

Magmatic filtering of mantle compositions at mid-ocean-ridge volcanoes

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The Earth's mantle constitutes over 80% of the planet's volume, and is therefore a key reservoir in global geochemical cycling. The magnitudes and length scales of heterogeneities in the composition of the mantle are an important aspect of this reservoir, but are inaccessible to direct sampling. Mid-ocean-ridge basalt (MORB), the dominant eruptive product of ridges, provides a geographically widespread first-order snapshot of the mantle in terms of the distribution of major and trace elements and its isotopic composition. However, a range of processes occur between melt generation at depth and eruption on the sea floor that modulate the chemical signals of mantle heterogeneity in MORB, making it an imperfect sample. Detailed observations over the past few years have revealed that regional mantle heterogeneity is generally preserved in MORB most accurately where the melt supply is low, and that timescales between melt generation and MORB eruption are relatively short. Nevertheless, because of the variety of volcanic and magmatic processes that act to preserve or destroy signatures of mantle heterogeneity in MORB, a much broader base of observations from different locations will be required to faithfully reconstruct upper mantle heterogeneity.

Earth's dominant form of magmatism occurs at mid-ocean ridges (MORs), producing the igneous crust for two-thirds of the planet's surface and conveying significant heat and material fluxes from the mantle to the world's oceans. Mid-ocean-ridge basalt (MORB) magmas form from upwelling compositionally heterogeneous mantle¹ by aggregation of near-fractional melts beneath spreading centres². Multiple processes modify magmatic composition during ascent and storage before eruption^{3–5}. MORBs can be used to probe upper-mantle composition^{1,5}, provided the chemical signals imparted by processes such as melting, magma transport, melt-rock reactions, mixing and differentiation can be disentangled from those of the mantle source rocks.

Melting conditions vary beneath MORs in multiple ways. Models predict that mantle composition and flow can affect the shape of the MOR melting region⁶, and that mantle of heterogeneous composition will melt progressively⁷. Uranium-series (U-series) radioactive disequilibria in MORBs constrain the melting, melt extraction and melt accumulation rates from decamillennial^{8,9} to decadal timescales¹⁰. Globally, MORB chemistry depicts variations in how MOR volcanism samples the mantle in space and time — geography, spreading rate and crustal structure emerge as important controlling variables^{1,3,5}. Lava composition patterns at 10 to 100-km length scales mimic physical ridge segmentation, and related variations in melt supply and uppermost mantle and crustal temperatures. The oceanic crust imparts multiple chemical fingerprints on erupted compositions. A relatively small fraction of MOR magma erupts to form MORB (typically <20%); the rest crystallizes as plutons at mid- to lower-crustal levels, forming a substrate that melts can react with¹¹. Magma mixing and differentiation in composite reservoirs also significantly affects MORB composition¹².

The global MOR is a large and complex volcanic system in which site-specific geological conditions affect MORB chemistry. These effects are being studied at high resolution, in ever more locales to investigate the scales and magnitudes of mantle compositional heterogeneity. Integrated geochemical, geophysical and geological data indicate that mantle compositions are significantly modified in range, magnitude and length scale at MORs by pre-eruptive

magmatic processes, such as shallow magma residence and transport through the upper mantle and lower crust, which thus must be evaluated as part of MOR mantle composition studies.

Compositional diversity on a regional scale

Many first-order, global-scale variations in MORB chemistry probably reflect differing mantle compositions and melting conditions^{1,3}. Spectral analysis of radiogenic isotope variations along the Mid-Atlantic Ridge reveals two classes of mantle compositional heterogeneity: that arising from hotspots and that arising from older heterogeneities not yet completely mixed into the mantle by convection¹³. A higher frequency of regional variability in radiogenic isotope compositions in Indian and Atlantic ocean MORB, compared with Pacific Ocean MORB, may also reflect more focused and diffuse patterns of mantle upwelling, respectively¹⁴. Hafnium and lead isotope studies suggest that the compositional contrast between Indian and Pacific ocean MORB is produced by regional upper-mantle entrainment of lower continental crust and subduction recycled material, respectively¹⁵.

But to what extent might some of these observations reflect magmatic overprinting on MORB compositions? Global MOR magmatism is strongly affected by the magnitude and temporal variability of melt supply (summarized in Fig. 1). For example, reduced variance of mantle parameters in Pacific Ocean MORB is a predicted consequence of post-melting magmatic processes at ridges with intermediate to high magma-supply¹² (Fig. 1a). A reduction in mantle-related variance in MORB occurs by magma mixing over a range of depths, and is almost certainly enhanced at higher average melt proportions in the mantle and crust (Fig. 1b). However, the coupling of mixing signatures with increased differentiation, which can be observed over a number of length scales (Fig. 2), implies that much of this mixing happens at shallow crustal levels, where magmas pool and differentiate in melt-rich lenses before eruption¹². A second important attribute of global MORB variations away from hotspots is a near constancy in the relative range of mantle compositional tracers, such as ⁸⁷Sr/⁸⁶Sr (Fig. 2a–c) or La/Sm, in the most magnesian (least differentiated) lavas. This suggests that ridges generally

