Geochemical Perspectives Letters EAG

Earth's foundational geological events stored in the fundamental mantle source of hotspots

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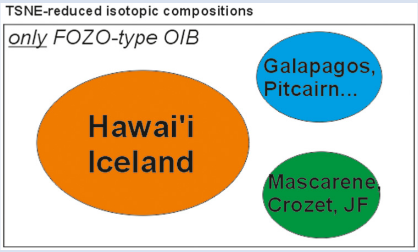
OPEN ACCESS
https://doi.org/10.7185/geochemlet.2553

Abstract



The geochemical signatures of nearly all Earth's volcanic hotspots converge on a common isotopic composition, which is often termed the 'focal zone' (FOZO) and has been associated with a shared deep mantle source. Yet, unlike other characteristic geochemical components of hotspots, the origin and nature of FOZO remain unclear. Geochemical evidence has been invoked to support both an ancient and a relatively young age for FOZO, and long lived radiogenic isotopic data support many potential geochemical relationships between geographically disparate hotspots. We examine this issue using the short lived ^{146}Sm-^{142}Nd isotopic system, which can identify diverse geochemical origins in the Hadean Eon, more than four billion years ago. Two hotspots with strong geochemical affinity to FOZO, the Crozet and Juan Fernandez hotspots, have statistically distinct ^{142}Nd compositions, meaning that despite the similarity in their long lived radiogenic isotopic compositions, they must reflect different Hadean-aged geological heritages. Detailed analysis of the isotopic compositions of global hotspots using machine learning further reveals that FOZO is most likely not singular but rather represents a spectrum of discrete domains that each have histories dating back to the first 10 % of Earth's history.

Received 15 January 2025 | Accepted 3 November 2025 | Published 23 December 2025

Introduction

The emergence of complex biogeochemical cycles on Earth is largely owed to the development of plate tectonics, yet it is also tectonics that has almost entirely destroyed Earth's geochemical record of its origins. For example, the zircon age record implies that nearly half of Earth's total crust was produced more than 2.5 Gyr ago (Korenaga, 2018), yet only ~5 % of Earth's modern surface is older than this age (Goodwin, 1996). This means that our knowledge of Earth's formational geological processes is fundamentally limited. There has been profitable research aimed at understanding Earth's development through intensive study of these remnants of ancient geological material (Wilde *et al.*, 2001; Bennett *et al.*, 2007; Reimink *et al.*, 2014); however, it is unknown whether these results present a complete perspective on Earth's evolution.

Earth's volcanic hotspots may represent a complementary view on early Earth processes that can partially remedy this preservation issue. It has long been recognised that the geochemical fingerprints of volcanic hotspots are among the most diverse of any terrestrial rock group. Some geochemical components of different volcanic hotspots have well constrained origins and may be more than 2.5 Gyr old, and therefore potential records of Earth's geological conditions before the emergence of complex life. The origins of one potential reservoir, variably termed the 'focus zone' (FOZO, used preferentially here; *cf.* Hart *et al.*, 1992), 'common component' (C), or 'prevalent mantle' (PREMA), have evaded conclusive agreement, but FOZO-like reservoirs have some remarkable geochemical characteristics. First, they have a geochemical signature that reflects less magmatic processing than the bulk upper mantle, but more magmatic processing than a theoretical chondritic primitive mantle—thus, FOZO reservoirs are said to be 'moderately depleted'. Second, nearly all volcanic hotspots appear to tap some form of FOZO, while other geochemical components are unique to one or more hotspots; thus, it has been hypothesised that FOZO reservoirs are widespread in the deep mantle sources of volcanic hotspots. Finally, only hotspot lavas (collectively termed ocean island basalts: OIBs) with geochemical affinity for FOZO reservoirs are known to possess elevated ^{3}He/^{4}He ratios (Class and Goldstein, 2005; Jackson *et al.*, 2007) (Fig. 1) compared to young mid-ocean ridge basalts (MORBs). Such elevated ^{3}He/^{4}He ratios are a primary signature of ancient geological material (Class and Goldstein, 2005). Thus, it is possible that these FOZO reservoirs are older than any other geochemical component of hotspot volcanism.

