Columbia River flood basalts from a centralized crustal magmatic system

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The Columbia River Basalt Group in the northwestern United States[1], comprising about 230,000 cubic kilometres of rock, exhibits unusual patterns in lava distribution, geochemistry and its apparent relationship to regional tectonics. Consequently, there is little consensus on the origin of its magmas[2–12]. Here, we examine the isotopic ratios of Sr, Nd, Pb and Os and trace-element abundances in Columbia River basalts. The results suggest that most of the lava was produced when magma derived from a mantle plume assimilated continental crust in a central magma chamber system located at the boundary between the North American craton and the accreted terranes of Idaho and Oregon. Other, related basalts are the product of mixing between the mantle plume and different types of regional upper mantle. Magma was then transported over a wide region by an extensive network of dykes, a process that has been identified in other flood basalt provinces as well[13]. Interactions of the plume with surrounding upper mantle, and of mantle-derived magmas with regional crust, provide a relatively simple[6,7,9,14,15] model to explain the more unusual features of the main-phase Columbia River Basalts.

The Columbia River Basalt Group (CRBG) consists of ~230,000 km^3 of tholeiitic basalt, basaltic andesite and scarce andesite that covers much of Oregon, Washington and western Idaho[2] (Fig. 1). Most of the volume of lava (Steens, Imnaha and Grande Ronde basalts) erupted between 16.7 and 16.0 Myr ago from vents associated with the Steens and Chief Joseph dyke swarms in eastern Oregon and Washington (Fig. 1), with a subsidiary area of eruption in north-central Oregon (Picture Gorge basalts) associated with the Monument dyke swarm. During this main phase, vent sites migrated rapidly northward from the Steens Mountain area through eastern Oregon to southeastern Washington (Fig. 1), resulting in an age-progressive distribution of Steens (older), Imnaha and Grande Ronde (younger) flows[2,12]. Initial activity at Steens Mountain produced Lower Steens lavas, followed by more evolved and widespread Upper Steens[12,16] and contemporaneous Imnaha flows, in turn followed by the 150,000 km^3 Grande Ronde Formation which accounts for >60% of the total volume of the CRBG, with some flows reaching the Pacific Ocean[17]. The Picture Gorge basalts represent a relatively localized, short-lived episode contemporaneous with mid-Grande Ronde activity. Following the main phase of activity, CRBG eruption rates went into a lognormal decline[12] with the later Wanapum and Saddle Mountains formations accounting for <10% of the total CRBG volume.

Numerous origins, source materials and contributing components have been proposed for CRBG flood lavas, including a mantle plume, convecting mantle ± subduction-related components, subcontinental lithospheric mantle, and lithologies within the continental crust[2–12,18,19]. Many workers agree that a mantle plume is ultimately responsible for the CRBG and the Snake River Plain–Yellowstone hotspot track to the east, although different models of plume–lithosphere interaction have been proposed[5–7,14]. Most also accept that the post-main phase, isotopically anomalous Saddle Mountains basalts, which are akin to basalts of the Snake River Plain to the east, are derived wholly or partly through melting of ancient, enriched, subcontinental lithospheric mantle.

In Sr–Nd–Pb isotopic space, main-phase CRBG lavas lie on trends that radiate from Imnaha basalt (Fig. 2). The 'Imnaha component' is therefore present in all main-phase CRBG lavas. This component has ^{3}He/^{4}He of 11.4±0.7 times the atmospheric ratio[18] (R_A), which is significantly elevated compared with mid-ocean-ridge basalt ($^3He/^4He = 8 \pm 1\ R_A$), and conforms closely to the 'moderately high ^{3}He/^{4}He' ocean-island basalt type of Class and Goldstein[20] in its Pb isotope and incompatible element abundance characteristics (see the Supplementary Information). Following others[5,9,18], we identify the 'Imnaha component' with the mantle plume responsible for CRBG volcanism and the Snake–Yellowstone hotspot trace.

