

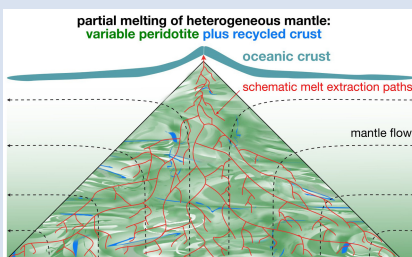
Basalts record a limited extent of mantle depletion: cause and chemical geodynamic implications

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Abstract



Radiogenic isotope ratios in basalts from mid-ocean ridges are commonly thought to represent the time-integrated extent of incompatible element depletion of the sub-ridge, peridotitic mantle. Earth's peridotitic mantle, however, is variably incompatible element depleted, and inherently heterogeneous as a consequence of prior melting. After aging for several 10^7 – 10^9 years in the mantle before remelting today, the heterogeneous peridotites are characterised by a much larger range of radiogenic isotope ratios than ridge basalts. The simple reason why ridge, but also ocean island basalts, reflect only a limited range of this enormous isotopic spectrum of peridotites is that mixing of melts from Earth's heterogeneous mantle moderates peridotite heterogeneity. Variable peridotite compositions may nevertheless be responsible for iso-

topic differences between ridge and ocean island basalts, and contribute significantly to the thermochemical buoyancy of mantle plumes, and density-driven mantle flow in general. Variable peridotite depletion therefore connects geochemical and geophysical observables, and is a critical parameter for advancing our understanding of basalt generation, plume formation, and chemical geodynamic models of mantle convection.

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Mantle Compositional Evolution

Earth's mantle evolves continuously by returning peridotite melted under mid-ocean ridges into the deeper mantle via subduction, and remelting these residual, variably incompatible element (ICE) depleted peridotites once they are transported back into the shallow mantle. This basic concept (e.g., Langmuir *et al.*, 1992; Willig *et al.*, 2020; Stracke, 2021; Fig. 1) explains why ICE depleted basalts erupt at mid-ocean ridges. The Nd-Hf isotope ratios of mid-ocean ridge basalts (MORB) further show that these peridotites have resided in the mantle for some 10^7 – 10^9 years before being remelted, because the Nd-Hf isotope ratios are higher, on average, than those of the Bulk Silicate Earth (BSE; White *et al.*, 2015; Stracke *et al.*, 2022). This cycle of melting and remelting of Earth's peridotitic mantle generates oceanic crust, and is the surface expression of the internal engine that drives plate tectonics. The number of melting cycles the peridotites may have undergone, their corresponding extent of ICE depletion, and their residence time in the mantle, however, remain major unknowns in our understanding of mantle compositional evolution, and mantle-crust mass fluxes in general.

An integral aspect of partial mantle melting, under mid-ocean ridges or the shallow mantle of actively upwelling mantle ("plumes"), is that peridotites that move on different paths through the melting region melt to different extents (Fig. 1). The peridotites that return and become recirculated within the mantle after partial melting are highly heterogeneous, and range from compositions similar to average "depleted mantle" (Salters

and Stracke, 2004) to peridotites, which are almost devoid of ICEs (Fig. 1). In other words, any ICE depleted mantle sampled today is, by origin, a highly heterogeneous assemblage of compositionally, and isotopically, variable peridotites.

During residence in the mantle, these heterogeneous peridotites are stretched, disintegrated, redistributed, stirred and become dispersed by the convective flow (Fig. 1), but they do not homogenise diffusively (Hofmann and Hart, 1978; Hart, 1993). An inevitable, but mostly neglected, consequence is that the radiogenic isotope ratios of variably ICE depleted and aged peridotites develop extreme values during several 10^7 – 10^9 years of residence in the mantle. These values reach far beyond the isotopic spectrum of MORB (Fig. 1), as observed in abyssal peridotites (e.g., Stracke *et al.*, 2011; Sani *et al.*, 2023). A fundamental question, therefore, is: why do oceanic basalts, *i.e.* MORB and basalts from oceanic islands (OIB), not mirror this enormous range of radiogenic isotope ratios of the peridotitic mantle?