Some of these unique geochemical characteristics have recently been linked to short-lived radiogenic isotope systems, which record the effects of early geological processes. Only OIBs with moderately depleted isotopic signatures preserve deficits in ^{182}W, which must have been generated in the first 1 % of Earth's history ($\gtrsim$4.5 Gyr ago), compared to the bulk Earth (Fig. 1c). Similarly, heterogeneous ^{142}Nd compositions, which were generated in the first 10 % of Earth's history ($\gtrsim$4.0 Gyr ago), are primarily observed in OIB samples with moderately

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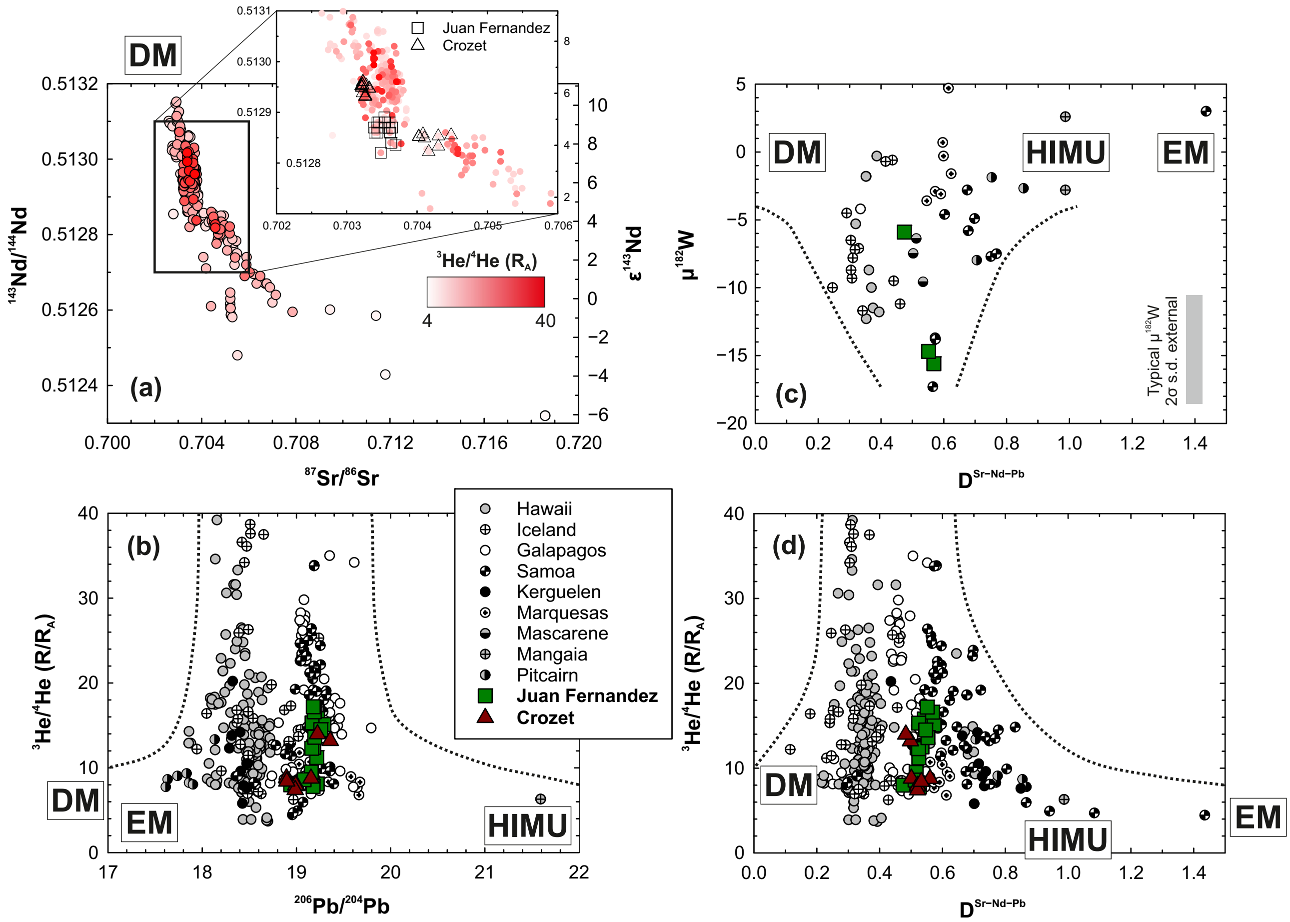

