Sr isotope disequilibrium in Columbia River flood basalts: Evidence for rapid shallow-level open-system processes

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ABSTRACT

 Geochemical variability among Columbia River Basalt Group flood lavas has been attributed to two different origins: derivation from heterogeneous mantle and modification of mantle-derived magmas by open-system processes involving continental crust. We present in situ analyses of Sr isotopes from core-to-rim transects of plagioclase phenocrysts and groundmass from each major Columbia River Basalt Group formation and show that plagioclase crystals are usually internally zoned in $^{87}Sr/^{86}Sr$ and are in $^{87}Sr/^{86}Sr$ disequilibrium with their host groundmass. These data unequivocally demonstrate that Columbia River basalt magmas, regardless of the nature of mantle sources, were modified by open-system processes operating at crustal depths. One-dimensional diffusion modeling indicates that observed isotopic heterogeneities cannot have existed at magmatic temperatures for more than a few years or decades. In general, results indicate that these flood basalt magmas were erupted while still in the process of assembly. A typical Columbia River flood basalt magma (melt plus phenocrysts) therefore only attains its final geochemical identity just before or during eruption, a fact that is generally obscured when evaluating conventional whole-rock isotope analyses.

 Keywords: flood basalts, laser ablation, Sr isotopes, magma chambers, residence times.

INTRODUCTION

 Flood basalt provinces and oceanic volcanic plateaus are products of the most intense volcanic episodes on Earth. The Columbia River Basalt Group of the northwestern United States is Earth's youngest and best-studied continental flood basalt province (Hooper, 1997; Camp and Ross, 2004). Activity began in the mid-Miocene (ca. 17 Ma) and continued episodically into the latest Miocene (ca. 6 Ma). Individual lava flows of this group are large (typically several hundred to thousands of cubic kilometers; Tolan et al., 1989; Thordarson and Self, 1998), with whole-rock compositions ranging from olivine tholeiite to andesite. Major element, trace element, and isotope studies of lavas suggest contributions from a range of source components, including plume, depleted, and enriched mantle components and variable crustal lithologies (Carlson et al., 1981; Carlson, 1984; Hooper and Hawkesworth, 1993; Dodson et al., 1997; Chesley and Ruiz, 1998), although there is no consensus as to the relative importance of these components, and few studies have focused on small-scale variations within whole rocks (e.g., Durand and Sen, 2004; Bryce and DePaolo, 2004).

 The bulk composition of a volcanic rock represents the sum of all the components and processes that have contributed to it, from sources to final crystallization and eruption, and imposes inherent limitations on petrogenetic interpretations. While it may be a relatively simple matter to distinguish different components in a suite of lavas on the basis of isotopic whole-rock data, it is rarely possible to usefully constrain the order in which components were blended, where the blending occurred, and the time scales involved. This information may, however, be obtained by isotope microanalysis of individual phenocrysts in volcanic rocks (Davidson and Tepley, 1997; Wolff et al., 1999; Bryce and DePaolo, 2004; Ramos and Reid, 2005; Davidson et al., 2005). In particular, improvements in laser ablation multi-collector inductively coupled plasma mass spectrometry (LA-MC-ICPMS) sampling now allow precise and accurate measurement of Sr isotope ratios in mineral phases in tholeiitic basalts at small spatial scales (Ramos et al., 2004). To date, few isotope microsampling studies have focused on intraplate basalts (Bryce and DePaolo, 2004; Ramos and Reid, 2005). Here we use LA-MC-ICPMS to examine Sr isotope variations in phenocrysts and groundmass of Columbia River basalt flows to gain insight into the mechanisms and timing of petrogenetic processes involved in flood basalt magmatism.

BACKGROUND

 The Columbia River Basalt Group is composed of several hundred individual flows that amount to ~234,000 km^3 of tholeiitic basalt, basaltic andesite, and andesite lava flows generated by the impingement of the Yellowstone plume on the base of the western edge of North American lithosphere (Camp et al., 2003; Camp and Ross, 2004). The Columbia River Basalts and correlative lavas cover large areas in the inland Pacific Northwest and extend along the Columbia River to the Pacific Ocean (Fig. 1; Hooper, 1997; Camp et al., 2003). Volcanic activity began ca. 17 Ma with eruption of Steens basalts (Hooper et al., 2002) and was followed between ca. 16.5 and 15.5 Ma by Imnaha Formation basalts and 150,000 km^3 of Grande Ronde Formation basalts, basaltic andesites, and andesites. Subsequent activity (15–14 Ma) is represented by Wanapum Formation basalts and later Miocene (13.5–6 Ma) Saddle Mountains Formation basalts.

