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# Crustal versus mantle-level aggregation of heterogeneous melts at mid-ocean ridges

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## ABSTRACT

**Mid-ocean ridge basalts (MORBs) have long been used to investigate the composition of the upper mantle. The isotopic heterogeneity of MORB correlates inversely with spreading rate, indicating that enhanced magma mixing at magmatically robust fast-spreading ridges mutes the signature of mantle heterogeneity. It has remained unclear, however, whether this mixing occurs during melt extraction from the mantle or in crustal magma reservoirs. To discriminate between mantle aggregation and crustal magma mixing, we measured the Nd isotopic composition of cumulus plagioclase and clinopyroxene cores within lower crustal gabbros from the fast-spreading crustal section exposed at Hess Deep (equatorial Pacific Ocean). Our data reveal that the mantle is heterogeneous at the scale of melt extraction, and the crystal record from the lower crust shows greater $^{143}$Nd/$^{144}$Nd heterogeneity than the overlying MORB. Hence, Pacific MORBs do not reflect the full heterogeneity of their mantle source, and some aggregation of melts occurs within the crust. However, isotopic heterogeneity in the lower crust at Hess Deep is lower than in slower-spreading settings, suggesting that the extent to which melts aggregate in the mantle versus the crust is controlled by spreading rate.**

## INTRODUCTION

Mid-ocean ridge basalts (MORBs) represent our main window into the composition and heterogeneity of the convecting upper mantle. Isotopic data have shown the MORB mantle to be heterogeneous on a range of length scales. For example, Pb-Nd-Sr-Hf isotopes of MORB glasses from the Mid-Atlantic Ridge reveal mantle heterogeneity on the scale of hundreds to thousands of kilometers (Schilling et al., 1994; Andres et al., 2004). Finer-scale heterogeneity (tens of kilometers) is preserved in MORB glasses from the Southwest Indian Ridge, which reveal Pb and Hf isotopic compositional streaks due to convective stirring of distinct mantle domains (Hanan et al., 2013). While MORB can record large-scale variations in source composition, it likely provides an incomplete picture of the true heterogeneity of the upper mantle. This is because MORB is processed in crustal magma chambers prior to eruption, where homogenization of heterogeneous melt batches reduces isotopic variance. Evidence for crustal processing comes from primitive lower-crustal cumulates along the Mid-Atlantic Ridge, at 30°N (Lambart et al., 2019) and 15°45′N (Wang et al., 2024). These cumulates show greater isotopic heterogeneity than is present in MORB at the same location, recording the delivery of heterogeneous melts to the crust, with crystallization predating magma mixing (Lambart et al., 2019). Similarly, plagioclase phenocrysts in individual samples of MORB preserve a range of Sr isotope values similar to that seen at the ridge segment scale (Lange et al., 2013). At slow- to intermediate-spreading ridges, significant isotopic heterogeneity in MORB crystal cargos appears to be the norm rather than the exception (Nielsen et al., 2020; Burton et al., 2024; Ou et al., 2024). Hence, more isotopically diverse melts are delivered to the crust than are captured by MORB, at least at slow-spreading ridges.

Fast-spreading ridges are more magmatically robust than slower spreading ridges, resulting in an enhanced potential for magma mixing. This is consistent with the observation that fast-spreading ridges generally erupt more homogeneous lavas (Batiza, 1984; Rubin et al., 2009). One key outstanding question is whether the observed isotopic homogeneity of fast-spreading MORB is due to enhanced mixing in crustal magma reservoirs, or to enhanced mixing of melts during transport in, and extraction from, the mantle. We address this question by investigating the Nd isotopic heterogeneity of melts delivered to a complete section of Hess Deep oceanic crust, accreted at the fast-spreading (133 mm/yr) East Pacific Rise (EPR). To do this, we targeted the Nd isotope record of cumulate plagioclase (Pl) and clinopyroxene (Cpx) in lower crustal gabbros, representing early crystallization products of melts delivered to the crust (Basch et al., 2024). Unlike MORB, the lower crustal gabbros have the potential to reveal the heterogeneity of primary melts in the EPR more accurately.