Figure 1 Long (He-Sr-^{143}Nd-^{206}Pb) and short lived (^{182}W) isotopic compositions of global ocean island basalts. The value of $D^{Sr-Nd-Pb}$ parameter refers to the deviation of sample isotopic compositions from a reference depleted composition (≡0) as defined in Jackson *et al.* (2020). Long lived radiogenic isotope data from GEOROC; W isotopic data from Mundl-Petermeier *et al.* (2020) and Herret *et al.* (2023). Dotted lines show approximate limits of present database.

depleted isotopic signatures (Horan *et al.*, 2018; Peters *et al.*, 2018). However, the high precision ^{142}Nd database for global hotspots remains relatively small and, thus, small scale ^{142}Nd heterogeneity in modern ocean island basalts may remain undetected. The convergence of global OIBs toward a moderately depleted isotopic signature, as well as the selectivity of this signature for predicting elevated ^{3}He/^{4}He ratios and heterogeneous ^{142}Nd and ^{182}W signatures, have led to the common conclusion that FOZO is a singular, ancient reservoir in Earth's deep mantle. This interpretation is particularly attractive when attempting to reconcile an ancient FOZO with the presence of two discrete large low shear velocity provinces (LLSVPs) identified in Earth's lower mantle. Despite this, evidence for the existence of multiple mantle components with elevated ^{3}He/^{4}He has been found both within single hotspots (Willhite *et al.*, 2019) and between global volcanic hotspots (Jackson *et al.*, 2007). Further, many hotspots that are spatially associated with different LLSVPs share common correlations between He and W isotopic compositions, implying that they have a shared ancient heritage that is independent of LLSVPs. Further, the lack of global correlations between ^{142}Nd and either short (^{182}W) or long lived (^{4}He, ^{87}Sr, ^{143}Nd, ^{187}Os, ^{206}Pb) isotopic tracers has complicated interpretations of Hadean-aged processes preserved in both geologically young and ancient rocks. Thus, the timing and nature of the evolution of moderately depleted isotopic signatures akin to FOZO, as well as their global extent, remains unclear.

The μ^{142}Nd Signatures of FOZO-Type Lavas From Volcanic Hotspots

We measured the μ^{142}Nd compositions (parts per million deviation of the ^{142}Nd/^{144}Nd ratio of a sample from that of the terrestrial standard) of OIBs from the Crozet (^{3}He/^{4}He ≤ 14 R_A, $n = 17$) and Juan Fernandez (^{3}He/^{4}He ≤ 17 R_A, $n = 13$) archipelagos, which display FOZO-like isotopic compositions and elevated ^{3}He/^{4}He ratios, and lack geochemical influence from non-FOZO end members. Notably, only hotspots that show clear geochemical influence from geochemical end member reservoirs, such as enriched mantle (EM), depleted mantle (DM), or high μ (high ^{238}U/^{204}Pb, HIMU), in addition to influence from FOZO, display very high ^{3}He/^{4}He (>30 R_A; *e.g.*, Jackson *et al.*, 2017). Our strategy was instead to focus on hotspot islands that display tightly distributed Sr-^{143}Nd-Pb isotopic compositions that lie near the convergence point of global OIB isotopic arrays, without showing geochemical influence from any non-FOZO end member (Fig. 1; *cf.* Stracke *et al.*, 2005, for different definitions of FOZO). We used high precision analytical methods (adapted from Garçon *et al.*, 2018; Wang and Carlson, 2022) designed to resolve very small scale μ^{142}Nd heterogeneity, since observed variations in μ^{142}Nd values are very small among post-Archean rocks (Horan *et al.*, 2018; Hyung and Jacobsen, 2020). We relied on intensive sample replication (more than 80 individual, high precision analyses) to constrain the μ^{142}Nd compositions of the two hotspots.

