

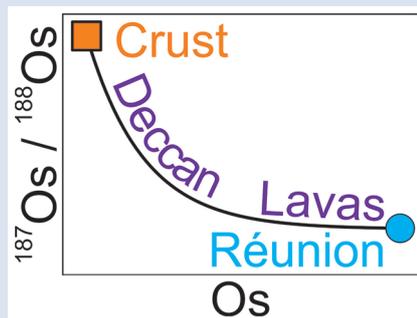
A geochemical link between plume head and tail volcanism

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doi: 10.7185/geochemlet.1742

Abstract



Geodynamical models of mantle plumes often invoke initial, high volume plume ‘head’ magmatism, followed by lower volume plume ‘tails’. However, geochemical links between plume heads, represented by flood basalts such as the Deccan Traps, and plume tails, represented by ocean islands such as La Réunion, are ambiguous, challenging this classical view of mantle plume theory. Using Sr-Nd-Os isotope data, we demonstrate a geochemical link between archetypal plume head and tail volcanism in the Réunion hotspot. Similar plume head-tail relationships have not been definitively shown in previous geochemical studies for Réunion or other global hotspots. Such a link is enabled by use of compatible elements, such as Os, which can circumvent complexities introduced by magmatic assimilation of crust or lithosphere because these elements are scarce in crust compared to primary mantle melts. We calculate Sr-Nd-Os isotopic compositions for the Réunion primary magma and find these are identical to predictions for the Deccan primary magma. Our result provides geochemical evidence for a temporally stable mantle plume that samples a primitive reservoir associated with the African large low-shear-velocity province and with a heritage beginning at the Cretaceous-Palaeogene boundary.

Received 5 April 2017 | Accepted 28 September 2017 | Published 3 November 2017

Letter

The origins of terrestrial intraplate “hotspot” volcanism remain controversial. One common model suggests that hotspots are derived from thermo-chemically buoyant mantle plumes that rise from the deep mantle, initiating short-lived, high volume ‘flood basalt’ volcanism that likely had collateral tectonic and environmental consequences (Richards *et al.*, 1989; Hill, 1991; Self *et al.*, 2008). Other models posit that hotspot magmatism is initiated by shallow melting in response to tectonic processes (*e.g.*, Foulger *et al.*, 2015). Three arguments currently favour a plume origin for intraplate magmatism. First, the formation of a continuous, age-progressive and roughly linear volcanic track independent of plate tectonic activity likely requires an active mantle source, such as a plume. Second, seismic tomography suggests deep, low-shear-velocity upwelling beneath some intraplate volcanic centres (French and Romanowicz, 2015). Third, the isotopic signatures of many modern hotspots are distinct from those of the mantle underlying continents and mid-ocean ridges and remain relatively consistent through time, suggesting that they have isolated, deep mantle source reservoirs that continually replenish shallow magma reservoirs (Hofmann, 1997).

One of the best studied examples of plume head and tail relationships along a linear, age-progressive volcanic track is the Deccan-Réunion hotspot. There, a volumetrically massive continental flood basalt (CFB) province, the Deccan Traps, is linked by aseismic, submarine ridges to ocean island basalts

(OIB) that actively erupt on the island of La Réunion (Fig. 1). A genetic link between Deccan CFB and Réunion OIB, and for other similar hotspot tracks, has often been implicitly assumed by mantle plume theory and is demanded by recent geodynamical models (Glišović and Forte, 2017). Such assumptions, however, are at odds with expected physical consequences of ancient mantle plumes; for example, modern heat flow measurements do not record increased thermal output beneath the Deccan Traps, where an ancient mantle plume might be expected to have thinned the continental crust and lithosphere and increased heat transfer from the mantle to the surface (Roy and Rao, 2000).