Steens and Picture Gorge basalts lie between the Imnaha component and depleted mantle, as represented by Pacific mid-ocean-ridge basalt, and hence are readily interpreted as the products of mixtures between the mantle plume and depleted mantle (Fig. 2). Despite isotopic similarity, Steens and Picture Gorge basalts have distinct incompatible trace-element ratios. Primitive Lower Steens lavas have similar ratios of large-ion lithophile elements to high-field-strength elements, as do Imnaha basalts (Fig. 3). In contrast, Picture Gorge lavas have elevated ratios of (Cs, Rb, Ba, U, K, Pb)/(Nb, Ta) despite having the lowest $^{87}Sr/^{86}Sr$ of any CRBG lavas. In fact, the most primitive Picture Gorge basalts strongly resemble primitive island-arc tholeiites. We attribute this to a proportion of a subduction-related component in the depleted mantle that forms part of the source region of the Picture Gorge basalts, consistent with some previous interpretations[3,11]. A slight tendency for increasing $^{87}Sr/^{86}Sr$ among more evolved Picture Gorge and Steens lavas may reflect contamination with young accreted crust[11,21]; note this trend is quite distinct from that of the Grande Ronde lavas, which have $^{87}Sr/^{86}Sr > 0.704$ (Figs 2,3). The

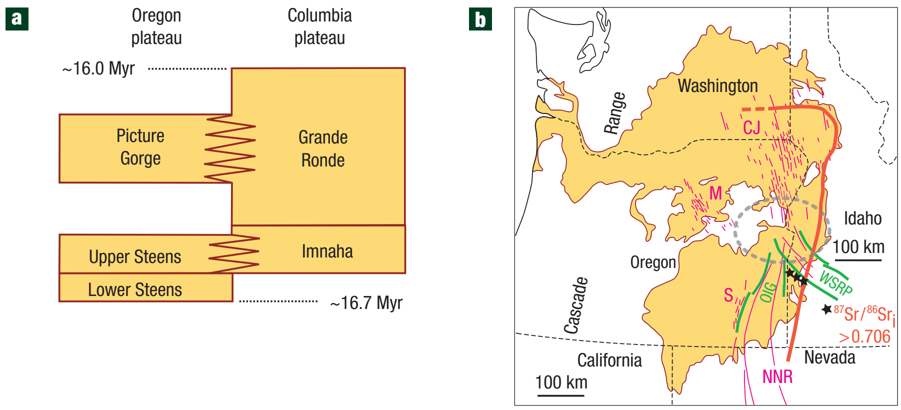

Figure 1 Stratigraphy and map of main-phase Columbia River basalts, based on ref. 2. a, Temporal relations. **b**, Map: Lavas, yellow; dyke swarms, magenta (CJ = Chief Joseph swarm; M = Monument swarm feeding Picture Gorge basalts; S = Steens swarm; NNR = northern Nevada Rift swarm); extensional structures, green (WSRP = western Snake River Plain graben; OIG = Oregon–Idaho graben); Miocene rhyolites representing crustal melts, black stars; Mesozoic initial $^{87}Sr/^{86}Sr = 0.706$ isopleth, red (cratonic crust lies to the east of the isopleth). The dashed grey ellipse encloses the present-day area within which the crustal-depth magma chambers for the flood lavas are inferred to lie.