## GEOLOGIC SETTING AND SAMPLES

Hess Deep is an ∼5400-m-deep rift valley (∼2°15′N, 101°30′W; Fig. 1) that dissects 1.3 Ma crust formed at the EPR (Francheteau et al., 1990; Rioux et al., 2012). The rift contains an uplifted block called the Intrarift Ridge, which, on its south slope, exposes the most extensive section of lower oceanic crust from a fast-spreading mid-ocean ridge (Hekinian et al., 1993; Coogan et al., 2002; Lissenberg et al., 2013) and has therefore been the target of several submersible, dredge, and drilling studies. Ocean Drilling Program (ODP) Leg 147 drilled ∼150 m into gabbroic rocks (at Site 894; Fig. 1) that represent a high stratigraphic level a few hundred meters below the sheeted dikes (Gillis et al., 1993). In 2008, the RSS *James Cook* cruise JC21 (using ROV *Isis*) recovered 93 primitive to evolved gabbroic rocks along a transect from the bottom to the top of the Intrarift Ridge (Macleod et al., 2008) (Fig. 1). Following JC21, drilling was undertaken along the southern depths of the Intrarift Ridge during Integrated Ocean Drilling Program (IODP) Expedition 345 (Gillis et al., 2014b) (Site U; Fig. 1), recovering primitive,

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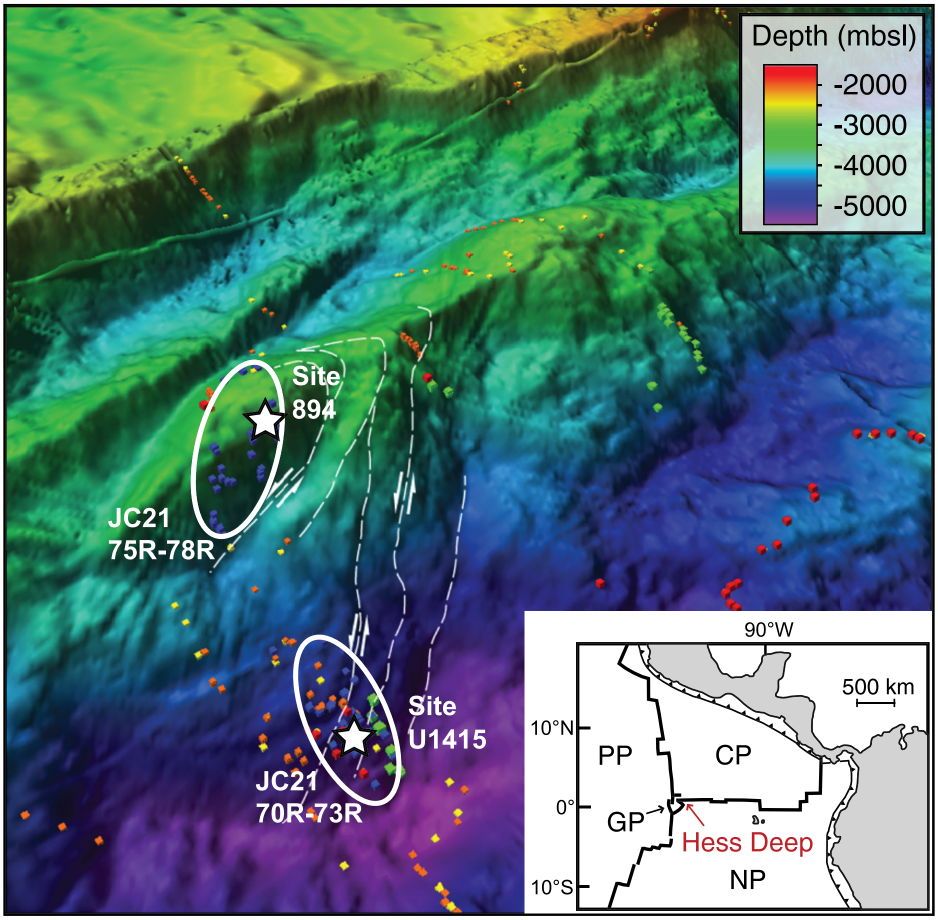