In cases like these, geochemistry is a potentially diagnostic tool for linking CFB and OIB magmatism. If flood basalts and later ‘plume tail’ magmas are found to originate from compositionally distinct sources, it would provide no definitive evidence for a long lived mantle plume; however, if they share a common geochemical source that is distinct from the modern accessible mantle, then the persistence of such signatures in the mantle would strongly implicate the existence of a mantle plume. Decades of geochemical research utilising lithophile isotope systems have resulted in dubious associations between plume heads and tails. For example, Sr-Nd isotopic compositions of Deccan basalts deflect away from a Réunion end member (*e.g.*, Fig. 2 of Peng *et al.*, 1994), which may be a consequence of extensive assimilation of lithospheric or crustal material into CFB magmas. This effect has also been observed for other hotspot systems (Gibson *et al.*, 1995; Peate, 1997;

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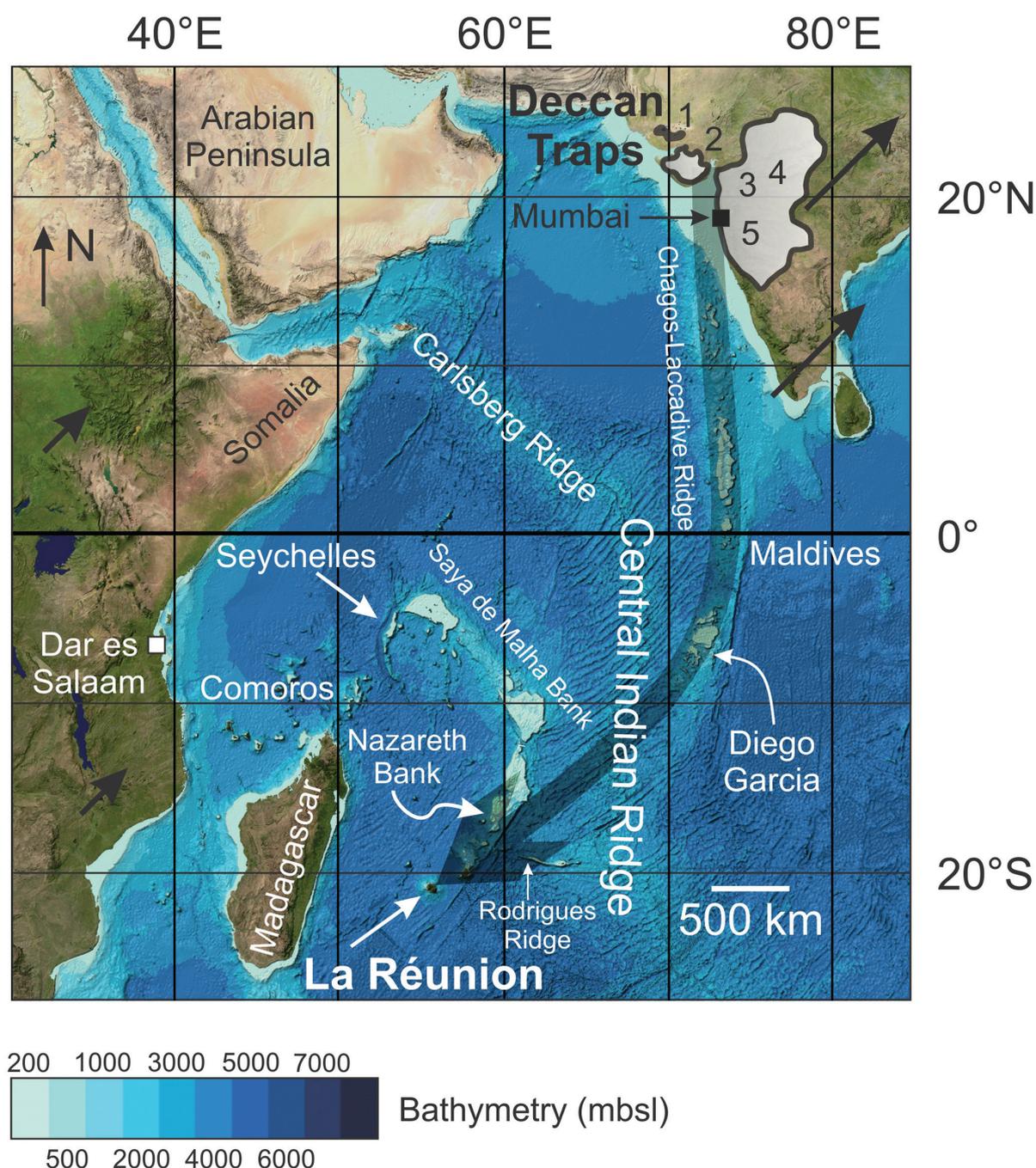