Melting Earth's Heterogeneous Mantle

The answer to the question above is simple: partial melting of peridotite produces basaltic oceanic crust, which is returned into the deeper mantle together with the residual, melt-depleted peridotites. The recycled crust and peridotites become stirred and dispersed within the mantle by convection. As a result, Earth's present mantle is chemically and lithologically heterogeneous, and consists of variably ICE depleted peridotite plus

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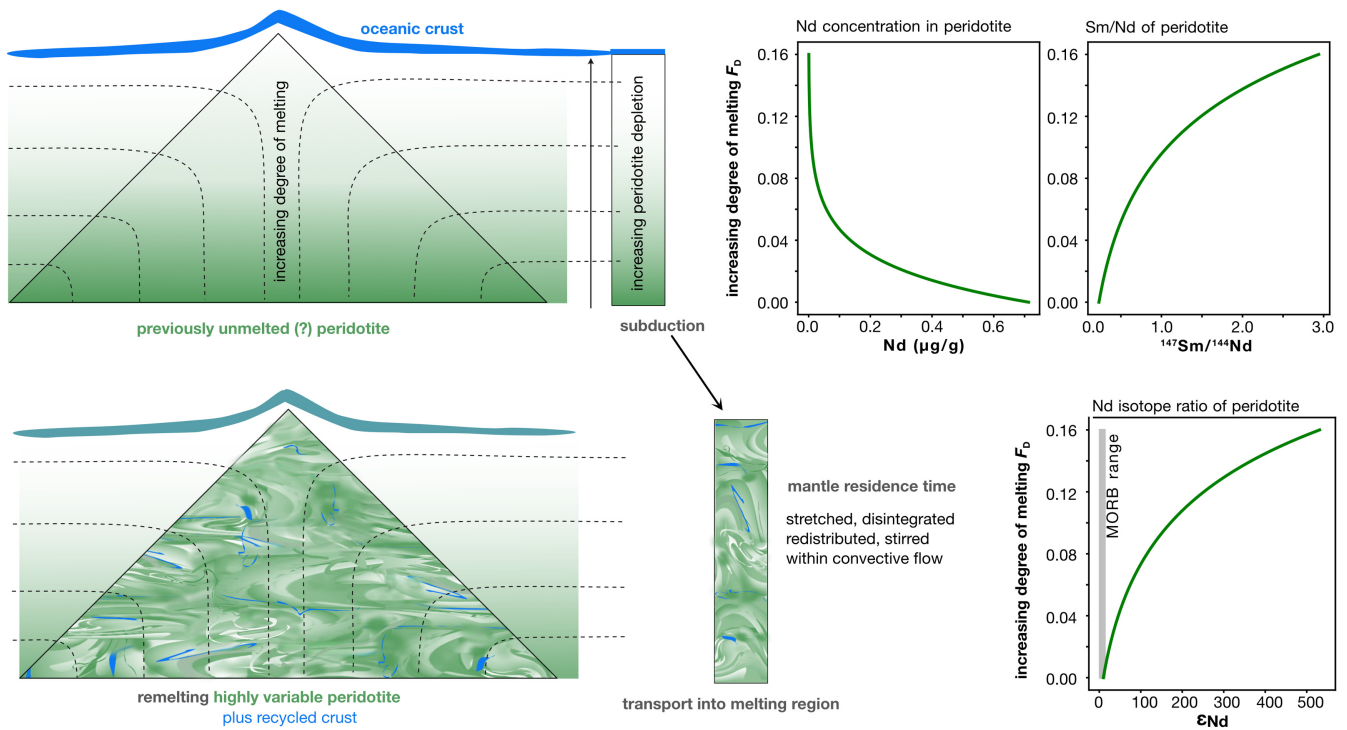


Figure 1 Generation of variably ICE depleted peridotite by partial melting average peridotitic mantle to a maximum extent of melting of 16 %. Lower right panel shows calculated isotopic evolution within 1.5 Myr. Elemental concentrations before depletion: $C^{Nd} = 0.713 \mu\text{g/g}$, $C^{Sm} = 0.270 \mu\text{g/g}$ (Salters and Stracke, 2004). Bulk partition coefficients: $D^{Nd} = 0.024$, $D^{Sm} = 0.037$ (Stracke and Bourdon, 2009). Depletion age: 1.5 Ga. Initial $^{143}\text{Nd}/^{144}\text{Nd}$ (at 1.5 Ga) = 0.510877. Decay constant: $\lambda^{147}\text{Sm} = 6.54 \times 10^{-12}$.

