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Key Points:

- Peridotites from the Mid Atlantic Ridge at 7°N show kilometer scale isotopic heterogeneity
- Past and recent reaction with migrating melts moderates chemical depletion soon after its creation
- Radiogenic isotopes of ridge basalts do not reflect the time-integrated amount of prior melt extraction of their peridotitic mantle sources

Supporting Information:

Supporting Information may be found in the online version of this article.

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Earth Mantle's Isotopic Record of Progressive Chemical Depletion

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Abstract Mid ocean ridge basalts are partial melts of mantle rocks that have become incompatible element depleted prior to recent sub-ridge melting. This prior extent of melt extraction and concomitant incompatible element depletion is often inferred from the radiogenic isotope ratios of ridge basalts, such as hafnium and neodymium. However, hafnium isotope ratios by far exceeding those in ridge basalts are observed sporadically in exposed mantle rocks, abyssal peridotites. At least locally, therefore, Earth's mantle has evolved with much larger extents of incompatible element depletion over geologic time periods $(10^8-10^9 \text{ years})$ than inferred from ridge basalts. Here we show that such "ultra-depleted" hafnium isotope signatures also characterize peridotites exposed at the Doldrums Fracture Zone in the equatorial Mid Atlantic. These peridotites are closely associated with peridotites characterized by hafnium-neodymium isotope ratios similar to ridge basalts, but extensive incompatible element depletion. Our results demonstrate that Earth mantle's isotopic record of prior melt extraction is dampened by ubiquitous past and recent reaction with migrating melts. Hence, a better understanding of chemically reactive flow is required for deducing the mantle's rate of incompatible element depletion by recurring processing through melting regions in the shallow mantle, which is the driving force for silicate Earth evolution. Ultimately, better constraining the rate of incompatible element depletion from Earth's mantle is therefore of first-order importance for understanding our planet's basic mode of operation.

Plain Language Summary Recurring melting of Earth's mantle continuously forms new oceanic crust. As a result, the remaining residual mantle becomes increasingly deprived of incompatible elements; those elements that do not easily fit into the crystal lattices of mantle minerals. The magnitude and rate of this chemical "depletion" has often been inferred from the radiogenic isotopes ratios of incompatible elements (Sr, Nd, Hf, Pb) in the generated oceanic crust. However, rare samples of the melted mantle, abyssal peridotites, often have different radiogenic (Hf-Nd) isotope ratios than the lavas of the oceanic crust. This observation suggests that, for billions of years, Earth's mantle has evolved with higher extents of chemical depletion than inferred from the lavas of the oceanic crust. We show here that reacting with melts during repeated processing through shallow melting regions dampens the mantle's extent of chemical depletion. Better constraining the magnitude of this effect is key for deducing the rate of mantle processing, which is the driving force for silicate Earth evolution. Ultimately, better constraining the rate of incompatible element depletion from Earth's mantle is therefore of first-order importance for understanding our planet's basic mode of operation.

1. Introduction

Earth's sub-ridge mantle consists primarily of peridotite that has become depleted in incompatible elements (e.g., K, Rb, Cs, Th, U, rare earth elements (REE)) during partial melting several 10⁸–10⁹ years ago, as inferred from Os isotope ratios (e.g., Alard et al., 2005; Day et al., 2017; Harvey et al., 2006; Lassiter et al., 2014; C. Z. Liu et al., 2022; Paquet et al., 2022). Calculating the Sm/Nd and Lu/Hf ratios of such residual peridotites, that is, peridotites that have only been affected by melt extraction, shows that they should develop extremely high Nd-Hf isotope ratios during residence in the mantle (Salters & Zindler, 1995; Stracke et al., 2011). Such "ultra-depleted" Nd-Hf isotope ratios, which are by far higher than those generally observed in mid ocean ridge basalts (MORB; Figure 1), should therefore be typical for peridotites exposed on the ocean floor, abyssal peridotites.

But extremely high Hf isotope ratios, similar to those expected for ancient, residual peridotites, have only been observed in abyssal peridotites from the Arctic Ocean (Stracke et al., 2011). These "ultra-depleted" Hf isotope





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ratios are not associated with correspondingly high Nd isotope ratios, however, showing that the Arctic peridottes are not strictly residual (Stracke et al., 2011). Abyssal peridotites with both ultra-depleted ¹⁷⁶Hf/¹⁷⁷Hf and ¹⁴³Nd/¹⁴⁴Nd have not been found. So far, however, only two studies have reported combined Nd-Hf isotope ratios of abyssal peridotites (Mallick et al., 2015; Stracke et al., 2011), and only a handful of studies have reported Nd isotope ratios (Brunelli et al., 2018; Cipriani et al., 2004; Mallick et al., 2014, 2015; Salters & Dick, 2002; Snow et al., 1994; Stracke et al., 2011; Warren et al., 2009). The few existing ¹⁴³Nd/¹⁴⁴Nd data of abyssal peridotites overlap with those of MORB, although sporadic higher values occur. This observation has led to the general notion that radiogenic isotope ratios (e.g., Sr, Nd, Hf, Pb) in sub-ridge peridotites should mirror those of MORB (e.g., Snow et al., 1994), but is in contrast to more recent observations (e.g., Salters & Dick, 2002), and to the ultra-depleted ¹⁷⁶Hf/¹⁷⁷Hf and ¹⁴³Nd/¹⁴⁴Nd predicted for ancient residual peridotites (Figure 1).

Further chemical and radiogenic isotope data of abyssal peridotites are critical, therefore, for assessing how abundant such ultra-depleted Nd-Hf isotope signatures are, and for accurately constraining the extent of incompatible element depletion of Earth's sub-ridge mantle. Independently, however, the Nd-Hf isotope variability of MORB (Salters et al., 2011; Sanfilippo et al., 2019, 2021), and the discovery of ultra-depleted Nd isotope ratios in olivine-hosted melt inclusions (Stracke et al., 2019), require that melts from peridotites with ultra-depleted Nd-Hf isotope signatures contribute significantly to the chemical and isotopic budget of oceanic basalts. These observations are a smoking gun that residual peridotites with ultra-depleted Nd-Hf isotope ratios are more abundant in Earth's mantle than generally thought, and raise several first-order questions: (a) Why are residual peridotites with ultra-depleted Nd-Hf isotope ratios than ancient, residual peridotites (Figure 1)? If a large fraction of the sub-ridge peridotites has indeed ultra-depleted Nd-Hf isotope ratios, (c) how does this change the general perception about the rate of incompatible element depletion, and thus oceanic crust formation over Earth's history?