**Figure 1.** Bathymetric map of Hess Deep (East Pacific Rise, ~2°15′N, 101°30′W) showing a three-dimensional perspective of the locations of samples collected during RSS *James Cook* cruise JC21 using ROV *Isis* (white ellipses; MacLeod et al., 2008) and drilling sites (white stars) used in this study. Site 894 is from Ocean Drilling Program (ODP) Leg 147; Site U1415 is from Integrated Ocean Drilling Program (IODP) Expedition 345. Inset map shows the regional tectonic setting. Figure modified from Rioux et al. (2012), with inset after Lonsdale (1988). mbsl—meters below sea level; CP—Cocos plate; NP—Nazca plate; PP—Pacific plate; GP—Galapagos microplate.

modally layered olivine gabbros and troctolites (Akizawa et al., 2023; Basch et al., 2024) from two ~110-m-deep holes (U1415J and U1415P) and one 35-m-deep hole (U1415I). Combined, these studies provide the most complete composite section of fast-spreading EPR crust to date (Gillis et al., 2014a). In our study, we selected 25 samples (Supplemental Material S1[1]) for in situ Nd isotope microanalysis, retrieved during each of these expeditions, covering the range of mineralogy and textural diversity, and over the full stratigraphic depth (4350 m to 25 m, estimated using the reconstruction of Lissenberg et al., 2013). For a comparison to local MORB compositions, we selected a set of 13 upper-crustal sheeted dikes collected on the RSS *James Cook* cruise JC21.

## METHODS

Relatively primitive domains of Pl and Cpx (high anorthite and high Mg# plus low $TiO_2$/$Cr_2O_3$ content, respectively) were selected for in situ microanalysis after polished blocks were element mapped on a Zeiss Sigma HD field emission gun scanning electron microscope (SEM) at Cardiff University, UK. Neodymium concentrations measured by laser ablation–inductively coupled plasma–mass spectrometry (LA-ICP-MS) (Applied Spectra Inc. RESOlution S-155 laser coupled to an Agilent 8900 ICP-QQQ) were used to predetermine the sample volume needed to be recovered from micromilling. Typical Pl and Cpx cores from each sample (no xenocrystic cores) were then drilled using a New Wave™ Research MicroMill. Sample powders were then digested in HF and $HNO_3$ prior to Nd separation by column chemistry. Isotopic analyses were performed on a Thermo Scientific TRITON *Plus* at the Vrije Universiteit in Amsterdam, following the methods of Koornneef et al. (2014). The long-term average and reproducibility (2019–2022) for the JNdi-1 standard is 0.512094 ± 0.000011 2 SD (standard deviation; n = 28) with $10^{11}$ Ω resistors (used for Cpx) and 0.512105 ± 0.000044 2 SD (n = 45) with four $10^{13}$ Ω resistors (used for Pl). Nd isotope ratios ($^{143}Nd/^{144}Nd$) of 13 whole-rock dike samples were measured on a Nu plasma II multicollector ICP-MS at Cardiff University. See Supplemental Material S2 for detailed methods.

## RESULTS

Data were obtained from mineral cores in 25 samples, including 25 Cpx and 19 Pl (from the same samples). Plagioclase cores range from ~An55 to An88 and Cpx cores from Mg# 73–88. Clinopyroxene $^{143}Nd/^{144}Nd$ values show a limited variation of 124 ppm and cover a similar range ($^{143}Nd/^{144}Nd$ = 0.513098–0.513222) to Pl ($^{143}Nd/^{144}Nd$ = 0.513073–0.513193, variation 120 ppm) (Fig. 2). The weighted mean of Cpx is 0.513158 ± 0.000004, compared to 0.513166 ± 0.000006 for Pl. Most data points are within error on one another with errors of ±7–65 ppm 2 SE for Cpx and ±13–77 ppm 2 SE (standard error of the mean) for Pl. However, the weighted means for Cpx and Pl have mean square weighted deviations (MSWD) of 3.7 and 4, respectively, and the weighted mean of the entire crystal population ($^{143}Nd/^{144}Nd$ = 0.513160 ± 0.000003, n = 44) has a MSWD of 3.8. Furthermore, some data points are not within error; e.g., the Pl sample at 2193 m (Fig. 2) is outside of the 2 SE of Pl at the base and top of the section. Taking all 2 SE errors into account, the minimum possible range of the entire crystal population is 77 ppm.