Figure 1 Satellite bathymetry map of the western Indian Ocean basin. Approximate aerial extent of Deccan Traps lava flows are shown by the gray fields on the Indian subcontinent. Numbers in the shaded region correspond to sampling regions: 1 – Kutch (samples 1-5), 2 – Saurashtra (samples 6-46), 3 – Pavagadh, Kalsubai, Amba Dongar and surroundings (samples 48-54, 63-78), 4 – Dhule and surroundings (samples 55-62), 5 – Mumbai, Western Ghats and coastal Maharashtra (samples 79-115, MMF7). Approximate trace of the Réunion hotspot is shown by the transparent black arrow, approximate plate motion vectors are shown by solid black arrows over land areas and are proportional to plate motions. Base map reproduced from the GEBCO world map 2014, www.gebco.net.

Dale *et al.* 2009; Day, 2016), meaning that it may be an inevitable consequence of magma ascent through lithosphere and crust, effectively masking primary magmatic signatures.

The siderophile ^{187}Re - ^{187}Os isotope system ($t_{1/2} \approx 42$ Gyr) (Shirey and Walker, 1998) provides an opportunity to resolve a geochemical link between plume head and tail volcanism. Rhenium is relatively incompatible while Os is highly compatible, leading to high Re/Os and long term radiogenic $^{187}\text{Os}/^{188}\text{Os}$ signatures in crust (>1 ; Peucker-Ehrenbrink and Jahn, 2001), while the primitive mantle preserves lower Re/Os and less radiogenic $^{187}\text{Os}/^{188}\text{Os}$ signatures (~ 0.1296) relative to chondrites (0.126–0.128; Meisel *et al.*, 1996; Day *et al.*,

2016). In contrast, long lived lithophile isotope systems (*e.g.*, Rb-Sr, Sm-Nd, Lu-Hf, U/Th-Pb) involve exclusively incompatible elements that are enriched in lithospheric melts and crustal materials relative to mantle-derived magmas. This explains why the Sr-Nd-Pb isotopic characteristics of flood basalts can be dominated by contributions from lithospheric melt and partially melted crust (*e.g.*, Peng *et al.*, 1994; Gibson *et al.*, 1995). Mantle Os isotopic signatures, however, may persist through variable extents of differentiation or assimilation of lithosphere or crust, making $^{187}\text{Os}/^{188}\text{Os}$ a diagnostic tool for examining geochemical links between plume head and tail magmatism. Notwithstanding, previous examination of the

$^{187}\text{Os}/^{188}\text{Os}$ composition of Deccan CFB lavas (Allegre *et al.*, 1999) indicated a near-chondritic initial composition (reported as 0.12843 ± 0.00047). This result is irreconcilable with the highly consistent and more radiogenic $^{187}\text{Os}/^{188}\text{Os}$ signature of Réunion igneous rocks (Schiano *et al.*, 2012; Peters *et al.*, 2016) (0.1324 ± 0.0014 ; Fig. 2a), suggesting that there is not a geochemical link in the Deccan-Réunion system and fundamentally challenging physical models of plume head and tail magmatism. Here, we re-evaluate this important relationship using new Sr-Nd-Os isotope data for Deccan Traps lavas.