In this study, we address these questions with new chemical and Nd-Hf isotope data of clinopyroxenes from peridotites exposed at the Doldrums Fracture Zone in the equatorial Mid Atlantic. Their heterogeneous chemical and isotopic compositions indicate that recurring cycles of partial melting have variably depleted these peridotites in incompatible elements, but also that ubiquitous past and/or recent reaction with migrating melts has dampened their chemical and isotopic record of prior melt extraction. The combined processes of partial melting and subsequent melt-rock reaction processes consequently determine the ultimate extent of incompatible element depletion and isotopic evolution of the peridotitic mantle that has been processed through sub-ridge melting regions.

The so-called "mantle processing rate" determines how much of Earth's mantle has been cycled through melting regions in the shallow mantle. Estimates of the mantle processing rate, based on current oceanic crust productions rate (e.g., Salters & Stracke, 2004; Stracke et al., 2003), or based on modeling the isotopic spectrum of oceanic basalts, range mostly from ca. 4 to 0.5 Ga for processing one mantle mass through melting regions in the shallow mantle (e.g., Albarède, 2005; Parai & Mukhopadhyay, 2018; Porcelli & Wasserburg, 1995; Rudge, 2006; Rudge et al., 2005). Although these estimates vary substantially, they suggest that partial melting and melt-rock reaction processes similar to those deduced in this study have affected all of the mantle at least once, if not multiple times, during Earth's history. The results of our study are therefore critical for understanding the global geochemical evolution of Earth's mantle, which scales with the mantle's convective vigor, and drives silicate Earth evolution in general. Hence, the presented results are of global significance and are crucial for understanding our planet's basic mode of operation.

2. Materials and Methods

2.1. Sample Selection

Abyssal peridotites were collected during three expeditions of the research vessel A.N. Strakhov (S06, S09, and S45) to the Doldrums Fracture Zone in the Equatorial sector of the Mid-Atlantic Ridge (7–8°N). The Doldrums Fracture Zone is a complex tectonic system composed by a 600×100 km-wide, lens-shaped and deformed portion of oceanic lithosphere (Figure 2). The thick and cold lithosphere is fragmented by five transform faults interspersed by four intra-transform ridge segments (Skolotnev et al., 2020). Peridotites were sampled along the transverse ridge along the northern transform fault of this system (dredge S45-15), and across the western and eastern flanks of the northern intra-transform ridge, at the inside corner high located at 16 km from the active intra-transform spreading segment (dredge and S09-73, Figure 2; see also Skolotnev et al., 2020). These sampling





Figure 1. Diagram showing the Hf and Nd isotope ratios of clinopyroxenes from abyssal peridotites (Indian Ridge peridotites: Mallick et al., 2014, 2015, Gakkel Ridge peridotites: Stracke et al., 2011) and depleted lithospheric peridotites (Bizimis et al., 2003; Byerly & Lassiter, 2014; Guarnieri et al., 2012; Sanfilippo et al., 2019) compared to global mid ocean ridge basalts (MORB) (compiled from PetDB, www.earthchem.org/petdb). Also shown are histograms of isotope ratios of MORB (light blue) and peridotites (dark green), including additional Nd isotope ratios from peridotites of the Atlantic and Indian Ridges (Brunelli et al., 2018; Cipriani et al., 2004; Mallick et al., 2014, 2015; Salters & Dick, 2002; Snow et al., 1994; Warren et al., 2009). Also shown are expected Hf-Nd isotopic evolution lines for depleted mantle residues after 5%, 7%, 10%, and 15% of partial melting at 0.5, 1, and 1.5 Ga ago (red, blue and brown lines, see Supporting Information S1 for details of the underlying calculations). Solid lines represent partial melting starting in the garnet stability field (3.5%) followed by further melting at spinel facies; dashed lines represent melting exclusively in the spinel stability field.

sites are located 150 and 180 km east of the Mid-Atlantic Ridge, roughly corresponding to a seafloor age between 10 and 12 Ma.

2.2. Analytical Techniques

2.2.1. Major and Trace Elements Compositions

A thorough description of the petrography and major-trace element mineral compositions of previously analyzed peridotites from expeditions S06 and S09 is given by Sani et al. (2020). New samples from expedition S45 were characterized with optical microscopy, and the original mineralogy was estimated by point counting (Tables S1 and S2 in Supporting Information S1). Serpentine with mesh texture and associated magnetite was attributed to olivine (ol), whereas bastitic serpentine was attributed to orthopyroxenes (opx). Selected peridotites range from harzburgites to cpx-poor Iherzolites. Major element compositions were measured by electronprobe microanalysis with a JEOL JXA8200 superprobe at the Department of Earth's Science Ardito Desio of Milano University using an accelerating voltage of 15 kV and a beam current of 15 nA. Major element compositions of cpx, and spinels (sp) are provided in Table S1 in Supporting Information S1. The trace element composition of clinopyroxenes was analyzed on thin sections by laser ablation ICP-MS using a QQQ-ICP-MS Agilent Series 8900 interfaced to a GeoLas 193 nm excimer ablation system (Lambda Physik, Germany) at the Istituto Geoscienze e Georisorse, Consiglio Nazionale delle Ricerche (CNR–IGG) S.S. of Pavia. The ablation system was operated at a 10 Hz repetition rate, 50 μ m spot size, with a fluence of about 9 J/cm². Helium was used as carrier gas and mixed with Ar downstream of the ablation cell. The NIST SRM 610 synthetic glass was used as external standard, with ⁴⁴Ca







as internal standard (Pearce et al., 1997). Background and signal were measured for about 60 s, and the raw data were processed with the software package GLITTER® (Griffin et al., 2008). The precision and accuracy was assessed by repeated analyses of the BRC-2g reference material and is generally better than $\pm 10\%$.

2.2.2. Nd and Hf Isotope Ratios of Clinopyroxene Separates

The Hf and Nd isotope ratio measurements of clinopyroxenes were performed at the Institut für Mineralogie, Westfälische Wilhelms-Universität Münster (WWU) (Table S2 in Supporting Information S1). We selected four peridotites from expeditions S09 (see Sani et al., 2020) and four from expedition S45. The clinopyroxene separates (~150 mg, hand-picked under binocular microscope) were leached with H_2O_2 in an ultrasonic bath for about 2 hr to remove Mn oxide coatings. Subsequently, the cpx were leached in 6 N HCl for about 2 hr in an ultrasonic bath, followed by leaching in 6 N HCl for about 2 hr at 100°C to remove the effects of seawater alteration.