ICE enriched recycled oceanic (\pm continental) crust (Fig. 1; e.g., Stracke 2012, 2021 and references therein). Hence, oceanic basalts are mixtures of melts from chemically and lithologically heterogeneous mantle. As such, oceanic basalts represent a weighted average of melts from the different mantle components, but their isotope ratios are rarely, if ever, identical to those of a single mantle component.

Specifically, isotope ratios in oceanic basalts are mixtures between melts from peridotites and recycled crust (\pm other components). Peridotites are the volumetrically dominant component (>85–90 %), but are also ICE depleted, whereas recycled crust is a minor (<10–15 %), but ICE enriched, component in Earth’s mantle (e.g., Stracke et al., 2022 and references therein). The isotopic range of the heterogeneous peridotites is, therefore, not conveyed unchanged to oceanic basalts, but rather significantly shifted toward the isotope ratio of melts from the ICE enriched mantle component(s). Because lithophile elements with geologically useful radiogenic isotope ratios (Sr, Ce, Nd, Hf, Pb) are all ICEs, their inventory in oceanic basalts derives mostly from melts of the ICE enriched mantle components (i.e. recycled oceanic \pm continental crust). The latter is demonstrated below with the example of melting of a two-component mantle that consists of ICE depleted peridotite (‘per’) and ICE enriched recycled crust (‘rc’, i.e. oceanic \pm continental crust). The isotope ratio (IR) of element i in the derivative basalt is the weighted average of melts from the two mantle components:

$$f_{\text{basalt}} C_{\text{basalt}}^i IR_{\text{basalt}}^i = f_{\text{per}} C_{\text{per}}^i IR_{\text{per}}^i + f_{\text{rc}} C_{\text{rc}}^i IR_{\text{rc}}^i$$

$$IR_{\text{basalt}}^i = (f_{\text{per}} C_{\text{per}}^i IR_{\text{per}}^i + f_{\text{rc}} C_{\text{rc}}^i IR_{\text{rc}}^i) / f_{\text{basalt}} C_{\text{basalt}}^i$$

Eq. 1

with f = mass fraction of melt, which relates to the mass fraction, m , in the mantle by $f = m \times F$, F being the degree of melting in %, and C^i being the concentrations of element i in melts from peridotite and recycled crust.

Equation 1 shows that the isotope ratios in basalts (IR_{basalt}^i) are a trade-off between the abundance (m) of the two mantle components, the extent to which the peridotite and recycled crust melt (F), the average composition of the melts from peridotite and recycled crust (C^i), and, of course, the corresponding isotope ratios in these melts (IR^i). Isotope ratios in peridotites (IR_{per}^i) can be extreme, but are coupled to exceedingly low ICE concentrations (Fig. 1). Hence, although extreme IR_{per}^i have a large leverage in Equation 1, these isotopic signatures are moderated by correspondingly low concentrations in the peridotites and their derivative melts (C_{per}^i). This is illustrated in Figure 2, which shows calculated IR_{basalt}^i that are a mix of a constant proportion of melts from recycled crust and peridotite from which variable amounts of melt have been extracted and aged for 1.5 Ga (Figs. 1, 2, Eq. 1). Although IR_{per}^i becomes extremely high with an increasing degree of ancient melt extraction (F_D , subscript D for depletion) and, thus, an increasing extent of ICE depletion before renewed melting (Fig. 1), IR_{basalt}^i peak at low to intermediate values of F_D in Figure 2, when $C_{\text{per}}^i IR_{\text{per}}^i$ reaches its maximum value (note that f_{per} and f_{rc} are constant in the calculation shown in Fig. 2). With increasing extent of peridotite depletion (F_D), $C_{\text{per}}^i \rightarrow 0$, and thus the term $f_{\text{per}} C_{\text{per}}^i IR_{\text{per}}^i$ also approaches 0. Effectively then, $f_{\text{basalt}} C_{\text{basalt}}^i IR_{\text{basalt}}^i \rightarrow f_{\text{rc}} C_{\text{rc}}^i IR_{\text{rc}}^i$ (Eq. 1), and $IR_{\text{basalt}}^i \rightarrow IR_{\text{rc}}^i$. Hence, there is a natural limit to which the range of isotope ratios of the peridotitic mantle, and especially the IR_{per}^i of the most ICE depleted peridotites, are conveyed to the basalts.