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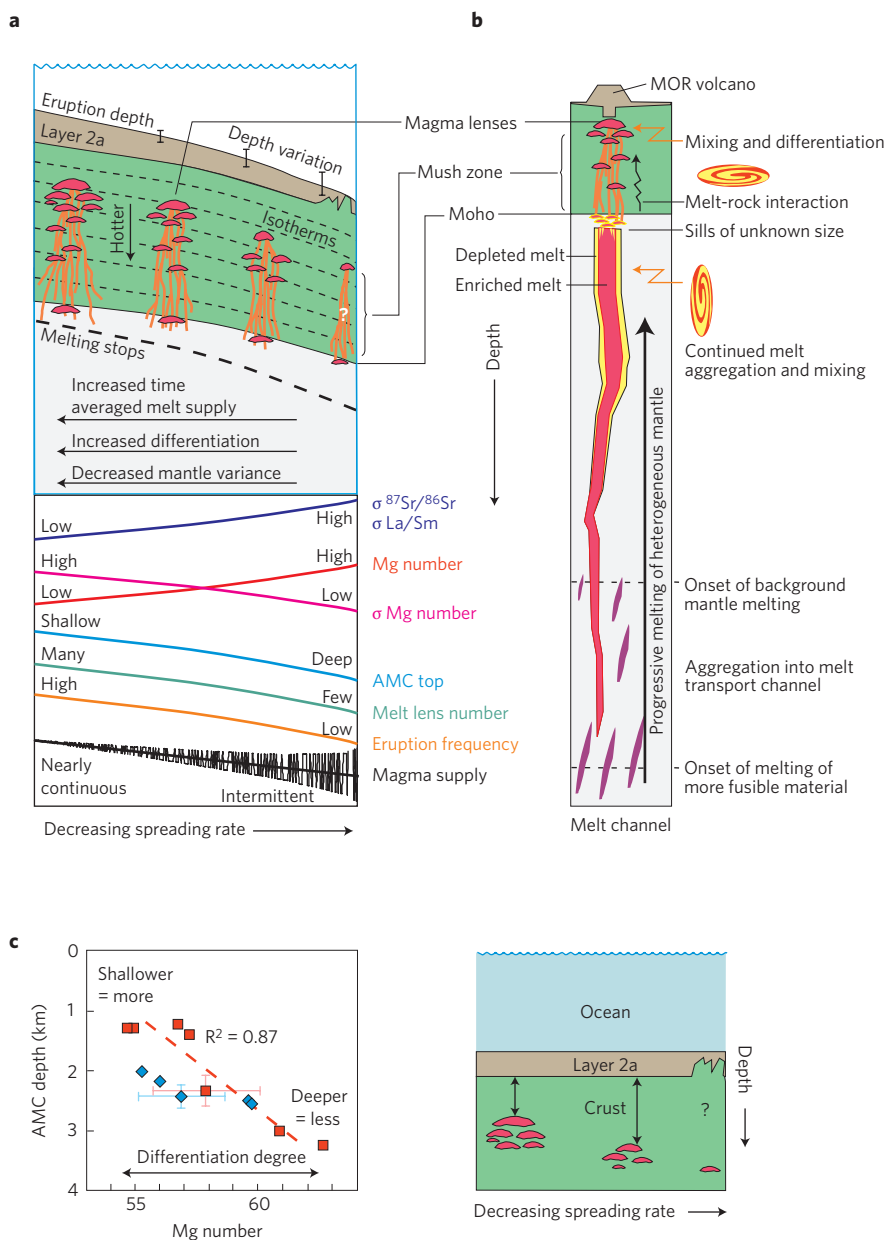


Figure 1 | Magmatic processes that affect MORB compositions. **a**, Variations with spreading rate (away from hotspots). The average number, size, depth, composition, temperature and mixing efficacy of the melt segregations versus spreading rate (which is a first-order melt-supply proxy at non-hotspot influenced ridges)¹². Mg number is the mole fraction of the element Mg, relative to the sum of Mg and Fe²⁺, in a specimen; $\sigma^{87\text{Sr}/86\text{Sr}}$, $\sigma \text{La/Sm}$ and $\sigma \text{Mg number}$ are the standard deviations of the mean of these parameters. The greatest uncertainty about the range of conditions is at the slowest spreading rates. **b**, Processes in the mantle and crust. Schematic of melt production from more and less fusible mantle compositions at different depths⁷, and processes that occur during aggregation, transport and magma mixing in high-porosity conduits⁴⁰, followed by melt interactions in the lower crust¹¹, and collected in crustal magma chambers¹². Little is known about the geometry or size of potential magma accumulation reservoirs beneath the moho. Melt channel width is greatly exaggerated. **c**, MORB chemistry and axial magma chamber (AMC) depth. Relationship of seismically imaged AMC depth, mean erupted MORB composition and spreading rate for slow- to fast-spreading ridges. Averages of various sections of the East Pacific Rise, Juan de Fuca ridge, and the Mid-Atlantic Ridge Lucky Strike segment (red squares) are included in the linear regression; individual segments of the Juan de Fuca ridge follow a similar trend (blue diamonds; data sources are in ref. 12). Crosses are approximate 1 σ variations in those means.