The grains were dissolved in concentrated HF-HNO3 (4:1) for 3 days at 140°C. After drying at 120°C, the samples were re-dissolved with 6 N HCl together with H_3BO_3 at 120°C for 1 hr. Strontium and the high field strength (HFSE) and REE fractions of the samples were separated using standard cation exchange

chromatography (Biorad® AG50W-X8, mesh size 200–400 μ m). Hafnium was purified from the HFSE fraction using Eichrom® Ln Spec columns (Münker et al., 2001). Neodymium was further purified from the REE fraction in a second column, using an Eichrom® Ln Spec resin (mesh size 50–100 μ m) (Pin & Zalduegui, 1997).

The Nd and Hf isotope ratios were determined on a Thermo Scientific NEPTUNE plus MC-ICP-MS at WWU. Repeated measurements of the JMC-475 Hf standard gave an average 176 Hf/ 177 Hf = 0.282160 ± 13 (2 S.D., n = 8, 10–30 ppb solution). All Hf isotope ratios are reported relative to 176 Hf/ 177 Hf = 0.282160 (Blichert-Toft et al., 1997). To verify accuracy of the isotope ratio measurements, the USGS rock reference materials BHVO-2 and BCR-2 were processed as unknowns and gave 176 Hf/ 177 Hf = 0.283096 ± 25 (2 S.D., n = 12) for BHVO-2 and 176 Hf/ 177 Hf = 0.282867 ± 20 (2 S.D., n = 10) for BCR-2. The JNdi-1 (20 ppb) Nd bracketing standard was determined at 143 Nd/ 144 Nd = 0.512067 ± 11 (2SD, n = 7), and all data are normalized to JNdi-1 143 Nd/ 144 Nd = 0.512641 ± 12 (2 S.D., n = 5) for BCR-2.

3. Results

Based on their texture and chemical compositions two groups of peridotites from the Doldrums Fracture Zone can be distinguished, termed "residual" and "refertilized" peridotites by Sani et al. (2020) (Figure 2) (see Tables S1 and S2 in Supporting Information S1).

Most peridotites selected for this study are residual peridotites, meaning they generally do not show textural evidence for interaction with melts during the recent melting process. Note that the term "*recent*" is used for melting processes during processing under the Mid Atlantic Ridge before emplacement on the ocean floor. Based on the maximum distance of the sampling sites from the Mid Atlantic Ridge axis and an average spreading rate of 15 mm/year, the last melting events occurred no more than 12 Ma ago (see Sani et al., 2020). Consistent with their texture, the chemical compositions of the residual peridotites show no obvious sign of concomitant incompatible element enrichment during recent melt-rock reaction (Figure 3). They have high Cr# (Cr/(Cr + Al), 30–50 mol%) and low TiO₂ contents (<0.1 wt.%) in spinel (Table S1 in Supporting Information S1), for example, but also low heavy REE abundances and light to middle REE ratios (Yb = $0.53-1.03 \ \mu g/g$ Ce/Sm = 0.13-0.42), as well as low high field strength element abundances (Zr = $0.23-0.31 \ \mu g/g$ and Hf = $0.02-0.1 \ \mu g/g$) relative to similarly incompatible REE in clinopyroxene (cpx, Figure 2).

Despite such very depleted incompatible element compositions, the residual peridotites have Nd-Hf isotope ratios similar to the local MORB (Figure 3; 143 Nd/ 144 Nd = 0.51301–0.51328 and 176 Hf/ 177 Hf = 0.28312–0.28328). Surprisingly, the cpx with the lowest 176 Hf/ 177 Hf and 143 Nd/ 144 Nd have the highest Lu/Hf, Sm/Nd, and the lowest Ce/Yb and Yb content (Figure 4). That is, they are most incompatible element depleted, although their isotope ratios document a time-integrated evolution with only modest incompatible element depletion (low, MORB-like Lu/Hf and Sm/Nd ratios).

The refertilized peridotites, on the other hand, show textural evidence for recent post-melting entrapment and crystallization of interstitial melts, such as interstitial cpx and rare plagioclase-bearing veins crosscutting the mantle porphyroclasts (Sani et al., 2020). These samples have high Cr# (51–52 mol%) with high TiO₂ contents (0.12 wt.%) in spinel (Table S1 in Supporting Information S1). Their heavy REE abundances (Yb = 0.65–0.82 µg/g) in clinopyroxene (cpx) are similar to those of the residual peridotites, but they have higher Na₂O (0.4 wt.%), high field strength element contents (Zr = 1.73–1.96 µg/g and Hf = 0.09–0.08 µg/g) and light to middle REE ratios (Ce/Sm = 1.13–1.24) (Figure 2).

Unlike the residual peridotites, the refertilized peridotites have Hf isotope ratios by far higher than MORB, but Nd isotope ratios within the MORB range (Figures 3 and 4; 176 Hf/ 177 Hf = 0.2841–0.2856, 143 Nd/ 144 Nd = 0.513 0–0.5133); similar to cpx of abyssal peridotites from the Arctic Ocean (Stracke et al., 2011), xenoliths from Hawaii (Bizimis et al., 2003), and peridotites from the sublithospheric continental mantle (e.g., Guarnieri et al., 2012; Sanfilippo et al., 2019). These isotope signatures indicate that the refertilized peridotites evolved with highly depleted incompatible element compositions for several 10^8 – 10^9 years, but have become partly re-enriched in incompatible elements by reacting with migrating melts during recent sub-ridge melting, consistent with their comparatively high light REE abundances (see detailed discussion below).





Figure 3. Diagram showing the Hf and Nd isotope ratios of clinopyroxenes from Mid-Atlantic Ridge peridotites reported in this study (error bars are smaller than the size of the symbols). Additional data are for abyssal peridotites from the Gakkel and Indian Ridges and Atlantic mid ocean ridge basalts (MORB) (data sources as in Figure 1, MORB data compiled from PetDB, www.earthchem.org/petdb). Note that clinopyroxenes of the "residual" peridotites analyzed this study overlap with those of MORB, whereas clinopyroxenes in the "refertilized" peridotites extend toward extremely high ¹⁷⁶Hf/¹⁷⁷Hf, similar to some of the peridotites from Gakkel Ridge.

4. Discussion

Mantle melting at mid ocean ridges creates a range of residual peridotites from which variable amounts of melts have been extracted (e.g., Langmuir et al., 1992; Stracke, 2021; Willig et al., 2020). The variably incompatible element depleted peridotites may also react to different extents with migrating melts in the sub-ridge melting region (e.g., Brunelli et al., 2006, 2014; Hellebrand & Snow, 2003; Seyler et al., 2007; Warren, 2016), either recently or during prior melting, or both. A diverse range of incompatible element (e.g., REE) depleted and re-enriched peridotites with highly variable Nd-Hf isotope ratios should therefore characterize the sub-ridge mantle, and thus abyssal peridotites sampled on the ocean floor (cf. Stracke et al., 2011).