Likewise, there is also a limit to which the isotope ratios of recycled components, IR_{rc}^i are reflected in basalts. For ICEs $f_{\text{rc}} C_{\text{rc}}^i > f_{\text{per}} C_{\text{per}}^i$, and thus IR_{basalt}^i also approaches IR_{rc}^i , especially if $IR_{\text{rc}}^i > IR_{\text{per}}^i$, e.g., for Sr isotope ratios. For compatible elements, however, $f_{\text{rc}} C_{\text{rc}}^i \ll f_{\text{per}} C_{\text{per}}^i$, i.e. that IR_{rc}^i only has a significant effect on IR_{basalt}^i if $IR_{\text{rc}}^i \gg IR_{\text{per}}^i$. The latter is critical for evaluating whether recycled components can have significant imprint on the stable isotope ratios of compatible elements in

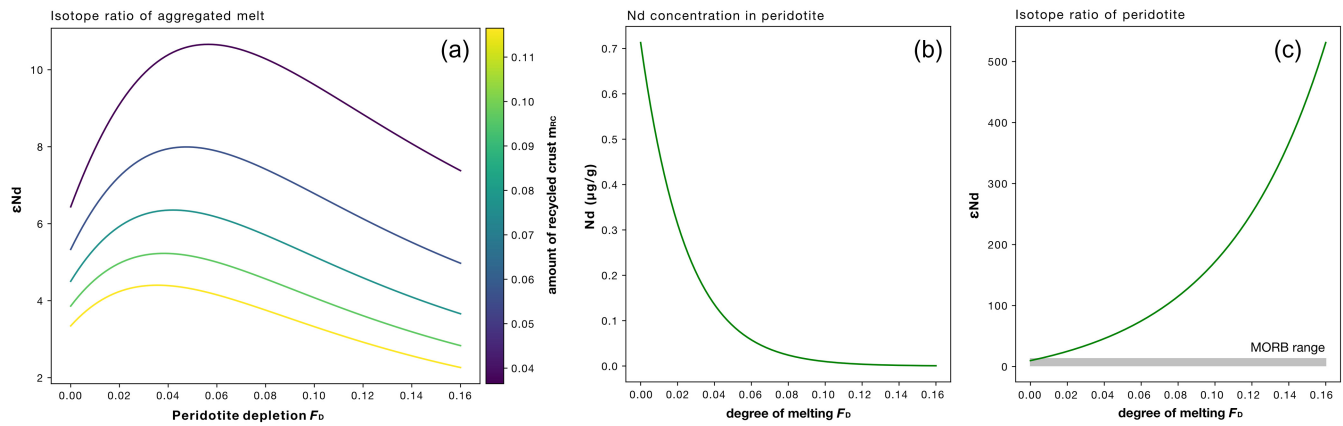


Figure 2 (a) Isotope ratio of aggregated melt (basalt) formed by mixing melts from variably ICE depleted peridotite and recycled crust as calculated with Equation 1, (b) Nd concentrations, and (c) Nd isotope ratios in variably ICE depleted peridotite aged for 1.5 Gyr before renewed melting. Recycled oceanic crust is a mixture of 96 % mafic crust ($C^{Nd} = 5.83 \mu\text{g/g}$, $C^{Sm} = 2.01 \mu\text{g/g}$) and 4 % sediments ($C^{Nd} = 27.6 \mu\text{g/g}$, $C^{Sm} = 6.0 \mu\text{g/g}$), also aged 1.5 Gyr with an initial $^{143}\text{Nd}/^{144}\text{Nd} = 0.509667$ for sediments and 0.510879 for mafic crust before melting at present. Present-day melting degrees are 8 % for peridotite and 64 % for recycled oceanic crust, and are constant for simplicity. Bulk partition coefficients used for calculating melt compositions, C_{per}^{Nd} and C_{rc}^{Nd} , are $D_{\text{rc}}^{Nd} = 0.024$, $D_{\text{per}}^{Nd} = 0.148$ (Stracke and Bourdon, 2009). Each curve in (a) corresponds to a distinct amount of recycled oceanic crust, m_{rc} , in the mantle source (4–12 %), and each point of a curve corresponds to a distinct degree of peridotite depletion F_D (0–16 %).

oceanic basalts, e.g., for Cr, Ni, Mg, but also Zn, Fe and other transition elements. Equation 1 allows evaluating if natural and/or partial melting induced stable isotope variation in recycled components suffice to affect IR_{basalt}^i but this is rarely considered (cf., Sodermann *et al.*, 2022).

Hence, the value of IR_{basalt}^i is determined by the parameters in Equation 1, i.e. the relative abundance, composition and intrinsic isotopic range of individual mantle components, which are, of course, inherently heterogeneous and not limited to only two components. The style and efficiency of mixing melts from individual components during extraction from the mantle and melt evolution in the crust also plays a crucial role for how the isotopic range of heterogeneous mantle components are reflected in the generated melts (e.g., Stracke and Bourdon, 2009; Koornneef *et al.