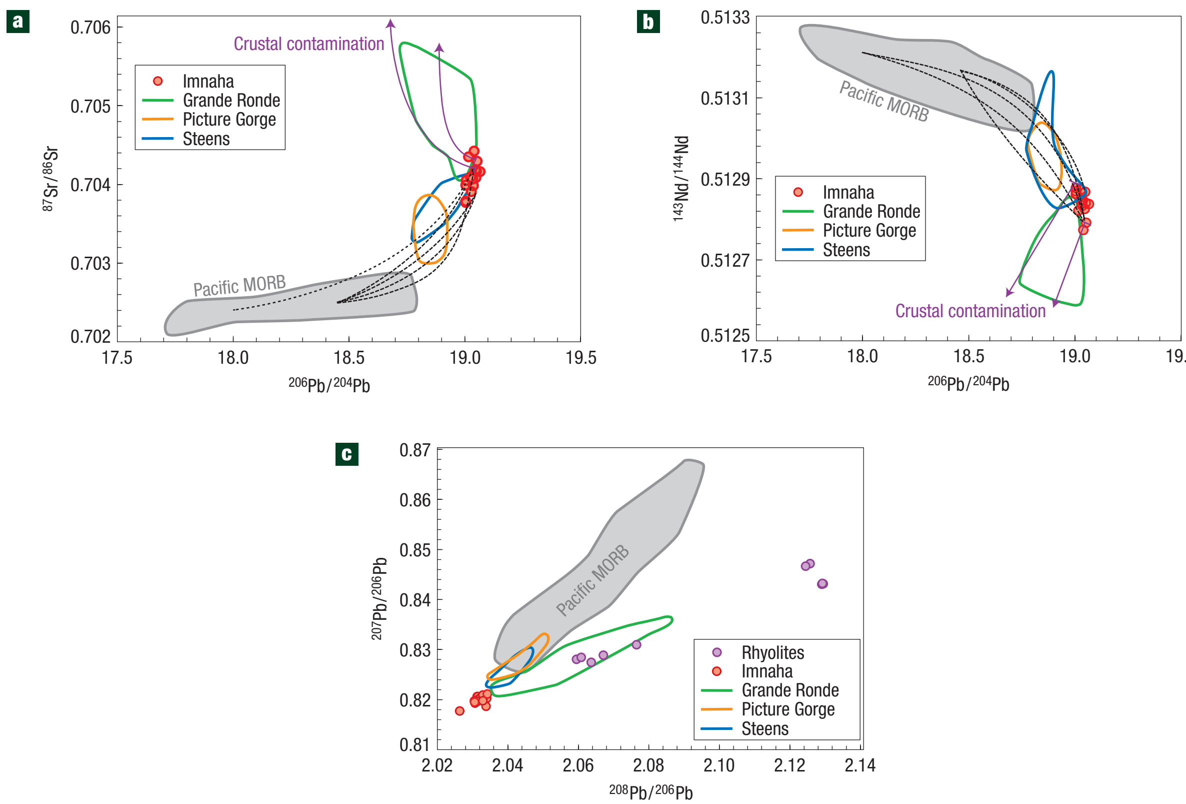

Figure 2 Sr–Nd–Pb isotope relations among main-phase CRBG lavas and Pacific mid-ocean-ridge basalt. MORB: mid-ocean-ridge basalt. **a–c**, Plots of $^{87}Sr/^{86}Sr$ (**a**) and $^{143}Nd/^{144}Nd$ (**b**) against $^{206}Pb/^{204}Pb$, and $^{207}Pb/^{206}Pb$ against $^{208}Pb/^{206}Pb$ (**c**). Black dotted lines, mixtures between Imnaha-source mantle and depleted mantle. Plum-coloured arrows labelled 'crustal contamination' represent the extent of interaction between Imnaha magmas and crust, which is represented by rhyolitic lavas in the vicinity of the CRBG magma storage zone (see Supplementary Information for details of modelling). Steens data from B. Hanan (personal communication); other data from refs 3,9,11,21,29.

CRBG lavas exhibit abundant mineralogical and chemical evidence for storage and modification in magma chambers within the crust[22–24]. The presence of distinct mixtures of mantle components in each of the Imnaha, Picture Gorge and Steens basalt formations therefore suggests derivation from different magma chambers fed by melts from different mantle source mixtures. In the case of the

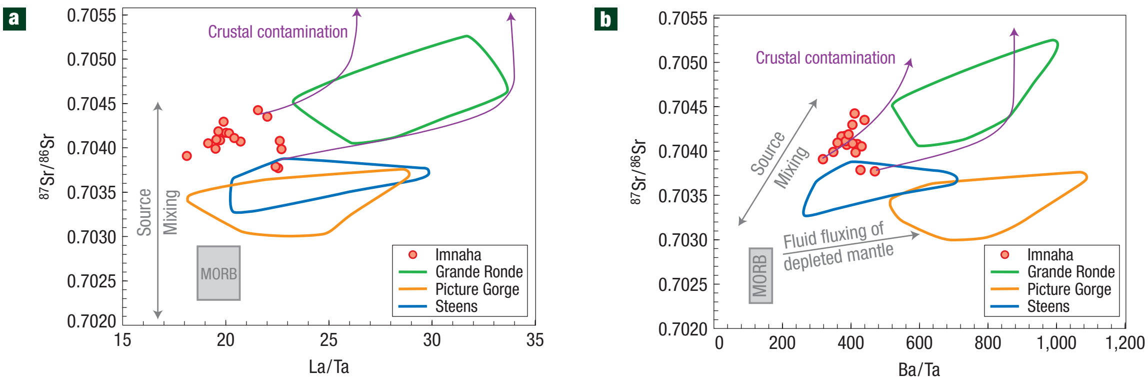

Figure 3 Relations between $^{87}Sr/^{86}Sr$ and incompatible trace elements among main-phase CRBG lavas. All trace-element data are from this study. **a**, Mid-ocean-ridge basalt, Imnaha, Picture Gorge and Steens lavas have overlapping La/Ta values but are isotopically distinct. Picture Gorge and Steens lavas extend to higher La/Ta owing to the influence of a fluid-fluxed arc component in the mantle and/or minor contamination by accreted arc crust. **b**, Similar relations between $^{87}Sr/^{86}Sr$ and Ba/Ta but the influence of the arc component is more clearly seen with Picture Gorge lavas displaced to high Ba/Ta. Steens data from B. Hanan (personal communication); other data from refs 3,9,11,21,29.

