



Processes of mantle enrichment and magmatic differentiation in the eastern Snake River Plain: Th isotope evidence

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Abstract

The ~85 km long Great Rift of southern Idaho bisects the volcanic depression that forms the eastern Snake River Plain. Thorium isotope systematics of compositionally diverse lavas of the Great Rift, including those of Craters of the Moon, record a spectrum of crust and mantle processes. $(^{230}\text{Th})/(^{232}\text{Th})$ ratios range from 0.87 to 1.11 and are enriched in (^{230}Th) with respect to (^{238}U) by up to 13%. Covariations in Th isotope systematics in lavas from Craters of the Moon reflect crustal assimilation accompanied by fractional crystallization involving accessory phases. Temperatures based on apatite and zircon saturation confirm other estimates of magmatic temperatures and, considered together with volcanic histories, suggest cooling in upper crustal magma chambers at rates of $> 10^\circ\text{C/ka}$. Thermal and chemical evolution of the Great Rift basalts support their differentiation at lower crustal conditions.

Although basalts of the eastern Snake River Plain are generally interpreted as having originated in ancient enriched mantle lithosphere beneath southern Idaho, they share remarkable chemical similarities with oceanic basalts derived from enriched sources attributed to mantle plumes. Thorium isotope signatures of the Great Rift basalts are those of depleted mantle, resulting in the most extreme case of disparity between $^{232}\text{Th}/^{238}\text{U}$ ratios delimited by Th and Pb isotope systematics. It is difficult to account for this decoupling by invoking subduction-related U enrichment. A more likely explanation is metasomatism of hybrid lithospheric mantle in the wake of the Yellowstone plume.

1. Introduction

Basalts from regions of lowest heat flow and greatest crustal thickness in the western United States yield Pb-Pb isochrons that are broadly contemporaneous with Proterozoic to Archean orogenic events, suggesting isolation of the basalt sources in the lithosphere at the time of crust formation [1]. Basalts from the eastern Snake River Plain (ESRP) of southern Idaho, a magmatically active region of normal crustal thickness, yield Pb-Pb isochrons [2] that are temporally

equivalent to isochron ages obtained for crustal xenoliths entrained in the basalts [3]. Pb isotope systematics in these basalts also constrain a $^{232}\text{Th}/^{238}\text{U}$ ratio (k) that is distinct from those typical of convecting upper mantle reservoirs, suggesting magmatic derivation in a lithospheric column created in the late Archean to early Proterozoic. On the other hand, Pb isotope similarity between these basalts and oceanic basalts attributed to enriched mantle sources [4], coupled with ^3He enrichments [5], strongly suggests a deep-seated, presumably plume source for ESRP

volcanism. To further illuminate possible origins for the ESRP basalts this study uses Th isotopes to obtain the present-day κ value of their source and contrasts this value with that constrained by Pb isotope signatures to delimit processes of basalt production and chemical evolution of subcontinental mantle.

Holocene lavas of the Great Rift in the ESRP, the largest volcanic field of this age in the contiguous United States, range from olivine tholeiites with > 9 wt% MgO to silicic lavas with > 64 wt% SiO_2 . Detailed field, petrologic, and geochemical studies (e.g., [6–10]) show that while more evolved lavas assimilated crustal material the basalts are relatively free of crustal contamination and are derived from enriched mantle. Further, although lavas of intermediate composition are rare, they may provide an important genetic link between the rhyolite that dominates the ESRP and subordinate basalt. Using the Th isotope systematics of the Great Rift lavas, timescales and processes of their magma genesis can be evaluated.

2. Geologic and geochemical background

The Snake River Plain is a curvilinear volcanic trough of low relief that traverses several tectonic provinces in southern Idaho (Fig. 1), geographically and temporally linking volcanism of the Columbia River province to that of the Yellowstone Plateau. In the ESRP, caldera-related ash flow tuffs young progressively from ~ 15 Ma in the southwest [11] to the present locus of magmatic activity of the Yellowstone area in the northeast. Basaltic lavas and interbedded sediments buried the ignimbrites in time-transgressive fashion. The eastward limit of this activity is west of a 2 Ma caldera in the Yellowstone volcanic field, but post-caldera shield and fissure-fed basaltic volcanism continued into the Holocene along the entire length of the ESRP. Basaltic eruption rates are within an order of magnitude of the historical productivity of Hawaii, and considering the large volume of the ESRP rhyolite the total basaltic flux may be greater than that of many plume-related islands (cf. [12,13]).

The apparent rate of magmatic migration along the ESRP is ~ 3.5 cm/yr [11] but migration was episodic; corrected for syn- and post-magmatic extension the rate is still somewhat larger than the absolute velocity of the North American plate [14]. West to east migration of the thermomagmatic anomaly is also evident in the eastward thickening of a mid-crustal velocity anomaly that is interpreted to be a mafic intrusion [15,16], and in an increase in elevation associated with thermal expansion of the crust and diminished loading by this dense mid-crustal layer [17]. Crust in the ESRP is thick compared to that of the Basin and Range province to the south (~ 42 km versus < 32 km [16,18]), in spite of evidence for extension concomitant with all stages of volcanic activity (summarized by [14]). It appears that crust is being reconstituted by mafic intrusions that balance crustal thinning and replenish silicic material extracted by rhyolitic volcanism such that the amount of extension (β) is probably < 1.5 . A seismically active wedge radiating from the Yellowstone Plateau to the north and south of the ESRP (Fig. 1) may also be due to magmatic intrusion associated with the northeastward migration of volcanism [17]. Consequently, of various models for the origin of the ESRP (summarized in [19]), passage of the North American continent over a mantle plume best explains the time-transgressive features, the magmatic production rates and the absence of extension-related structures parallel to the trend of the ESRP. Although westward extension of the plume trace into Oregon, particularly with respect to the Columbia River flood basalts, remains conjectural ([20] and references therein), Holocene volcanism downstream of the plume, like that of the Great Rift of southern Idaho, may simply reflect juxtaposition of Basin and Range extension on mantle heated to near-solidus by the plume.

The Great Rift is a NW–SE trending extensional feature transverse to the general trend of the ESRP (Fig. 1). The Wapi and Kings Bowl lava fields lie close to the axis of the ESRP, whereas vents belonging to the Craters of the Moon (COM) volcanic field lie dominantly near the northern margin of the plain. A 6.5 Ma ignimbrite in the Heise volcanic field east of the

Fig. 1. Map of volcanic complexes. A

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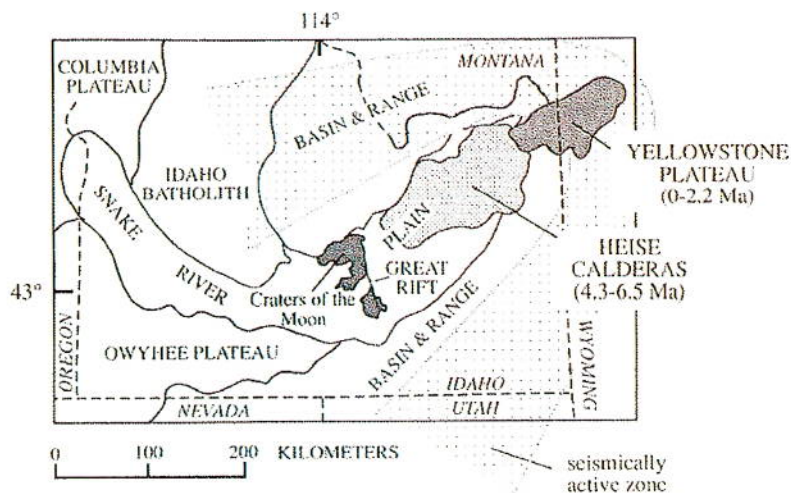


Fig. 1. Map of the eastern Snake River Plain showing location of the Great Rift and of the Heise and Yellowstone caldera complexes. Also shown is the envelope of seismically active crust from [17].

Great Rift provides a minimum age for the onset of volcanic activity in the region (Fig. 1). Detailed volcanic stratigraphy and ^{14}C dating [9] provide an insight into the evolving nature of lava flows erupted along the Great Rift. Eruptions of basaltic lavas at 15.1 ± 0.2 ka were followed at intervals of roughly 2 ka by eruptions of increasing compositional variance. Intermediate to silicic lavas appeared at ~ 6 ka and most lavas with > 50 wt% SiO_2 contain xenocrysts and crustal xenoliths, macroscopic evidence for crustal contamination. The lava flows are typically zoned in composition and the compositional range of both xenocryst-bearing and xenocryst-free lavas increased in time towards the present. The most recent lavas (~ 2.1 ka) vary in composition from basalt at Wapi and Kings Bowl to ferrolatite at COM, representing a range of almost 20 wt% SiO_2 .

