents 6–10% nearly anhydrous melting of depleted mantle that had previously been enriched with a modest amount of subduction component (e.g., Donnelly-Nolan et al. 1991). We accept this model, and suggest that other HAOT compositions in the northern California to southern Washington Cascades can be explained by combinations of variation in the amount of a subduction component added to the source and differences in degree of melting (owing primarily to source fertility, as reflected by amount of clinopyroxene (Clynne 1993), but also to H2O content). Positive Eu anomalies probably result from the reduced nature of HAOT and the presence of residual clinopyroxene (Donnelly-Nolan et al. 1991) at the site of last equilibration in the mantle. Higher Sc contents in HAOT in comparison with arc basalts and basaltic andesites also may reflect a larger contribution from clinopyroxene in the HAOT source, relative to the less fertile source of the arc magmas, in which all clinopyroxene may be consumed and Sc in melts thereafter diluted by high degrees of melting. Alternatively, residual garnet, if present in the source of the arc magmas but not in that of HAOT, would result in lower Sc contents of the arc magmas.

The origin of arc basalt and basaltic andesite is commonly linked to the effects of H2O on melting in a subduction-component-enriched mantle. Morris & Hart (1983), Hickey et al. (1986), Luhr (1992), Stolper & Newman (1994), Baker et al. (1994), and others have suggested that melt fraction during genesis of arc basalt and basaltic andesite is a function of the H2O content (and relative fertility) of the mantle source. High pre-eruptive H2O contents of mafic arc magmas have been reported by Anderson (1974), Sisson & Layne (1993), and Sobolev & Chausssid (1996). For example, Sisson & Layne (1993) documented up to 3.3% dissolved H2O in melt inclusions in olivine from basaltic andesite erupted near Mount Shasta. Baker et al. (1994) summarized evidence for the importance of H2O on extent of melting at upper mantle pressures and presented a model for the origin of calc-alkaline basalt and magnesium basaltic andesite of the Mount Shasta area. They argued that these magmas contained between 3.5 and 6% H2O, lost equilibrated with harzburgite at ~1200°C at ca. 10 kbar, and represent melting extents of up to ~30%. The comparatively low HREE, Y, and Sc contents of the arc lavas would be a result of high degrees of melting of a depleted, relatively fertile source that had been enriched in H2O, LILE, and LREE by addition of a subduction component.

**Origin of sigmoidal REE patterns**

The sigmoidal REE patterns of arc basalt and basaltic andesite from Lassen, Shasta, and Crater Lake appear to be consistent with subduction-component enrichment of magma sources. The Quaternary abarokite described by Conroy et al. (1997; sample RC93–50) from the northern Oregon fore-arc provides an extreme example of a sigmoidal REE pattern in a subduction-component-rich primitive lava (Ce ~300×, Yb ~7× chondrites).

Generation of sigmoidal REE patterns cannot be modeled by melting spinel or garnet lherzolite (e.g., Martin 1987) with either LREE-depleted or monotonically decreasing (negative slope) chondrite-normalized REE abundances, such as are characteristic of many peridotite xenoliths and massifs (McDonough & Frey 1989). Neither can fractional crystallization of liquids with such REE patterns produce the sigmoidal pattern because bulk distribution-coefficients for the HREE must be significantly greater than 1 and must decrease with increasing REE atomic number (limiting any role of garnet). Rather, melting and crystallization models require that the sigmoidal REE pattern be a characteristic of the source peridotite (Stern et al. 1989).

McCulloch & Gamble (1991) argued that fluid extracted from the subducted slab would carry LREE but that HREE would be retained in the slab. Addition of such a fluid-transported subduction component to depleted mantle could produce the required REE pattern that would yield melts with a sigmoidal REE pattern. Infertile peridotite xenoliths with a sigmoidal REE pattern and LREE 4–10× chondritic values have been described by Ionov et al. (1995), who suggested that these rocks had experienced large degrees of partial melting and melt extraction, followed by metasomatism by (LREE-bearing) fluids. Calculated compositions of partial melt for such metasomatized peridotites have a sigmoidal REE pattern and abundances similar to those observed in the Cascade lavas.