Samples from both studied islands of the Juan Fernandez hotspot samples display homogeneous μ^{142}Nd compositions with an average of $\mu^{142}\mathrm{Nd} = +1.0 \pm 0.9$ (all uncertainties represent 95 % c.i., $n = 13$; Fig. 2, Tables S-1, S-2). Among Crozet hotspot OIBs, samples from Penguin Island similarly display homogeneous compositions ($\mu^{142}\mathrm{Nd} = -0.6 \pm 0.9$, $n = 11$), whereas samples from Possession Island have somewhat more heterogeneous and negative μ^{142}Nd values ($\mu^{142}\mathrm{Nd} = -1.4 \pm 1.7$, $n = 6$), producing a hotspot average μ^{142}Nd of -0.8 ± 0.8 (Fig. 2). The μ^{142}Nd compositions of Crozet and Juan Fernandez OIBs are thus resolved at the 95 % confidence level and pass a t-test for the statistical resolution of their sample means ($p = 0.006$). Importantly, statistical resolution of μ^{142}Nd compositions between individual samples or between sample groups requires that these samples or groups recorded distinct Hadean-aged histories even when no samples or sample groups are statistically resolved from the JNdi-1 terrestrial standard (*cf.* Horan *et al.*, 2018). Further, the presence of statistically resolvable μ^{142}Nd values in modern rocks implies that their mantle sources previously preserved much greater μ^{142}Nd heterogeneity, since this tends to be erased by mantle convection over time (*e.g.*, Hyung and Jacobsen, 2020).

Although the Sr-^{143}Nd isotopic compositions of Crozet and Juan Fernandez OIBs fall into a global FOZO-type compositional range (Breton *et al.*, 2013; Truong *et al.*, 2018) (Fig. 1), there are also observable differences between the compositions of the two hotspots (Figs. 2b and 3). In particular, the Sr-^{143}Nd isotopic compositions of Penguin and Possession Island OIBs (Crozet) bracket those of both studied islands of Juan Fernandez, meaning that the Sr-^{142,143}Nd isotopic compositions of the islands could potentially be attributed to discrete, shared compositional domains that are variably mixed into the sources of these islands. We tested this possibility using several binary mixing models (Fig. 3). Model 1 assumes that Penguin and Possession represent unmixed FOZO-like components, and that Juan Fernandez OIBs represent an intermediate mixture of these components. This model can explain the Sr-^{143}Nd isotopic compositions of Juan Fernandez OIBs, albeit at comparatively extreme trace element abundances (Table S-3). However, mixing two components (Penguin and Possession) that both possess negative μ^{142}Nd values cannot produce an intermediate composition (Juan Fernandez) with a positive μ^{142}Nd value. Mixing model 2 instead assumes that Penguin Island represents a discrete FOZO component and that the isotopic compositions of Juan Fernandez and Possession OIB are explained by minor admixing of an EM component (*cf.* Breton *et al.*, 2013). This model can successfully reproduce the Sr-^{142,143}Nd compositions of Juan Fernandez lavas assuming that the EM end member possesses a μ^{142}Nd value of $\gtrsim +8$. However, this assumption cannot simultaneously explain the negative μ^{142}Nd compositions of Possession OIBs, which would require the EM end member to have $\mu^{142}\mathrm{Nd} \lesssim -5$. Further, there is no independent evidence that 1) such an EM component exists in Juan Fernandez lavas (Truong *et al.*, 2018), and 2) that this EM component would possess a resolvable positive or negative μ^{142}Nd value.

