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# Yellowstone plume–continental lithosphere interaction beneath the Snake River Plain

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## ABSTRACT

The Snake River Plain represents 17 m.y. of volcanic activity that took place as the North American continent migrated over a relatively fixed magma source, or hotspot. The identification of a clear seismic image of a plume beneath Yellowstone is compelling evidence that the Miocene to recent volcanism associated with the Columbia Plateau, Oregon High Lava Plains, Snake River Plain, Northern Nevada Rift and Yellowstone Plateau represents a single magmatic system related to a mantle plume. A remaining enigma is, why do radiogenic isotope signatures from basalts erupted over the Mesozoic–Paleozoic accreted terrains suggest a plume source while basalts erupted across the Proterozoic–Archean craton margin indicate an ancient subcontinental mantle lithosphere source? We show that ancient cratonic lithosphere like that of the Wyoming province superimposes its inherent isotopic composition on sublithospheric plume and/or asthenospheric melts. The results show that Yellowstone plume could have a radiogenic isotope composition similar to the mantle source of the early Columbia River Basalt Group and that the plume source composition has persisted to the present day.

**Keywords:** Yellowstone, Snake River Plain, Pb isotopes, Sr isotopes, Nd isotopes, basalt, mantle plume.

## INTRODUCTION

The Snake River Plain of southern Idaho is the archetype of a continental hotspot track, formed by the trace of the Yellowstone plume as it propagated northeastward over the past 17 m.y. (Fig. 1). Volcanic products erupted within the Snake River Plain comprise rhyolite ignimbrites overlain by a thin basalt veneer erupted from small shield volcanoes and cinder cones. The hotspot track is underlain at depth by a 10-km-thick mafic sill complex that contains much of the basaltic melt introduced into the continental crust, and now forms a layered mafic intrusion in the middle crust (Shervais et al., 2006).

The origin of the Snake River–Yellowstone hotspot is controversial. Major element, trace element, and He isotope systematics of the basaltic rocks are consistent with a deep, sublithospheric mantle source, similar to the source of ocean island basalts (e.g., Craig et al., 1978; Vetter and Shervais, 1992; Hughes et al., 2002; Graham et al., 2006). In contrast, the radiogenic Pb isotopes in these basalts are indistinguishable from melts derived from the ancient lithosphere that underlies the plume track, while Sr and Nd isotope ratios are intermediate between depleted mantle and continental crust or lithospheric mantle values (Church, 1985; Leeman et al., 1985; Hughes et al., 2002). This conundrum has been a major problem for all plume-oriented models presented in the past.

We present here new Pb, Sr, and Nd isotopic analyses for basalts from the Snake River Plain, including the Idaho National Laboratory in the eastern plain, and the Bruneau-Jarbridge eruptive center and the Glens Ferry area, both

in the central plain. Our results show that these isotope compositions are compatible with a deep mantle plume source, which interacted with lithosphere that varies in age, composition, and thickness from west to east, and are compatible with a mantle plume origin for the Snake River Plain basalts.

## BACKGROUND GEOLOGY

The Snake River Plain volcanic province is part of a regional array of volcanic activity that includes coeval magmatism in the Columbia, Oregon, and Owyhee plateaus, and the Northern Nevada Rift (Fig. 1). The interrelationships of the provinces in time, space, and geology are consistent with a single magmatic system resulting from the interaction of a mantle plume with the continental lithosphere of North America (Camp and Ross, 2004). Recent geophysical investigations have imaged a 100-km-diameter thermal anomaly in the upper mantle below Yellowstone that plunges 65° NW and extends to a depth of ~500 km, near the top of the mantle transition zone (Yuan and Dueker, 2005; Waite et al., 2006).

Volcanic activity in the Snake River–Yellowstone system began with eruption of the main phase of the Columbia River Basalt Group ca. 16.5–15 Ma (Camp and Ross, 2004) through Paleozoic and Mesozoic lithosphere accreted to the Precambrian continental margin of North America. Volcanism shifted to the east, across the cratonic margin into the Snake River Plain, ca. 15 Ma and advanced with time to its current position at Yellowstone (Camp and Ross, 2004). Basalts of the Snake River–

Yellowstone system were emplaced through cratonic lithosphere of Idaho, Montana, and Wyoming (Leeman et al., 1985; Wooden and Mueller, 1988). Mafic igneous rocks of the Beartooth Mountains of Montana and Wyoming suggest a lithosphere stabilization age of ca. 2.8 Ga (Wooden and Mueller, 1988; Mueller and Frost, 2006); farther west stabilization ages are Late Archean to Paleoproterozoic (Foster et al. 2006). Deep crustal xenoliths confirm that ancient basement extends beneath the Snake River Plain and shows a pattern of decreasing age (ca. 3.2–2.5 Ga) from Archean in the east to Proterozoic in the west (Leeman et al., 1985; Wolf et al., 2005).