Alternatively, a slab-derived melt might carry a sigmoidal REE signature to the depleted mantle wedge. Support for this mechanism can be found in rocks of the tonalite – trondjhemite – granodiorite (TTG) suite, which commonly have sigmoidal REE patterns and are believed to be formed by partial melting of eclogite or garnet granulite (metabasalt), leaving a garnet + clinopyroxene ± amphibole residue (Arth & Hanson 1972, Arth et al. 1978, 1979, Drummond & Defant 1990, Rapp & Watson 1995). Note that we are not suggesting that primitive Cascade lavas are slab melts, only that such melts may be responsible for the sigmoidal character of REE patterns. In either case, fluid or melt transport, melting of peridotite in the wedge is incapable of producing the sigmoidal REE pattern without prior enrichment of that source by a slab-derived fluid or melt.

We favor a model in which variation in concentrations of SiO2 and incompatible elements in arc basalt and basaltic andesite are tied to the amount of subduction-component enrichment, which, along with source fertility, determines the extent of melting at a given temperature and depth. This model is consistent with the adjacent occurrence of both HAOT and lavas with strong trace-element signatures of arc magmas. Note that the most
silica-rich basaltic andesite (LC86-1009) has a sigmoidal REE pattern (Fig. 7), similar to arc basalt (LM87-1384), but relatively low abundances of all REE (and Sc), consistent with its origin as a high degree melt, presumably leaving a harzburgitic residue, as suggested by Baker et al. (1994) for magnesian basaltic andesite at Shasta.

The steep, straight REE patterns and high HREE concentrations of our alkali basalt sample from the Simcoe volcanic field imply a low degree of melting of enriched mantle. Although the arc basalt from the Mount Adams volcanic field has a similar REE pattern (Fig. 7), we suggest that it has lower abundances of moderately incompatible elements because it represents a higher melt-fraction, enriched in a subduction component.

**THE CASCADE UPPER MantLE**

**Composition**

We have presented compositional data indicative of at least three end-member primitive magmas at the five Cascade volcanoes studied. These imply three mantle components in the sources of HAOT, arc basalt and basaltic andesite, and intraplate basalt: depleted sub-arc mantle, mantle enriched by a modern subduction component, and OIB-source-like intraplate mantle. The sizes of domains within the mantle are unknown, but the spatial association of vents for all three lava types indicates either limited areal extent or a layered structure. It does not appear to be possible to discriminate between mixing of sources in the mantle and blending of melts from different sources in order to produce the continuum of lava compositions.

Universal presence of HAOT with minor LILE enrichment relative to N-MORB requires widespread depleted sub-arc mantle. The arc signature present in the HAOT source may be an old one, as HAOT with similar LILE enrichment (commonly including Cs±Pb) is found far to the east of the modern Cascade arc (Fig. 4d). At Lassen (Borg et al. 1997) and, apparently, Medicine Lake, the intraplate signature tends to increase to the east, whereas the arc character decreases. Hughes (1990) found geochemical evidence for both depleted and OIB-source-like mantle beneath the central Oregon Cascades (approximate lat. 44°-45°N, north of Crater Lake), Conrey et al. (1997) reported within-plate basalts from northern Oregon and southern Washington, and some analyses of basaltic andesite from the Mount Bachelor chain (lat. 44°N) reported by Gardner (1994) also have an intraplate signature. A thorough search at Crater Lake failed to provide any evidence for an intraplate signature (Bacon 1990, and unpubl. data); data available for the Shasta area are insufficient for any conclusion. The intraplate component does not lead to high \(^{87}\text{Sr}^{86}\text{Sr}\) ratios or low \(\varepsilon_{\text{Nd}}\) values, as would be expected of old continental lithosphere. More likely, it is similar to OIB-source mantle, as suggested by Hughes (1990). A heterogeneous mixture of depleted and OIB-source mantle domains, enriched by a subduction component, has been identified as the source of arc lavas in many studies (e.g., Morris & Hart 1983, Gill 1984, Hickey et al. 1986).

A possible answer to the question of how OIB-source-like mantle domains occur beneath the Cascades is that asthenosphere may rise locally east of the arc, such as beneath the Simcoe volcanic field, and become entrained in the westward flowing upper part of the wedge. Alternatively, OIB-source-like domains may be an integral part of the relatively young continental margin lithosphere. This lithosphere is composed of accreted oceanic and island-arc terranes, presumably including a mix of MORB- and OIB-source mantle, variously affected by Cenozoic and Mesozoic arc magmatism and related fluids. Lack of evidence for OIB-source mantle beneath Crater Lake results either from a failure of volcanism to sample it, perhaps because the volcanic zone is much narrower (~30 km) than in southeastern Washington or northern California (≥100 km), or to a real absence of OIB-source “plums” there.