 Columbia River Basalt Group lavas are tholeiitic and span a range of compositions from basalt to andesite, with primitive lavas (MgO
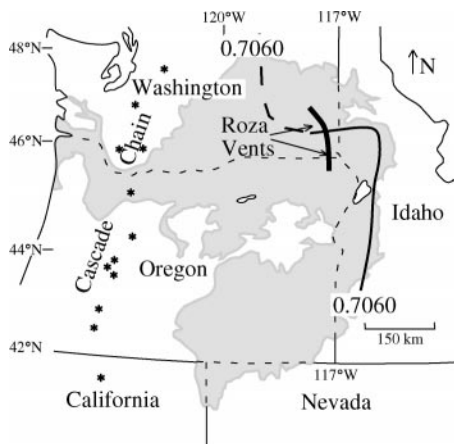
Figure 1. Location map of Columbia River Basalt Group (gray field) of northwestern United States (modified after Camp and Ross, 2004). Included is $^{87}Sr/^{86}Sr$ = 0.7060 line (solid line, Fleck and Criss, 2004; dashed line, projected from Armstrong et al., 1977), which demarcates western edge of North American craton. Also illustrated are approximate positions (thick solid line, Martin, 1989) of Roza Member (Wanapum Formation) vents that transect $^{87}Sr/^{86}Sr$ = 0.7060 line.

>8%) absent. They display a wide range of isotopic signatures, best exemplified by $^{87}Sr/^{86}Sr$ which ranges from 0.7034 in early erupted basalts to 0.7145 in late-erupted flows. Large variations in Nd and Pb isotope ratios are also seen (Carlson et al., 1981; Carlson, 1984). Hooper and Hawkesworth (1993) concluded that the magmas originate from plume- and lithosphere-related mantle sources, whereas others (Carlson et al., 1981; Carlson, 1984; Brandon and Goles, 1995; Chesley and Ruiz, 1998) invoke open-system evolution involving crustal contamination as an important process in generating this isotopic variability.

Although many Columbia River lavas lack phenocrysts, plagioclase-phyric flows are found in all formations, sometimes with small amounts of pyroxene and/or olivine phenocrysts. Durand and Sen (2004) found, on the basis of textures, major element chemistry, and phase relations, that Grande Ronde Formation magmas underwent complex shallow-level processing involving devolatilization, crystal fractionation, and magma mixing. Caprarelli and Reidel (2004) also concluded that pyroxenes in Grande Ronde Formation basalts crystallized at crustal pressures (~0.6 GPa).

SIGNIFICANCE OF PLAGIOCLASE

The common occurrence of plagioclase in Columbia River basalts suggests that magmas resided at crustal pressures during at least part of their differentiation history. The stability field of calcic plagioclase in basalts is restricted to crustal and near-crustal pressures, typi-

cally ≤1.5 GPa. In an experimental study, Takahashi et al. (1998) found plagioclase stable in Columbia River basalt compositions up to 2.25 GPa and cited An_{60} as the typical liquidus plagioclase found in their highest Ca/(Ca + Na) bulk composition. High-pressure plagioclase is expected to be relatively sodic (Bender et al., 1978). All of the samples we have studied are more evolved, with lower Ca/(Ca + Na) ratios, than the most primitive composition used by Takahashi et al. (1998), yet they contain plagioclase with core compositions of An_{65}–An_{73}. These crystals are unlikely to have grown at pressures >1 GPa. Simulations of Takahashi et al.'s bulk compositions using MELTS/pMELTS software (Ghiorso and Sack, 1995; Ghiorso et al., 2002) at 0.1 MPa–2 GPa reproduce both the experimental occurrence and composition of plagioclase (and, incidentally, augite), demonstrating that MELTS/pMELTS adequately models Columbia River phenocryst assemblages and phase compositions. However, MELTS/pMELTS consistently fails to produce the relatively calcic plagioclase compositions that we observe in our lower Ca/(Ca + Na) lavas at 1–2 GPa over a range of modest (0%–2%) magmatic water contents. The plagioclase compositions are, however, predicted by MELTS for all the lavas we studied at 0.5 GPa or less. We conclude that plagioclase phenocrysts found in Columbia River basalts for which we have laser ablation $^{87}Sr/^{86}Sr$ data precipitated in magmas at <1 GPa (i.e., at crustal pressures).