The Nd isotopic composition of the sheeted dikes is similar to that of the crystal record ($^{143}Nd/^{144}Nd$ = 0.513150–0.513203, with precision ±7–11 ppm 2 SE, mean = 0.513171 ± 0.00003 2 SD), but the variation is significantly smaller (range of 53 ppm). The sheeted dike data capture the full range in Nd isotope compositions of whole-rock data of gabbros from ODP Site 894 (mean = 0.513188, range 38 ppm; Pedersen et al., 1996).

The isotopic variability in the Hess Deep gabbro samples covers a large proportion of published Nd isotopes in MORB along the length of the EPR (Fig. 3). For example, they cover a significant range of the well-defined, 1000-km-scale oscillations in Nd isotopic compositions of EPR lavas between 3°S and 25°S (Fig. 3). Together, these observations highlight the importance of targeting the lower crustal crystal record to investigate mantle heterogeneity. All data measured in this study are presented in Supplemental Material S3.

## DISCUSSION

The mineral $^{143}Nd/^{144}Nd$ values through the Hess Deep lower crust show a 148 ppm variation, with a MSWD of 3.8, indicating that the

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[1] Supplemental Material. Item S1 contains element maps of all samples used in this study; item S2 contains full details of the methods; item S3 is a spreadsheet containing all data from this manuscript. Please visit https://doi.org/10.1130/GEOL.S.28485770 to access the supplemental material; contact editing@geosociety.org with any questions.