Upper Steens lavas, multiple eruptive centres may also point to the establishment of shallow subvolcanic magma chambers[16].

Any acceptable petrogenetic model for the CRBG must account for the geochemical features of the volumetrically dominant and compositionally evolved (52.5–58.7% SiO_2; 2.8–6.0% MgO) Grande Ronde lavas. Past explanations include contamination of primitive basaltic magma by continental crust[3,4,11,19,24], melting of oceanic crust recycled in the mantle plume[10] and an origin in the subcontinental lithospheric mantle[9]. It is obvious from Figs 2 and 3 that the Grande Ronde lavas contain an isotopically distinct component that is different from both depleted and plume mantle. Grande Ronde lavas form a geochemical continuum with, but are more differentiated than, Imnaha basalts (48.4–52.5% SiO_2). Therefore, the 'Grande Ronde component' is either itself silicic ($\geq$59% SiO_2), and/or its addition to Imnaha magma promotes magmatic differentiation for thermal reasons. This component is very unlikely to be recycled oceanic crust in a mantle plume[10] because recycled oceanic crust that has been processed through a subduction zone should be depleted in large-ion lithophile elements with respect to high-field-strength elements, the opposite of that observed (Fig. 3).

Existing osmium isotope data[19] effectively rule out an origin for the Grande Ronde component in the ancient subcontinental lithospheric mantle. $^{187}Os/^{188}Os = 0.134$–$0.158$ in Imnaha lavas, similar to those of ocean-island basalts[25] (consistent with other geochemical data noted above), and 0.201–0.404 in the Grande Ronde[19]. However, subcontinental lithospheric mantle has $^{187}Os/^{188}Os < 0.13$ (ref. 25), and its involvement in Grande Ronde petrogenesis should therefore produce lower $^{187}Os/^{188}Os$ values than in the Imnaha lavas, the opposite of what is seen. It is worth noting that a decrease in $^{187}Os/^{188}Os$ is seen in cases of undoubted contamination of plume-derived magmas by lithospheric mantle[26]. Instead, the elevated $^{187}Os/^{188}Os$ in the Grande Ronde lavas are consistent with the presence of a Re/Os-enriched component such as is provided by continental crust.

Most of the Chief Joseph feeder dykes for the Grande Ronde lavas are located in accreted terranes to the west of the craton boundary as defined by the surface $^{87}Sr/^{86}Sr = 0.706$ isopleth (Fig. 1). These terranes consist of Palaeozoic to Mesozoic island arcs that were extracted from the mantle too recently to have Sr and Nd isotopic ratios required of the enriched 'Grande Ronde component' (Fig. 4). Only cratonic crust has the geochemical and isotopic properties required of this component. Although post-collisional thrusting during the late Cretaceous period caused eastward displacement of the craton boundary marked by the $^{87}Sr/^{86}Sr = 0.706$ isopleth (Fig. 1), the thrust décollement probably lies within the mantle and the suture zone dips steeply from the surface to the base of the crust[27]. Hence, it is unlikely that there are significant subsurface volumes of cratonic crust to the west of the isopleth. We propose, therefore, that laterally extensive crustal magma chambers associated with the volumetrically dominant Imnaha–Grande Ronde phase of CRBG magmatism were located in the broad region where dyke swarms and other regional tectonic elements (Oregon–Idaho graben, Western Snake River Plain) converge in eastern Oregon, and extended eastward across the craton boundary allowing plume-derived basaltic magma to assimilate ancient cratonic crust lying east of the suture (Fig. 1). Lead isotope data for ~11 Myr old western Snake River Plain rhyolite lavas that represent melts of transitional[27] and cratonic crust are shown in Fig. 2c; they lie on and east of the suture zone (Fig. 1) and have the exact characteristics required of the 'Grande Ronde component'. Co-variations among Sr, Nd and Pb isotopes and incompatible trace elements among the Grande Ronde lavas are reproduced by models of Imnaha magmas assimilating such crust (Figs 2,3). We also note that the post-main-phase Wanapum basalts (about 15.3–14.5 Myr old)[12] have Sr, Nd, Pb and Os isotope ratios that are very similar to those of the Grande Ronde flows[3,4,9] and conclude that they have a similar petrogenesis involving assimilation of cratonic crust by mantle-derived magma.