SAMPLES AND ANALYTICAL METHODS

We have used LA-MC-ICPMS for in situ analysis of Sr isotope ratios in phenocrysts of plagioclase from basalt of the Imnaha Formation, andesite of the Grande Ronde Formation, basalts of the Roza Member of the Wanapum Formation, and basalts of the Pomona, Elephant Mountain, Ice Harbor, and Lower Monumental Members of the Saddle Mountains Formation. Samples were polished to ~1 μm finish and cleaned in alcohol and ultrapure water. Analytical procedures, interference corrections, equipment for in situ Sr isotope analyses, and a discussion of data quality in this study were addressed in Ramos et al. (2004). In addition to phenocrysts, groundmass samples were also analyzed using microdrilling (Davidson and Tepley, 1997) and chromatographic purification procedures (described in Wolff et al., 1999). After purification, Sr groundmass samples were redissolved in 2% HNO_3 and analyzed at Washington State University, using the same ThermoFinnigan Neptune MC-ICPMS used for laser ablation analyses.

RESULTS AND DISCUSSION

Sr isotope variations in Columbia River Basalt Group phenocryst and groundmass samples are presented in Figure 2 and Table DR1[1]. Core-to-rim variations are present in plagioclase in all but two samples. Perhaps the most striking observation is that, in all but one case, plagioclase phenocrysts are in Sr isotopic disequilibrium with their groundmass. Clearly, these phenocrysts did not grow from liquids now represented by their respective host groundmasses. With the exception of the Grande Ronde lava (Fig. 2B), Sr is less radiogenic in plagioclase than in the enclosing groundmass. The Grande Ronde sample, which is an andesite with 58.4 wt% SiO_2 and 3.0 wt% MgO, shows the reverse relationship similar to that seen in intermediate arc rocks, which has been attributed to recharge of crustal magma chambers by mantle-derived magma with relatively low $^{87}Sr/^{86}Sr$ following phenocryst growth (Davidson and Tepley, 1997).

The $^{87}Sr/^{86}Sr$ ratios within most plagioclase phenocrysts are either near constant or gradually increase toward the rims of crystals. Symmetric profiles (Figs. 2A, 2C, 2F) attest to the reproducibility of results. Columbia River basalt plagioclase profiles have only minor, usually unidirectional, internal variations and lack the spiked shifts in Sr isotopes seen in plagioclase from subduction-related lavas that are attributed to repeated magmatic recharge during crystal growth (Davidson et al., 2005). Only plagioclase from the Elephant Mountain Member (Fig. 2F) records a more complex profile. Internal rimward decreases in $^{87}Sr/^{86}Sr$ indicate that this crystal interacted with magma with lower $^{87}Sr/^{86}Sr$ prior to incorporation into the higher $^{87}Sr/^{86}Sr$ liquid represented by the groundmass. This phenocryst stands out in that two episodes of isotopic modification are sequentially recorded. We analyzed clinopyroxene as well as plagioclase in one Saddle Mountains lava (Fig. 2H): plagioclase, clinopyroxene, and the host groundmass in this flow show strongly contrasting isotopic compositions.

Diffusion of Sr acts to eradicate isotopic disequilibrium between phenocrysts and their host melt. Diffusion modeling therefore has the potential to constrain maximum phenocryst residence ages (Fig. 2). Gradual isotopic gradients (Figs. 2A, 2C) may arise either through this mechanism or through growth from a liquid that is changing in isotopic composition. Where a strong or step-function gra-