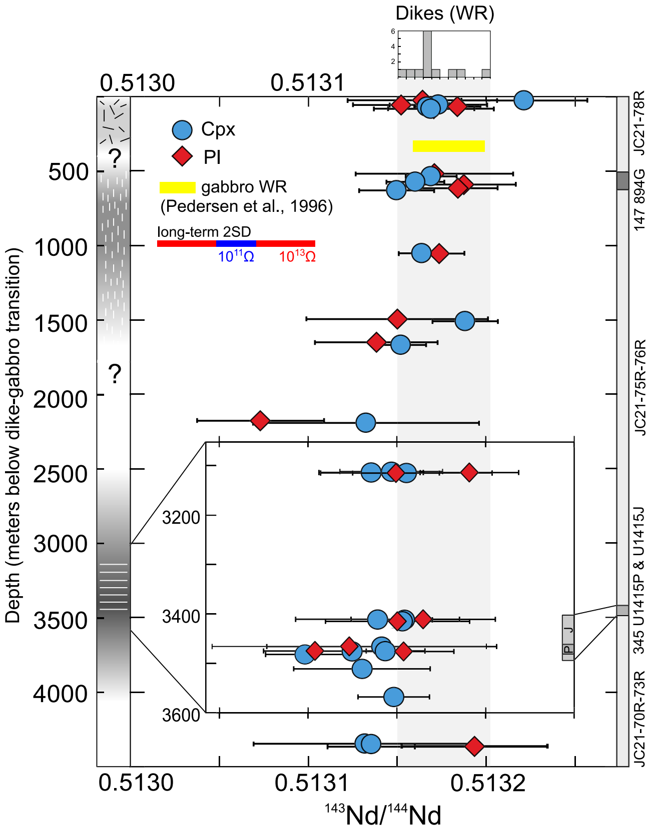

**Figure 2. Nd isotopic compositions of Hess Deep (East Pacific Rise) cumulate clinopyroxene (Cpx, blue circles) and plagioclase (Pl, red diamonds) cores. Error bars are 2 SE (standard error of the mean). Depth from 3050 m to 3600 m is expanded in the inset box. Gray band and histogram represent dike whole-rock (WR) data measured in this study. Yellow bar represents whole-rock gabbros from Pedersen et al. (1996). Stratigraphy is summarized on the left, which comprises layered gabbros at the base, foliated gabbros above, and isotropic gabbros at the top (from Lissenberg and MacLeod, 2016). The right axis shows expedition sample numbers. JC21—RSS *James Cook* cruise JC21 in 2008, using ROV *Isis*; 345 U1415—Integrated Ocean Drilling Program (IODP) Expedition 345 Site U1415; 147 894—Ocean Drilling Program (ODP) Leg 147 Site 894. Long-term reproducibility (2 SD) of the Nd reference JNdi-1 is shown by the blue ($10^{11}$ Ω resistors) and red ($10^{13}$ Ω resistors) bars.**

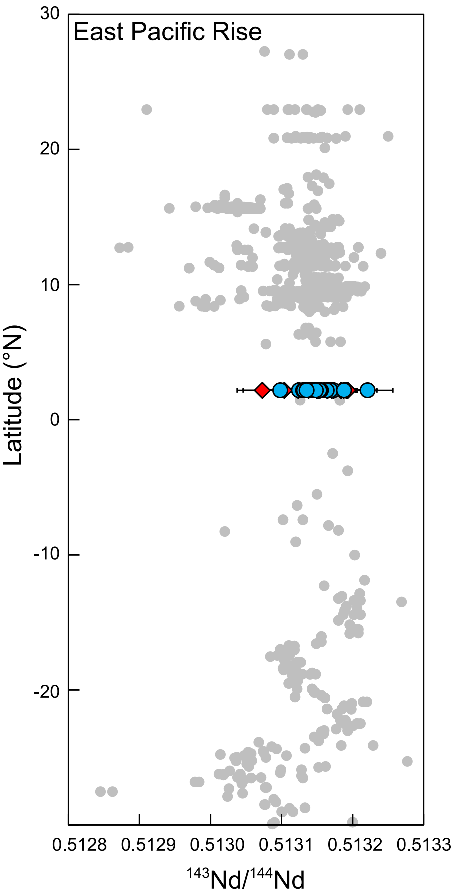

**Figure 3. Isotopic compositions from minerals measured in this study at Hess Deep (East Pacific Rise) (colored symbols as in Fig. 2), compared with mid-ocean ridge basalt (MORB) compositions along the East Pacific Rise (gray circles) from the PetDB Database (https://search.earthchem.org; Lehnert et al., 2000).**

Nd isotope variation is statistically significant and represents true heterogeneity. Three of the crystal isotope ratios are not within uncertainty of the range in dike values (Fig. 2) and represent more-enriched Nd compositions (lower $^{143}Nd/^{144}Nd$ values) than the whole-rock record. To a first order, our data suggest that the magmas delivered to the crust at Hess Deep are compositionally heterogeneous at the scale of melt extraction.

The observation that the lower crust is more heterogeneous (148 ppm variation) than the upper crust (53 ppm variation) indicates that Pacific MORBs underestimate the heterogeneity of their source mantle, and some homogenization occurs in the crust. The latter is consistent with major- and trace-element compositions of MORBs, which show clear evidence for magma mixing in their petrogenesis (e.g., Dungan and Rhodes, 1978; O'Neill and Jenner, 2016).