Mixing models 3 and 4 take the alternative perspective that Juan Fernandez OIBs represent a discrete FOZO component, and that Penguin and Possession lavas reflect admixing of a depleted MORB mantle (DMM) or an EM component, respectively. These models can successfully reproduce the Sr-^{142,143}Nd isotopic compositions of both Penguin and Possession lavas; however, they require that the bulk DMM

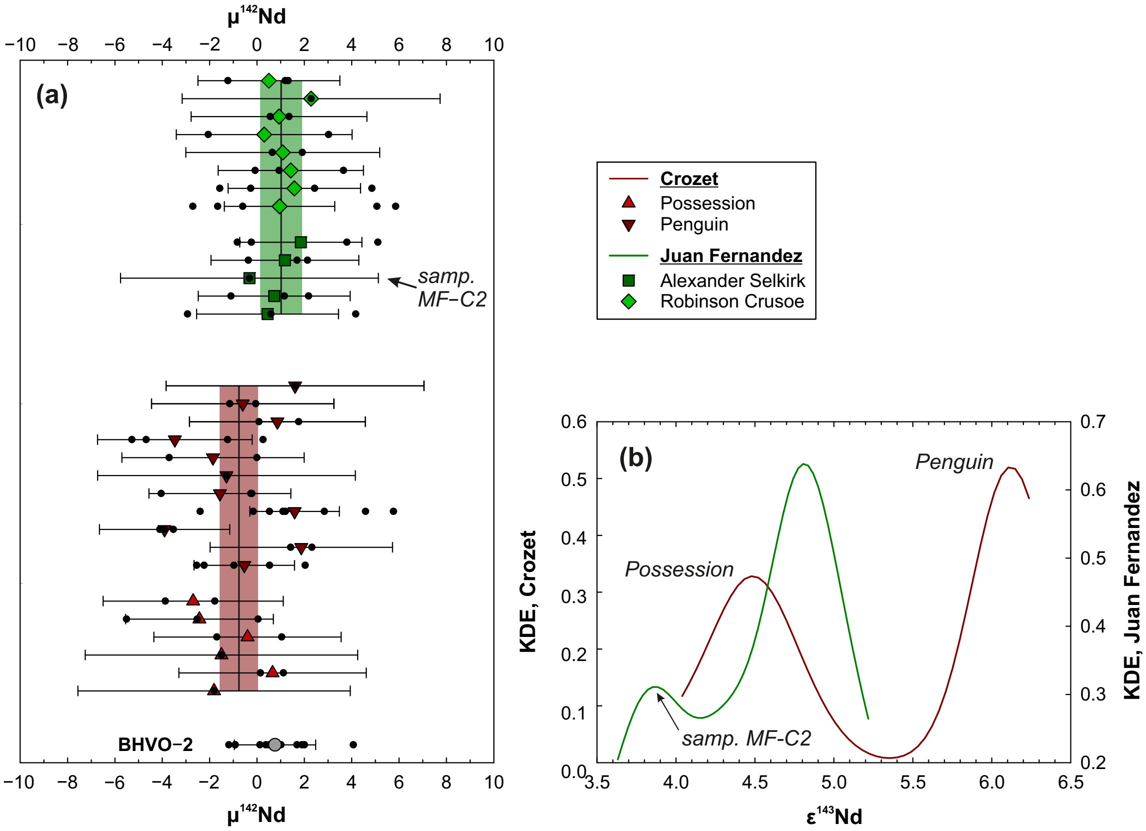

Figure 2 Neodymium isotopic compositions of ocean island basalts measured in this study. Small circles represent individual measurements, larger coloured symbols and error bars represent sample averages and 95 % confidence intervals, respectively. Vertical lines and coloured fields represent the average and 95 % confidence intervals of each hotspot. Values of ε^{143}Nd represented as a kernel density estimate (KDE).