Basalts from deep drill cores in the eastern Snake River Plain show that fractionation and magma recharge took place in sill-like layered intrusions at mid-crustal depths (Shervais et al., 2006). The limited range of major and trace element composition, mantle  $\delta^{18}\text{O}$  signatures, and lack of any correlation between  $^{87}\text{Sr}/^{86}\text{Sr}$  (or  $\delta^{18}\text{O}$ ,  $^{206}\text{Pb}/^{204}\text{Pb}$ , and  $^{208}\text{Pb}/^{204}\text{Pb}$ ) and major and trace element, and rare earth element abundances in the basalts indicate minimal crustal interaction (Menzies et al., 1983; Leeman, 1982; Carlson, 1984; Hart, 1985; Church, 1985; Shervais et al., 2006). Nash et al. (2006) showed that the early rhyolites represent mixtures of crustal melts with evolved plume basalts, but later basalts passed through the previously depleted crust with little or no interaction.

## METHODS

The analytical procedures and methods for preparing the basalts for isotope analysis, the mass spectrometer analytical methods, and mixing model parameters are given in the GSA Data Repository.<sup>1</sup>

## RESULTS

The Pb, Sr, and Nd isotope ratio data for the analyzed basalts define quasi-linear arrays in multi-isotope plots (Fig. 2). The Pb–Pb arrays have a continental-like signature with more radiogenic  $^{207}\text{Pb}/^{204}\text{Pb}$ ,  $^{208}\text{Pb}/^{204}\text{Pb}$ , and  $^{87}\text{Sr}/^{86}\text{Sr}$  ratios, and lower  $^{143}\text{Nd}/^{144}\text{Nd}$  relative to Pacific

<sup>1</sup>GSA Data Repository item 2008014, Part A: Data Tables, Methods, and Sample Locations; and Part B: Model Data Tables and Description, is available online at [www.geosociety.org/pubs/ft2008.htm](http://www.geosociety.org/pubs/ft2008.htm), or on request from [editing@geosociety.org](mailto:editing@geosociety.org) or Documents Secretary, GSA, P.O. Box 9140, Boulder, CO 80301, USA.