An intraplate mantle component is present in lavas from the Mount Adams and Lassen volcanic fields and appears also to be present in some rocks from Medicine Lake (Fig. 4d). At Lassen (Borg et al. 1997) and, apparently, Medicine Lake, the intraplate signature tends to increase to the east, whereas the arc character decreases. Hughes (1990) found geochemical evidence for both depleted and OIB-source-like mantle beneath the central Oregon Cascades (approximate lat. 44°-45°N, north of Crater Lake), Conrey et al. (1997) reported within-plate basalts from northern Oregon and southern Washington, and some analyses of basaltic andesite from the Mount Bachelor chain (lat. 44°N) reported by Gardner (1994) also have an intraplate signature. A thorough search at Crater Lake failed to provide any evidence for an intraplate signature (Bacon 1990, and unpubl. data); data available for the Shasta area are insufficient for any conclusion. The intraplate component does not lead to high \(^{87}\text{Sr}^{86}\text{Sr}\) ratios or low \(\varepsilon_{\text{Nd}}\) values, as would be expected of old continental lithosphere. More likely, it is similar to OIB-source mantle, as suggested by Hughes (1990). A heterogeneous mixture of depleted and OIB-source mantle domains, enriched by a subduction component, has been identified as the source of arc lavas in many studies (e.g., Morris & Hart 1983, Gill 1984, Hickey et al. 1986).

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In the part of the arc included in this study, the sub-arc lithosphere probably is Cenozoic in age north of Crater Lake and definitely contains crustal rocks at least as old as Paleozoic to the south, beneath Shasta and probably Lassen. It is in the last two areas of relatively old, and thus more “mature” crust, where we find isotopic evidence suggestive of contamination of some primitive lavas by crustal material.

**Thermal structure**

Eruption of HAOT implies that temperatures in the uppermost Cascade mantle are higher than indicated by traditional models of subduction zones (Baker et al. 1994). High temperatures at low pressures for separation of HAOT magma from the mantle required by phase-equilibrium studies (~1290°C at 11 kbar: Bartels et al. 1991), reinforced by the low pre-eruptive H2O content of HAOT magmas (Sisson & Layne 1993), demand that the uppermost mantle beneath the Cascades is, at least locally, impressively hot. This is consistent with the youth of the subducting slab (Fig. 1), high heat flow (Blackwell et al. 1990), and extensional environment (Rogers 1985) of the southern Washington to northern California Cascades. The low 10Be/9Be ratios and B concentrations in the few published compositions of Cascade lavas also argue for a high-temperature thermal regime in comparison to many arcs (Leeman et al. 1990). As pointed out by Baker et al. (1994), magmas that give rise to arc basalt and basaltic andesite also must have traversed this same thermal regime, and owe their distinctive composition to melting of hydrous domains within it, although the temperature of last equilibration apparently was ~1200°C. They suggested that lower temperatures of last equilibration for arc basalt and basaltic andesite than for HAOT result from the steeper adiabatic melting curve for hydrous compositions, assuming onset of melting at a common depth of ~60 km.

The model presented by Baker et al. (1994) for the origin of magnesian lavas at Mount Shasta, which we believe applies to the primitive lavas of this study, calls upon adiabatic upwelling and melting of sub-arc mantle in the wedge that is locally enriched with variable amounts of a modern, hydrous subduction-derived component. Support for this hypothesis is found in the model of Furukawa (1993) for induced flow in the wedge owing to mechanical coupling with the subducting slab and in the observations by Zhao et al. (1994) of low P-wave velocities in the uppermost mantle beneath northern Honshu. Ongoing lithospheric extension in the northern California to southern Washington Cascades is consistent with mantle upwelling and promotes escape of primitive magmas. The required temperatures of 1200–1300°C virtually at the base of the Cascade crust must be transient, local phenomena, or the lower crust must be quite refractory, as otherwise voluminous crustal melts would be expected. Because HAOT has been erupted in the central Oregon Cascades from at least 7 Ma (Conrey et al. 1997; D.R. Sherrod, written comm., 1995), the uppermost mantle must have been gradually heated owing to relaxation of horizontal thermal gradients near local high-temperature regions. Although sustained temperatures as high as 1200–1300°C may not be everywhere characteristic of the uppermost mantle beneath the southern Washington to northern California Cascades, the mantle in this region is nonetheless anomalously hot.

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