Figure 5 illustrates how recurring cycles of partial melting and melt-rock reaction affect the REE abundances and Nd-Hf systematics of mantle peridotites and provides the context for evaluating the new major-trace element and Nd-Hf isotope data of the Doldrums peridotites in the following. A detailed description of the underlying calculations is included in Supporting Information S1.

4.1. Partial Melting and Melt-Rock Reaction Processes in the Sub-Ridge Mantle

Figure 5a shows that partial melting produces residual peridotites with high Sm/Nd and Lu/Hf, which develop extremely high ¹⁴³Nd/¹⁴⁴Nd and ¹⁷⁶Hf/¹⁷⁷Hf over geologic timescales (10⁸–10⁹ years); by far higher than those





Figure 4. Diagrams showing Hf and Nd isotope ratios versus trace element indices of depletion in clinopyroxenes from peridotites of the Doldrums Fracture Zone and global abyssal peridotites. Clinopyroxenes in residual peridotites from this study (dark green squares) have MORB-like isotope ratios and incompatible element depleted trace element compositions indicating that they have developed with moderate incompatible element depletion for several 100–1,000 million years before additional recent melt depletion at the Mid-Atlantic Ridge (symbols as in Figure 2). The clinopyroxenes from the refertilized peridotites (light green squares) have very high ¹⁷⁶Hf/¹⁷⁷Hf coupled with MORB-like ¹⁴³Nd/¹⁴⁴Nd, but high Ce/Yb, low Sm/Nd and variable Lu/Hf suggesting that highly depleted peridotites were recently re-enriched with incompatible elements by melt-rock reaction. (c), (d) Close-ups of (a), (b) showing correlations between ¹⁷⁶Hf/¹⁷⁷Hf, ¹⁴³Nd/¹⁴⁴Nd and Yb contents in residual peridotites. Note that these are in opposite direction to those of abyssal peridotites from the Indian Ocean, where progressively more incompatible element enriched samples also have lower isotope ratios, resulting from recent reaction with isotopically less depleted melts (Mallick et al., 2014, 2015; Warren, 2016).

generally observed in MORB (see also Figures 1 and 3). Figures 5c and 5e show how variable extents of reaction with migrating or trapped melts re-enriches the REE contents of the residual peridotites. Because residual peridotites have much lower Nd/Hf ratios than typical MORB-like melts, even low extents of melt-rock reaction result in melt-like Sm/Nd in the reacted peridotite, whereas high Lu/Hf close to those of the residual peridotites can be preserved (Figure 5c). After several 10^8 – 10^9 years (1×10^9 Ga in Figures 5a, 5c, and 5e), the reacted peridotites will have developed low, MORB-like 143 Nd/ 144 Nd, but retained high 176 Hf/ 177 Hf similar to residual peridotites (Figure 5c). For larger extents of melt-rock reaction (Figure 5e), both Sm/Nd and Lu/Hf become melt-like (Figure 5e), and the reacted peridotites develop MORB-like Nd-Hf isotope ratios after several 10^8 – 10^9 years (1×10^9 Ga in Figure 5e). In this case, ancient melt-rock reaction effectively counteracts mantle depletion soon after its creation, and fully conceals the isotopic record for its extent and timing of prior melt extraction (Figure 5e).

Figures 5b, 5d, and 5f illustrate how renewed melting and melt-rock reaction affect the REE abundances and the Nd-Hf isotope ratios of the diverse peridotites produced by variable extents of ancient partial melting and melt-rock reaction shown in Figures 5a, 5c, and 5e. The residual peridotites (Figure 5a), for example, may simply melt again, which further depletes their REE contents (Figure 5b left panels). Because there is no time for radiogenic

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ingrowth after recent sub-ridge melting, the residual peridotites preserve their "ultra-depleted" Nd-Hf isotope ratios (Figure 5b left panels; cf. Stracke et al., 2011).

Variable reaction with typical MORB-like melts after renewed melting, however, re-enriches the incompatible element contents of the residual peridotite to different extents, and changes their Nd-Hf isotope ratios (Figure 5b, right panels). The ¹⁴³Nd/¹⁴⁴Nd are readily shifted toward those of the interacting, MORB-like melt, even for low extents of melt-rock reaction, whereas high ¹⁷⁶Hf/¹⁷⁷Hf similar to those of the residual peridotite may be preserved (Figure 5b, orange line, orange dot). For larger extents of melt-rock reaction, the melt fully imposes its ¹⁴³Nd/¹⁴⁴Nd -¹⁷⁶Hf/¹⁷⁷Hf onto the peridotites and completely erases the pre-existing Nd-Hf isotope signatures of ancient mantle depletion (Figure 5b, red line, red dot).

Figures 5d and 5f show how recent melting and melt-rock reaction affect the REE content and Nd-Hf isotope ratios of peridotites that have already been re-enriched by past melt-rock reaction processes (Figures 5c and 5e). Recent melting depletes the REE contents but preserves the high ¹⁷⁶Hf/¹⁷⁷Hf and MORB-like ¹⁴³Nd/¹⁴⁴Nd of peridotites resulting from limited amounts of past melt-rock reaction (Figure 5d left panels). In comparison, peridotites that have been partially reset by recent melt-rock reaction, but did not react with migrating melts during past melting processes have similar Nd-Hf isotope ratios, but different REE patterns (Figure 5b right panel). Hence, the relative light to heavy REE enrichment for peridotites with high ¹⁷⁶Hf/¹⁷⁷Hf but MORB-like ¹⁴³Nd/¹⁴⁴Nd can discern if small extents of melt-rock reaction occurred recently or in the past.

If peridotites affected by limited extents of past melt-rock reaction (Figure 5c) also react with MORB-like melts during recent sub-ridge processing, their REE become re-enriched and their Nd-Hf isotope values shift toward those of the reacting melt (Figure 5d right panels). The extent of this isotopic change depends on the extent of recent melt-rock reaction and the Nd-Hf isotope ratios of the reacting melt (orange and red lines and dots in Figure 5d right panels). In this case it is difficult to distinguish peridotites that are only affected by recent melt-rock reaction (Figure 5b right panels) from peridotites that melted and reacted to a limited extent with migrating melts both recently and in the past (Figure 5d right panels).