process and mix parental magmas to a similar degree during mantle and lower-crustal transport (that is, before shallow aggregation)¹², although a future challenge is to determine the relative roles of mantle and magmatic effects on compositional variations at regional scales.

Long-term melt flux to the crust affects regional MORB composition by determining the depth, size, mixing efficacy and

thermal state of crustal magma reservoirs. When the melt supply is low, magma accumulates episodically and resides in poorly connected, deeper and hotter reservoirs, erupting less differentiated lavas that apparently better preserve mantle-derived compositional variations, such as radiogenic isotope compositions and incompatible trace element ratios¹² (Fig. 2c). In contrast, higher melt-supply promotes magma differentiation accompanied by

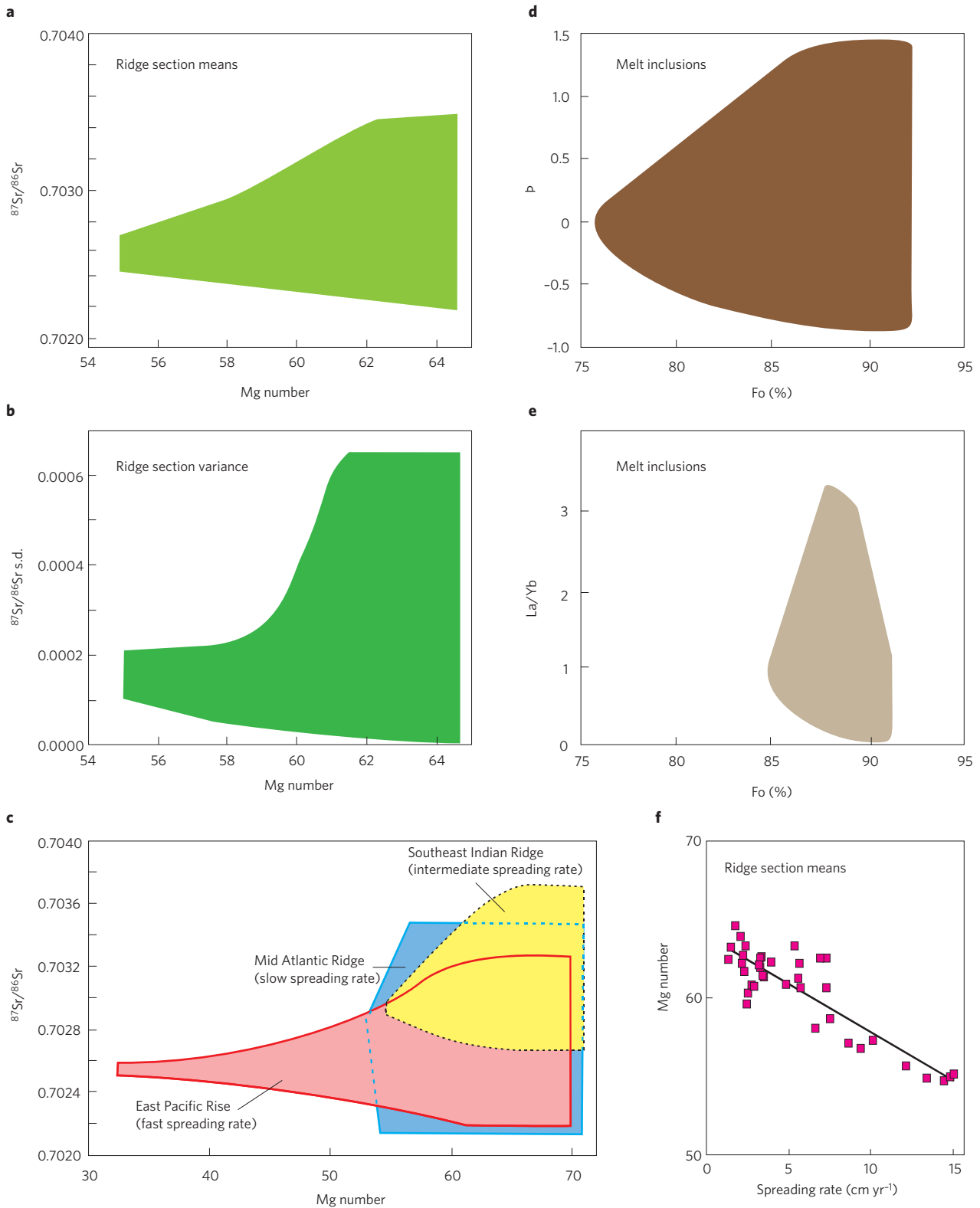


Figure 2 | Mantle compositional variance loss coupled to differentiation. These compositional attributes observed at multiple spatial scales constrain how and where MORB magmas mix and cool (composite figure after data in refs. 12 and 40). **a, b**, The variance in mean magmatic $^{87}\text{Sr}/^{86}\text{Sr}$ decreases with decreasing molar Mg number between and within non-hotspot influenced submarine ridge sections. **c**, Individual MORB samples from well-sampled ridges at different spreading rates. **d**, The melt inclusion deviation from flow mean: P, the deviation of Icelandic melt inclusion compositions from the average of the host lava decreases as host