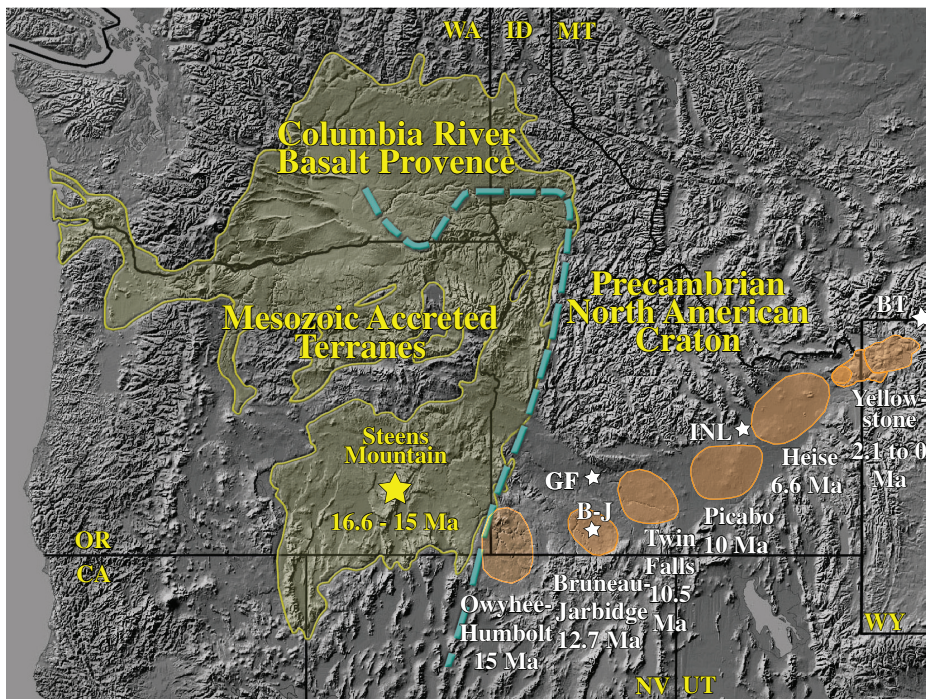


Figure 1. Relief map of Pacific Northwest (after Camp and Ross, 2004). Blue dashed line is boundary between Mesozoic–Paleozoic accreted terranes and Precambrian North American craton. Locations are shown for the Idaho National Laboratory (INL) core WO-2, Bruneau-Jarbridge (B-J), Glens Ferry lavas (GF), and the Beartooth Mountains (BT). Snake River Plain and Yellowstone Plateau volcanic centers and approximate ages are shown in orange, Columbia River Basalt Group is shown in yellow.

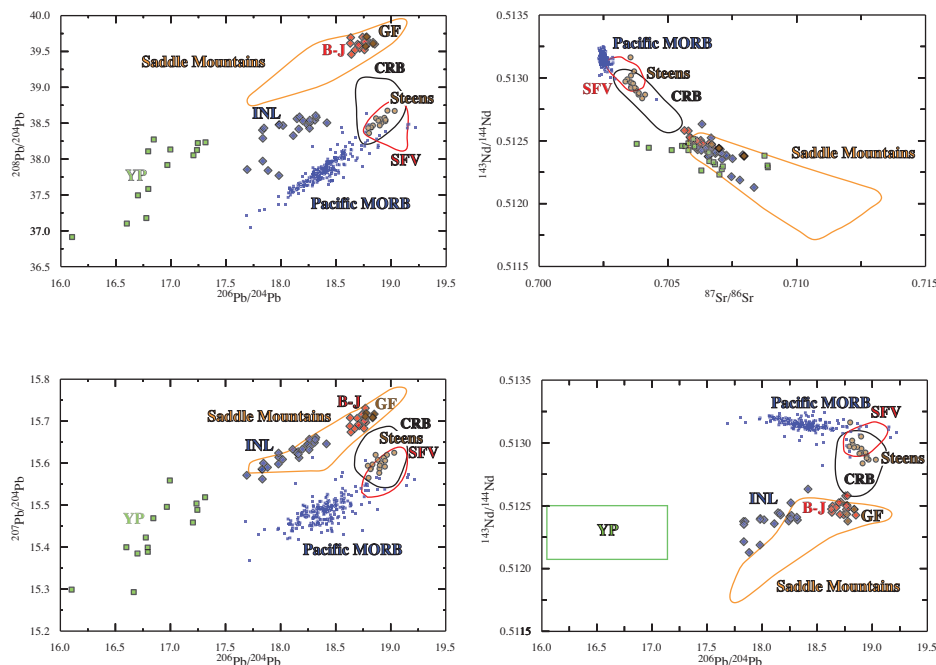


Figure 2. Pb, Sr, and Nd isotope data for the central plain Bruneau-Jarbridge (B-J, red diamond), Glens Ferry (GF, brown), and eastern plain Idaho National Laboratory (INL, blue) basalts. Also shown for comparison are Pacific mid-oceanic ridge basalts (MORB; Hanan and Graham, 1996), Yellowstone basalts (YP, green box; Doe et al., 1982; Hildreth et al., 1991); Columbia River Basalt group (CRB, black outline; GEOROC database), Saddle Mountains lavas (orange outline; GEOROC database), the Steens basalts (Camp and Hanan, 2007), and for comparison, basalts from the Stonyford Volcanic Complex (SFV, red outline; Shervais et al., 2005). Stonyford field represents isotope composition of alkali basalts from Mesozoic oceanic lithosphere, associated with Coast Range Ophiolite. GEOROC—<http://georoc.mpch-mainz.gwdg.de/georoc/start.asp>.