Similar systematics apply for peridoities that were affected by past melting and extensive melt-rock reaction processes, and are characterized by MORB-like Nd-Hf isotope ratios today (Figure 5e). That is, they may simply melt again and become more incompatible element depleted while retaining their inherited MORB-like isotope signatures (Figure 5f left panels). Alternatively, they may melt and react again to various extents with migrating melts during recent sub-ridge processing, and thus become more REE enriched (Figure 5f right panels). Depending on the extent of melt-rock reaction and the isotope ratios of the migrating melt, the inherited, MORB-like ¹⁴³Nd/¹⁴⁴Nd -¹⁷⁶Hf/¹⁷⁷Hf of the peridoities may shift further toward those of the reacting melt (Figure 5f right panels).

Overall, Figure 5 shows that the combined REE content and Nd-Hf isotope ratios of mantle peridotites depend strongly on their prior history of melt depletion and extent of past and/or recent reaction with migrating or trapped melts. To what degree melt-rock reaction processes affect global mantle evolution, as opposed to creating second-order isotopic heterogeneity on a cm-m scale (Brunelli etal., 2006, 2014; Laukert et al., 2014; Le Roux et al., 2007; Sani et al., 2020; Seyler et al., 2001, 2004, 2007; Suhr et al., 2008; Tartarotti et al., 2002; Warren, 2016) is therefore critical for understanding the mechanisms and rate of incompatible element depletion from Earth's mantle. The latter scales with the rate of melt extraction (ocean crust formation), and thus the processing rate and internal dynamics of Earth's mantle, which are the two most fundamental parameters for better constraining silicate Earth evolution.

Figure 5. Diagrams showing the effects of past and recent partial melting and melt-rock reaction on the REE and Nd-Hf isotope ratios of mantle peridotites. Details of the underlying calculations of the melting and melt-rock reaction processes are given in Supporting Information S1. (a) Ancient REE-depletion after 7% degree of partial melting of a primitive mantle (compositions from McDonough & Sun (1995)) and isotopic evolution of the mantle residue for 1 Ga. (b) Effect of present-day melting and melt rock reactions on REE and isotope compositions on mantle residue produced in (a) (in orange partial resetting; in red total resetting, see Supporting Information S1 for further details). (c) Low degrees of past melt-rock reaction (1 Ga ago) of the mantle residue shown in panel (a). The low Sm/Nd and high Lu/Hf of the reacted mantle develop high ¹⁷⁶Hf/¹⁷⁷Hf coupled with MORB-like ¹⁴³Nd/¹⁴⁴Nd. (d) Effects of recent melting and melt-rock reaction of the mantle produced in (c). (e) High degrees of ancient melt-rock reaction of the mantle residue shown in (a). The low Sm/Nd and low Lu/Hf of the reacted mantle causes MORB-like ¹⁷⁶Hf/¹⁷⁷Hf and ¹⁴³Nd/¹⁴⁴Nd isotopic ratios. (f) Effect of recent melting and melt-rock reaction of the mantle produced in (e). Dashed lines in REE diagrams refer to the initial rock composition. Dashed lines in isotope spaces (b, d, f) refer to the isotopic evolution after radiogenic ingrowth. Empty and solid dots represent the initial and final rock compositions. Isotopic compositions of mid ocean ridge basalts are also reported as gray dots (PetDBdataset_PetDB05September2020). For detailed further discussion see Section 4.1.





Figure 6. Diagrams showing the effects of partial melting and melt–rock reaction on the elemental and Hf–Nd isotope ratios of the peridotites from the Doldrums Fracture Zone. Shown in panel (a) are the 176 Lu/¹⁷⁷Hf-¹⁴⁷Sm/¹⁴⁴Nd (bulk rock) of pure melting residues (F = 5%, 7%, 10%, 15%, as indicated by italic numbers). Melting in the garnet and spinel stability field is indicated in solid and dashed black lines, respectively (see Figure 1a). The 176 Lu/¹⁷⁷Hf-¹⁴⁷Sm/¹⁴⁴Nd evolution of these mantle residues after melt–rock interaction is indicated by gray lines. Details on the melting and melt-rock reaction models are given in Supporting Information S1. (b) Present-day isotopic compositions after ancient melt–rock interaction (500 Ma) of a heterogeneous mantle residue (melting in garnet stability field as in panel a) compared to clinopyroxenes from global abyssal peridotites and Atlantic mid ocean ridge basalts (MORB) (symbols as in Figure 1). Each gray trend refers to the isotopic composition of a single melting residue (F = 5%, 7%, 10%, 15%, as indicated by italic numbers) modified by melt-rock reaction at steps of F = 0.5% (filled or unfilled gray dots). Trends connecting the same degree of interaction are shown by solid black lines. The close-up at the lower-right shows the model results in the MORB isotope range. Note that ancient melt-rock interaction shifts the isotope ratios of the modified peridotites toward the melt composition, although never coinciding with the melt as an effect of difference in parent/daughter ratios.

4.2. Peridotites From the Doldrums Fracture Zone

4.2.1. "Refertilized" Peridotites: Ancient Depletion, Recent Re-Enrichment

Textural evidence for post-melting entrapment and crystallization of small aliquots of interstitial melts at near lithospheric conditions for the "refertilized" peridotites shows that melt-rock reaction occurred recently, that is, immediately after partial melting at the Mid Atlantic Ridge (Sani et al., 2020). Notably, any textural record of past melt-rock reaction would have been erased by recrystallization of the deep-mantle assemblage to an olivine-pyroxene mineral assemblage during recent upwelling into the melting region under the Mid-Atlantic Ridge. Textural evidence for melt-rock reaction can therefore only be attributed to recent processes.

The high ¹⁷⁶Hf/¹⁷⁷Hf of the refertilized peridotites, however, reflect a time-integrated evolution with strong incompatible element depletion (high Lu/Hf and Sm/Nd) for billion-year timescales before being processed recently at the Mid Atlantic Ridge (e.g., up to 20% melt extracted from a primitive mantle (PM) up to ~2 Ga ago, Figure 1). Similar to the scenario in Figure 5b (right panels), their MORB-like ¹⁴³Nd/¹⁴⁴Nd indicate that recent melt-rock reaction processes have partly reset their isotopic record of ancient melt depletion. But comparison to Figures 5c and 5d show that it cannot be fully excluded that the high ¹⁷⁶Hf/¹⁷⁷Hf but MORB-like ¹⁴³Nd/¹⁴⁴Nd may also result from past melt-rock reaction (Figure 5c), or both past and recent melt-rock reaction processes (Figure 5d, right panels).