olivine composition (forsterite end member (Fo) percentage) becomes more differentiated. **e**, The melt inclusion variation in the Borgarhraun lava flow in northeast Iceland: the La/Yb of melt inclusions becomes less variable as the host olivine becomes more differentiated. **f**, The mean molar Mg number decreases (becomes more differentiated) as spreading rate increases indicating the relationship between differentiation degree and average melt supply for MOR sections globally.

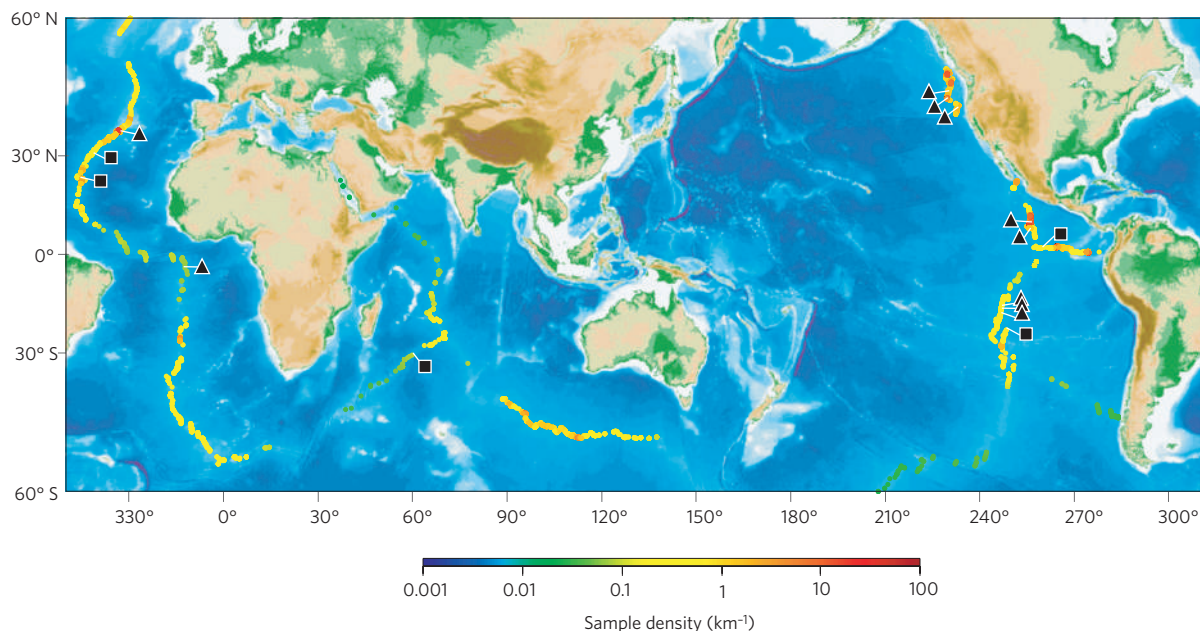


Figure 3 | Sample sites on the global MOR. Locations (circles) are colour coded for estimated sample density (km^{-1}) as indicated in the scale bar. Sample sites were compiled from the petrologic database (<http://www.petdb.org>). Black triangles and squares denote mapped/sampled eruption sites and well-studied gabbro sites, respectively.

loss of chemical variance in many of these same parental magma parameters. The number of places along the ridge where axial magma lenses have been imaged seismically is small, although where they have been observed the shallowest lenses occur at higher melt-supply rates. These shallow lenses also tend to erupt MORB that is more differentiated (Fig. 1c). Other regional-scale indicators of average differentiation depth of erupted magmas come from He, Ar and CO_2 abundances in MORB, which indicate high-pressure degassing at slower spreading rates¹⁶, where magmas also display reduced Cl/K variance, implying deeper crystallization farther from active hydrothermal circulation zones¹⁷.