mid-ocean ridge basalts (MORB) derived from depleted asthenosphere. Except for two samples, central plain basalts have more radiogenic Pb isotope ratios than eastern plain lavas and plot in a separate field. The central and eastern basalt Pb-Sr-Nd isotope signatures are similar to the Saddle Mountains basalts (Columbia River Basalt Group), but more radiogenic than lavas from Yellowstone (Doe et al., 1982). The Yellowstone basalts (Doe et al., 1982) have continental-like isotope signatures that plot along an extension of the central and eastern arrays. In contrast, Columbia River basalts (excluding Saddle Mountain) that were emplaced through the Mesozoic–Paleozoic accreted terranes have isotope signatures more characteristic of oceanic mantle sources, overlapping the enriched end of the Pacific MORB array. Columbia River, Snake River Plain, and Yellowstone basalts show an exponential decrease in  $^{206}\text{Pb}/^{204}\text{Pb}$  from west to east, from oceanic island basalt (OIB) like values in Oregon and Washington toward values typical of the lower crust and lithosphere of the Wyoming Province (Leeman et al., 1985; Church, 1985; Wooden and Mueller, 1988).

## DISCUSSION

Although Yellowstone and Snake River Plain basalts have Pb, Sr, and Nd isotope signatures similar to mafic volcanic rocks and deep crustal xenoliths derived from the Wyoming craton, the high  $^3\text{He}/^4\text{He}$  isotope ratios observed at Yellowstone (Craig et al., 1978) provide strong evidence that the hotspot represents the manifestation of a deep mantle plume. This conclusion is reinforced by the major and trace element compositions of the lavas, which are nearly identical to those of OIBs (Vetter and Shervais, 1992; Hughes et al., 2002; Shervais et al., 2006). Helium isotope data for olivine basalts from the Snake River Plain show the  $^3\text{He}$  anomaly to be long lived and not restricted to the Yellowstone caldera (Graham et al., 2006).

Lithosphere beneath the Snake River Plain and Yellowstone stabilized in the Late Archean to Paleoproterozoic (Mueller and Frost, 2006). Compared to other Late Archean rocks, the Pb and Sr initial ratios are higher, and the Nd initial ratios are lower, than expected for a depleted upper mantle source (Wooden and Mueller, 1988; Menzies et al., 1983). These isotope data, and mantle xenolith Os, Sr, Nd, and Pb isotopes (Carlson and Irving, 1994), suggest that crustal material was mixed into the lithosphere during Late Archean subduction and later Proterozoic metasomatic events (Church, 1985; Wooden and Mueller, 1988). However, this enriched lithosphere is not conducive to preserving ancient high  $^3\text{He}/^4\text{He}$ . An appropriate mantle with high time-integrated  $^3\text{He}/(\text{U} + \text{Th})$  that would allow preservation of ancient  $^3\text{He}$  enrichments cannot exist within or below the continents, and is unlikely to exist within the upper

mantle based on the  $^3\text{He}/^4\text{He}$  in MORB (Day et al., 2005). The high  $^3\text{He}$  of the Snake River–Yellowstone province suggests that there is a flux of deep mantle material across the 660 km mantle transition zone into the upper mantle plume imaged at Yellowstone.

We propose that the apparent conflict between the isotopic and chemical data can be resolved by considering mass balance between the contrasting components. The Pb, Sr, and Nd concentrations in the plume source are low compared to subcontinental mantle lithosphere, and melts derived from this source are expected to have concentrations of Pb, Sr, and Nd on the order of 0.3–3, 90–660, and 7–40 ppm, respectively, based on observed concentrations in OIBs and on trace element melting models of inferred plume sources (e.g., Sun and McDonough, 1989; see the Data Repository [Part B] for melting models). In contrast, low percent fractional melts of ancient subcontinental lithosphere, such as the Leucite Hills volcanics (Vollmer et al., 1984; Mirnejad and Bell, 2006), are strongly enriched in Pb (23–120 ppm), Sr (1652–7233 ppm), and Nd (97–300 ppm), and provide an estimate for these concentrations in melts assimilated by the plume basalts as they rise through the lithosphere (data references in the Data Repository [Part B]). Lithosphere:plume proportions implied by these concentrations are ~38–400 for Pb, ~11–80 for Sr, and 11–41 for Nd. As a result, the assimilation of lithospheric melts into partial melts derived from plume-source mantle will result in hybrid magmas whose isotopic compositions are controlled by the isotopic composition of the Archean lithosphere.