It is striking that all the data points that are outside of error of the sheeted dikes are located in the deeper part (>1800 m below the dike-gabbro boundary) of the lower crust. At Hess Deep, the lower crust is characterized by primitive layered gabbros (Lissenberg et al., 2013; Gillis et al., 2014a; Lissenberg and MacLeod, 2016; Akizawa et al., 2023; Basch et al., 2024), which are petrologically distinct from the more-evolved, yet unlayered, shallower part of the lower crust (Natland and Dick, 1996; Pedersen et al., 1996; Lissenberg et al., 2013; Lissenberg and MacLeod, 2016). These deeper gabbros, containing the most primitive crystals (Lissenberg et al., 2013), also record a greater level of Nd isotopic heterogeneity (MSWD = 3.0) compared to the shallower gabbros (MSWD = 2.1), consistent with petrological evidence for the presence of unaggregated melts at this deeper level (Coogan et al., 2002). Therefore, our data indicate that most of the crustal mixing takes place in the deeper lower crust, potentially in magma-rich lenses (e.g., Marjanović et al., 2014). These lenses provide locations for magma mixing associated with both rapid replenishment by primitive melts (O'Neill and Jenner, 2016) and slow replenishment by variably evolved melts transported through the lower crust by porous flow (Lissenberg et al., 2013).

On average, the lower crust appears to be offset to more-enriched Nd compositions compared to the upper crust (Fig. 2). A more-enriched lower crust is contrary to recent predictions that suggested that the lower crust preferentially retains crystallization products of depleted melts (Neave et al., 2019; Burton et al., 2024). This may, in part, relate to a sample bias, with most of the enriched samples representing a short (tens of meters) interval drilled during IODP Expedition 345 (Fig. 2). Alternatively, some enriched gabbros may represent the plumbing systems of near-axis seamounts that are prevalent along the EPR and erupt abundant enriched melts (Zindler et al., 1984). This is consistent with large variations in cooling rates in the deep lower crust, with faster-cooled samples potentially representing gabbro intrusions emplaced off-axis in already-cooled lower crust (Sun and Lissenberg, 2018).

There are now Nd isotopic data for both slow- and fast-spreading ridges, enabling a comparison of the level of heterogeneity recorded in the lower oceanic crust and the degree of crustal versus mantle-level aggregation of mantle melts. The Nd isotopic heterogeneity in Hess Deep lower crust is similar to that observed in Pl and Cpx (203 ppm variation) from the Semail Ophiolite, Oman (Jansen et al., 2018), which also formed at a fast-spreading ridge (Fig. 4). In contrast, the Nd isotopic variability at Hess Deep is significantly smaller than the heterogeneity observed in slow-spreading crust. For example, Nd isotope variations are ~500 ppm in Pl and Cpx from the lower crust of the Atlan-