We conclude that the principal CRBG magma system that fed the Grande Ronde lavas was at least partly hosted in transitional to cratonic crust, at depths (15–30 km) that are consistent with phenocryst compositions[22–24], and with bulk lava major-element compositions that require an important role for clinopyroxene in the evolution of the magmas[22]. Our model implies that magma travelled up to 300 km northward through the Chief Joseph dyke swarm to erupt on the western slope of the Rocky Mountains, from where most of the flood lavas flowed westward to form the Columbia Plateau. Vent sites moved farther from the magmatic centre as eruption rates increased[12] during Imnaha to Grande Ronde time; similar behaviour is seen in other dyke swarms associated with large igneous provinces[13]. A corollary of our model is therefore that the degree of magma–crust interaction simultaneously increased; all these effects may be directly linked

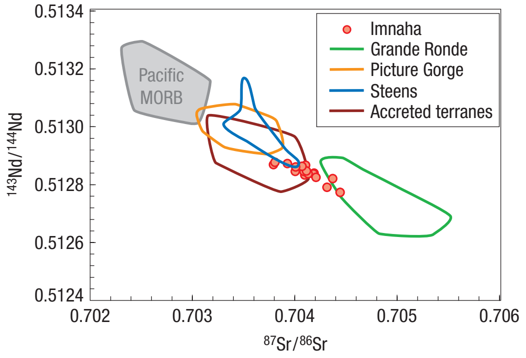

Figure 4 Sr–Nd isotope variations among main-phase CRBG lavas compared with accreted volcanic arc terranes[30], age-corrected to 16 Myr.

to the flux of magma from the mantle into the crust. Our model for CRBG volcanism, dictated by consideration of basalt geochemistry alone, is fully consistent with recent interpretations derived from geologic and geophysical data[2,8,28] that identify the zone of dyke convergence as fundamentally linked to the flood basalt activity, perhaps as a consequence of plume impact at the base of the lithosphere[28].

There is no geochemical evidence for the presence of significant amounts of cratonic crust in the Steens or Picture Gorge lavas. Their distinct isotopic characteristics (Figs 2–4) are inconsistent with derivation from the same crustal magma chambers as the Imnaha and Grande Ronde basalts, but, if the flows were fed by magma moving laterally through dykes as we have concluded for the Grande Ronde lavas, Steens and Monument dyke distributions (Fig. 1) then suggest that their source magma systems also lay within the same 'convergence zone'. If so, the Picture Gorge and Steens magma chambers were probably hosted within accreted terrane crust, which provides little isotopic leverage on the magmas and is therefore difficult to detect (Fig. 4), although the slight variations in $^{87}Sr/^{86}Sr$ and $^{143}Nd/^{144}Nd$ among Picture Gorge lavas are probably due to crustal contamination[11]. Upper Steens lavas were erupted from numerous centres in southeast Oregon[16] that may themselves have been fed by dykes radiating from a parent system located in accreted crust within the 'convergence zone'.

We conclude that the geochemistry of Columbia River flood basalts, in particular the volumetrically dominant Imnaha–Grande Ronde lavas, is most simply explained by derivation of the magmas from a single centralized crustal storage system. This requires lateral transport of magma to vent sites through conduits now represented by the exposed dyke swarms and removes the need for the assumption implicit in many previous studies that magmas rose more or less vertically to the surface, hence requiring unusual sublithospheric distribution of the mantle plume source[2,6,7], and in fact places few constraints on the geometry of the plume head or the location of the plume axis.

METHODS

All samples were analysed for major and trace elements in the GeoAnalytical Laboratory at Washington State University using X-ray fluorescence and inductively coupled plasma mass spectrometry. See http://www.wsu.edu/~geolab/ for details of sample preparation, equipment and analytical methods. Sr, Nd and Pb isotopes were measured using thermal ionization mass spectrometry (Sr, Nd) and multi-collector inductively coupled plasma mass spectrometry; see Supplementary Information for details.

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