Intermediate-spreading ridges sit near the threshold for well-developed, quasi-steady-state, seismically detectable crustal magma reservoirs⁴. Generally, MORB erupted at such ridges should better preserve mantle signals compared with magmatically more robust ridges. On the North Gorda Ridge, an increase in compositional diversity correlates with ridge morphology and waning melt-supply from a likely temporal shift in melt production and aggregation¹⁸. A regional gradient in melt supply over thousands of kilometres along the Southeast Indian Ridge correlates with pronounced variations in ridge morphology and lava composition probably arising from gradients in mantle temperature, melting rate and source composition. At the lowest melt supply a few per cent of highly fusible mantle pyroxenite veins dominate aggregate melt composition, but not melt flux¹⁹. Hafnium isotopic compositions in MORB from this region mirror striations in mantle composition, with dimensions and Poisson distribution probably controlled by stretching of compositionally distinct domains during convection²⁰. Magmatically feeble oceanic transform faults at ridges with high spreading rates offer another low to moderate melt-supply window to the mantle, showing a greater range²¹ but similar pattern²² of melt compositional diversity coupled to U-series signatures — interpreted to reflect incomplete mixing of deep and shallow melts.

Melt supply is highly uneven at the slowest spreading rates, so MORB erupted along the ultraslow spreading Gakkel and Southwest Indian ridges shows signatures of fine-scale mantle compositional and thermal heterogeneities^{23–25}, consistent with less magma

homogenization at these low-melt-flux ridges¹². Some Gakkel Ridge basalts carry a mantle signature of ancient delaminated subcontinental lithosphere, resembling the ‘Dupal’ composition of some Southern Hemisphere basalts²⁶. Ancient, refractory abyssal peridotites indicate that a large proportion of the upwelling mantle beneath Gakkel and perhaps other ridges contributes little magma to the ridge axis²⁷.

In summary, melt supply and MORB chemical signals of regional mantle heterogeneity are strongly interrelated, with generally a better signal preservation at low melt-supply.

Individual volcanoes and single eruptions

Significant MORB chemical heterogeneity at sub-kilometre length scales provides a high-resolution record of how the ‘ridge filter’ of magmatic processing operates on mantle compositions. There are few sites where the products of individual submarine MOR eruptions have been mapped and studied in detail^{28,29} (Fig. 3), but chemical variances in these lava flows indicate that coexisting primary magma batches are incompletely mixed and variably differentiated before eruption³⁰. At this scale, chemical variance is related to eruption size and local melt-supply, with greater variance within and between large lava flows, and between flows erupted at intermediate to low melt-supply^{29,30}.

However, even at high melt-supply, single flows can show substantial, systematic compositional heterogeneity. Near 17.5° S on the East Pacific Rise two recent lava flows preserve coupled spatial patterns in mantle composition, differentiation and U-series signatures, all of which follow binary mixing trends (Fig. 4), implying that two magma compositions were fed at different times and then variably mixed in the axial magma lens before both eruptions³¹. The spatial patterns suggest limited along-axis magma transport before eruption, indicating emplacement by near vertical dyking (Fig. 4f). This high-resolution sampling exercise indicates that a chemically heterogeneous melt lens repeatedly fed eruptions while preserving a geographic composition pattern over tens of years and about 20 km (ref. 31). The Pb isotopic variation in these lava units is much greater than anticipated from a previously described, long-wavelength (~500 km) compositional gradient (Fig. 4g), indicating