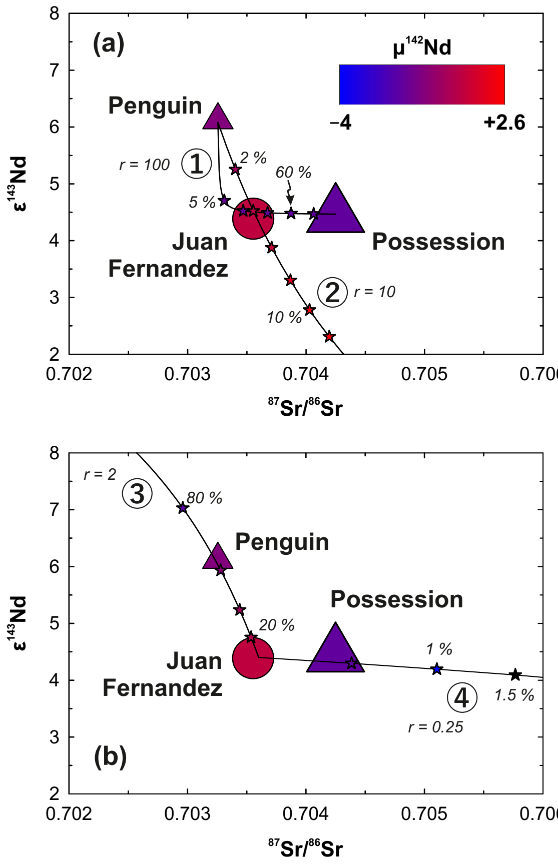

Figure 3 Mixing models (labelled by circled numbers as described in the text) for Sr-Nd isotopic compositions of studied ocean island basalts. Stars represent regular intervals of mixing as defined on each mixing curve; the colour of each curve corresponds to the μ^{142}Nd composition of the mixing interval as defined by the colour bar in panel **(a)**. The symbol size for each island covers the full range of its Sr-^{143}Nd isotopic compositions. Model inputs are summarised in Table S-2.

has μ^{142}Nd $\lesssim -4$ and the Possession EM component has μ^{142}Nd < -100 (Table S-3). Although there is evidence that global MORBs possess slightly negative μ^{142}Nd values (*ca.* μ^{142}Nd $= -1$ to -2; Peters *et al.*, 2024), there is no indication that the bulk DMM systematically possesses more negative μ^{142}Nd compositions. Similarly, there is no evidence that EM components have μ^{142}Nd compositions significantly more extreme than what has been observed in the Archean rock record (*ca.* −20 to +20). Thus, we infer that the μ^{142}Nd compositions of Crozet and Juan Fernandez OIBs cannot be reconciled by binary mixing processes. Instead, they must be explained by the existence of multiple mantle domains with similar, FOZO-like long lived isotopic compositions but heterogeneous μ^{142}Nd signatures. This conclusion expands the long held view of FOZO as a diffuse component without the clear, singular end member compositions exhibited by EM and HIMU (Hart *et al.*, 1992; Stracke *et al.*, 2005).

The Hadean-Aged Heritage of FOZO

The short half-life of the ^{146}Sm-^{142}Nd system (recently updated to 92 ± 3 Ma; Chiera *et al.*, 2024) requires that detectible μ^{142}Nd heterogeneity was generated before *ca.* 4 Ga ago, during the Hadean Eon. This means that the differing μ^{142}Nd compositions of Crozet and Juan Fernandez OIBs reflect distinct FOZO domains that experienced different geochemical histories during the first *ca.* 10 % of Earth's history. This finding implies that FOZO is not a singular component, but rather reflects different silicate differentiation histories that began in the Hadean Eon and have been partially preserved until the present. This result is particularly striking given the long lived isotopic characteristics of Crozet and Juan Fernandez OIBs. In particular, the ^{3}He/^{4}He ratios of lavas from both archipelagos do not extend to the very high values observed in other hotspots (Jackson *et al.*, 2017). However, the He-Pb isotopic characteristics of Crozet and Juan Fernandez OIBs overlap with the trend toward high ^{3}He/^{4}He ratios defined by Galápagos and Samoa OIBs, implying that they have primitive components with comparable origins (*cf.* Jackson *et al.*, 2007) (Fig. 1b). Further, Juan Fernandez lavas record some of the lowest known ^{182}W/^{184}W ratios among OIBs, well below OIBs from other hotspots with similar or higher ^{3}He/^{4}He ratios, such as Samoa (Mundl-Petermeier *et al.*, 2020). Identifying hotspots with shared ancient heritage is therefore clearly complicated, and a better view may be obtained by combining multi-dimensional isotopic data to explore isotopic heterogeneity within FOZO-type OIBs. A baseline analysis, utilising the normalisation scheme of Jackson *et al.* (2020) (Fig. 1d) for the combined long lived radiogenic (He-Sr-^{143}Nd-^{206}Pb) compositions of global OIBs, suggests that there are at least three distinct trends to high ^{3}He/^{4}He values. Some hotspots, such as Iceland, appear to transverse multiple trends. This raises the possibility that primitive mantle domains are not discrete and may rather be unique to each hotspot system.