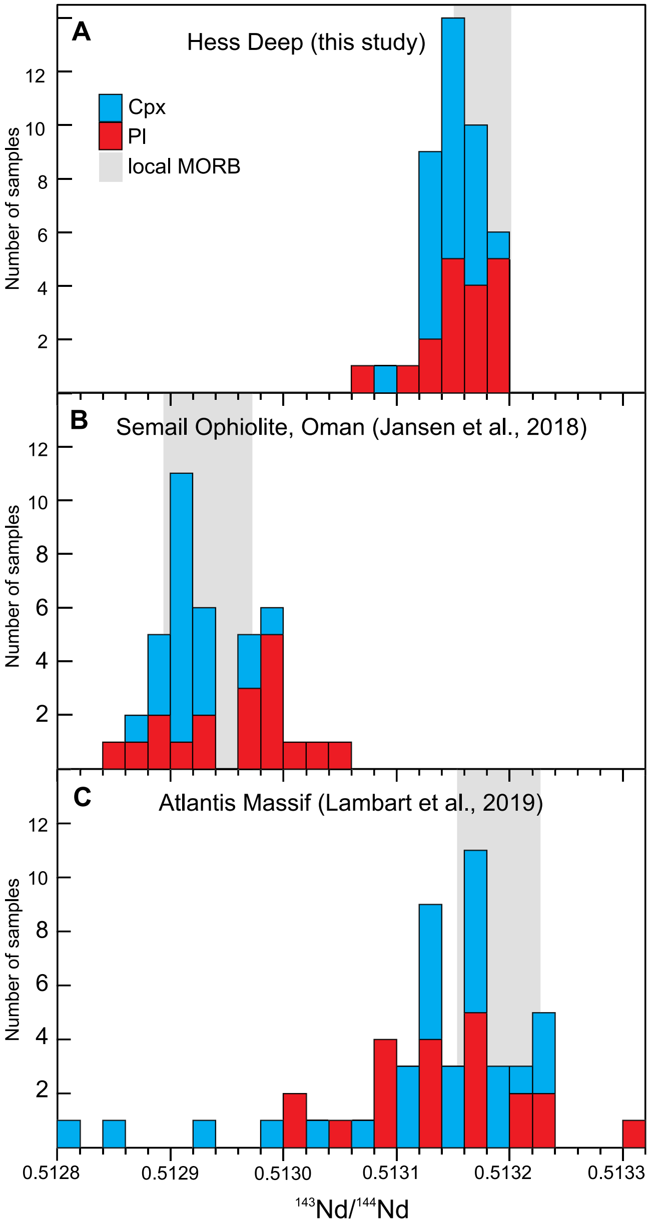

**Figure 4. Histograms showing cumulate plagioclase (Pl, red) and clinopyroxene (Cpx, blue) Nd isotopic variability from (A) Hess Deep on the East Pacific Rise (this study); (B) the Semail Ophiolite, Oman (Jansen et al., 2018); and (C) Atlantis Massif, northern Mid-Atlantic Ridge (Lambart et al., 2019). Gray bands represent range in local mid-ocean ridge basalt (MORB).**

tis Massif, northern Mid-Atlantic Ridge (Fig. 4; Lambart et al., 2019). This high degree of isotopic variability in primitive crystal domains provides clear evidence for the delivery of highly heterogeneous mantle melts to the crust, further suggesting that crustal level melt aggregation takes place at slow-spreading ridges. In contrast, the reduced isotopic heterogeneity recorded here through fast-spreading crust indicates that, although some homogenization occurs in the crust, most of the mixing occurs in the mantle, or that EPR mantle is less heterogeneous. Hence, there appears to be a spreading rate control on the amount of mantle-level aggregation of melts. We attribute the limited heterogeneity in fast-spreading lower crust to the increased amount of mantle melting and the accompanying increase in partial melt batches being transported upward through the mantle. If this melt transport is focused in dunite channels, as widely hypothesized (e.g., Kelemen et al., 1995), these channels could provide an opportunity for magma mixing. Alternatively, or in addition, mixing may occur during melt aggregation at the top of the mantle. If melts collect in sill-like bodies near the Moho, such as that detected (albeit off-axis) by geophysical data along the East Pacific Rise (Garmany, 1989), and suggested by the observations of sills in the Moho transition zone of the Oman ophiolite (Boudier and Nicolas 1995), then these melt bodies may homogenize heterogeneous mantle melts prior to their intrusion into the lower crust.

## CONCLUSIONS

Cumulate minerals of a complete section of lower oceanic crust at Hess Deep preserve Nd isotopic heterogeneity that is obscured in both the whole-rock record of lower crustal gabbros and in the upper crust. This finding confirms the importance of using the crystal record from the lower oceanic crust to investigate mantle heterogeneity. At Hess Deep, the mantle melts delivered to the crust are heterogeneous at the scale of melt extraction, and these melts are homogenized by aggregation within the lower oceanic crust. A comparison of the Nd isotopic record from Hess Deep with that of the fast-spreading Semail ophiolite and the slow-spreading Atlantis Massif indicates that isotopic heterogeneity preserved in the lower crust correlates with spreading rate. This is attributed to enhanced mantle-level melt aggregation at fast-spreading ridges prior to further homogenization in the crust.

## CRediT AUTHOR STATEMENT

**George Cooper:** Methodology, Investigation, Writing—Original Draft, Visualization. **Johan Lissenberg:** Conceptualization, Funding acquisition, Writing—Review & Editing. **Janne Koorneef:** Methodology, Writing—Review & Editing. **Max Jansen:** Investigation, Writing—Review & Editing. **Marc-Alban Millet:** Conceptualization, Writing—Review & Editing.

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