The Wapi and Kings Bowl lavas are similar compositionally and mineralogically to other ESRP olivine tholeiites [9,21], which are distinctive in their high concentrations of TiO_2 , P_2O_5 and FeO . COM basalts contain even higher concentrations of these elements, which is largely attributable to fractionation in lower crustal magma chambers [22]. The Sr, Nd and Pb isotope characteristics of the ESRP are consistent with

an origin in enriched mantle with little crustal contamination; a sample from Kings Bowl (69-G) has the highest $^{143}\text{Nd}/^{144}\text{Nd}$ obtained so far for the ESRP tholeiites [10,23,24]. The Nd and Pb isotope characteristics of the COM basalts overlap with those of other ESRP basalts but have higher $^{87}\text{Sr}/^{86}\text{Sr}$ and trend to lower $^{143}\text{Nd}/^{144}\text{Nd}$ and $^{206}\text{Pb}/^{204}\text{Pb}$ ([6]; Leeman, pers. commun.). In detail, the isotopic characteristics of the COM lavas, including the $\delta^{18}\text{O}$ characteristics [7], vary sympathetically with gross compositional features, which is consistent with a progressively greater component of crustal derivatives in the more silicic lavas.

3. Analytical background

Isotopic compositions of Th and ratios of $^{238}\text{U}/^{232}\text{Th}$ were measured by thermal ionization mass spectrometry. The Th isotope analyses were performed at UC Los Angeles on a VG dual sector mass spectrometer equipped with a 30 cm electrostatic filter and an ion counting system. The abundance sensitivity over the course of the analyses was < 0.5 ppm at one mass unit separation. U and Th concentrations were measured at UC Santa Barbara and UCLA by standard iso-

tope dilution methods using a ^{230}Th - and ^{235}U -enriched spike. When making comparisons it should be noted that the U concentrations reported here are uniformly 3.0% lower than those determined in other laboratories on identical or similar samples ($n = 4$, Table 1) and that the Th/U ratios are $\sim 0.7\%$ lower than those obtained elsewhere ([25]; D. Pickett, pers. commun.) on splits of the same powders.

Several analyses were performed expressly to evaluate the accuracy and reproducibility of the Th isotope measurements. Repeat analyses ($n = 10$) of a Th standard solution provided by Z. Palacz (UC Santa Cruz) yielded a mean of $17.11 \pm 9(\times 10^4)$ (1 SD), in good agreement with other

thermal ionization measurements ($17.03 \pm 9(\times 10^4)$, Z. Palacz, pers. commun.). Duplicate analyses of Th standard solution 170900 yielded a mean of $17.19 \pm 1(\times 10^4)$, within error of the analyses performed at VG Isotech ($17.10 \pm 20(\times 10^4)$) and of the alpha counting value ($17.05(\times 10^4)$) [26]. Two international rock standards analyzed for their ^{230}Th and ^{238}U characteristics represent rocks sufficiently old (> 1 Ma) for secular equilibrium to obtain. As Table 1 shows, the $(^{230}\text{Th})/(^{238}\text{U})$ ratios are within 1.5% of secular equilibrium, even for the extremely high $^{232}\text{Th}/^{230}\text{Th}$ of JB-1 ($> 30 \times 10^4$). Similarly, a 0.39 Ma rhyolite from the Yellowstone Plateau can reasonably be assumed to be within 2% of

Table 1
U-Th isotope analyses of rock standards, Great Rift lavas and a Yellowstone rhyolite

Flow unit	Age ¹ (ka)	SiO ₂	U ² (ppm)	Th ² (ppm)	$^{232}\text{Th}/^{238}\text{U}$	$^{232}\text{Th}^3$ ^{230}Th	$(^{238}\text{U})^4$ (^{232}Th)	$(^{230}\text{Th})^4$ (^{232}Th)	$(^{230}\text{Th})^4$ (^{238}U)
<i>x 10⁻⁴</i>									
INTERNATIONAL ROCK STANDARDS									
JB-1			1.609	8.901	5.573	$33.50 \pm 15^*$ 33.15 ± 18 $33.36 \pm 22^*$ 34.14 ± 25	0.5484	0.555 0.561 0.557 0.544	1.012 1.022 1.016 0.993
AGV-1			1.869	6.115	3.295	20.11 ± 13 20.01 ± 12	0.9276	0.924 0.914	0.996 1.001
GREAT RIFT									
COM9106 ⁴ Wapi		45.5	0.382	1.174	3.097	17.85 ± 7	0.9869	1.041	1.055
COM9107 ⁴ Kings Bowl		45.9	0.316	0.944	3.009	16.78 ± 12	1.0158	1.108	1.090
Craters of the Moon									
69-28 fissure lava	>10	45.1	0.927	2.919	3.170	18.98 ± 16	0.9643	0.979	1.015
69-22 Lava Creek	13	44.4	<i>1.26</i>	<i>3.79</i>	<i>3.03</i>	18.30 ± 15	0.9943	1.016	1.021
70-42 Lava Creek	13	44.3	1.218	3.718	3.074	18.47 ± 18		1.006	1.012
SBR-5 Big Craters	6	51.5	1.825	6.089	3.360	19.75 ± 19	0.9096	0.941	1.035
69-17 SE margin	4	52.1	2.050	6.861	3.371	19.97 ± 10 19.92 ± 8	0.9066	0.931 0.933	1.026 1.029
69-35 ejecta block		56.9	<i>2.65</i>	<i>9.20</i>	<i>3.50</i>	21.45 ± 7	0.8491	0.866	1.020
69-20 Devils Orchard	2	62.1	3.098	11.072	3.600			0.872	1.034
V31 Devils Orchard	2	62.6	<i>3.25</i> <i>3.161</i>	<i>11.80</i> 11.375	<i>3.66</i> 3.625	21.62 ± 14 21.31 ± 8	0.8432	0.860	1.019
V27 Highway	2	63.5	3.252	12.774	3.957	21.29 ± 5	0.7724	0.873	1.130
YELLOWSTONE PLATEAU									
YP-53-121 Cougar Creek			<i>6.000</i>	<i>35.000</i>	<i>5.876</i>	36.17 ± 22	0.5131	0.514	1.001
6YC-138 Cougar Point	390	76.8	5.812	34.371	5.957	36.10 ± 23 $35.87 \pm 31^*$		0.515 0.518	1.003 1.010

¹ Ages from [9,27]. ² Italicized data from [24,26] (see text for details). ³ Errors are 2σ of in-run precision; asterisk indicates baseline measured at 229.5 only. ⁴ Calculated using the following decay constants: $\lambda_{232} = 4.9475 \times 10^{-11} \text{ y}^{-1}$; $\lambda_{230} = 9.1952 \times 10^{-6} \text{ y}^{-1}$; $\lambda_{238} = 1.55125 \times 10^{-10} \text{ y}^{-1}$. ⁵ Isotopic compositions for COM9106 and COM9107 measured at UC Los Angeles are, respectively, as follows: $^{87}\text{Sr}/^{86}\text{Sr} = 0.706748 \pm 8$ and 0.705981 ± 8 ; $^{143}\text{Nd}/^{144}\text{Nd} = 0.512453 \pm 9$ and 0.512538 ± 9 .

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secular equilibrium and yields a $(^{230}\text{Th})/(^{238}\text{U})$ of 1.005 ± 0.005 (Table 1). Replicate analyses of this sample and JB-1 suggest that baseline measurements on the low mass side alone rather than on both sides of ^{230}Th had no systematic effect on $^{232}\text{Th}/^{230}\text{Th}$. Duplicate Th isotope analyses of COM lavas yielded results within 1.5% of each another. Collectively, these data indicate reproducibility and accuracy of $^{238}\text{U}/^{232}\text{Th}$ - $^{230}\text{Th}/^{232}\text{Th}$ determinations to better than 1.5%, but the $^{238}\text{U}/^{232}\text{Th}$ ratios reported here may overestimate the true value by $\sim 1\%$.

4. Results

The results for the Great Rift lavas and a rhyolite from the Yellowstone Plateau are plotted on a U-Th isochron diagram in Fig. 2. Ratios of the activities of the nuclides are denoted by parentheses (e.g., $(^{230}\text{Th})/(^{238}\text{U})$) and are calculated from atomic ratios using the decay constants summarized in Table 1. The COM samples analyzed span most of the range in SiO_2 observed in the volcanic field (44–64%, Table 1) and represent a variety of eruptive phases [6]. They are

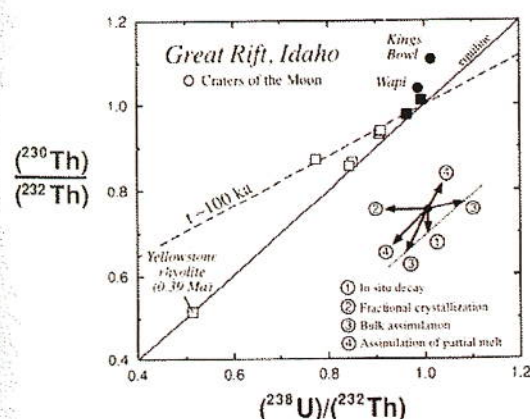


Fig. 2. U-Th isochron diagram for Great Rift lavas and a Yellowstone Plateau rhyolite. Basalts indicated by filled symbols. Also shown is an 100 ka reference isochron. Schematic diagram illustrates effects of in-situ decay, fractional crystallization and crustal assimilation on the COM lavas (these are not intended to be exhaustive and only include possibilities to left of the equiline).

characterized by greater than three-fold increases in U and Th concentrations (Table 1) and by sympathetic decreases in $(^{238}\text{U})/(^{232}\text{Th})$ and $(^{230}\text{Th})/(^{232}\text{Th})$ with increasing differentiation (Fig. 2). In general, the lavas are enriched in (^{230}Th) with respect to (^{238}U) . The mafic lavas are nearly within analytical uncertainty of secular equilibrium ($(^{230}\text{Th})/(^{238}\text{U}) \sim 1.016$) while the most silicic lava is enriched in (^{230}Th) relative to (^{238}U) by $\sim 13\%$. $(^{230}\text{Th})/(^{238}\text{U})$ ratios of lavas intermediate in composition to these extremes are bracketed by these values but do not define a single array. Because most of the lavas lie within a few percent of the equiline, these observations are not significantly affected by the effects of in-situ decay since eruption: the $^{230}\text{Th}/^{232}\text{Th}$ ratios could only have differed from those measured by $< 1\%$.