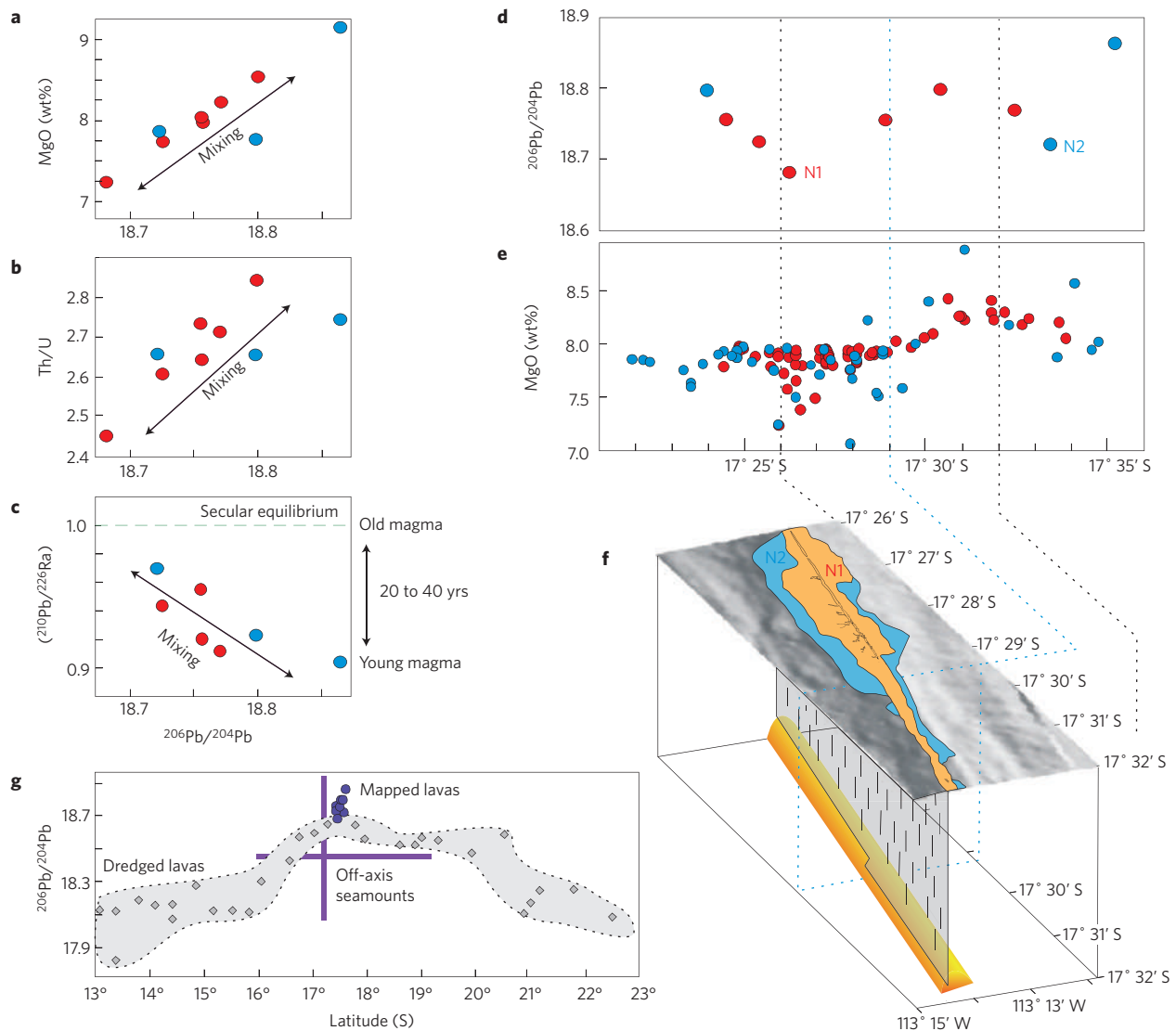


Figure 4 | Mantle, crustal and temporal compositions mapped into MORB lava flows. Two lava units (N1, red circles; N2, blue circles) that erupted at 17.5° S on the East Pacific Rise, display well correlated signatures of **a**, Differentiation (MgO), **b**, Mantle composition (Th/U) and **c**, Short-lived radioactive disequilibria ($^{210}\text{Pb}/^{226}\text{Ra}$) versus $^{206}\text{Pb}/^{204}\text{Pb}$ (a mantle compositional tracer); both flows follow the same mixing trends and the same patterned compositional variations along-axis, in **d**, $^{206}\text{Pb}/^{204}\text{Pb}$ and **e**, MgO. **f**, The outline of the N1 (youngest) and N2 lava flows overlay on shaded seafloor bathymetry plus underlying magma lens schematic (colour coded for cooler magma temperatures at the top) and a possible eruptive dyke geometry. **g**, The compositional variation in these two flows is significant compared with a smooth, long wavelength regional isotopic gradient in samples dredged from the ridge axis (diamonds); the range of regional mantle compositions is reflected in nearby off-axis seamounts (purple cross). Data from ref. 31.

that the gradient is largely a function of how two mantle compositions were magmatically processed, rather than the physical along-axis disposition of compositions in the mantle.

Icelandic volcanoes provide another opportunity to observe and map analogous eruption products with relative ease, and study magmatic processes at high spatial and temporal resolution. Chemical variability in successive western volcanic zone eruptions correlates with eruptive style, such that short-lived fissure eruptions have more homogeneous lava compositions than long-lived lava-shield building eruptions³². These observations have implications for submarine MOR magmagenesis, where fissure-fed and lava-shield eruption deposits can coexist in close proximity²⁹. Compositional variability in the densely sampled Borgarhraun flow (northeast Iceland) reflects incomplete mixing of variable mantle melts, with a spatial distribution of compositional domains that might represent discrete magma lens or magma recharge volumes³³.

Collectively, these and other studies demonstrate how different volcanic and magmatic processes act to preserve or destroy magmatic compositional heterogeneity, providing both context and challenges to global and regional petrogenetic models of comparatively sparsely sampled ridges.