[1]GSA Data Repository item 2005086, Table DR1, Sr isotope ratios of Columbia River Basalt Group phenocrysts and groundmass, is available online at www.geosociety.org/pubs/ft2005.htm, or on request from editing@geosociety.org or Documents Secretary, GSA, P.O. Box 9140, Boulder, CO 80301-9140, USA.
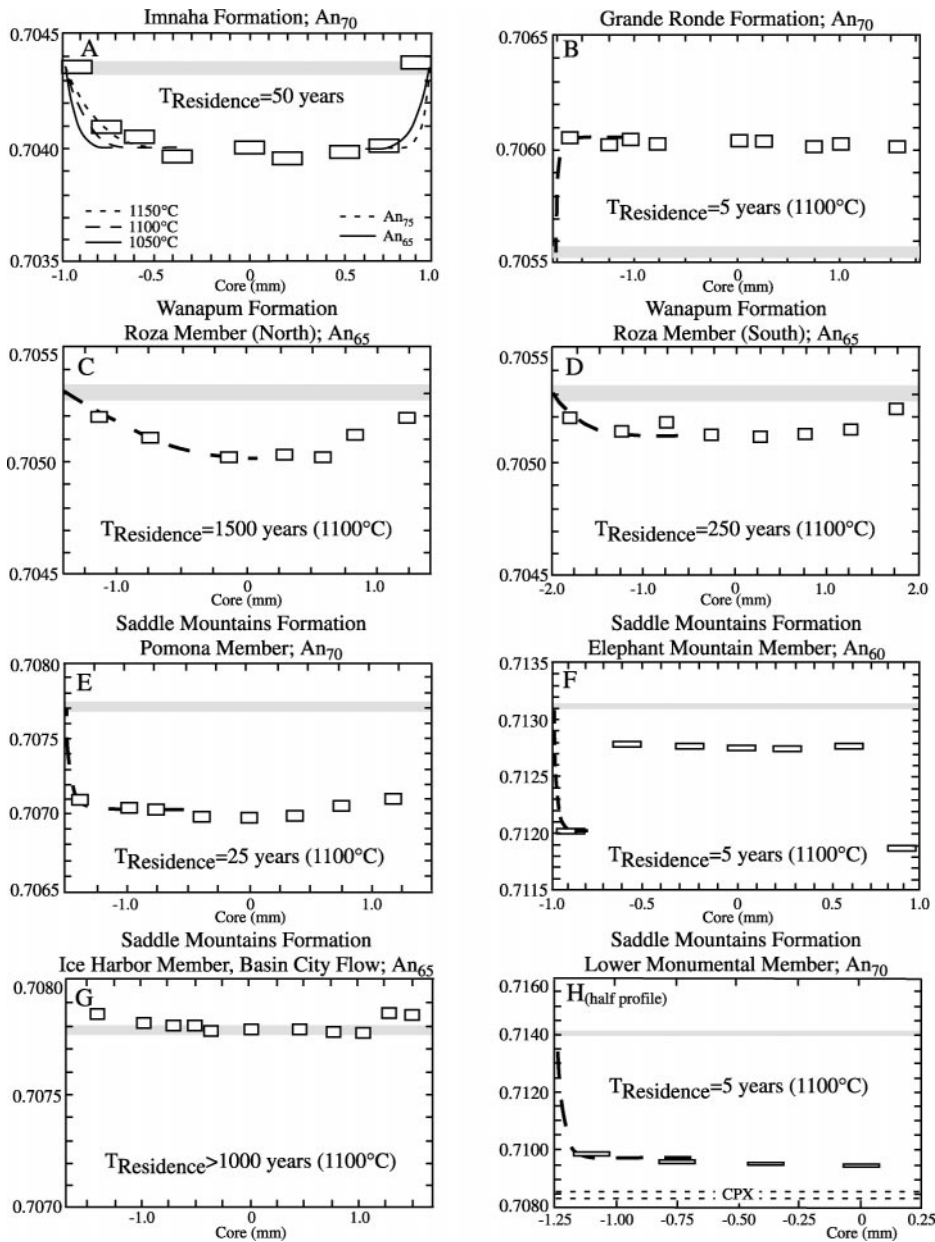
Figure 2. Representative $^{87}Sr/^{86}Sr$ profiles (open rectangles) of plagioclase phenocrysts from Columbia River Basalt Group lavas and their comparison with groundmass (gray bar) in same samples. Core at 0 mm denotes midpoint of crystal section for each sampling traverse and margins of each graph correspond to edges of crystal along same line (H represents half-profile). Vertical and horizontal dimensions of each rectangle correspond respectively to analytical error and sampling pit length along each profile (see Ramos et al., 2004, for detailed description of analytical procedures). Note crystal size variations in individual graphs, and that Saddle Mountains Formation lavas (E–H) are overall much more radiogenic than rest of Columbia River Basalt Group (Carlson et al., 1981; Carlson, 1984; Hooper and Hawkesworth, 1993). Curves represent simple diffusion models calculated using $C = C_o \text{erfc}[x/(4Dt)^{1/2}]$, where $C = {}^{87}Sr/^{86}Sr$ in plagioclase at distance x from boundary; C_o = far-field $^{87}Sr/^{86}Sr$ in plagioclase; D = tracer diffusion coefficient of Sr at An content of plagioclase calculated from Giletti and Casserly (1994); and t = time in years. Model assumes magmatic temperature of 1100 °C (Caprarelli and Reidel, 2004; Durand and Sen, 2004), that melt surrounding plagioclase is well-stirred infinite volume, and that $^{87}Sr/^{86}Sr$ is initially uniform within crystal at a value now represented by core composition (except in F). Curves are calculated and matched to analyzed profiles; they represent maximum time over which observed profiles could have survived under magmatic conditions. Effect of varying temperature and An content on calculated diffusion curves is shown in A; note that maximum observed compositional variation of plagioclase is 5% An content. In C and D, (North) and (South) refer to sampling locations for near-vent Roza Member scoria and lava, respectively north and south of Precambrian craton boundary (Fig. 1).