We developed a machine learning model to approach the challenge of visualising and interpreting multi-dimensional isotopic data in this context. We initially compiled He-Sr-^{143}Nd-Pb isotopic and trace element data from 33 hotspots using the individual pre-compiled files available on the GEOROC database (DIGIS, Geoscience Centre Göttingen). Due to the requirement of machine learning models for relatively large datasets, the small amount of available ^{142}Nd and ^{182}W data precluded their direct inclusion in our model. We used the t-distributed stochastic neighbor embedding (TSNE) method to reduce the dimensionality of the data to produce simpler visual representations of the multi-dimensional data (*e.g.*, Fig. S-1). We found that the inclusion of He isotopic or trace element compositions made geological interpretation significantly more complex (Supplementary Information), and so we focused on the interpretation of results for Sr-^{143}Nd-Pb isotopic data alone. We used the initial findings for all compiled hotspots to guide the development of a refined K-means cluster analysis for nine hotspots with the greatest data availability, plus Juan Fernandez and Crozet. This resulted in the appearance of clusters with clear association to established mantle end member compositions, such as EM and HIMU (Fig. 4a; *e.g.*, White *et al.*, 2025). We then used this cluster analysis as an objective criterion to filter out samples that represented significantly depleted or enriched isotopic compositions relative to FOZO, and subsequently repeated the TSNE dimensionality reduction on the filtered data alone. For a full overview of the model development, see the Supplementary Information.

Among the FOZO-filtered dataset, at least three visually resolved groups are apparent (Fig. 4b). One is comprised of nearly all Hawaii and a majority of Iceland OIBs, which show strong overlap and are distinct from other hotspots. A second group is comprised primarily of the remaining Iceland and Hawaii lavas, along with Galápagos, Pitcairn and most Marquesas lavas, along with all but one sample from Penguin Island (Crozet). The final group is comprised of a few Iceland lavas along with Mascarene (Réunion), Samoa, Juan Fernandez and the remaining Marquesas and Crozet lavas. Although these groups are clearly distinct from one another,