Many early surveys of the Deccan Traps focused primarily on the relationship between mantle sources of Deccan lavas and depleted upper mantle domains since relatively high concentrations of Sr and Nd in Indian continental crust likely obscured isotopic signatures of deep sources (*e.g.*, Peng *et al.*, 1994). We examined >60 samples of Deccan CFB and related rocks that represent a broad stratigraphic and compositional range (MgO = 0.5–15.7 wt. %; Supplementary Information). Most of the high MgO samples are dykes and flows from the northwestern regions of Saurashtra and Kutch, however such geochemically primitive samples are also found in samples from in and around Mumbai and in the Pavagadh volcanic complex. In contrast, high Ti ($\text{TiO}_2 > 1.5$ wt. %) samples from Saurashtra and samples from the Deccan “main sequence” near Mahabaleshwar tend to have more evolved compositions (MgO commonly <8 wt. %). Age-corrected $^{187}\text{Os}/^{188}\text{Os}$ ratios for Deccan lavas range from 0.1128 to 0.6713 (Fig. 2a) and span a large range of Os concentrations. No sample has a geochemical composition similar to potassic lavas likely representing small degree partial melts of continental lithospheric mantle (CLM, represented by nephelenite sample DC14-79 and lamprophyre sample DC14-83B). However, several samples display age-corrected $^{187}\text{Os}/^{188}\text{Os}$ less than 0.128, strongly implying that some samples experienced interaction with lithospheric materials. Some other samples show crustal $^{187}\text{Os}/^{188}\text{Os}$ signatures that may have overprinted their original $^{187}\text{Os}/^{188}\text{Os}$ compositions. In contrast, the most primitive samples have Os concentrations lower than the average depleted mantle. The majority of the measured samples preserve a $^{187}\text{Os}/^{188}\text{Os}$ signature very close to that of Réunion (Fig. 2a).

While a previous study of Os isotopes in the Deccan Traps claimed isochronous behaviour (Allegre *et al.*, 1999), our samples do not show a statistically significant isochron ($\text{MSWD} > 10^2$) and do not support a near-chondritic initial $^{187}\text{Os}/^{188}\text{Os}$ (Fig. 2b). This is likely due to regional variations in magma differentiation and assimilation of lithospheric and crustal materials, meaning that careful filtering of samples is required to identify samples that are strongly affected by these processes. We exclude samples that may have experienced significant fractional crystallisation (MgO < 6 wt. % or >14 wt. %; *e.g.*, Fig. S-6) and altered samples with LOI > 2.5 %, extreme Re/Os (>100) or $^{187}\text{Os}/^{188}\text{Os}$ (<0.125 or >1) compositions (Table S-5), which would imply extensive fractional crystallisation or lithospheric/crustal assimilation. The choice of filter ranges has a direct impact on the calculated $^{187}\text{Os}/^{188}\text{Os}$ and its precision, but our rejection criteria are relatively inclusive. A York-type regression of our filtered data yields an isochron initial $^{187}\text{Os}/^{188}\text{Os}$ of 0.1336 ± 0.0031 ($n = 21$), identical, within uncertainties, to the Réunion end member (0.1324 ± 0.0014) (Peters *et al.*, 2016).

Since Deccan lavas have universally assimilated some amount of continental crust, constructing an isochron requires projecting a best fit line through low $^{187}\text{Re}/^{188}\text{Os}$ space, in which there are few data. This characteristic is an unavoidable consequence of working with CFB and results in somewhat limited precision. Regional complexities of crustal assimilation may be overcome by attempting to calculate initial $^{187}\text{Os}/^{188}\text{Os}$ for