*, 2012; Rudge *et al.*, 2013; Shorttle *et al.*, 2014, 2016; Neave *et al.*, 2019; Genske *et al.*, 2019; Stracke, 2021). Although understanding the mechanisms and effects of melt mixing on the relation between mantle and basalt heterogeneity is still in its infancy (e.g., Rudge *et al.*, 2013), it has become clear that the isotopic range of oceanic basalts is offset from and much smaller than that of the peridotitic mantle, as long as some degree of mixing between melts from heterogeneous peridotites and ICE enriched mantle components occurs (Eq. 1, Fig. 2). Melt mixing is unavoidable, because melts from several 10–100 km wide and deep melting regions are funnelled to the localised eruption sites at the ridge axis or volcano at the surface (e.g., Stracke, 2021).

Implications for Mantle-Crust Mass Fluxes

Another critical effect of melt mixing is that oceanic basalts do not reflect the average extent of ICE depletion of the underlying peridotitic mantle. A column of peridotitic mantle that melted between 0 and 16 % and is 1.5 Ga old (Fig. 1), for example, has average $^{143}\text{Nd}/^{144}\text{Nd} = 0.514327$ ($\epsilon_{\text{Nd}} = +33.1$), and $^{176}\text{Hf}/^{177}\text{Hf} = 0.285310$ ($\epsilon_{\text{Hf}} = +89.3$). If a mantle source consisting of such heterogeneous peridotite also contains 3 % of recycled crust with $^{143}\text{Nd}/^{144}\text{Nd} = 0.512762$ ($\epsilon_{\text{Nd}} = +2.6$), and $^{176}\text{Hf}/^{177}\text{Hf} = 0.282756$ ($\epsilon_{\text{Hf}} = -1.0$), and the peridotites melt, on average, to 8 % and recycled crust to 64 %, the total

aggregated melt has $^{143}\text{Nd}/^{144}\text{Nd} = 0.512866$ ($\epsilon_{\text{Nd}} = +4.6$), and $^{176}\text{Hf}/^{177}\text{Hf} = 0.283029$ ($\epsilon_{\text{Hf}} = +8.6$) (Eq. 1).

Using this average isotope ratio of the total extracted melts from such a heterogeneous mantle source, i.e. the isotope ratios of oceanic basalts, to evaluate the extent of mantle depletion will, therefore, by far underestimate the extent of ICE depletion of the peridotitic mantle, and thus the average rate of processing mantle through melting regions in the shallow mantle, which scales with the mantle's convective vigor. This also means that mantle-crust mass fluxes may be higher than inferred from MORB-based estimates of mantle depletion (e.g., Jacobsen and Wasserburg, 1979; Galer *et al.*, 1989; Kumari *et al.*, 2016; Tucker *et al.*, 2020).

