

The Columbia River Flood Basalts: Consequence of subduction-related processes

[Alexei V. Ivanov](#)

*Institute of the Earth's Crust, Siberian Branch, Russian Academy of Sciences, Irkutsk,
Russia*

aivanov@crust.irk.ru

Introduction

Many, if not all, continental flood basalts are characterized by subduction-like trace-element fingerprints. Conventionally, this is interpreted as evidence for a lithospheric contribution to magmatism (e.g., Hooper & Hawkesworth, 1993, [Hooper et al., 2007](#)). Recently, a lithospheric source for such magmas was ruled out using Ethiopian and Siberian flood basalts as example ([Kieffer et al., 2004](#); [Ivanov, 2007](#)). The question then remains, regarding what process may result in sublithospheric subduction-like trace-element signatures in regions remote from subduction? [Kieffer et al. \(2004\)](#) advocate a plume source for such magmas. [Ivanov \(2007\)](#) suggests water recycling through the mantle transition zone. This question was recently highlighted as a part of an [open, web-hosted discussion](#) of the paper by [Hooper et al. \(2007\)](#), which concerns the Columbia River flood basalts. According to [Hooper et al. \(2007\)](#), these basalts are the consequence of a lower-mantle plume. The Columbia River flood basalts bear prominent subduction-like trace-element signatures, and this was interpreted as a result of contamination of an OIB-like plume component by the lower crust. The Columbia River flood basalts are an excellent example with which to test whether subduction-like trace-element signatures are the result of contamination of plume material or simply the result of subduction itself.

Contamination

In Figure 1, I plot $\Delta 8/4\text{Pb}$ versus $^{87}\text{Sr}/^{86}\text{Sr}$ for three formations, the Imnaha, Grande Ronde and Saddle Mountains. The Saddle Mountains formation is considered to be contaminated by mafic lower crust ([Chesly & Ruiz, 1998](#)). This may be *in situ* contamination, or recycling of a mafic component (e.g., delaminated continental and/or oceanic crust; [Escrig et al., 2004](#); [Ivanov & Balyshev, 2005](#); [Ivanov, 2007](#)). Regardless, the linear trend in Figure 1 shows the involvement of two end-members, a "mantle" and a "crustal" one. The Imnaha basalts belong to the mantle end-member. They are not contaminated.

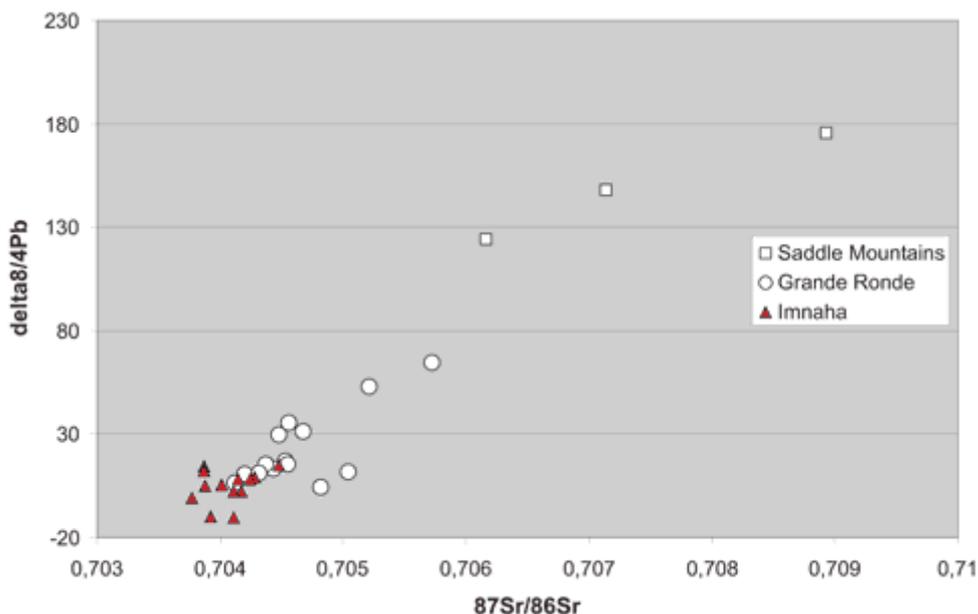


Figure 1. $\Delta 8/4Pb$ versus $^{87}Sr/^{86}Sr$ in three formations of the Columbia River flood basalt province. Original data are after (Hooper & Hawkesworth, 1993). $\Delta 8/4Pb$ is $100 \times [(^{208}Pb/^{204}Pb)/(1.209(^{206}Pb/^{204}Pb)+15.627)]$ (Hart, 1984). Saddle Mountains shows typical DUPAL values (Hart, 1984).