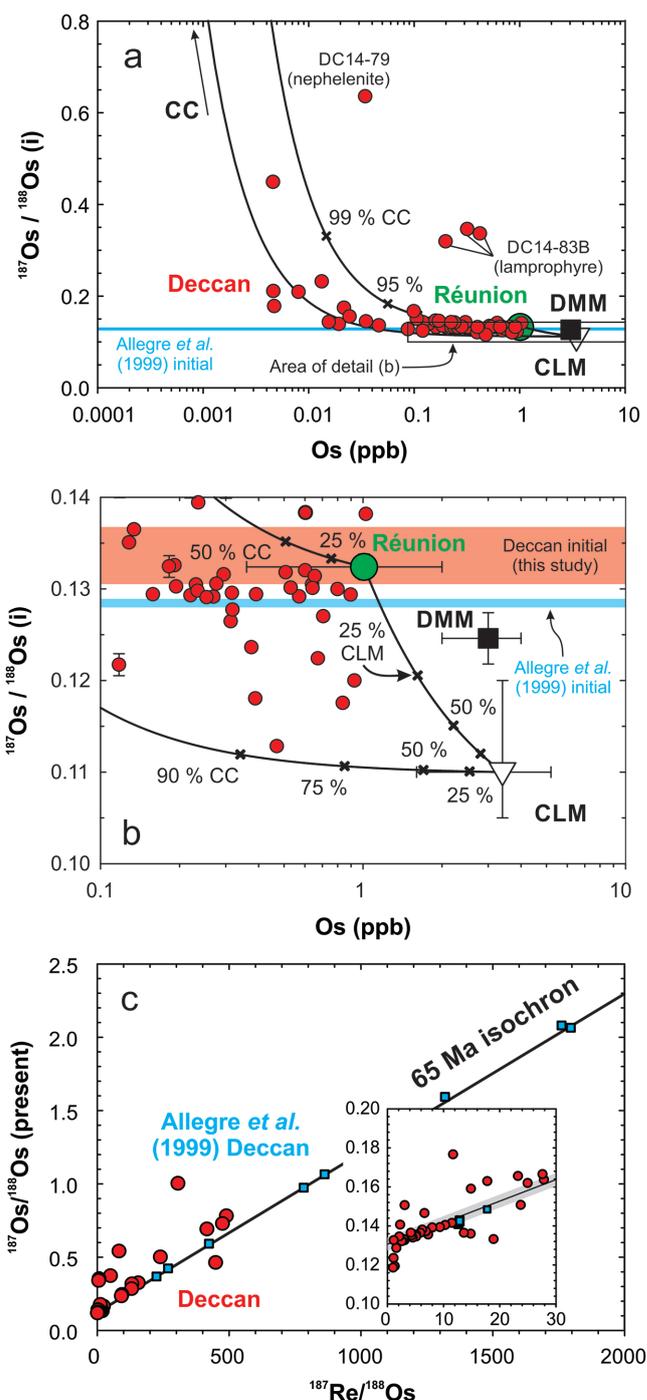


Figure 2 (a) $^{187}\text{Os}/^{188}\text{Os}$ versus [Os] for Deccan lavas (red circles), with inferred compositions of the Réunion primary magma (green circle) (Peters *et al.*, 2016), crust (CC: continental crust) and lithosphere (DMM: depleted mid-ocean ridge basalt mantle, CLM: continental lithospheric mantle) and mixing lines. Initial $^{187}\text{Os}/^{188}\text{Os}$ reported in literature data (Allegre *et al.*, 1999) shown as blue. (b) Small scale view of (a) showing end member compositions and uncertainties with initial $^{187}\text{Os}/^{188}\text{Os}$ calculated in this study (transparent red box with range indicated by bidirectional arrow) and in Allegre *et al.* (1999) (blue box with outline). (c) Rhenium-osmium isotopes for Deccan lavas in this study (red circles) and from Allegre *et al.* (1999) (blue squares), with inset for low Re samples. For reference, a 65 Ma isochron with initial $^{187}\text{Os}/^{188}\text{Os} = 0.1336 \pm 0.0031$, as determined from our samples, is shown. Uncertainty on the isochron is thinner than line thickness in panel (c) and is represented by the shaded region in the inset. A 65 Ma isochron corresponding to the initial $^{187}\text{Os}/^{188}\text{Os}$ determined by Allegre *et al.* (1999) is approximately equivalent to a line following the lower bound of the shaded region, given the precision noted in that study. Model end members are given in Table S-4.