Basalts from Wapi and Kings Bowl have U/Th ratios similar to those of the COM basalts but are more enriched in (^{230}Th) with respect to (^{238}U) . In contrast, the U/Th ratio of the Yellowstone Plateau rhyolite is significantly lower than that of the COM lavas and the $(^{230}\text{Th})/(^{232}\text{Th})$ ratio is also very low (0.52), as would be expected given the relative antiquity of this rhyolite. Low U/Th ratios are characteristic of rhyolites of the Yellowstone Plateau (data of [23,27]); collectively this suggests that the decrease in U/Th in the COM lavas may be linked in some fashion to the production of silicic magmas.

5. Crustal processes: Magmatic differentiation of the Great Rift lavas

Differentiation of the Great Rift lavas is characterized by dramatic increases in Th and U, and by a pronounced and generally coupled decrease in U/Th and $(^{230}\text{Th})/(^{232}\text{Th})$. Unlike changes observed in the other radiogenic isotope systems, the decrease in $(^{230}\text{Th})/(^{232}\text{Th})$ with increasing differentiation of the lavas does not a priori require input of crustal material with Th isotope signatures different from those of the basalts. Timescales of magmatic processes are comparable to the half-life of ^{230}Th such that in-situ decay of ^{230}Th will occur in response to changes in

U/Th during differentiation. A reference Th isochron in Fig. 2 shows that if the Th isotope systematics of the COM lavas are dominated by crystal fractionation, the lower $(^{230}\text{Th})/(^{232}\text{Th})$ of intermediate to silicic lavas compared to associated mafic lavas require ≥ 100 ka of in-situ decay since differentiation. Given other evidence for isotopic heterogeneity in the COM lavas, the Th isotope systematics are more likely the sum of vectors representing fractional crystallization and assimilation of a crustal melt. Bulk assimilation will displace the paired $(^{230}\text{Th})/(^{232}\text{Th})$ - $(^{238}\text{U})/(^{232}\text{Th})$ systematics of affected lavas along or towards the equiline, provided the U/Th systematics of the assimilant have not been modified in the very recent past. Because the $(^{230}\text{Th})/(^{232}\text{Th})$ of the assimilant could plausibly be lower or higher than that of the COM lavas, assimilation may have occurred over shorter or longer times than that predicted by closed system crystallization. In this section, the relative roles of these processes and their consequences for temporal and chemical evolution of the Great Rift are evaluated.

5.1. Role of assimilation and accessory phase fractionation in generation of the Craters of the Moon lavas

Paired isotopic compositions of the lavas to the left of the equiline on the Th isochron diagram (Fig. 2) indicate equilibration with a phase(s) having a U/Th greater than that of the magma. Because U and Th are strongly partitioned into melts in the presence of major mineral phases, significant changes in U/Th ratios require either large degrees of closed system differentiation or crystallization of accessory phases that preferentially incorporate U with respect to Th. Progressive removal of observed phenocryst assemblages—including apatite, magnetite and zircon—from the COM lavas [6] can explain covariations in their major and trace element compositions. Apatite segregation explains plummeting P_2O_5 contents with increasing SiO_2 in all but the most mafic COM lava, and preferential enrichments in LREE and HREE with respect to the MREE during differentiation [6,25]. Maximum P_2O_5 con-

tents correspond to the first appearance of modal apatite in the COM lavas. In an analogous fashion, peak Zr contents correspond to the appearance of zircon in the lavas and to changes in the ratios of LREE to HREE. Magnetite segregation is also required, in the proportion of 2:1 to apatite. These three phases concentrate U with respect to Th and could be responsible for the decrease in U/Th that accompanies differentiation.

Pronounced increases in Th and U concentrations in the COM lavas are mirrored by comparable increases in abundances of other LILE [6] and require $> 70\%$ closed system fractionation. The relative incompatibility of U and Th in the fractionating assemblage is however at variance with the large amount of apatite fractionation required by the decrease in P_2O_5 . The maximum D_{Th} for apatite permitted by the change in Th concentration (< 0.8) is less than published partition coefficients ([28,29] and references therein), even when the compatibility of this element in magnetite is disregarded.

Addition of crustal material during differentiation could decrease P_2O_5 as well as account for compositionally dependent Sr, Nd, Pb and O isotopic variations in the COM lavas. Crustal assimilation may also decrease U/Th and $(^{230}\text{Th})/(^{232}\text{Th})$, with consequences for magmatic residence times. Fig. 3 summarizes the paired Th isotopic compositions and concentrations of possible upper and lower crustal assimilants. As representatives of the upper crust beneath the Great Rift and possible crustal derivatives, granitic rocks from the southern Idaho Batholith, rhyolites of the ESRP, and late Archean igneous rocks from the Beartooth Mountains have U/Th ratios lower than those of the Great Rift basalts. Some of the granulite xenoliths recovered from ESRP lavas have equivalently low U/Th ratios. In Fig. 3, the paired Th- $(^{230}\text{Th})/(^{232}\text{Th})$ characteristics of these assimilants are contoured for ratios of bulk assimilation to fractional crystallization required to explain those same characteristics in COM lavas. Most assimilants lie to the left of the $r = 0.25$ contour, indicating that assimilation of limited quantities of these contaminants during differentiation is capable of producing the present-day

Th isotope consistent with the observed isotope variations. The contribution of lower crustal assimilants is precluded by the system fractionation composition.

The likelihood of assimilation accounts for the codependent variations in the trace element patterns on the COM lavas. The magmas are saturated in P_2O_5 at $< 1100^\circ\text{C}$ and saturation of apatite as a component will enhance the precipitation of apatite and enhance the U/Th ratio.

$(^{230}\text{Th})/(^{232}\text{Th})$ 0.000000
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Fig. 3. Th isotope systematics of possible crustal assimilants. The diagram shows the paired Th- $(^{230}\text{Th})/(^{232}\text{Th})$ characteristics of these assimilants are contoured for ratios of bulk assimilation to fractional crystallization required to explain those same characteristics in COM lavas. Most assimilants lie to the left of the $r = 0.25$ contour, indicating that assimilation of limited quantities of these contaminants during differentiation is capable of producing the present-day

Th isotope compositions of the lavas. This is consistent with a previous interpretation of Sr isotope variations [8]. The considerably greater contribution from assimilation required by the lower concentrations of Th and higher $(^{230}\text{Th})/(^{232}\text{Th})$ of some of the granulite xenoliths is probably precluded by the success of closed system fractionation models in accounting for compositional variation in the COM lavas [6,25].

The likelihood that accessory phase fractionation accompanies assimilation is demonstrated by the codependence of apatite saturation temperatures on the P_2O_5 and SiO_2 contents of the magmas (Fig. 4). Mixtures of a COM basalt and a representative granodiorite of the Idaho Batholith are saturated with apatite at temperatures of $< 1100^\circ\text{C}$ over most of the mixing interval. Once saturation occurs, assimilation of a crustal component with SiO_2 contents greater than or equal to those of the COM lavas will further apatite precipitation because of the strong dependence of apatite saturation on SiO_2 . Fractionation also enhances apatite precipitation by increasing the

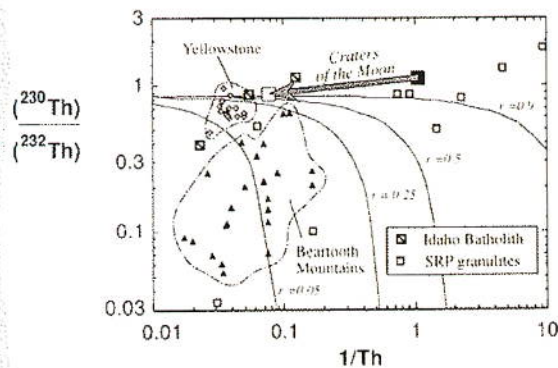


Fig. 3. Th isotopic and concentration characteristics of possible crustal assimilants for COM lavas, contoured for the ratio of assimilation to fractionation (r) required to satisfy the Th isotope systematics of the lavas. Trend from basalt to dacite shown for reference (indicated by arrow, symbols as in Fig. 2). $(^{230}\text{Th})/(^{232}\text{Th})$ of the assimilants is calculated from U/Th ratios assuming secular equilibrium. Distribution coefficient for Th calculated assuming fractionation of apatite in amounts required to explain decreasing P_2O_5 contents of magmas beyond the effect of assimilation and magnetite fractionation in the proportion to apatite of 2:1 [6]. Assimilant data are by isotope dilution [3,27,62].