Differentiation of the Imnaha basalts

The Imnaha basalts are too low in Mg# to be primary mantle-derived melts (Figure 2). The trend in Mg# versus Sr/Pr shows that olivine and plagioclase fractionation controls their composition. The curve through the data represents an equilibrium back-addition of these two minerals to restore the primary melt composition. The proportion of olivine and plagioclase was kept constant through the model (olivine/plagioclase = 0.55/0.45). The primary melt had a Mg# close to 60 and Sr/Pr close to 160 (Figure 2).

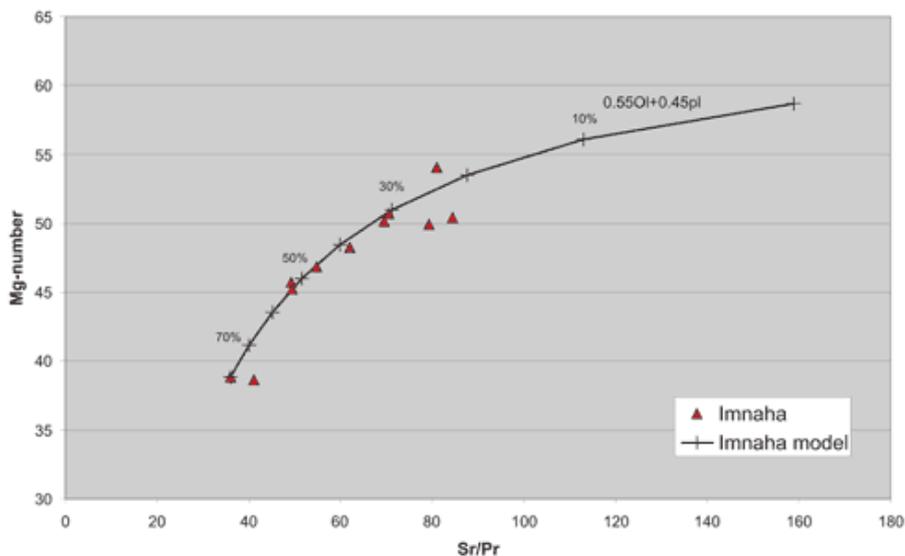


Figure 2. Mg# [$Mg/(Mg+0.85Fe)$] vs Sr/Pr in Imnaha basalts. Original data are after Hooper & Hawkesworth (1993). Curve represents equilibrium crystallization of olivine and plagioclase (Shaw, 1970). Degree of fractionation increases with decreasing Mg# and Sr/Pr values. $D^{MgO/FeO}$ and $D^{Sr/Pr}$ are taken as 2.8 and 31 respectively for olivine and plagioclase.

Trace elements in the primary Imnaha melt

Figure 3 gives an overview of trace element patterns in uncontaminated Imnaha basalts (a few contaminated samples shifted towards higher $\Delta 8/4\text{Pb}$ and $^{87}\text{Sr}/^{86}\text{Sr}$ are excluded in Figure 3). These Imnaha basalts are significantly different from the modeled uncontaminated ocean island basalt (OIB) of Sun & McDonough (1989). Instead, they show similarities with island arc basalts (IAB in Figure 3 is an average of high-Mg basalts of Klyuchevskoi volcanics, Kamchatka (Dorendorf et al., 2000)). These similarities become more obvious if real basalt compositions are recalculated to their primary melt composition (Figure 4). All peaks and troughs of typical IAB, with no exceptions, are mirrored by the primitive Imnaha melt (Figure 4). The only difference is the magnitude of the Th and Nb troughs. The difference with the OIB is striking (Figure 4).

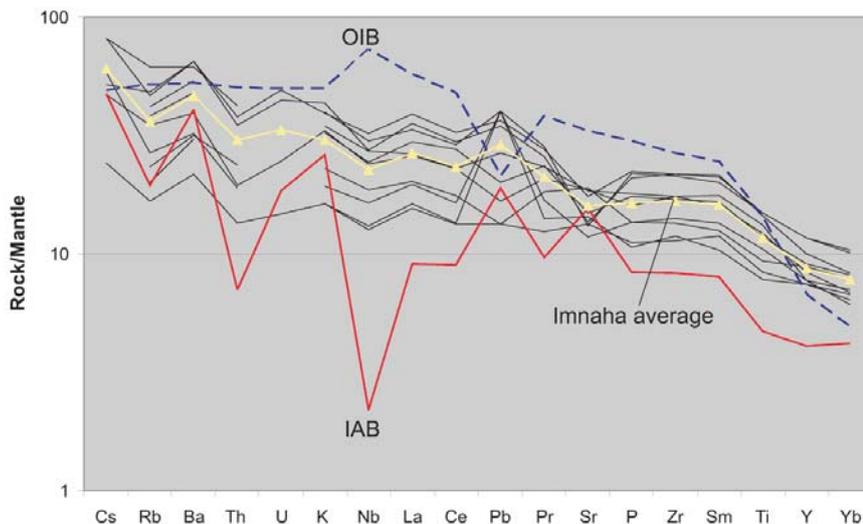


Figure 3. Primitive, mantle-normalized trace-element patterns of uncontaminated Imnaha basalts compared with OIB and IAB. Original data for Imnaha basalts are after Hooper & Hawkesworth (1993). OIB and IAB are after Sun & McDonough (1989) and Dorendorf et al. (2000).