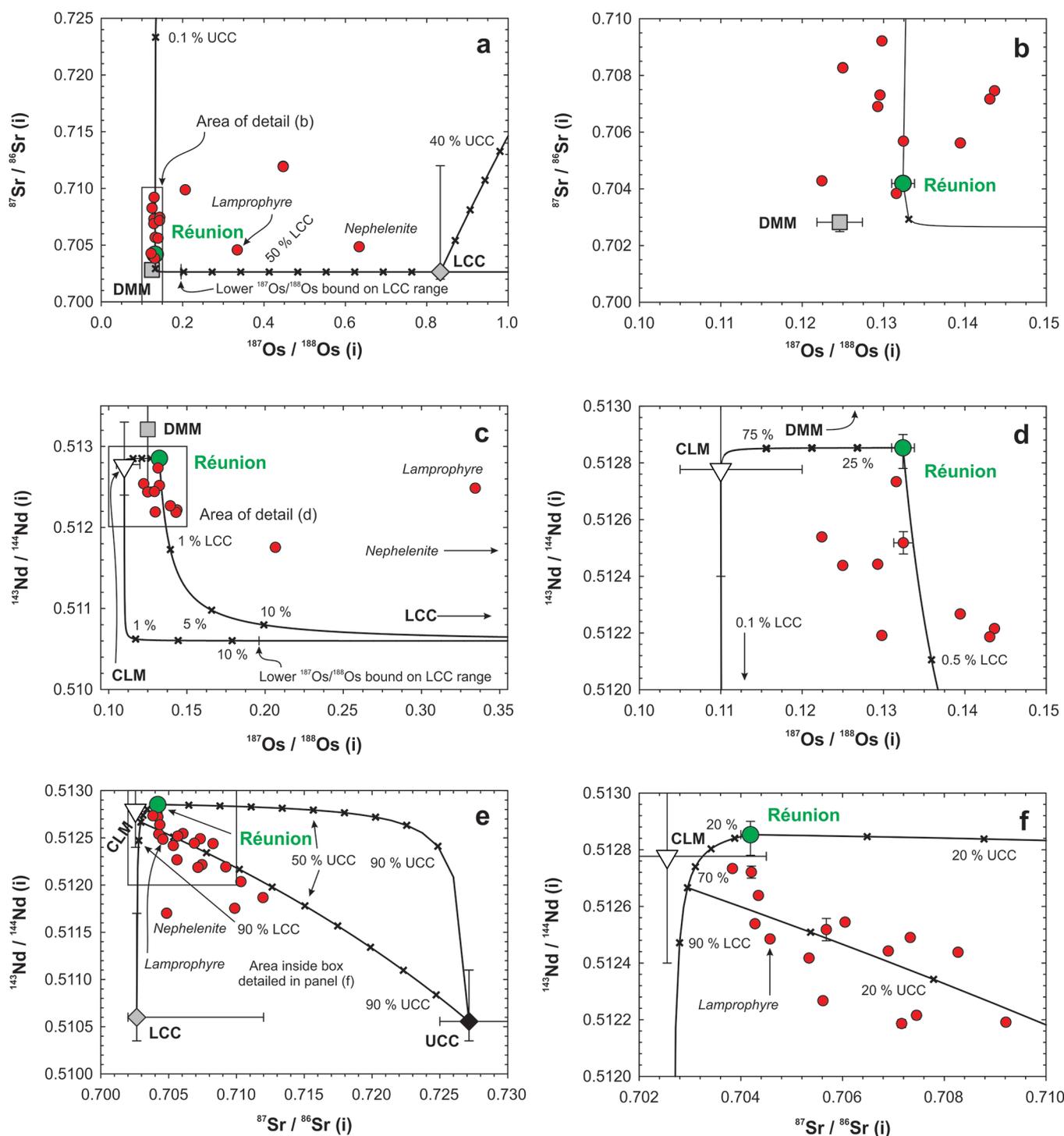


Figure 3 (a,b) Strontium-osmium, (c,d) Nd-Os and (e,f) Sr-Nd isotopic variations for Deccan basalts plotted with a Réunion end member, crustal (LCC: lower continental crust, UCC: upper continental crust) and lithospheric assimilants as in Figure 2. Small 'x' marks denote 10 % mass intervals of mixing unless otherwise marked. In (e,f), a secondary mixing curve between a 20 % Réunion-80 % lower continental crust end member and an upper continental crust end member is shown to illustrate the effects of two stage crustal assimilation. For clarity, not all possible mixing arrays or end member compositions are shown in every panel. Model end members are given in Table S-4.