Detailed modeling of the Nd-Hf isotope signatures of the refertilized peridotites (Figure 6; Figure S1 in Supporting Information S1) shows that ancient melt-rock interaction of an intrinsically heterogeneous residual mantle





Figure 7. Diagram showing the effects of two successive partial melting events on the REE contents of clinopyroxenes of originally primitive mantle (PM), compared to those in the average Doldrums residual peridotites. The parameters of the partial melt models are same as in Figure 5 and detailed in Supporting Information S1. Ancient (1 Ga ago) REE-depletion after 2% degree of partial melting of a PM (compositions from McDonough & Sun (1995)) leads to mildly light REE depleted REE patterns (orange line) and Nd-Hf isotopic compositions of the Doldrums residual peridotites (not shown). However, the clinopyroxene in this mantle residue (in orange) has similar heavy rare earth elements (HREE) but much higher light rare earth elements contents than the average clinopyroxene in the Doldrums residual peridotites (dashed green line). Additional partial melting (4%) during recent processing under the Mid Atlantic Ridge results in further REE-depletion. The modeled REE patterns match the light REE but have much lower HREE contents than the Doldrums peridotite clinopyroxenes. Hence, although the Nd-Hf isotope signatures of the Doldrums residual peridotites are consistent with a 1 Ga-old extraction of 2% melt from an initially PM, their REE patterns require ancient melt-rock reaction to increase the overall HREE concentrations (see left panel in Figure 5f).

and migrating MORB-like melts can reproduce their trace element and isotope signatures. Independent of the initial degree of mantle depletion, low degrees of melt-rock interaction cause strong light REE enrichment, shifting the Sm/Nd and thus the Nd isotope ratios of the reacted rock toward that of the interacting melt, whereas Hf and the middle to heavy REE are less affected (Figure S1 in Supporting Information S1). The Lu/Hf ratios, however, are only partially reset by melt-rock reaction, producing reacted peridotites with high present-day Hf isotope ratios (Figure 6a). Therefore, the Nd-Hf isotopic signatures of the refertilized peridotites could be partly inherited from past melt-rock reaction events (see Figure 5d), but further modified during recent partial melting and melt-rock interaction. Indeed, the low TiO_2 contents and the relatively modest light to heavy REE enrichment of the clinopyroxene, as well as the low TiO_2 and Cr# in spinel, imply low degrees of recent interaction with melts, and further complicate assessing the magnitude of past versus recent melt-rock reaction processes (compare to Figures 5b–5d). Owing to the multitude of unknowns involved (e.g., extent of melting and melt-rock reaction, composition of melt and rock, timing of these processes, etc.), it is therefore exceedingly difficult to disentangle in retrospect to what extent the incompatible and isotopic signatures of the refertilized peridotites have been affected by ancient versus recent melt-rock reaction processes, or both (cf. Stracke et al., 2011).

4.2.2. "Residual" Peridotites: Ancient Depletion and Re-Enrichment, Young Depletion

Unlike the refertilized peridotites, the texture and major element compositions of the residual peridotites from the Doldrums Fracture Zone indicate that they did not react with melts during recent melting at the Mid Atlantic Ridge (Sani et al., 2020). Clinopyroxenes from these samples are light REE depleted and range to very high Lu/Hf and Sm/Nd ratios (Figures 2 and 4), but are associated with MORB-like Nd-Hf isotope ratios (Figures 2 and 4). The latter indicate that they must have developed with comparatively low Lu/Hf and Sm/Nd for several 10^8-10^9 years before the recent melting event, reinforcing that their high degree of incompatible element depletion is a young feature.

One possibility for explaining the MORB-like Nd-Hf isotope ratios of the residual peridotites is that they reflect ancient mantle that became mildly depleted during past melting, followed by additional partial melting during recent processing under the Mid Atlantic Ridge. The isotope signatures of the residual peridotites are consistent with extraction of about 1%-3% melt from an initially PM or <2% melt from a depleted mantle with a melting age between 0.5 and 2 Ga (Figures 1 and 5a). But it is impossible to match the REE patterns, especially the light REE versus heavy REE abundances, by two such successive partial melting events. The reason is that the heavy REE abundances of the residual peridotites are similar to those in cpx in equilibrium with PM (McDonough & Sun, 1995; Figures 2c, and 7). Ancient partial melting of PM would decrease the REE contents of the initially

PM, followed by further lowering of the REE during recent melting. Matching the light REE depletion of the residual peridotites by repeated partial melting consequently leads to much lower heavy REE abundances than observed in the residual peridotites (Figure 7). Without concomitant or subsequent re-enrichment of the heavy REE by reaction with migrating melts, therefore, this scenario is impossible to reconcile with the high heavy REE contents of the residual peridotites (Figure 7).

An alternative explanation for the combined isotopic and REE element composition of the residual peridotites could be that ancient partial melting without melt-rock reaction, has produced peridotites with strong incompatible element depletions which have developed Nd-Hf isotope ratios by far higher than MORB prior to the recent melting event (Figure 5a). The observed MORB-like isotope ratios of the residual peridotites then require complete resetting by recent reaction with melts with MORB-like isotope ratios. But again, even with light REE depleted MORB-like melts, matching the light REE depletion and strong heavy REE enrichment of the residual peridotites that are associated with the residual peridotites (Sani et al., 2020). These plagioclase-impregnated" peridotites that are associated with the residual peridotites (Sani et al., 2020). These plagioclase-bearing rocks are strongly light REE depleted but have even higher heavy REE contents than the residual peridotites. These features were reproduced by Sani et al. (2020) by recent reaction of light REE depleted melts (MORB-like or ultra-depleted melt) with originally ultra-depleted peridotites (cf. Brunelli et al., 2014). Comparison of the distinct light to heavy REE abundances of the "plagioclase-impregnated" and residual peridotites (Sani et al., 2020) therefore confirms that this alternative scenario of strong ancient depletion coupled to recent partial melting and extensive interaction with light REE depleted melts is also impossible to reconcile with the combined REE abundances and Nd-Hf isotope ratios of the residual peridotites (Figures 2, 5b, and 7).