This process is well illustrated quantitatively by mass balance calculations for the radiogenic isotopes of Pb assuming a lithosphere:plume ratio of 100. Figure 3 shows the effects of mixing a plume component similar in Pb isotopes to the Steens basalts, the earliest Columbia River eruption, and to Pacific Mesozoic oceanic crust (e.g., Shervais et al., 2005) with fractional melts derived from Archean lithosphere with Pb isotopic composition represented by the ca. 2.8 Ga isochron for the Beartooth Mountain igneous rocks (Wooden and Mueller, 1988). Heterogeneity in the lithosphere is expected to be much greater than for the plume source (see Fig. 2). For ease in modeling and visualization we have chosen a single point located in the overlap between the Steens and Stonyford fields to represent the plume isotope composition. The Beartooth rocks are a good proxy for the Paleoproterozoic–Archean lithosphere because they show the whole range of  $^{206}\text{Pb}/^{204}\text{Pb}$  isotope compositions observed in the Snake River Plain basalts and crustal xenoliths, the Saddle Mountain lavas, and the Yellowstone plateau basalts. Two effects are observed. First, the mass fraction of plume component increases

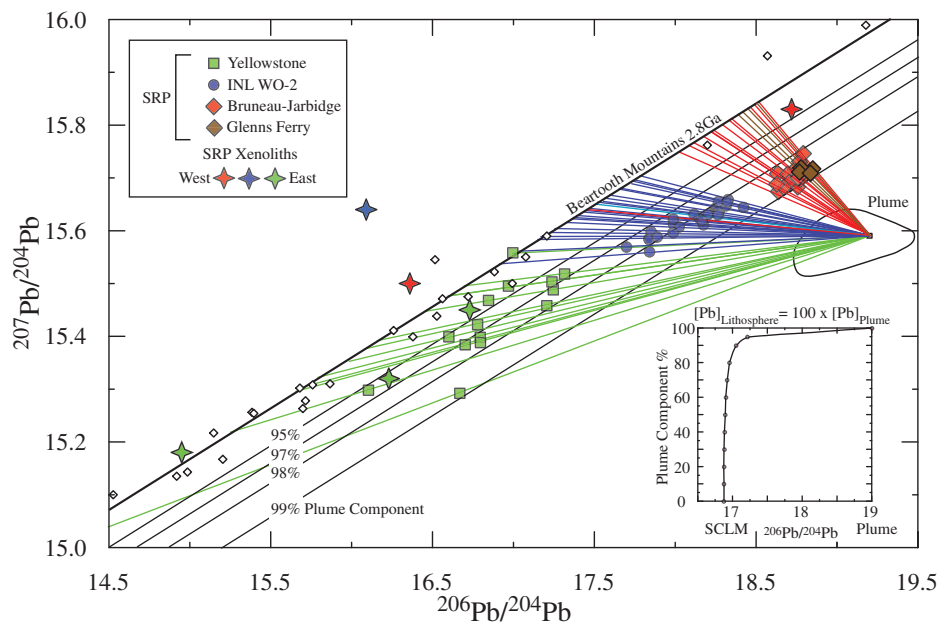


**Figure 3.** The  $^{206}\text{Pb}/^{204}\text{Pb}$  and  $^{207}\text{Pb}/^{204}\text{Pb}$  ratios for the Yellowstone Plateau, Idaho National Laboratory (INL), Bruneau-Jarbridge, and Glens Ferry lavas decrease from west to east. Isochron and data (small open diamonds) for Beartooth Mountains mafic igneous rocks (Wooden and Mueller, 1988) represent Pb isotope composition of lithosphere underlying Yellowstone Plateau and Snake River Plain (SRP). Deep crustal xenoliths of Leeman et al. (1985) plot about the Beartooth 2.8 Ga isochron, and like the Snake River Plain basalts, the  $^{206}\text{Pb}/^{204}\text{Pb}$  ratios of the xenoliths decrease from west to east. Field for the Columbia River Steens basalts and Stonyford Volcanic Complex (black line field labeled Plume; Camp and Hanan, 2007; Shervais et al., 2005) represents plume component. Red, brown, blue, and green lines represent mixing tie lines between average plume and distinct lithospheric Pb reservoirs along the Beartooth isochron for Snake River Plain and Yellowstone Plateau basalts. Solid lines labeled 95%–99% Plume component indicate proportion of plume component in the basalt mixes where the lines intersect the tie lines. Note that Snake River Plain data define pseudo-isochrons with slopes lower than the 2.8 Ga Beartooth reference isochron. Inset plot shows mixing curve between enriched lithosphere with  $^{206}\text{Pb}/^{204}\text{Pb} = 16.87$  and  $^{207}\text{Pb}/^{204}\text{Pb} = 15.44$  and plume source with  $^{206}\text{Pb}/^{204}\text{Pb} = 19.0$  and  $^{207}\text{Pb}/^{204}\text{Pb} = 15.55$ . Pb concentration in the lithosphere is 100× that of the plume. Note that with plume proportions >95% the isotope composition of the mix is dominated by lithosphere Pb signature. SCLM—subcontinental lithospheric mantle.