Implications for Isotopic Differences Between MORB and OIB

Another implication of Equation 1 and Figures 2 and 3 is that isotopic differences between oceanic basalts can be explained in several ways. For example, $\epsilon_{\text{Nd}}^{\text{basalt}}$ can decrease from +8 to +5 because there is a larger contribution of melts from recycled crust with $\epsilon_{\text{Nd}}^{\text{rc}} = -1$, or because the peridotite melts derive from, on average, more ICE depleted peridotite (Fig. 3). The latter may, at first, be counterintuitive, because highly ICE depleted and aged peridotites have extremely high $\epsilon_{\text{Nd}}^{\text{per}}$ (Figs. 1, 2). However, because they are highly ICE depleted, high $\epsilon_{\text{Nd}}^{\text{per}}$ are compensated by $C_{\text{per}}^{Nd} \rightarrow 0$, i.e. the contribution of Nd from peridotite melts, $f_{\text{per}} C_{\text{per}}^{Nd} \epsilon_{\text{Nd}}^{\text{per}} \rightarrow 0$, and thus $\epsilon_{\text{Nd}}^{\text{basalt}} \rightarrow \epsilon_{\text{Nd}}^{\text{rc}}$ irrespective of high $\epsilon_{\text{Nd}}^{\text{per}}$ (Fig. 3). Hence, the, on average, lower Hf-Nd and higher Ce isotope ratios of OIB compared to MORB (White, 2015; Willig *et al.*, 2020; Stracke *et al.*, 2022) could either mean that 1) the mantle sources of OIB contain more recycled crust (for similar average peridotite compositions) than most MORB sources, or that 2) OIB sources contain similar amounts of recycled crust as MORB sources, but, on average, more extensively depleted peridotites (Fig. 3).

There are more aspects to consider. For example, it is clear that OIB range to different Sr-Nd-Hf-Pb isotope ratios than MORB (Zindler and Hart, 1986; White, 2015; Stracke, 2021; Stracke *et al.*, 2022 and references therein), and their mantle sources may, thus, not only contain different proportions, but