Compositional diversity in melt inclusions

Phenocryst-hosted melt inclusions preserve a high fidelity record of melt compositional diversity within the plumbing system of MOR volcanoes and the processes occurring between inclusion entrapment and eruption. Although the interpretation of their compositional heterogeneity is complex, melt inclusions have been used to better understand both the origins of compositional variations in MOR magmas and the magmatic processes that filter this signal before eruption^{34–37}. Olivine-hosted melt inclusions, such as those in basalts from the Mid-Atlantic Ridge (MAR)³⁸ and Iceland^{39,40}, demonstrate a broader range of melt compositions

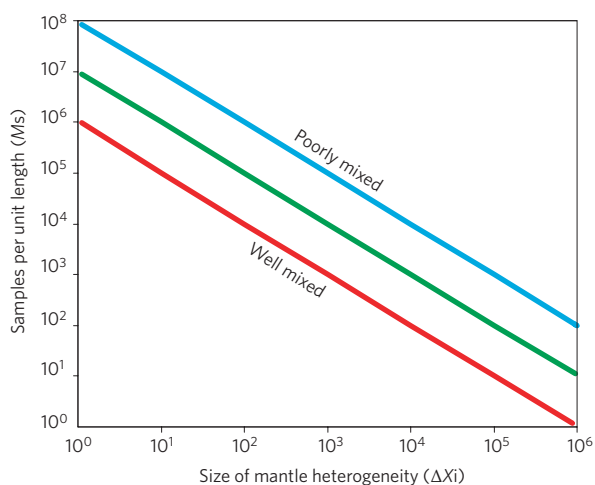


Figure 5 | Sampling density and mantle heterogeneity. A log-log plot illustrating the relationship between the relative length-scale of mantle heterogeneities (ΔX_i) and the relative MORB sampling density along-axis (M_s) required to estimate the average regional mantle composition. Calculations were made for three different strengths of mixing and plotted as red ($N_m = 1,000$), green ($N_m = 100$) and blue ($N_m = 10$) coloured lines, where N_m is the number of equal-volume melt batches of heterogeneous mantle that are mixed together to make an erupted composition. More details are provided in the Supplementary Methods, along with the rest of quantitative model and simplifying assumptions related to this figure. The calculations illustrate that a greater sampling density is required to characterize smaller heterogeneities. More efficient magma mixing (high N_m) will reduce the sampling density required to recover the average mantle composition (although greater numbers of samples are required to estimate unmixed endmember compositions).

attributable to the mantle than the aggregated melts that form most MORB (Fig. 2d). The Pb isotopic compositions of inclusions from a single Icelandic hand-specimen³⁹ span >50% of the range in MAR glasses¹¹, indicating high-amplitude, short length-scale compositional variations beneath ridges of the order of 20 m to 100 km (ref. 39). Understanding the sampling and preservation of this variability requires next generation models of mantle melting and melt transport.

Channelized melt flow may produce binary mixing trends in melt inclusion datasets and suites of temporally and spatially restricted whole-rock compositions^{35,39}, damping the signal of mantle heterogeneity through partial mixing before melt inclusion entrapment. Later-stage magma mixing and concurrent crystallization is recorded in both whole rock¹² and melt inclusion compositions^{33,40} (Fig. 2), providing fluid dynamical information about the relative rates of mixing and cooling within crustal magma chambers.

Magmatic timescales

Recent observational evidence from U-series disequilibria in MORB implies short timescales between melt generation and eruption, and provides an impetus for refining the models of the physics of mantle melting and melt transport, as well as magma storage and evolution in the crust. As these chemical tracers are radioactive, they also distinguish chemical signatures of magmatic fractionation and long-lived chemical features of the mantle source. The U-series disequilibria provide especially high-resolution information when focused on individual historical volcanic units. In Iceland, combined ^{226}Ra - ^{230}Th and O-isotope data demonstrate thousand year timescales for crustal assimilation in the huge 1783–1784 Laki basaltic fissure eruption⁴¹. Furthermore, ^{226}Ra - ^{230}Th - ^{238}U and compositional data from recent Veidivötn fissure system eruptions indicate that

compositionally distinct, closely spaced magma lenses can coexist for hundreds of years in the crust, yet remain hydraulically disconnected over time periods longer than the ~700 yr volcanic repose⁴².