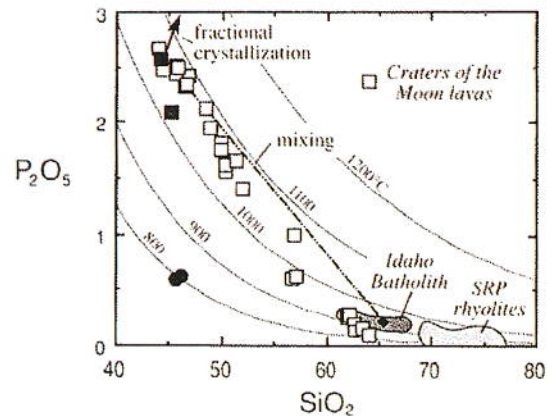


Fig. 4. Plot of P_2O_5 versus SiO_2 showing isotherms of apatite saturation from [63]. Symbols as in Fig. 2, except that filled symbols are only those basalts studied here. Fields for Idaho Batholith and Snake River Plain rhyolites are from [64] and Leeman (pers. commun.). Mixing curve of Craters of the Moon basalt with granodiorite of the Idaho Batholith and trend of fractional crystallization shown for reference.

SiO_2 content of the residual liquid [6]. Only assimilation of components lying to the left of the COM compositional array could putatively produce magmas that escape apatite fractionation, but fractional crystallization of such mixtures cannot account for the combined major and trace element characteristics of the COM lavas. In detail, assuming that assimilants lie on the equiline, removal of apatite in abundances required by progressive depletion in the P_2O_5 contents of the lavas produces good fits to deviation of the lavas from the equiline. For a Th partition coefficient of 1.6 for apatite and magnetite combined, that required for U (1.9–2.4) is well within the reported range ([28,29] and references therein). Similarly, zircon precipitation probably accounts for the greater U/Th fractionation exhibited by sample V27.

5.2. Thermal evolution of Great Rift magmas

Relatively recent fractionation of U from Th by accessory phase segregation from the COM lavas supports application of apatite and zircon geothermometers. Temperatures calculated for apatite saturation decrease steadily from 1090 to

< 900°C with increasing fractionation (Fig. 4) and excellent agreement with a zircon thermometer [30] occurs where Zr contents peak in the lavas ($T \sim 970^\circ\text{C}$). Best estimates of liquidus temperatures delimited by chemical exchange equilibria [25] are well correlated to these saturation temperatures and, since they rely on different kinetically controlled phenomena, the concordance of temperatures provides convincing evidence of their validity. Moreover, because the lavas are virtually aphanitic, temperatures obtained by these methods are probably within 25°C of the true temperatures.

Timescales of magmatic events cannot be easily separated from the effect of assimilation (Fig. 2). As indicated above, assimilation successfully accounts for the observed decrease in Th isotope compositions of the lavas without significant in-situ decay. Lavas with $\text{SiO}_2 > 50\text{ wt\%}$ do not appear until 8 ka after the earliest dated lavas of the COM and compositions become increasingly differentiated after that time [9]. Hence, assuming that assimilation rather than long magmatic

residence times caused $(^{230}\text{Th})/(^{232}\text{Th})$ to decrease, and that the more differentiated magmas developed after the onset of COM magmatism (15 ka), average cooling rates for their reservoir are $> 10^\circ\text{C/ka}$. Considered together with the suitability of upper crustal assimilants as end members of the isotopic trend defined by the COM lavas, evolution in upper crustal magma chambers seems likely.

Temperatures obtained for the COM basalts and the absence of clinopyroxene in microphe-nocryst assemblages [6] are consistent with experimentally determined near-liquidus phase equilibria at shallow depths [31]. Similar Ca/Al ratios among the Great Rift basalts, despite apparent plagioclase fractionation, probably require buffering by clinopyroxene, and therefore differentiation at depth. Similar Th/HFSE [8] and U/Th ratios in the Great Rift basalts further suggest that they may share a common trajectory in Th isotope evolution, despite differences in $^{87}\text{Sr}/^{86}\text{Sr}$, P_2O_5 and LILE. Limited changes in U/Th ($< 2\%$) are expected of even relatively

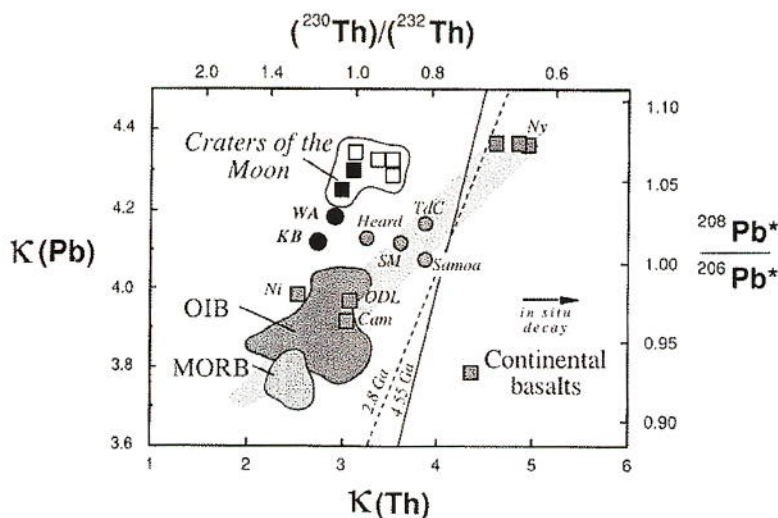


Fig. 5. $^{208}\text{Pb}^*/^{206}\text{Pb}^* - \kappa(\text{Th})$ diagram comparing Great Rift lavas to data fields for MORB and OIB [65]. Pb isotope data for Great Rift lavas from [25]. Shaded band is the mantle array as delimited in [29]. $^{208}\text{Pb}^*/^{206}\text{Pb}^*$ is radiogenic Pb relative to primordial Pb ($[(^{208}\text{Pb}/^{204}\text{Pb} - 29.476)/(^{206}\text{Pb}/^{204}\text{Pb} - 9.307)]$) (cf. [32]); $\kappa(\text{Th})$ is $^{232}\text{Th}/^{238}\text{U}$ in equilibrium with the $^{230}\text{Th}/^{232}\text{Th}$ of basalts. WA = Wapi and KB = Kings Bowl. Enriched mantle basalts are shown with shaded circles, where abbreviations are for Sao Miguel (SM) (data of [66]) and Tristan de Cunha (TdC). Abbreviations for continental basalts: Ni = Niyragongo; Cam = Mt. Cameroon; ODL = Ol Doinyo Lengai; Ny = Nyamuragira. 2.8 Ga $^{232}\text{Th}/^{238}\text{U}$ 'isochron' assumes $^{238}\text{U}/^{204}\text{Pb}$ that gives present-day $^{206}\text{Pb}/^{204}\text{Pb}$ like that of mafic ESRP lavas and shows that Great Rift lavas require at least three stages of Pb evolution.

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6. Mantle processes: Enriched mantle signatures and their origin

Radiogenic isotopes track secular changes in relative trace element abundances which can in turn be related to the chemical dynamics of

magma sources in the mantle and deep crust. Both Th and Pb isotope systematics reveal changes in $^{232}\text{Th}/^{238}\text{U}$ (κ) (Fig. 5), but the timescales integrated by the systems are quite different. At current levels of detection, Th isotope ratios reveal fractionation of U from Th within the past ~ 350 ka, offering profound insight into the processes of magma production, extraction, transport and storage. In contrast, $^{208}\text{Pb}/^{206}\text{Pb}$ ratios reflect time-integrated evolution of $^{232}\text{Th}/^{238}\text{U}$ over the past 4.55 Ga. In spite of potential complexity in the Pb isotope systematics arising from multiple stages of Th/U fractionation, time-integrated $^{232}\text{Th}/^{238}\text{U}$ ratios derived from assuming a single-stage ^{208}Pb - ^{206}Pb evolution ($\kappa(\text{Pb})$) and from Th isotope ratios ($\kappa(\text{Th})$) in many basalts define a relatively narrow band in isotopic space (Fig. 5). Paired $\kappa(\text{Th})$ - $\kappa(\text{Pb})$ signatures largely represent reservoirs with time-integrated Th/U ratios less than that of primordial Earth (~ 3.9 , [32]). The relatively shallow