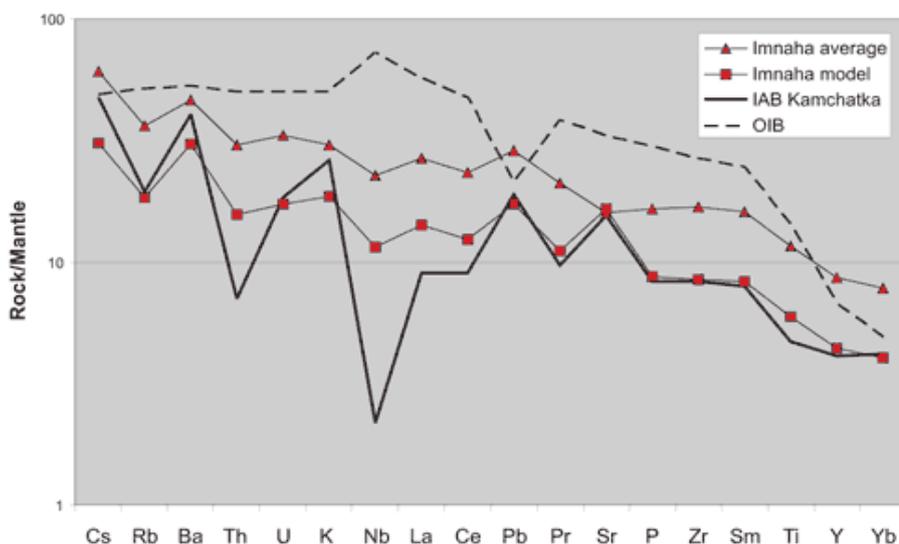


Figure 4. Primitive mantle-normalized trace-element patterns for average of Imnaha basalt and its modeled primary melt compared with IAB. Distribution coefficients for modeling are listed in Table 1.

Table 1. Mineral/melt distribution coefficients for selected elements used for derivation of trace-element patterns of evolved IAB melt (see Figure 1). Values for plagioclase and olivine are based on Dunn & Sen (1994). Values for clinopyroxene are after a compilation of Zack et al. (1997). Asterisks mark extrapolated values.

	Plagioclase	Clinopyroxene	Olivine
Cs	0.034	0.001	0.0001*
Rb	0.023	0.0047	0.0085
Ba	0.69	0.0007	0.001*
Th	0.064	0.012	0.01*
U	0.078	0.01	0.01*
K	0.5*	0.05*	0.003*
Nb	0.024	0.0077	0.0035
La	0.12	0.054	0.00001*
Ce	0.097	0.086	0.024
Pb	0.44	0.1*	0.0055
Pr	0.077	0.14	0.031
Sr	2.38	0.13	0.012
P	0.1*	0.125*	0.013
Zr	0.00018	0.12	0.015*
Sm	0.048	0.29	0.016
Ti	0.037	0.38	0.015*
Y	0.012	0.47	0.029
Yb	0.0098	0.43	0.053

Discussion and conclusions

Primitive mantle-derived melt from the Columbia River flood basalt province is similar to typical IAB and remarkably different from OIB. Thus, its origin should be similar to the origin of IAB, which is the partial melting of a subduction mantle wedge (e.g., Ulmer, 2001). The mantle wedge is a part of the depleted upper mantle enriched by water-soluble elements (e.g., Cs, Ba, K, Sr, Pb). High-field-strength elements (e.g., Ta, Nb, Zr, Ti) and heavy rare-earth elements are not transported by water. Other elements (e.g., Rb, Th, La, Ce, Pr) are moderately soluble in water (e.g., Ulmer, 2001). These make the IAB trace-element patterns recognizable throughout geological history.

There is no problem in explaining Columbia River flood basalts in terms of subduction-related processes – a subduction zone is nearby. However, many other flood basalt provinces show similar subduction-like trace-element geochemistry and some of them were far from active subduction zones when they erupted. A new model for the formation of flood basalt provinces would involve five steps (Ivanov, 2007);

1. transport of water deep into the upper mantle, perhaps even into the transition zone, via slab subduction,
2. release of water from the slab as a result of heating of the slab to ambient mantle temperature,
3. rising of buoyant, water-saturated peridotitic diapirs,
4. partial melting of rising diapirs on crossing the wet solidus, and accumulation of melt beneath the lithosphere,
5. a drainage event.