dient exists between crystal and host melt, simple one-dimensional diffusion modeling (Fig. 2) yields a maximum residence time. This is as short as 5–50 yr for grains in the Imnaha, Grande Ronde, and Saddle Mountains flows (Figs. 2A, 2B, 2E, 2F, 2H). These short residence times indicate rapid modification of magmatic Sr isotopes and/or crystal transfer between coexisting contrasting magmas just prior to, and in some cases on the likely time scales (years to decades; Thordarson and Self, 1998) of, Columbia River Basalt Group eruptions. These processes are recorded in plagioclase and hence occurred at crustal depths, consistent with the findings of Caprarelli and Reidel (2004) and Durand and Sen (2004).

Although we cannot unequivocally identify the source components that are contributing to isotopic variability on the basis of Sr isotopes alone, some inferences are possible on the basis of general similarity between small-scale variations within individual flows and the literature data on whole-rock variations at the formation level. The volumetrically dominant Imnaha, Grande Ronde, and Wanapum basalts form a coherent group in which K/Nb, La/Nb, and $^{87}Sr/^{86}Sr$ tend to increase and $^{143}Nd/^{144}Nd$ decreases with increasing silica content. This is most easily explained by contamination of an asthenosphere-derived basaltic magma with continental crust (e.g., Columbia River basalt component C4 of Carlson, 1984). The relatively small isotopic shifts seen within our samples (Figs. 2A–2D) are consistent with minor magma-crust interaction. In this context it is interesting to note that contrasting magma-crust interaction in the Roza Member of the Wanapum Formation on either side of the North America craton boundary (Fig. 1), recorded by Os isotope variations (Chesley and Ruiz, 1998), has left little imprint on $^{87}Sr/^{86}Sr$ (Figs. 2C, 2D), a likely consequence of the much greater sensitivity of the Re-Os system to crustal input.

In contrast, Saddle Mountains basalts are much more radiogenic in Sr than the older formations (Carlson et al., 1981; Carlson, 1984; Hooper and Hawkesworth, 1993), and flows tend to exhibit greater internal variations (Figs. 2E, 2F, 2H). These variations are likely the result of mixing of magmas derived from different domains within ancient, variably enriched lithospheric mantle, perhaps with additional crustal contamination (Carlson, 1984; Brandon and Goles, 1995). The presence of Sr isotope disequilibrium in the Pomona Member basalt suggests modification of even the least evolved (~7 wt% MgO) Columbia River lavas. It is noteworthy that the $^{87}Sr/^{86}Sr$ variation among clinopyroxene, plagioclase, and groundmass from the Lower Monumental

Member (Fig. 2H) is comparable to that within the entire Saddle Mountains Formation (0.706–0.714: Carlson, 1984; Hooper and Hawkesworth, 1993).

CONCLUSIONS

Columbia River basalts exhibit measurable and, in some cases, extreme Sr isotopic heterogeneity within individual phenocrysts and between different phases on the scale of a single thin section. The observed variations result from open-system processes that occur during residence in or transport through the continental crust, and in some cases cannot have existed at magmatic temperatures for more than a few years or decades. In these cases it is likely that phenocrysts and host melt were derived from different locations in a magma system and mixed during the eruption. A typical Columbia River flood basalt magma (melt plus phenocrysts) therefore only attains its final geochemical identity just before or during eruption. Although the data do not yet permit unequivocal identification of contributing components, it is clear that shallow-level mixing is an important and perhaps the dominant process by which they become blended, and that this process was interrupted only by quenching. On the Columbia Plateau, flood basalt magmas were erupted while still in the process of assembly.

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