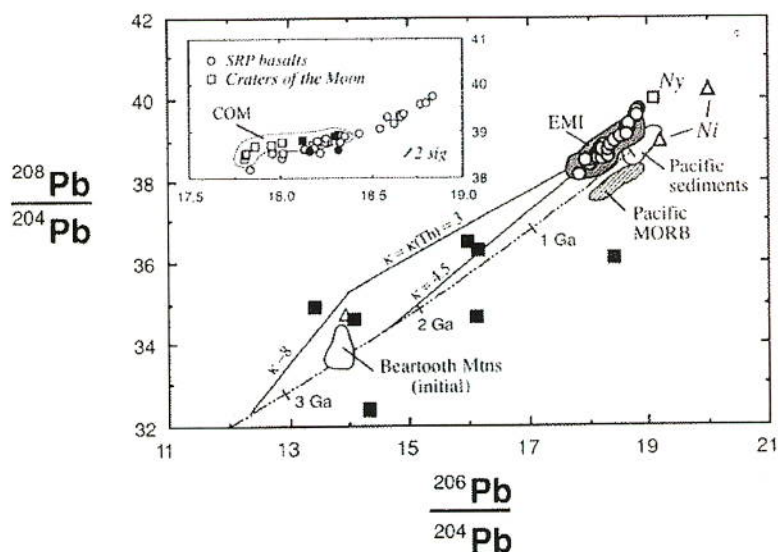


Fig. 6. $^{208}\text{Pb}/^{204}\text{Pb}$ - $^{206}\text{Pb}/^{204}\text{Pb}$ diagram comparing Pb isotope characteristics of Snake River Plain basalts (open circles, data of [24] and Leeman, pers. commun.) to reference Pb isotope reservoirs and to limiting Pb isotope evolutionary paths. Dot-dash line is orogenic Pb evolution curve. $\kappa = 4.5$ is best fit to Snake River Plain basalts overall. Also shown is the trend of $\kappa = \kappa(\text{Th}) = 3$ through the Great Rift basalts and a possible Archean Pb evolution curve. Field of Beartooth granitoids [62] does not include disparate data point indicated by adjacent open triangle. Initial ratios shown for granulite xenoliths (filled squares) calculated from data of [3]. Field of EMI includes Tristan de Cunha, Kerguelen, Gough and Heard Islands ([67,68] and references therein). Other data from [69] and in references summarized for Fig. 5. Inset shows Pb isotope characteristics of Snake River Plain basalts (circles) including those from Craters of the Moon (squares); filled symbols indicate basalts analyzed in this study.

slope defined by 'isochrons' through primordial Earth and most basalts shows that depleted Th/U ratios cannot be long-standing features of the convecting upper mantle. Rather, the Pb isotope composition of the upper mantle is buffered by that of a more enriched source [33] or low $\kappa(\text{Th})$ reflects the preferential flux of U into the upper mantle [34].

Single-stage $\kappa(\text{Pb})$ values for the Great Rift basalts are high (~ 4.1 , Fig. 5). Well-correlated Pb isotope systematics of these and other Snake River Plain basalts (Fig. 6) yield a similarly high apparent $^{232}\text{Th}/^{238}\text{U}$ ratio of ~ 4.5 for the basalt source for the past 2.5 Ga [22]. In contrast, Th isotope ratios in Great Rift basalts are similar to those of many oceanic basalts and correspond to $\kappa(\text{Th})$ values ≤ 3 (Fig. 5), which is more than 30% lower than that delimited by the Pb isotope characteristics. This disparity between $\kappa(\text{Pb})$ and $\kappa(\text{Th})$ cannot reflect U enrichment associated with radioactive decay since melt formation—the Great Rift basalts are depleted in U with respect to the equiline. Rather, differences between Great Rift and most oceanic basalts require divergent Th/U evolution in their sources. Specifically, the high $\kappa(\text{Pb})$ of the ESRP lavas requires an extended period of Pb isotope evolution in a domain with Th/U higher than most sources in the mantle underlying the oceans, while the low $\kappa(\text{Th})$ does not. The complex tectonic evolution of southern Idaho suggests that several factors may have affected the origin of the Great Rift basalts, including thermochemical influence of a mantle plume, the presence of ancient mantle lithosphere, and the proximity to an active continental margin since the Mesozoic.

The chemical characteristics of the ESRP basalts have been little affected by crustal contamination, as detailed elsewhere [8,10]. Nevertheless, it is important to consider whether contamination could account for decoupling of the Th-Pb isotopic characteristics in the Great Rift basalts with respect to oceanic basalts. As recorded by the COM lavas, crustal assimilation increases $\kappa(\text{Th})$ but not $\kappa(\text{Pb})$ (Fig. 2) and therefore acts to decrease the $\kappa(\text{Th})$ - $\kappa(\text{Pb})$ discrepancy. Producing the Pb isotope signatures of the Great Rift and other ESRP basalts from those of

most oceanic basalts by contamination would require a coherent and apparently fortuitous shift in the entire Pb-Pb array towards higher $^{208}\text{Pb}/^{204}\text{Pb}$ and lower $^{206}\text{Pb}/^{204}\text{Pb}$ (Fig. 6); 75% of the ESRP basalts have $\kappa(\text{Pb}) \geq 4.2$ while the lowest $\kappa(\text{Pb})$ is 4.0. Decreasing $\kappa(\text{Th})$ instead by assimilation requires a component with low Th/U and, as can be surmised from Fig. 3, a high proportion of assimilation to fractionation for a significant decrease in $\kappa(\text{Th})$; this cannot be reconciled with the relatively undifferentiated nature of the Wapi and Kings Bowl samples. Consequently, the discordant $\kappa(\text{Th})$ - $\kappa(\text{Pb})$ of the Great Rift basalts must be derived dominantly from their mantle source(s).

6.1. Dynamic decoupling of Th and Pb

Before addressing possible models for generating a reservoir with Th and Pb isotope characteristics like those of the Great Rift basalts, it is useful to consider how Th isotope systematics may be affected by melt generation and percolation. When the duration of melting and melt extraction is long with respect to the half-life of ^{230}Th , significant differences between the Th isotope characteristics of the melt and the initial source characteristics can ensue. Differential decreases in $\kappa(\text{Th})$ by this mechanism is not expected given the similarity of magma production rates in the Great Rift to those of many oceanic islands. In addition, for the degree of melting responsible for ESRP olivine tholeiites (e.g., $> 5\%$; [35]), the Th/U of the melt is likely to be elevated by $< 5\%$ relative to that of their source [36]. Thus, as an additional estimate of κ in their source, the Th/U ratios in the Great Rift basalts are still $\sim 30\%$ lower than predicted by Pb isotope systematics.

The Th and Pb isotope systematics of the Great Rift basalts could be related to interplay between isotopically distinct sources associated with impingement of a plume on the lithosphere of southern Idaho. Simple mixing between depleted and enriched mantle, as for example by plume entrainment of asthenosphere or lithosphere, requires a high contrast in Th/Pb ratios between end members (> 5) in order to decouple

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Th from Pb. Time-integrated differences in Th/Pb of $< 25\%$ are delimited by the range in present-day $^{208}\text{Pb}/^{204}\text{Pb}$ signatures of possible mantle reservoirs. Bulk partition coefficients for Th and Pb (≤ 0.001) and relative differences between them ($D_{\text{Pb}}/D_{\text{Th}} < 10$) are small ([37] and references therein). Hence, decoupling of $\kappa(\text{Th})$ - $\kappa(\text{Pb})$ simply by melt infiltration is unlikely since migration of extremely small melt fractions ($F \leq D_{\text{Th}} < 0.0003$) would be required. Melt percolation through mantle lithosphere subjacent to southern Idaho may however enhance small differences in partition coefficients. A salient feature of this process is that basalts from depleted sublithospheric sources could acquire isotopic and trace element signatures of enriched mantle lithosphere without melting it directly. Decoupling between two elements becomes significant as the porosity (ϕ) of the matrix approaches the distribution coefficient of the more compatible trace element; in the case of Th-Pb, this is likely to occur as $\phi \rightarrow 0.001$. Disequilibrium between (^{230}Th) and (^{238}U) requires magma to reach the surface appreciably faster than recovery to secular equilibrium (i.e., $< \sim 350$ ka). Ascent rates through mantle of $\phi < 0.005$ are < 25 km/Ma [35]. Hence (^{230}Th)-(^{238}U) disequilibrium limits melt percolation through a zone of such low porosity to thicknesses of < 8 km and only melt extracted from the upper kilometer of this zone should exhibit Th-Pb decoupling. While this scenario may apply to the Great Rift basalts it does not seem generally applicable to the ESRP basalts given their ubiquitously high $\kappa(\text{Pb})$ and melt thicknesses. For melt percolation to retain high $\kappa(\text{Pb})$, the effective distribution coefficient of Pb in the mantle lithosphere must be enhanced by phases such as amphibole, apatite, carbonate and sulphides [38], all of which are likely to decompose in the presence of percolating melts.

6.2. Mantle enrichment by plume-related processes

The ESRP basalts (Fig. 6, [10,23]) share remarkable isotopic and chemical affinities with oceanic basalts derived from enriched mantle (EM) sources [39,40], suggesting a common origin. Trace element ratios in the ESRP tholeiites

that deviate slightly from those of transitional to alkaline basalts from EM1 ocean islands in particular can be ascribed to differences in the degree of partial melting. Trace element ratios involving Ba are the exception, but Ba enrichment in the ESRP basalts simply extends the range observed on EM1 islands and may be symptomatic of processes responsible for the development of enriched mantle [41].