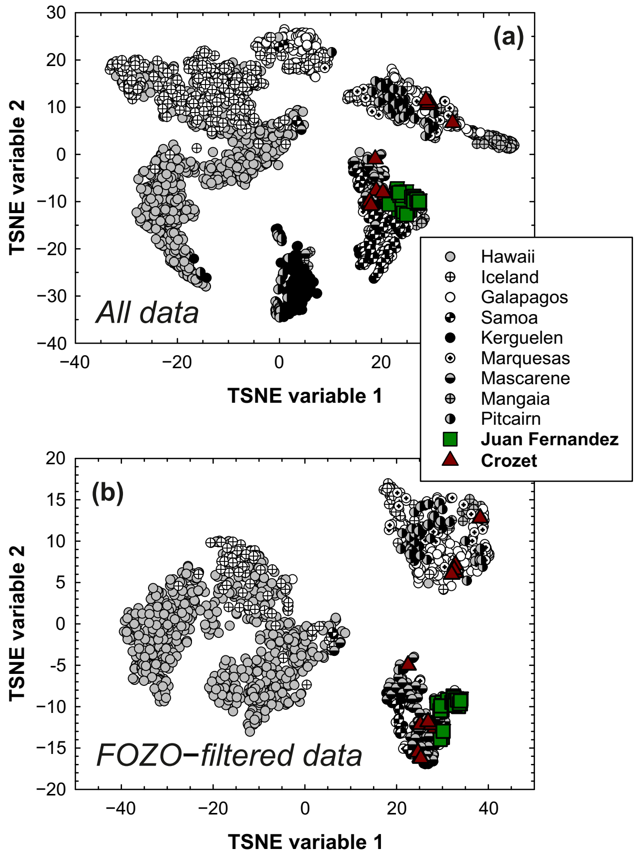

Figure 4 TSNE-reduced Sr-^{143}Nd-Pb isotopic data for selected hotspots using **(a)** all data for each hotspot or **(b)** data filtered FOZO-like isotopic compositions according to a K-means cluster model. See text and Supplementary Information for model details.

they each include OIBs that have differing compositions on binary isotope plots alone (Fig. 1). For example, the Sr-^{143}Nd-Pb and He-W isotopic systematics of Galápagos OIBs appear to be unlike those of Pitcairn or Marquesas OIBs; however, in the filtered TSNE analysis (Fig. 4b) these three hotspots mainly occupy the same cluster. Further, the TSNE analysis preserves apparent compositional differences between Penguin and Possession Island OIBs. However, Penguin Island lavas are not associated with either Juan Fernandez or Mascarene lavas, which share their FOZO-like Sr-^{143}Nd-Pb and moderately elevated ^{3}He/^{4}He compositions. Likewise, the association of Juan Fernandez and Possession OIBs, which have distinct μ^{142}Nd compositions, highlights that there must also be multiple independent geological histories preserved within a single TSNE group, since the TSNE reduction was done using only long lived isotopic compositions. One exception to these associations is lavas from Hawaii and Iceland OIBs, which were previously noted to have similar isotopic signatures (*e.g.*, Jackson *et al.*, 2007) and likewise have strongly overlapping TSNE compositions for a variety of multi-dimensional analyses, among them those including He isotopic compositions (Figs. 4, S-2), despite their geographic distance and association with different LLSVP.

Given these results, it is clear that the geological interpretation of machine learning models is not straightforward (*cf.* Stracke *et al.*, 2022; White *et al.*, 2025). In particular, given that the model associates OIBs with differing μ^{142}Nd compositions, the observed sample grouping must represent a minimum number of discrete FOZO components present in the mantle. Further, the presence of heterogeneous μ^{142}Nd values in a single TSNE cluster implies that Hadean-aged heterogeneity could be present throughout global OIBs and more high precision data is required in order to detect it. Our results thus highlight an opportunity for further tests of the geochemical relationship between potential common components of global hotspots. Given the lack of clear association between FOZO compositional clusters and geographic position of LLSVPs, further spatial analysis is required to understand where Hadean-aged components are stored and protected within the mantle. Further, as the ^{142}Nd and ^{182}W datasets for modern OIBs are expanded (Mundl-Petermeier *et al.*, 2020), the Hadean origins of modern volcanism can be better understood through multi-dimensional analysis and the geological processes responsible for Earth's development can be scrutinised more closely.

Acknowledgements

This project was supported by ETH Zürich/Marie Skłodowska-Curie Actions COFUND (18-1 FEL-28 to BJP) and the Swiss National Science Foundation (PZ00P2_186064 to BJP). The authors thank editor Raúl Fonseca for editorial handling and for thoughtful reviews from Catherine Chauvel, Bill White, and Erik Scherer, which helped improve the manuscript.

Editor: Raúl O.C. Fonseca

Data Availability Statement

All data generated in this study are available in the Supplementary Tables and have also been archived in the EarthChem database at https://doi.org/10.60520/IEDA/113771.

Additional Information

Supplementary Information accompanies this letter at https://www.geochemicalperspectivesletters.org/article2553.

Cite this letter as: Peters, B.J., Nauret, F., Moine, B., Castillo, P.R. (2025) Earth's foundational geological events stored in the fundamental mantle source of hotspots. *Geochem. Persp. Let.* 38, 34–39. https://doi.org/10.7185/geochemlet.2553

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