from east to west: Yellowstone ~95%–98%, eastern plain ~97%–98.5%, and central plain ~98%–99% plume component (Fig. 3). Second, the Pb isotopic composition of the lithospheric component changes from east to west: Yellowstone  $^{206}\text{Pb}/^{204}\text{Pb}$  ~15.5–17.0, central basalts  $^{206}\text{Pb}/^{204}\text{Pb}$  ~17.1–17.8, and eastern lavas  $^{206}\text{Pb}/^{204}\text{Pb}$  ~18.0–18.5 (Fig. 3). Modeling Snake River Plain basalt Sr and Nd isotopes using these end-member compositions gives results consistent with plume mass fractions >95%.

These mass-balance models can be understood in terms of two processes. First, the increase in plume component from east to west most likely reflects a progressive decrease in the thickness of the cratonic lithosphere from east to west as the craton margin is approached. This decrease in thickness will result in a decrease in the volume of lithosphere available to react with the plume-derived melts, and hence a decrease in the proportion of lithosphere component assimilated. The depth of plume melting will also decrease, resulting in

a higher degree of melting of the plume. Second, the regular increase in  $^{206}\text{Pb}/^{204}\text{Pb}$  isotopic composition of the lithosphere component in the mix, from east to west, results from the concomitant decrease in lithosphere age and from compositional heterogeneity of the lithosphere. Spatial compositional differences are reflected by the lack of regular covariation between  $^{208}\text{Pb}/^{204}\text{Pb}$ ,  $^{87}\text{Sr}/^{86}\text{Sr}$ , and  $^{143}\text{Nd}/^{144}\text{Nd}$  ratios along the Snake River Plain (Fig. 2), corresponding to heterogeneity in Th/Pb, U/Pb, Rb/Sr, and Sm/Nd and the time-integrated effect of radioactive decay in the lithosphere. The similarity between the radiogenic isotope signatures of the Snake River Plain and the Saddle Mountain basalts, and their contrast to the Yellowstone basalts, indicates that the lithosphere between the Yellowstone Plateau and the craton margin is not the same as that underlying the Archean Wyoming province, but likely a transitional lithosphere containing a complex mixture Archean and Proterozoic components (e.g., Foster et al., 2006).

## CONCLUSIONS

The final conclusion that can be drawn from this mass-balance model of isotope mixing is that we cannot use the radiogenic (Pb, Sr, Nd) isotopic composition of basalts erupted through thick cratonic lithosphere as a reliable indicator of their provenance. Ancient cratonic lithosphere like that of the Wyoming Province will superimpose its inherent isotopic composition on sublithospheric plume or asthenospheric melts, until that ancient lithosphere becomes sufficiently thinned by thermal or mechanical erosion, or depleted in low-temperature melting components, so that sublithospheric melts may pass through with little or no pollution. This is apparently the case beneath the Great Basin today, where lithospheric thinning has proceeded to the extent that sublithospheric melts arrive at the surface with isotopic compositions similar to their primary source region (e.g., Fitton et al., 1991). These results suggest that the Pb, Sr, and Nd isotope signature of the Yellowstone plume is represented by the mantle source of the early Columbia River main phase basalts and has remained constant since ca. 16.4 Ma. The spatial and temporal variability shown by the Yellowstone plume, from the Columbia River to Yellowstone, is due to shallow mantle plume-lithosphere interaction. The Yellowstone plume, like the Iceland plume, has an isotope signature similar to the common component C (Hanan and Graham, 1996). Similarly, temporal and spatial variability in Iceland basalts (0–16 Ma) is attributed to shallow interaction with North Atlantic upper mantle, which is polluted by continental material (Hanan et al., 2000).

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