Other basalts derived from EM sources exhibit variable degrees of Th-Pb discordancy, as indicated in Fig. 5. EM may be generated in ancient subcontinental mantle lithosphere. For ocean island basalts, the enriched lithosphere must be incorporated in their source through delamination [42] or entrainment into the suboceanic mantle during continental breakup [43]. Lithospheric enrichment may have occurred by metasomatic processes [44] in the mantle wedge at convergent plate margins [45]. Alternatively, EM sources may be produced by (re)assimilation of crustal material subducted into the deep mantle [45,46]. Wholesale recycling of oceanic sediments should not decrease Th/U ratios preferentially: on average, subducted sediments will tend to have high rather than low Th/U ratios, and dehydration reactions associated with devolatilization will probably only enhance this [47]. U enrichment in some volcanic arc lavas [47,48] and in CO_2 -enriched continental basalts of alkaline but not tholeiitic affinity [49] probably reflect invasion of mantle lithosphere by U-bearing fluids. Relatively recent U enrichment could produce the observed decoupling of $\kappa(\text{Th})$ - $\kappa(\text{Pb})$ in the Great Rift basalts but is not diagnostic of whether the EM source lies in mantle lithosphere or is characteristic of a plume. Alternatively, reservoirs with high $\kappa(\text{Pb})$ may be long-lived features of mantle isolated from convection [50], such that the decoupling between Th and Pb isotopes reflects an ancient fractionation event.

Unradiogenic He isotope signatures in the ESRP basalts ($> 16 R_a$, [5]) and in the volcanic gases at Yellowstone ($> 15 R_a$, [51]) probably require tapping of largely undegassed deep mantle by a plume. In this respect, the ESRP basalts are quite distinct from many EM ocean island basalts studied to date which have radiogenic He

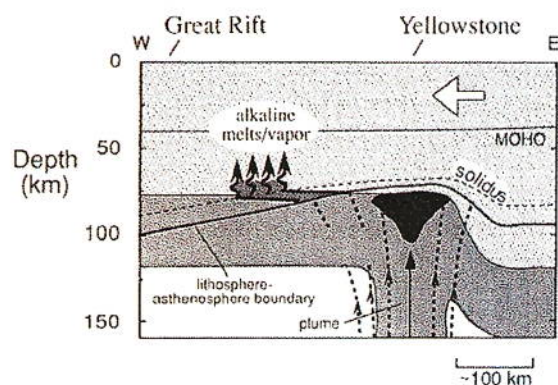


Fig. 7. Cartoon illustrating hybridization and metasomatism of mantle lithosphere in the wake of the Yellowstone plume. Stippled region is ancient lithosphere; shaded region is composed of plume mantle; black triangular region represents zone of major melt production in the plume. Dashed vertical lines represent small volume melts and fluids. These penetrate and react with mantle lithosphere both upstream (not shown) and downstream of the plume. Horizontal scale is for reference only and depends on a variety of factors, including diameter of the plume and plate velocity. See [55] for further details.

isotope signatures ($< 6.3 R_a$, [52]), presumably because of ^4He ingrowth in the latter. Metasomatized harzburgite xenoliths from Western Samoa have high $^3\text{He}/^4\text{He}$ and enriched Sr, Nd and Pb isotope characteristics. Processes responsible for these characteristics may be analogs for those operating in the mantle under the ESRP. The enriched chemical characteristics of these xenoliths are related to recent hotspot-related metasomatism of the lithosphere by carbonatitic fluids derived from volatile-rich plume melts and recycled sediments [53,54]. CO_2 -rich fluids and highly alkaline magmas probably invade the lithosphere in the marginal regions of plume impingement [55] and may influence lavas erupted downstream of the plume (Fig. 7). In keeping with this, high $\text{TiO}_2/\text{K}_2\text{O}$ and low $\text{TiO}_2/\text{P}_2\text{O}_5$ in Snake River Plain olivine tholeiites could reflect metasomatism of their sources by alkaline magmas and/or fluids [56,57].

The carbonate-bearing melilitites from Nyiragongo (Fig. 5) are similar to basalts of the Great Rift in their apparent Th-Pb discordancy, with U enrichment attributable to carbonate

metasomatism of their source [49]. In addition to lowering $\kappa(\text{Th})$, He transport in carbonate-dominated fluids exsolved from volatile-bearing plume melts may account for the relatively more primordial rare gas signatures of the ESRP lavas. Plume-related fluids could have percolated into pre-existing mantle lithosphere or into plume material that has been incorporated in the thickening lithospheric boundary layer downstream of the hotspot (Fig. 7). This potentially hybrid mantle lithosphere, at near-solidus conditions as a result of plume impingement, may undergo melting during modest amounts of crustal extension (evident as rifts transverse to the ESRP). Distinguishing between the role of an enriched mantle plume versus old lithosphere may thus be obscured. The dramatic shift in isotopic ratios to the west of the Mesozoic $^{87}\text{Sr}/^{86}\text{Sr} = 0.706$ line [58,59] in southeastern Oregon could suggest that the enriched character of these lavas is intimately associated with the lithosphere, but the transition also coincides with the western limit of the hotspot track. Chemical dissimilarity between the Columbia River basalt province and the ESRP olivine tholeiites could be taken to preclude wholesale derivation of the ESRP basalts from a plume if the more voluminous Columbia River basalts are representative of the Yellowstone plume ([20] and references therein). Alternatively this chemical transition could reflect diminished entrainment of upper mantle following collapse of the plume head. In any case, high $^3\text{He}/^4\text{He}$ in the ESRP basalts can be reconciled with melting of old mantle lithosphere only if rare gases have preferentially faster percolation rates compared to other radiogenic isotope tracers, such that only He in the lithospheric source is dominantly plume-derived [13].

6.3. U enrichment of mantle lithosphere by subduction-related processes

The alternative explanation for the paired $\kappa(\text{Pb})$ - $\kappa(\text{Th})$ characteristics of the Great Rift basalts is that mantle lithosphere in southern Idaho has been affected by subduction-related processes. Enrichment of mantle lithosphere by Mesozoic to Cenozoic subduction-related fluids is

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frequently invoked to explain the chemical signatures of basalts in the western United States, most notably enrichments in Ba and other LILE, and depletions in Nb and other HFSE [56,60]. Although the chemistry and behavior of subduction-related fluids are poorly understood, the apparent magnitude of U enrichment in the Great Rift basalts is unprecedented in continental arcs [47,48]. Moreover, U enrichment seems to be a near-trench feature of volcanic arcs, while subduction-related fluids away from the volcanic front may have high rather than low Th/U ratios [61]. In addition, the HFSE depletions expected for subduction-related basalts are not observed in the ESRP basalts [10]. Subduction-related modification of the mantle is not likely to account for the $\kappa(\text{Pb})$ ratios of the ESRP basalts either (Fig. 6). Not only is the subducting slab inappropriate as an end member for generation of the high $^{208}\text{Pb}/^{206}\text{Pb}$, but even the least radiogenic ESRP basalt has high $^{208}\text{Pb}/^{206}\text{Pb}$, indicating high time-integrated Th/U.

As already summarized, the Pb isotope characteristics of ESRP basalts yield a coherent model wherein high κ mantle is isolated from convection at the time of crust formation [22]. In spite of this, high $\kappa(\text{Pb})$ could alternatively reflect a late Archean to early Proterozoic interval of Pb evolution in a reservoir with high Th/U (Fig. 6). This can be visualized in Fig. 5, where a 2.8 Ga isochron fit to the Great Rift basalts would intersect the single-stage geochron at very high $\kappa(\text{Pb})$. According to this interpretation the Pb isotope array exhibited by the ESRP basalts does not accurately reflect the Th/U of the mantle, but rather the initial Pb isotope composition of the mantle lithosphere lies on the locus of $^{208}\text{Pb}/^{204}\text{Pb}$ – $^{206}\text{Pb}/^{204}\text{Pb}$ ratios related by $\kappa(\text{Th})$ of ~ 3 (Fig. 6). The observed slope of the Pb isotope array would thus require a relatively large variation in Th/U ($\sim 30\%$) and a sympathetic change in μ of comparable magnitude; this observation is not significantly affected by the choice of initial Pb isotope signature or range in plausible ages of the mantle lithosphere.

A salient feature of attributing low κ to mantle lithosphere beneath the ESRP is that a very high $^{208}\text{Pb}/^{206}\text{Pb}$ must have obtained in the Archean.

$\kappa(\text{Pb}) > 4.1$ is a widespread feature of mafic rocks of presumed lithospheric origin erupted since the late Mesozoic in the northwestern United States, but, except for the Saddle Mountain basalts of the Columbia River province [56], their Pb isotope signatures converge to $\kappa(\text{Pb}) < 3.9$ at $^{206}\text{Pb}/^{204}\text{Pb} < 16.5$. High initial $^{208}\text{Pb}/^{206}\text{Pb}$ ratios (Fig. 6) found in late Archean igneous rocks of the eastern Beartooth Mountains, < 300 km to the east of the ESRP, are significantly lower than predicted for the mantle source of the ESRP basalts. Two granulite xenoliths of probable Archean origin entrained in ESRP lavas [3] have initial Pb isotope characteristics close to a $\kappa = 3$ Pb evolution curve for the Great Rift, but their significance is suspect since the initial Pb isotope ratios of other xenoliths fall well below plausible mantle evolution curves (Fig. 6). Hence there is no convincing support for very high $^{208}\text{Pb}/^{206}\text{Pb}$ ratios in the Archean. A multistage enrichment model wherein mantle lithosphere subjacent to southern Idaho acquired $^{208}\text{Pb}/^{206}\text{Pb}$ ratios like those of the Beartooth granitoids during the Archean and was later enriched by Phanerozoic subduction still requires U enrichment ($> 20\%$) greater than that observed in continental arcs in order to explain the low $\kappa(\text{Th})$ of the Great Rift basalts solely by derivation from mantle lithosphere.