Step 3 may be termed the “plume event”, because the water-saturated diapirs would rise by virtue of their own buoyancy. The addition of water into olivine significantly increases its volume. For example, the addition of 0.5 wt. % of H₂O into forsterite causes volumetric expansion equal to that which would result from heating by 240°C at zero pressure (Smyth et al., 2006). Such plumes, however, have nothing to do with the classical plume concept involving thermal boundary layers (Campbell, 2005).

References

- [Campbell, I.H., 2005. Large igneous provinces and the mantle plume hypothesis:](#)

[Elements, 1, 265-270.](#)

- Chesley, J.T. and Ruiz, J., 1998. Crust-mantle interaction in large igneous provinces: Implications from Re-Os isotope systematics of the Columbia River flood basalts. *Earth Planet. Sci. Lett.*, **154**, 1-11.
- Dorendorf, F., Wiechert, U. and Wörner, G., 2000. Hydrated sub-arc mantle: a source for the Klyuchevskoy volcano, Kamchatka/Russia. *Earth Planet. Sci. Lett.*, **175**, 69-86.
- Dunn, T. and Sen, C., 1994. Mineral/matrix partition coefficients for orthopyroxene, plagioclase, and olivine in basaltic to andesitic systems: A combined analytical and experimental study: *Geochimica et Cosmochimica Acta*, **58**, 717-733.
- Escrig, S., Capmas, F., Dupré, B. and Allègre, C.J., 2004. Osmium isotopic constraints on the nature of the DUPAL anomaly from Indian mid-ocean-ridge basalts, *Nature*, **431**, 59-63.
- Hart, S.R., 1984. A large-scale isotope anomaly in the Southern Hemisphere mantle. *Nature*, **309**, 753-757.
- Hooper, P.R. and Hawkesworth, C.J., 1993. Isotopic and geochemical constraints on the origin and evolution of the Columbia River basalts: *Journal of Petrology*, **34**, 1203-1246.
- [Hooper, P.R., Camp, V., Reidel, S., and Ross M., 2007. The origin of the Columbia River flood basalt province: Plume versus nonplume models. In: Foulger, G.R., Jurdy, D.M. \(Eds.\). *Plates, Plumes and Planetary Processes*. Princeton: Geological Society of America Special Paper 540, in press.](#)
- [Ivanov, A.V., 2007. Evaluation of different models for the origin of the Siberian Traps. In: Foulger, G.R., Jurdy, D.M. \(Eds.\). *Plates, Plumes and Planetary Processes*. Princeton: Geological Society of America Special Paper 540, in press.](#)
- [Ivanov A.V., Balyshev S.V. Mass flux across the lower-upper mantle boundary: vigorous, absent, or limited?, in: Foulger G.R., Natland J.H., Presnall D.C., Anderson D.L., eds., *Plates, Plumes and Paradigms: Geological Society of America Special Paper 388, 2005, p. 327-346.*](#)
- Kieffer, B., Arndt, N., Lapierre, H., Bastien, F., Bosch, D., Pecher, A., Yirgu, G., Ayalew, D., Weis, D., Jerram, D.A., Keller, F., and Meugniot, C., 2004, Flood and shield basalts from Ethiopia: Magmas from the African superswell: *Journal of Petrology*, **45**, 793-834.
- Shaw, D.M., 1970. Trace element fractionation during anatexis. *Geochim. Cosmochim. Acta.*, **34**, 237-243.
- Smyth, J.R., Frost, D.J., Nestola, F., Holl, C.M., Bromiley, G., 2006. Olivine hydration in the deep upper mantle: Effect of temperature and silica activity. *Geophys. Res. Lett.*, **33**, L15301.
- Sun, S.-S., McDonough, W.F., 1989. Chemical and isotopic systematics of oceanic basalts: Implications for mantle composition and process. In: Saunders, A.D., Norry M.J. (Eds.). *Magmatism in the oceanic basins*. Geol. Soc. Spec. Publ. No. 42, 313-345.
- Ulmer, P., 2001. Partial melting in the mantle wedge – the role of H₂O in the genesis of mantle-derived 'arc-related' magmas. *Phys. Earth. Planet. Interiors*, **127**, 215-232.
- Zack, T., Foley, S.F. and Jenner, G.A., 1997, A consistent partition coefficient set for clinopyroxene, amphibole and garnet from laser ablation microprobe analysis of garnet pyroxenites from Kakanui, *New Zealand: Neues Jahrbuch für Mineralogie-Abhandlungen*, **172**, 23-41.

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