sample groups based on geography, but for our data this does not yield a more precise result. Our $^{187}\text{Re}/^{188}\text{Os}$ data range is 1 to 490 (average = 64), while published data range from 13 to 1800 (average = 633). The more limited amount of assimilation experienced by our samples leads us to reject a chondritic Os isotope composition for the Deccan primary magma; instead, our data demonstrate that the initial $^{187}\text{Os}/^{188}\text{Os}$ for the Deccan CFB is identical, within uncertainty, to that of Réunion, and distinct from CLM, depleted mantle or the estimate of Allegre *et al.* (1999).

A persistent Réunion-like Sr-Nd isotope signal is also present in our Deccan samples. Age-corrected $^{87}\text{Sr}/^{86}\text{Sr}$ ratios range from 0.70383 to 0.71195 and are negatively correlated with age-corrected $^{143}\text{Nd}/^{144}\text{Nd}$ ratios (Fig. 3a), which range from $\epsilon^{143}\text{Nd}_{\text{CHUR}(65 \text{ Ma})} = -16.6$ to $+3.6$. These results extend to compositions among the most geochemically primitive of published Deccan Sr-Nd isotope data (*e.g.*, Melluso *et al.*, 2006; Sheth and Melluso, 2008). Relatively depleted Sr-Nd isotope signatures, with values approaching those of Réunion OIB, are most common in samples from Kutch. These samples also



possess incompatible element abundances like those in OIB (Fig. S-6a) and the most primitive highly siderophile element (HSE) patterns (Fig. S-7a). To test the quantitative geochemical relationship between Deccan and Réunion Sr-Nd-Os isotopic signatures, we establish Réunion end members according to Peters *et al.* (2016) (Os) and from published Réunion geochemistry data (Sr-Nd; Table S-4). Because the range in isotopic compositions of Réunion OIB is more limited than any other OIB, uncertainty in the end member composition is relatively low. We establish crust end members from published data on regional (Sr-Nd) and global (Os), crustal rocks (Peucat *et al.*, 1989, 2013; Asmerom and Walker, 1998; Ray *et al.*, 2008) and mantle lithospheric end members from published global data (Snow and Reisberg, 1995; McBride *et al.*, 1996; Roy-Barman *et al.*, 1998; Aulbach *et al.*, 2016). Using these end members, we explain Sr-Nd-Os isotopic co-variations by assimilation of crustal reservoirs into a Réunion-like primary magma (Fig. 3).

Co-variations of Sr and Nd with Os isotopes (Fig. 3a-d) imply a limited role for crustal assimilation because, as revealed by Figure 2a, the mixing relationship is dominated by the strong enrichment of Os in mantle-derived magmas relative to the crust. In contrast, Sr-Nd isotope co-variations (Fig. 3e,f) reveal a much stronger influence of crustal materials because both elements are more abundant in the crust. The cause of scatter in the Sr-Os and Nd-Os isotope arrays relative to the mixing curves in Figure 3 is likely a consequence of several factors. First, Sr, Nd and their respective parent elements are lithophile, while Re and Os are siderophile, meaning that assimilated domains have distinct compositions of each element that may affect each of these arrays differently. For example, some samples in the Nd-Os isotopic array (Fig. 3c,d) may have witnessed assimilation of high REE potassic melts (Gibson *et al.*, 1995), which may be represented by nephelinite sample DC14-79, causing some scatter to the right of the Réunion-lower continental crust join. Second, the different isotope systems we use may preserve analogous records of the same processes, but regional differences in differentiation processes mean that each individual datum corresponds to a mixing line not explicitly shown on the figures. Finally, the ^{187}Re - ^{187}Os system, which is sensitive to sulphide fractionation, may be most sensitive to early melt differentiation, when immiscible sulphide liquids are isolated during olivine fractionation. In contrast, ^{87}Rb - ^{87}Sr and ^{147}Sm - ^{143}Nd , which are hosted by silicates such as plagioclase and clinopyroxene, may be most sensitive to later differentiation involving these phases. As a result, the data arrays shown in Figure 3a-d may not be as well-represented by simple mixing compared to data in Figure 2a and Figure 3e,f.