7. Conclusions

Basaltic to dacitic lavas of the Great Rift in the eastern Snake River Plain are characterized by Th isotopic heterogeneity which is sympathetic with variations in Sr, Nd and Pb. Simultaneous consideration of Th isotope and concentration data shows that ratios of assimilation to fractional crystallization of < 0.25 can account for the Th isotope signatures of evolved lavas from Craters of the Moon, and that their differentiation may have occurred relatively rapidly in upper crustal magma chambers. In contrast, Th isotopes in the Great Rift basalts may not be significantly affected by assimilation, and correlations with indices of differentiation are consistent with long residence times in deep-seated magma chambers.

The Th isotope signatures of the Great Rift basalts are those of depleted mantle yet other chemical characteristics reflect an enriched source similar to that of some oceanic islands. As a result the Great Rift basalts exhibit the most extreme case of disparity between κ indicated by time-integrated $^{208}\text{Pb}/^{204}\text{Pb}$ – $^{206}\text{Pb}/^{204}\text{Pb}$ and by $(^{230}\text{Th})/(^{232}\text{Th})$. Discrepancy between these two isotope systems does not reflect crustal assimilation, as other chemical similarities to oceanic island basalts demonstrate, and is probably too large to be the result of subduction-related modification of the mantle lithosphere. The paired $\kappa(\text{Th})$ – $\kappa(\text{Pb})$ characteristics of the Great Rift basalts probably arose through metasomatism of ancient and/or plume-source-enriched mantle by alkaline melts and CO_2 -rich fluids in the wake of the Yellowstone hotspot.

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Bill Leeman generously provided splits of powders from Craters of the Moon lavas that he has characterized compositionally and isotopically. Discussions with Bill during the course of this work led to significant improvements in my understanding of the origin and evolution of the Snake River Plain lavas. Initial results were obtained at VG Isotech with the able and congenial assistance of Zenon Palacz. Suggestions by two anonymous reviewers and particularly by Dave Graham considerably improved the focus of this paper. This work was begun under the aegis of a Faculty Career Development Award from UCLA and was supported by NSF EAR9118015. [CL]

References

- [1] M.A. Menzies, Cratonic, circumcratonic and oceanic mantle domains beneath the western United States, *J. Geophys. Res.* 94, 7899–7915, 1989.
- [2] W.P. Leeman, Development of the Snake River Plain–Yellowstone Plateau province, Idaho and Wyoming: An overview and petrologic model, in: *Cenozoic Geology of Idaho*, B. Bonnichsen and R.M. Breckenridge, eds., Idaho Bur. Mines. Geol. Bull. 26, 155–177, 1982.
- [3] W.P. Leeman, M.A. Menzies, D.J. Matty and G.F. Embree, Strontium, neodymium and lead isotopic compositions of deep crustal xenoliths from the Snake River Plain: evidence for Archean basement, *Earth Planet. Sci. Lett.* 75, 354–368, 1985.
- [4] M.R. Reid and W.P. Leeman, Enriched mantle source of Snake River Plain basalts: plume or lithosphere?, *EOS* 74, 602, 1993.
- [5] H. Craig, Yellowstone hotspot: a continental mantle plume, *EOS* 74, 602, 1993.
- [6] W.P. Leeman, C.J. Vitaliano and M. Prinz, Evolved lavas from the Snake River Plain: Craters of the Moon National Monument, Idaho, *Contrib. Mineral. Petrol.* 56, 35–60, 1976.
- [7] W.P. Leeman, Evolved and hybrid lavas from the Snake River Plain, Idaho, in: *Cenozoic Geology of Idaho*, B. Bonnichsen and R.M. Breckenridge, eds., Idaho Bur. Mines. Geol. Bull. 26, 193–202, 1982.
- [8] M.A. Menzies, W.P. Leeman and C.J. Hawkesworth, Geochemical and isotopic evidence for the origin of continental flood basalts with particular reference to the Snake River Plain, Idaho, *Philos. Trans. R. Soc. London A310*, 643–660, 1984.
- [9] M.A. Kuntz, D.E. Champion, E.C. Spiker and R.H. Lefebvre, Contrasting magma types and steady-state, volume-predictable, basaltic volcanism along the Great Rift, Idaho, *Geol. Soc. Am. Bull.* 97, 579–594, 1986.
- [10] C.C.L. Lum, W.P. Leeman, K.A. Foland, J.A. Kargel and J.G. Fitton, Isotopic variations in continental basaltic lavas as indicators of mantle heterogeneity: examples for the western U.S. cordillera, *J. Geophys. Res.* 94, 7871–7884, 1989.
- [11] R.L. Armstrong, W.P. Leeman and H.E. Malde, K-Ar dating, Quaternary and Neogene volcanic rocks of the Snake River Plain, Idaho, *Am. J. Sci.* 275, 225–251, 1975.
- [12] D.C. Gerlach, Eruption rates and isotopic systematics of ocean islands: Further evidence for small-scale heterogeneity in the upper mantle, *Tectonophysics* 172, 273–289, 1990.
- [13] W.P. Leeman, Origin and development of the Snake River Plain (SRP)—an overview, in: *Volcanism and Plutonism of Western North America 2*, T305, pp. 4–12, Am. Geophys. Union, Washington, D.C., 1989.
- [14] D.W. Rodgers, W.R. Hackett and H.T. Orc, Extension of the Yellowstone plateau, eastern Snake River Plain, and Owyhee plateau, *Geology* 18, 1138–1141, 1990.
- [15] M.A. Sparlin, L.W. Braile and R.B. Smith, Crustal structure of the eastern Snake River Plain determined from ray trace modeling of seismic refraction data, *J. Geophys. Res.* 87, 2619–2633, 1982.
- [16] L.W. Braile, R.B. Smith, J. Ansgore, M.R. Baker, M.A. Sparlin, C. Prodehl, M.M. Schilly, J.H. Healy, St. Mueller and K.H. Olsen, The Yellowstone–Snake River Plain seismic profiling experiment: crustal structure of the eastern Snake River Plain, *J. Geophys. Res.* 87, 2597–2609, 1982.
- [17] M.H. The hotspots
- [18] R.B. Lehm and Snake structure Geol
- [19] D.R. River Bonr Mine
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- [22] W.P. River Bonr Mine
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- [27] B.R. Hedg elemi lite–t canic
- [28] G.A. ing ir Acta
- [29] J.B. in: Earth and 1992
- [30] E.B.