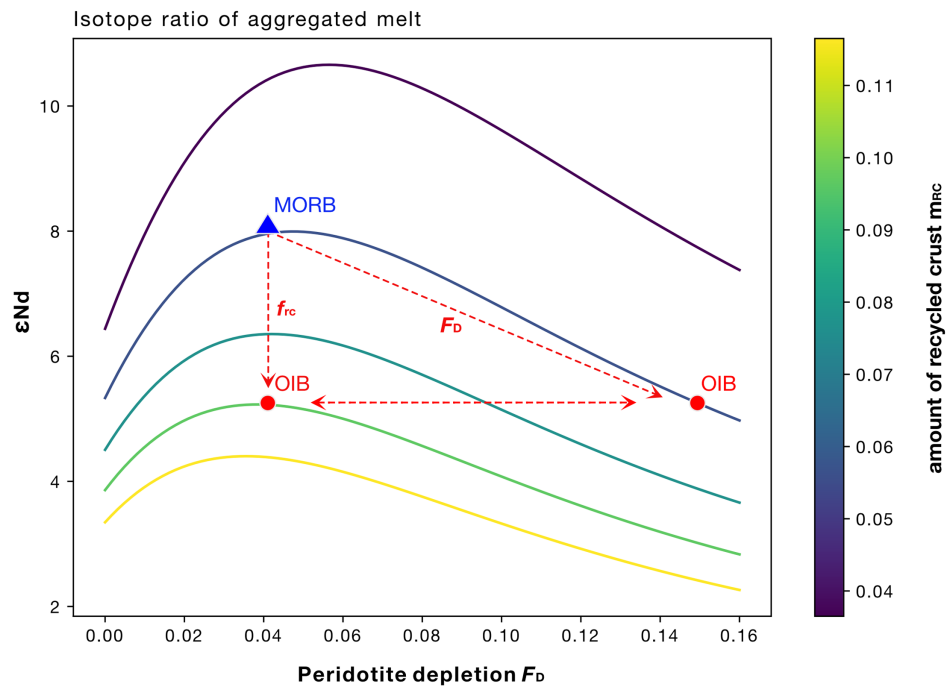


Figure 3 Isotope ratio of aggregated melt (basalt) formed by mixing melts from variably ICE depleted peridotite and recycled crust (parameters as in Fig. 2), showing that there are two principal reasons why OIB, on average, have lower Hf and Nd isotope ratios than MORB: 1) they contain more recycled crust (for similar average peridotite compositions), or 2) they contain similar amounts, but, on average, more extensively depleted peridotite (for similar recycled crust compositions).

also different types of recycled components. Broad linear trends in various combinations of Ce-Nd-Hf isotope ratio diagrams (e.g., Willig *et al.*, 2020) make it difficult to distinguish between different types of recycled crust, but Sr and Pb isotope ratios, in combination with Ce-Nd-Hf isotope ratios, may distinguish between different types of oceanic ± continental crust (e.g., Stracke, 2012 and references therein). On the other hand, extremely high Nd-Hf and low Ce isotope ratios in ICE depleted and aged peridotites are a sensitive tracer of variably ICE depleted peridotite (Willig *et al.*, 2020). This is because mixing melts from heterogeneous peridotites and ICE enriched components forms linear trends subparallel to the global trends in Ce-Nd-Hf isotope diagrams, which are variably displaced toward high Hf-Nd and low Ce isotope ratios (Salters *et al.*, 2011; Béguelin *et al.*, 2019; Willig *et al.*, 2020; Sanfilippo *et al.*, 2021; Stracke, 2021).

Implications for Plume Buoyancy

Many OIB form above mantle upwellings, so called mantle “plumes”, whose buoyancy is driven by thermochemical density deficits relative to the ambient mantle. Higher amounts of recycled crust make plumes denser, meaning that high temperatures are required to make them less dense than the ambient mantle (*i.e.* positively buoyant). Peridotites, however, also become less dense with increasing extent of melt depletion. Hence, lower temperature excesses are required to make melt-depleted peridotite positively buoyant.

For example, the compositional density of peridotite, $\Delta\rho_c$, scales with the extent of melt depletion, F_D ($\Delta\rho_c \approx 214.5 \text{ kg m}^{-3} \times F_D$; Afonso and Schutt, 2012). That is, for *ca.* 8 % of melt extraction, peridotite density decreases by ~ 0.5 % (reference mantle density, $\rho_0 = 3300 \text{ kg m}^{-3}$). Density deficits of similar magnitude due to temperature alone require temperature excesses >150 °C (Fig. 4, T at $F_D = 0$), assuming that the

thermal density deficit, $\Delta\rho_T$, is due to thermal expansion of peridotite by $\Delta\rho_T = -\rho_0 \times \alpha \times \Delta T$, with α being the thermal expansivity of $3 \times 10^{-5} \text{ (K}^{-1}\text{)}$, and ΔT being the excess temperature relative to ambient mantle potential temperature T_p ($\Delta T = T_p - T_0$; with $T_0 = 1350$ °C, Ballmer *et al.*, 2013). For an excess density of the recycled oceanic crust of 180 kg m^{-3} (Ishii *et al.*, 2019), adding ~ 9 % of recycled oceanic crust to a peridotitic mantle source ($\rho_0 = 3300 \text{ kg m}^{-3}$) increases the density by ~ 0.5 %. A temperature excess of ~ 150 °C, or assuming a more melt-depleted peridotite from which ~ 8 % of melt has been extracted, would make this heterogeneous peridotite-recycled crust assemblage neutrally buoyant (Fig. 4).

Whether different proportions of recycled crust or more extensively depleted mantle is responsible for observed isotopic differences between MORB and OIB is, therefore, also a central question for understanding the thermochemical driving forces of active mantle upwellings (e.g., Shorttle *et al.*, 2014; Stracke *et al.*, 2019, 2022), and mantle convective motion in general, and key for relating geochemical observations and geodynamic constraints.