The negative correlation between age-corrected $^{87}\text{Sr}/^{86}\text{Sr}$ and $^{143}\text{Nd}/^{144}\text{Nd}$ (Fig. 3e,f) matches a two stage assimilation scenario, in which a Réunion-like parental magma first assimilates a relatively large proportion of lower continental crust (estimated as 50–90 % of the Sr-Nd mass) followed by smaller amounts of upper continental crust (0–50 % by mass). Alternatively, assimilation may be single stage and involve crust with a composition intermediate to our chosen end members. For all combinations of Sr-Nd-Os isotopes, data arrays of Deccan lavas can be explained by a Réunion-like mantle source that has assimilated lower and/or upper continental crust with no required role from lithosphere or a primitive mantle-like source (Meisel *et al.*, 1996).

We also find that measured HSE variations in Deccan basalts can be quantitatively related to a Réunion parental magma (Supplementary Information). Accounting for localised ‘nugget’ effects, differentiation of a Réunion-like parental magma that has undergone sulphide saturation can produce HSE abundances similar to those measured in the most evolved lavas of the Maharashtra “main sequence” and Saurashtra low

Ti lavas. These findings do not require contributions from a source similar to the modern Comoros hotspot, as suggested by Glišović and Forte (2017), however they cannot definitively exclude such contributions. Additional geochemical data for the ancient Comoros hotspot may be needed to evaluate this hypothesis.

A geochemical link between canonical plume head and plume tail volcanism demonstrates that mantle plumes and their mantle sources can remain physically resilient through tens of millions of years of Earth’s history. Similar geochemical links may also exist for intraplate volcanism displaying physiographic ties between ‘head’ and ‘tail’ provinces, such as the Iceland or Tristan da Cunha hotspots. These hotspots, as well as the Réunion hotspot, lie above the edge of the African large low-shear-velocity province (LLSVP), which may serve as the lower mantle source to many plumes (Zhao *et al.*, 2015). If this is the case, the African LLSVP must actively transport material with primordial compositions to Earth’s surface (Peters *et al.*, 2016). If the LLSVP serves as the source for Réunion primary magmas, this is consistent with the notion that LLSVP’s are not only presently stable (Zhao *et al.*, 2015), but that they have remained stable through at least the Cenozoic. The temporal geochemical homogeneity in the Réunion plume source strongly implies that there are regions of the mantle capable of preserving signatures of their provenance since very early in Earth’s history, remaining exempt from processes that otherwise act to keep the mantle well-mixed.

Acknowledgements

We acknowledge the support of A. Basu Sarbadhikari in the field effort and H. Sheth for providing sample MMF7. Field work was supported by the National Geographic Society (NGS 8330-07) to JMDD. General support was provided from NSF EAR grants 1116089 and 1447130 to JMDD and the Devendra and Aruna Lal Fellowship to BJP. These sources of funding are gratefully acknowledged. The authors declare no conflicts of interest.

Editor: Helen Williams

Additional Information

Supplementary Information accompanies this letter at www.geochemicalperspectivesletters.org/article1742

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Cite this letter as: Peters, B.J., Day, J.M.D. (2017) A geochemical link between plume head and tail volcanism. *Geochem. Persp. Let.* 5, 29–34.

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