- [17] M.H. Anders and N.H. Sleep, Magmatism and extension: The thermal and mechanical effects of the Yellowstone hotspot, *J. Geophys. Res.* 97, 15379–15393, 1992.
- [18] R.B. Smith, M.M. Schilly, L.W. Braile, J. Ansorge, J.L. Lehman, M.R. Baker, C. Prodehl, J.H. Healy, S. Mueller and R.W. Greensfelder, The 1978 Yellowstone–eastern Snake River seismic profiling experiment: Crustal structure of the Yellowstone region and experiment design, *J. Geophys. Res.* 87, 2583–2596, 1982.
- [19] D.R. Mabey, Geophysics and tectonics of the Snake River Plain, Idaho, in: *Cenozoic Geology of Idaho*, B. Bonnicksen and R.M. Breckenridge, eds., Idaho Bur. Mines. Geol. Bull. 26, 139–153, 1982.
- [20] D. Geist and M. Richards, Origin of the Columbia Plateau and Snake River Plain: Deflection of the Yellowstone plume, *Geology* 21, 789–792, 1993.
- [21] M.A. Kuntz, H.R. Covington and L.J. Schorr, An overview of basaltic volcanism of the eastern Snake River Plain, Idaho, in: *Regional Geology of Eastern Idaho and Western Wyoming*, P.K. Link, M.A. Kuntz and L.B. Platt, eds., *Geol. Soc. Am. Mem.* 179, 227–267, 1992.
- [22] W.P. Leeman, Olivine tholeiitic basalts of the Snake River Plain, Idaho, in: *Cenozoic Geology of Idaho*, B. Bonnicksen and R.M. Breckenridge, eds., Idaho Bur. Mines. Geol. Bull. 26, 181–191, 1982.
- [23] M.A. Menzies, W.P. Leeman and C.J. Hawkesworth, Isotope geochemistry of Cenozoic volcanic rocks reveals mantle heterogeneity below western U.S.A., *Nature* 303, 205–209, 1983.
- [24] W. Hildreth, A.N. Halliday and R.L. Christiansen, Isotopic and chemical evidence concerning the genesis and contamination of basaltic and rhyolitic magma beneath the Yellowstone Plateau volcanic field, *J. Petrol.* 32, 63–138, 1991.
- [25] W.P. Leeman, Petrology of basaltic lavas from the Snake River Plain, Idaho (part I), and experimental determination of partitioning of divalent cations between olivine and basaltic liquid (part II), Ph.D. Thesis, Univ. Oregon, 1974.
- [26] Z.A. Palacz, P.A. Freedman and A.J. Walder, Thorium isotope ratio measurements at high abundance sensitivity using a VG 54–30, an energy-filtered thermal ionization mass spectrometer, *Chem. Geol.* 101, 157–165, 1992.
- [27] B.R. Doe, W.P. Leeman, R.L. Christiansen and C.E. Hedge, Lead and strontium isotopes and related trace elements as genetic tracers in the upper Cenozoic rhyolite–basalt association of the Yellowstone plateau volcanic field, *J. Geophys. Res.* 87, 4785–4806, 1982.
- [28] G.A. Mahood and J.A. Stinac, Trace-element partitioning in pantellerites and trachytes, *Geochim. Cosmochim. Acta* 54, 2257–2276, 1990.
- [29] J.B. Gill, D.M. Pyle and R.W. Williams, Igneous rocks, in: *Uranium-Series Disequilibrium: Applications to Earth, Marine, and Environmental Sciences*, M. Ivanovich and R.S. Harmon, eds., pp. 207–258, Clarendon, Oxford, 1992.
- [30] E.B. Watson and T.M. Harrison, Zircon saturation revisited: temperature and composition effects in a variety of crustal magma types, *Geochim. Cosmochim. Acta* 64, 295–304, 1983.
- [31] R.N. Thompson, Primary basalts and magma genesis II. Snake River Plain, Idaho, U.S.A., *Contrib. Mineral. Petrol.* 52, 213–232, 1975.
- [32] R.K. O’Nions and D. McKenzie, Estimates of mantle thorium/uranium ratios from Th, U and Pb isotope abundances in basaltic melts, *Philos. Trans. R. Soc. London A342*, 65–77, 1993.
- [33] W.M. White, $^{238}\text{U}/^{204}\text{Pb}$ in MORB and open system evolution of the depleted mantle, *Earth Planet. Sci. Lett.* 115, 211, 1993.
- [34] M.T. McCulloch, The role of subducted slabs in an evolving earth, *Earth Planet. Sci. Lett.* 115, 89–100, 1993.
- [35] D. McKenzie and R.K. O’Nions, Partial melt distributions from inversion of rare earth element concentrations, *J. Petrol.* 32, 1021–1091, 1991.
- [36] M. Spiegelman and T. Elliott, Consequences of melt transport for uranium series disequilibrium in young lavas, *Earth Planet. Sci. Lett.* 118, 1–20, 1993.
- [37] P. Beattie, Uranium–thorium disequilibria and partitioning on melting of garnet peridotite, *Nature* 363, 63–65, 1993.
- [38] A. Meijer, T.-T. Kwon and G.R. Tilton, U–Th–Pb partitioning behavior during partial melting in the upper mantle: Implications for the origin of high μ components and the ‘Pb paradox’, *J. Geophys. Res.* 95, 433–448, 1990.
- [39] A. Zindler and S. Hart, Chemical geodynamics, *Annu. Rev. Earth Planet. Sci.* 14, 493–571, 1986.
- [40] B.L. Weaver, The origin of ocean island basalt end-member compositions: trace element and isotopic constraints, *Earth Planet. Sci. Lett.* 104, 381–397, 1991.
- [41] S.-S. Sun and W.F. McDonough, Chemical and isotopic systematics of oceanic basalts: implications for mantle composition and processes, in: *Magmatism in the Ocean Basins*, A.D. Saunders and M.J. Norry, eds., *Geol. Soc. London Spec. Publ.* 42, 313–345, 1989.
- [42] D. McKenzie and R.K. O’Nions, Mantle reservoirs and ocean island basalts, *Nature* 301, 229–231, 1983.
- [43] C.J. Hawkesworth, M.S.M. Mantovani, P.N. Taylor and Z. Palacz, Evidence from the Parana of south Brazil for a continental contribution to Dupar basalts, *Nature* 322, 356–359, 1986.
- [44] S.H. Richardson, A.J. Erlank, A.R. Duncan and D.L. Reid, Correlated Nd, Sr and Pb isotope variation in Walvis Ridge basalts and implications for the evolution of their mantle source, *Earth Planet. Sci. Lett.* 59, 327–342, 1982.
- [45] A.W. Hofmann and W.M. White, Mantle plumes from ancient oceanic crust, *Earth Planet. Sci. Lett.* 57, 421–436, 1982.
- [46] B.L. Weaver, D.A. Wood, J. Farney and J.L. Joron, Role of subducted sediment in the genesis of ocean-island basalts: Geochemical evidence from South Atlantic Ocean islands, *Geology* 14, 275–278, 1986.

- [47] F. McDermott and C. Hawkesworth, Th, Pb, and Sr isotope variations in young island arc volcanics and oceanic sediments, *Earth Planet. Sci. Lett.* 104, 1–15, 1991.
- [48] J.B. Gill and R.W. Williams, Th isotope and U-series studies of subduction-related volcanic rocks, *Geochim. Cosmochim. Acta* 54, 1427–1442, 1990.
- [49] R.W. Williams and J.B. Gill, Th isotope and U-series disequilibria in some alkali basalts, *Geophys. Res. Lett.* 19, 139–142, 1992.
- [50] S.R. Hart, A large-scale isotope anomaly in the Southern Hemisphere mantle, *Nature* 309, 753–757, 1984.
- [51] H. Craig, J.E. Lupton, J.A. Welhan and R. Poreda, Helium isotope ratios in Yellowstone and Lassen Park volcanic gases, *Geophys. Res. Lett.* 5, 897–900, 1978.
- [52] M.D. Kurz, W.J. Jenkins and S.R. Hart, Helium isotopic systematics of oceanic islands and mantle heterogeneity, *Nature* 297, 43–47, 1982.
- [53] E.H. Hauri, N. Shimizu, J.J. Dieu and S.R. Hart, Evidence for hotspot-related carbonate metasomatism in the oceanic upper mantle, *Nature* 365, 221–227.
- [54] K.A. Farley, Rapid mantle cycling of an EM2 mantle component, *Nature*, submitted.
- [55] P.J. Wyllie, Solidus curves, mantle plume, and magma generation beneath Hawaii, *J. Geophys. Res.* 93, 4171–4181, 1988.
- [56] R.W. Carlson and W.K. Hart, Flood basalt volcanism in the northwestern United States, in: *Continental Flood Basalts*, J.D. Macdougall, ed., pp. 35–61, 1988.
- [57] S.K. Vetter and J.W. Shervais, Continental basalts of the Boise River Group near Smith Prairie, Idaho, *J. Geophys. Res.* 97, 9043–9061, 1992.
- [58] W.K. Hart, Chemical and isotopic evidence for mixing between depleted and enriched mantle, northwestern U.S.A., *Geochim. Cosmochim. Acta* 49, 131–144, 1985.
- [59] W.P. Leeman, J.S. Oldow and W.K. Hart, Lithosphere-scale thrusting in the western U.S. Cordillera as constrained by Sr and Nd isotopic transitions in Neogene volcanic rocks, *Geology* 20, 63–66, 1992.
- [60] J.G. Fitton, D. James and W.P. Leeman, Basic magmatism associated with late Cenozoic extension in the western United States: Compositional variations in space and time, *J. Geophys. Res.* 96, 13693–13711, 1991.
- [61] E. Stolper and S. Newman, The role of water in the petrogenesis of Mariana Trough magmas, *Earth Planet. Sci. Lett.* 121, 293–325, 1994.
- [62] J.L. Wooden and P.A. Mueller, Pb, Sr, and Nd isotopic compositions of a suite of Late Archean igneous rocks, eastern Beartooth Mountains: implications for crust-mantle evolution, *Earth Planet. Sci. Lett.* 87, 59–72, 1988.
- [63] T.M. Harrison and E.B. Watson, The behavior of apatite during crustal anatexis: equilibrium and kinetic considerations, *Geochim. Cosmochim. Acta* 48, 1467–1477, 1984.
- [64] W.P. Leeman, Rhyolites of the Snake River Plain–Yellowstone Plateau province, Idaho and Wyoming: A summary of petrogenetic models, in: *Cenozoic Geology of Idaho*, B. Bonnichsen and R.M. Breckenridge, eds., Idaho Bur. Mines. Geol. Bull. 26, 203–212, 1982.
- [65] C.J. Allegre, B. Dupre and E. Lewin, Thorium/uranium ratio of the Earth, *Chem. Geol.* 56, 219–227, 1986.
- [66] E. Widom, Z.A. Palacz, J.B. Gill and H.-U. Schmincke, Th-Sr-Pb isotope correlations in the Azores, *EOS* 73, 651, 1992.
- [67] J. Barling and S.L. Goldstein, Extreme isotopic variations in Heard Island lavas and the nature of mantle reservoirs, *Nature* 348, 59–62, 1990.
- [68] S.-S. Sun, Lead isotopic study of young volcanic rocks from mid-ocean ridges, ocean islands and island arcs, *Philos. Trans. R. Soc. London A297*, 409–445, 1980.
- [69] S.E. Church, Limits of sediment involvement in the genesis of orogenic volcanic rocks, *Contrib. Mineral. Pet.* 39, 17–32, 1973.



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