More likely, therefore, the MORB-like isotope ratios of the residual peridotites reflect variably incompatible element depleted peridotites which reacted with migrating melts during one or several past melting episodes (compare to Figures 5e and 5f left panels). Detailed modeling of the Nd-Hf isotope signatures (Figure 6), shows that very high degrees of melt-rock interaction of highly depleted mantle more than ~ 0.5 Ga ago are required for reproducing the MORB-like Nd-Hf isotope ratios of the residual peridotites. In this scenario, extensive ancient melt-rock reaction entirely resets the Sm/Nd and Lu/Hf ratios of originally incompatible element depleted peridotites (Figure S1 in Supporting Information S1), leading to MORB-like Nd-Hf isotope signatures today, depending on the ¹⁷⁶Hf/¹⁷⁷Hf and ¹⁴³Nd/¹⁴⁴Nd of the reacting melts versus those of the residual peridotite. A melt with identical Nd and Hf isotope ratios to the mantle residues at the time of past interaction, for example, would result in peridotites with higher Hf isotope ratios than observed for the residual peridotites (Figure S2 in Supporting Information S1). In contrast, pervasive reaction (>95% melt-rock reaction) between an ultra-depleted residual mantle (e.g., F = 10-15%) and a melt that has lower Nd and Hf isotope ratios than the mantle residues at the time of past interaction match the Nd and Hf isotopes of cpx from the residual peridotites (Figure 6). Lower Nd (Hf) isotope ratios in MORB compared to abyssal peridotites from the same ridge segment are often observed (Brunelli et al., 2018; Cipriani et al., 2004; Mallick et al., 2014, 2015; Salters & Dick, 2002; Warren et al., 2009), and are an unavoidable consequence of melting isotopically heterogeneous mantle (e.g., B. Liu & Liang, 2017; Rudge et al., 2013; Stracke, 2012, 2021; Stracke & Bourdon, 2009).

Notably, the residual peridotites with the highest Lu/Hf and Sm/Nd have the lowest ¹⁷⁶Hf/¹⁷⁷Hf and ¹⁴³Nd/¹⁴⁴Nd (Figure 4). This indicates that the peridotites that experienced extensive past melt-rock reaction recently melted to the largest extent, but did not react with migrating melts, which would have caused strong light versus heavy REE enrichment (Figure 5f right panels). The residual peridotites therefore became highly depleted and strongly re-enriched by melt-rock reaction during past melting, before recent partial melting without concomitant melt-rock reaction caused their strong incompatible element depletion (compare to Figure 5f left panels).

4.3. Implications for the Long-Term Isotopic Evolution of the Depleted Mantle

At the Doldrums Fracture Zone, isotopically heterogeneous peridotites are exposed within ~ 15 km, attesting to a manifold history of melt depletion and melt-rock interaction. Notably, both ultra-depleted Hf and MORB-like Nd-Hf isotope ratios characterize the peridotites from the Doldrums Fracture Zone (Figure 3). The small-scale isotopic heterogeneity observed in this study thereby conveys a large part of the global compositional spectrum expected for variably incompatible element depleted and refertilized peridotites (Figure 5), and by analogy, the global sub-ridge mantle (Figure 3).





Figure 8. Schematic isotopic evolution of the sub-ridge mantle (a), and (b) and (c) illustration of the melting region and melt-rock reaction zones below mid ocean ridges modified after (Katz, 2008; Katz & Weatherley, 2012). The blue dashed lines in panel (a) show the evolution of purely residual depleted mantle and the solid blue lines the evolution of variably depleted mantle after different extents of melt-rock reaction, the slopes depending on the modified parent/daughter ratio. Each vertical step of the blue lines represents different melting and melt-rock reaction events throughout the Earth's history (see Figure S5 in Supporting Information S1 for further details). The melting region under a mid-ocean ridge shown in panel (b) consists of variably depleted mantle ranging from mildly to highly incompatible element depleted mantle (light to dark blue colors) and regions of high melt porosity (gray areas). Melt-rock reaction may occur especially in zone of melt extraction and toward the peripheral portions of the melting region, as shown in (c) (modified after Katz, 2008). A high porosity layer is localized at the lithosphere-asthenosphere boundary where the decrease in temperature may enhance reactive crystallization of migrating melts. Variably incompatible element depleted mantle that reacted to different extents with migrating or trapped melts will be transported laterally away from the ridge axis and, eventually, into the deeper mantle, evolving to isotopically highly heterogeneous mantle domains.

Consistent with the abundant evidence for melt-rock reaction for the residual and refertilized peridotites of the Doldrums Fracture Zone, pervasive melt-rock reaction is a ubiquitous corollary of present ridge melting (Brunelli & Seyler, 2010; Brunelli et al., 2014; Laukert et al., 2014; Le Roux et al., 2007; Sani et al., 2020; Seyler et al., 2001, 2004, 2007; Stracke et al., 2011; Suhr et al., 2008; Tartarotti et al., 2002; Warren & Shimizu, 2010) and affects most of the recovered abyssal peridotites (Warren, 2016). Especially the chemical and Nd-Hf isotope signatures of most abyssal peridotites from the Indian Ocean (for which chemical and Nd isotope data are available) show evidence for almost complete overprinting by recent melt-rock reaction (Brunelli et al., 2014; Seyler et al., 2001, 2004, 2011; Warren & Shimizu, 2010; Warren, 2016; Figure 4) despite Os isotope evidence for prior melt extraction (Day et al., 2017). In addition, although the residual peridotites do not show any textural evidence for melt-rock reaction, their clinopyroxenes do not follow simple fractional melting models in terms of their light to heavy REE abundances (see Sani et al., 2020, discussion above, Figure 7). Similar features are common in abyssal peridotites world-wide (e.g., Warren, 2016) and indicate that, even for light REE depleted peridotites, some extent of melt-rock reaction, either recently or in the past, is generally required for explaining their REE patterns (Brunelli et al., 2006, 2014; Godard et al., 2008; Liang & Peng, 2010). Taking recent processes as analogs for past ridge processes, it is therefore by no means extreme or unusual that the residual peridotites from Doldrums Fracture Zone may represent residual mantle that became re-enriched during ancient melting episodes, although they experienced no, or only very modest melt-rock reaction recently.

Ubiquitous reaction of variably incompatible element depleted peridotites with migrating melts during past and recent melting events has fundamental implications for assessing the chemical and isotopic record of the rate of incompatible element depletion from Earth's mantle. "Ultra-depleted" Hf and Nd isotope ratios can only develop

in strictly residual mantle that remains chemically isolated for several 10^8-10^9 years (Figures 1, 5, and 6). Notably, such signatures have not been observed in abyssal peridotites sampled to date (Figure 3). For low extents of reaction of incompatible element depleted peridotites with migrating melts, "ultra-depleted" Hf but not Nd isotope ratios may be preserved (Figures 5b–5d). For large extents of melt-rock reaction, the reacted mantle evolves with only moderate incompatible element depletion and is now characterized by isotope ratios similar to MORB (Figures 5d and 5f). Importantly, despite having quite contrasting isotope ratios today, peridotites in these latter two cases have reacted with migrating melts, but deceptively, these reactions partly to fully conceal the isotopic record of the extent and timing of past melt extraction (Figure 8a). For extensively reacted peridotites, evidence for past melt extraction and the minimum time since the last melt extraction event is only discernible if subchondritic Os isotope ratios are preserved (Day et al., 2017).