Summary and Perspectives

Highly heterogeneous peridotites with isotope ratios far beyond the MORB spectrum are a natural consequence of oceanic crust generation and mantle residence, and characterise the majority (>85 – 90 %) of Earth’s mantle (Fig. 1). Heterogeneous peridotite-derived melts, therefore, always influence oceanic basalt isotope ratios, even if subtly so (Eq. 1, Figs. 2, 3). Equation 1 is a basis for evaluating how basalt compositions reflect individual components of heterogeneous mantle sources, and for better constraining basalt-forming processes (Figs. 2, 3). A key question to address further is whether peridotites in plume sources of OIB are more melt-depleted, and thus lighter than the peridotites of MORB sources. If composition is, indeed, a large factor

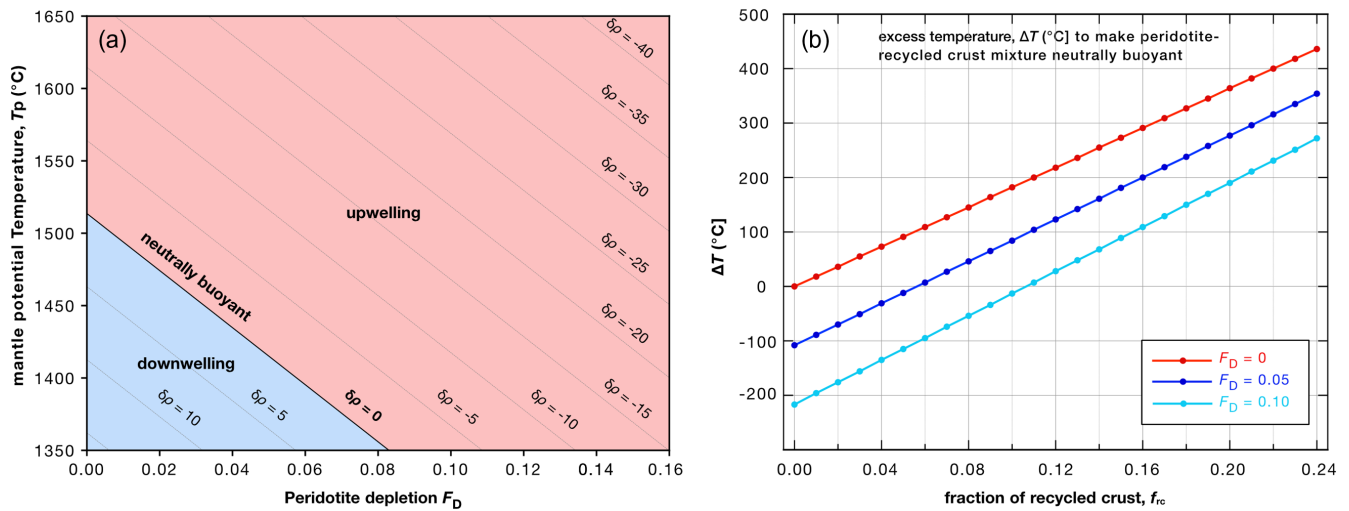


Figure 4 (a) Peridotite depletion F_D (%) versus temperature T (°C) of a model mantle source with 9 % of recycled oceanic crust ($f_{rc} = 0.09$). (b) Excess temperature, ΔT (°C), required to make a mixture of variably depleted peridotite (F_D) and recycled crust neutrally buoyant. $\delta\rho$ is the difference to the reference density $\rho_0 = 3300 \text{ kg m}^{-3}$. Shown here is $\delta\rho$ for all combinations of F_D and T_p , as discussed in the text.

for thermochemical plume buoyancy, plumes may not necessarily have to originate from thermal boundary layers and peridotite composition may also influence evolving plume structures. Variable peridotite depletion, therefore, connects geochemical and geophysical observables, and is a critical parameter for advancing our understanding of basalt generation, plume formation, and chemical geodynamic models of mantle convection.

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Additional Information



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