Hence for assessing the global-scale chemical and isotopic evolution of Earth's mantle it is critical to constrain the extent and fraction of mantle affected by melt-rock reaction during sub-ridge melting. Owing to their high degree of incompatible element depletion, peridotites that melted to a large extent are more susceptible to resetting of their incompatible element signatures by melt-rock reaction than less depleted peridotites (Figures 4 and 5). Paradoxically, therefore, the isotopic record of significant prior melt extraction is more readily preserved in peridotites from which little melt has been extracted, either during past or recent partial melting events. Perhaps more so than a peridotite's chemical susceptibility to incompatible element resetting, it is therefore the fluid dynamics of melt migration -the formation of melt networks that set the boundary conditions for chemically reactive flow- that determines the fraction of reacted versus purely residual mantle during sub-ridge melting (Katz, 2008; Katz & Weatherley, 2012; Kelemen et al., 1997; Keller et al., 2017; B. Liu & Liang, 2017; B. Liu & Liang, 2019) (Figure 8b). Focused eruption at the ridge axis leads to a coalescing melt network (Katz, 2008; Katz & Weatherley, 2012; Kelemen et al., 1997; Keller et al., 2017; Sparks & Parmentier, 1991) (Figure 8b). The mantle that experienced the highest extent of decompression (i.e., partial melting) in the central part of the melting region is transferred to the base of the lithospheric boundary layer, and moves laterally along with the lithospheric plate through high porosity melt channels at the fringes of the melting region, where it has a high probability for reacting with migrating melts (Figure 8c). The most pronounced chemical depletion signatures generated during sub-ridge melting are therefore least likely to be preserved. When moving laterally out of the melting region, residual mantle in deeper parts of the melting region also moves through the "melt channel" which could promote extensive interactions with melts, that could affect most of the mantle when these channels are active (Figure 8c). As eruptions are periodic at mid ocean ridges, there must be periods where these melt channels are more or less inactive (little melt is present), but the mantle moves constantly out of the melting region, and thus there is less chance to react with melts during these periods of quiescence. The expectation thus is that the residual mantle that is re-integrated into the convective flow after being processed under mid ocean ridges, shows a very heterogeneous distribution of variably depleted (by partial melting) and refertilized (by meltrock reaction) peridotites. A more detailed understanding of the physico-chemical mechanisms of melt transport and probability for reaction with peridotitic mantle (Katz, 2008; Katz & Weatherley, 2012; B. Liu & Liang, 2017; B. Liu & Liang, 2019) is therefore required for gaining an accurate understanding of the peridotitic mantle's rate of incompatible element depletion and time-integrated isotopic record of melt extraction. The latter is a crucial parameter, because it scales with the frequency of processing through sub-ridge melting regions -the mantle's processing rate- and thus vigor of convection. The peridotitic mantle's isotopic record of prior melt depletion and melt-rock reaction is also critical for interpreting the radiogenic isotope ratios of MORB (cf. Stracke, 2021; Willig et al., 2020), as discussed in the following.

4.4. Implications for Interpreting MORB Isotope Signatures

MORB are aggregated melts from isotopically heterogeneous mantle sources. The vast majority (>90%) of the MORB source is probably residual peridotitic mantle that became incompatible element depleted during prior partial melting. Hence the isotopic signatures of MORB should reflect the full diversity of isotopic signatures observed at the Doldrums Fracture Zone and predicted in Figure 5. The higher isotopic variability of MORB compared to ocean island basalts has indeed been attributed to contribution of melts with "ultra-depleted" Nd-Hf isotope signatures (Salters et al., 2011). But the isotopic range of MORB is much more muted than expected for melting such isotopically diverse peridotites (Figure 1).

In addition to isotopically highly variable peridotites (Figures 1 and 3), the MORB source contains minor incompatible element enriched components (<ca. 10%, e.g., Lambart et al., 2016; Salters & Stracke, 2004; Stracke et al., 2003; Sobolev et al., 2007; Yang et al., 2020), perhaps mostly recycled oceanic and continental crust (Stracke, 2012 and references therein). The radiogenic isotope signatures of MORB thus reflect a weighted average of melts from the different source constituents (e.g., Stracke, 2021; Stracke & Bourdon, 2009; Willig et al., 2020). At least three source components can be discerned from the subparallel arrays in Hf versus Nd-Sr-Pb isotope space observed for MORB (Blichert-Toft et al., 2005; Salters et al., 2011; Sanfilippo et al., 2019, 2021). In order of increasing impact on the final Sr-Nd-Hf-Pb isotope signatures of the aggregate melt (MORB) these are: (a) highly incompatible element depleted, strictly residual peridotites with extremely high Nd-Hf isotope ratios (Figure 5a), (b) variably incompatible element depleted and re-enriched peridotites whose isotope composition trends toward MORB-like signatures (Figures 5b–5f), and (c) incompatible element enriched recycled crustal components.

Because peridotites with "ultra-depleted" radiogenic isotope compositions are much more incompatible element depleted than those with MORB-like isotope signatures, extreme Nd-Hf isotope ratios of ultra-depleted peridotites have little influence on the isotopic composition of MORB (Byerly & Lassiter, 2014; Salters et al., 2011). The radiogenic isotope ratios of MORB therefore primarily reflect the less incompatible element depleted peridoticic and recycled source components (B. Liu & Liang, 2017, B. Liu & Liang, 2019; Salters & Dick, 2002; Salters et al., 2011; Sanfilippo et al., 2021; Stracke, 2012, 2021; Stracke et al., 2011; Willig et al., 2020). In essence, even <10% recycled oceanic crust in the mantle source can supply up to two-thirds of the incompatible element inventory of the erupted melt (e.g., Stracke & Bourdon, 2009). The radiogenic isotope ratios of MORB are thus heavily biased toward the composition of the melts from the recycled crustal components.

The natural consequence is that MORB do not convey the full extent of isotopic heterogeneity, nor do they accurately reflect the time-integrated amount of prior melt extraction of their peridotitic mantle source constituents. Estimating the mantle's rate of incompatible element depletion based on the radiogenic isotope ratios of MORB may therefore considerably underestimate the rate of oceanic crust production, that is, the mantle's processing rate and thus vigor of convection. The magnitude of this effect is difficult to predict, but the discussion above suggests that Earth's mantle has likely evolved through a multi-stage history of mantle processing toward a more mature evolutionary stage than currently thought.

Conflict of Interest

The authors declare no conflicts of interest relevant to this study.

Data Availability Statement

The geochemical data used in this study are included as tables in Supporting Information S1. The data published are contributed to the Petrological Database (www.earthchem.org/petdb) and available to the EarthChem Library at https://doi.org/10.26022/IEDA/112764.

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