Co-variation of short-lived ^{210}Pb - ^{226}Ra disequilibria (half-life = 22 yr) and other compositional attributes of <20 yr old submarine MOR lavas indicate that magmatic conditions can fluctuate rapidly at intermediate- to fast-spreading ridges¹⁰. Even accounting for magma mixing, the disequilibria constrain melt transport and accumulation rates for a significant fraction of the magma chamber volume to just a few decades before eruption, pointing to rapid differentiation and crustal heat-replenishment timescales¹⁰. The ^{210}Pb - ^{226}Ra disequilibria in successive eruptions separated by roughly two decades at 17.5° S on the East Pacific Rise with very similar compositions (Fig. 4c) suggest that the same magmas fed both eruptions with little change in between³¹. Mantle-melting models can simulate observed ^{210}Pb - ^{226}Ra disequilibria, but rapid melt-transport is required to preserve this signature in erupted MORB. Such transport is unlikely to occur by diffuse porous flow⁸. Channelized melt flow^{2,35} may provide sufficient melt velocities, however the full range of MOR melt-transport conditions remains to be modelled. Lower-crustal melt reactions may also have a role in modifying these and other U-series disequilibria, although preliminary models⁴³ do not yet incorporate realistic lower-crustal conditions or predict other coupled geochemical observations in these MORBs.

Insights from deep crustal rocks

Mantle compositions and melting conditions have been deduced from global MORB compositions that have been corrected for fractional crystallization^{3,5}, but the strength of those insights depends strongly on assumed fractionation conditions. Direct observations on the plutonic lower crust inform these estimates, but these are hard to come by, particularly along fast-spreading ridges, where the lower crust is only accessible in tectonic windows and fracture zones (Fig. 3). At slow-spreading ridges, drillhole studies indicate that episodic melt supply leads to small, faster cooling crustal plutons than at fast-spreading ridges^{11,44}, yet magmas erupted there are apparently hotter¹².

In contrast to relatively homogeneous residual abyssal peridotites⁴⁵, lower crustal lithologies show strong compositional heterogeneities on scales ranging from millimetres to hundreds of metres^{11,44,46,47}. There is insufficient data on MORB at this sampling scale to indicate the extent to which this heterogeneity affects erupted magma, and some heterogeneity in the crust may form after pluton isolation from the magma plumbing system that feeds eruptions. Although eruptive products preserve evidence for small-scale heterogeneity in mantle melt compositions^{29–31}, such variability has rarely been identified in lower-crustal gabbros, and the physical scale of its imprint in the lower crust has yet to be determined. Spatially restricted sampling has not helped in this regard, although recently developed geochronological⁴⁸ and geospeedometric⁴⁴ methods are beginning to provide the context to understand compositional relationships within and between plutonic cooling units.

Reactive melt migration may also affect compositional variance in the lower oceanic crust and impart chemical signatures to erupted magmas. An extreme example may be the complete transformation of mantle peridotites to primitive crustal troctolites⁴⁷. A more widespread reaction is primitive clinopyroxene crystallization at the expense of plagioclase and olivine resorption^{46,47}, leading to decreased Ca/Al ratios of transient melt⁴⁶, a magma signature more commonly attributed to high-pressure crystallization^{49,50}.

Mid-ocean ridges as windows into the mantle

Despite these impressive advances, much work remains to be done to infer mantle compositions from MORBs with high fidelity. Pioneering early studies relying on reconnaissance-scale

sampling was sufficient for determining many first-order upper mantle compositional characteristics. More recent studies at higher spatial and temporal resolution, and covering a greater aerial and internal extent of the system, have uncovered much more of the compositional complexity arising from MOR magmatic processes. This complexity defines the scope of what is needed to fully comprehend the magmatic sampling of mantle compositions at MORs. We know that MORB eruptions can be fed by multiple chemically discrete magma batches that sample the mantle at small length scales, that melt–rock reaction in the upper mantle and crust influence those compositions, and that higher melt supply can mix out the signals of these processes. Some of these processes, such as melt aggregation and magma mixing, can reduce compositional variability whereas others, such as reactive processes in the crust and mantle, can potentially enhance compositional variability in ways unrelated to primary source compositions. All of these processes must be evaluated before MORB compositions can unambiguously be used to infer the scales and magnitudes of mantle compositional heterogeneity.

Our understanding of these magmatic processes and compositional scales remains limited by insufficient MOR sampling density and geological control. Very little of the MOR system has been observed with sample densities capable of capturing heterogeneity length-scales of 100 m or less (for example, Fig. 3). The number of observations required probably varies from site to site and measurement to measurement, but future MOR sampling campaigns should be designed to investigate a range of heterogeneity sizes and mixing length-scales (Fig. 5). There are not yet enough observations in space and time to quantify temporal variability in melt supply or its effects on MORB compositions and MOR structure. The physical and temporal scales of melt injection to the crust, pluton formation and erupted compositions are also still poorly defined.

Thus, many more targeted observations will be required at many more locales covering the full range of spatial scales and geological conditions to confidently set the boundaries on operative volcanic conditions, pre-eruptive processes and mantle compositions at the tens of thousands of volcanoes along the global MOR. A next generation of melting and melt-transport models that explore relationships among processes, sampling and preservation of mantle heterogeneities, the causes and effects of melt supply fluctuations, and the extent of physical mixing during different modes of melt transport, must also be developed and tested against this growing database of observations. With sufficient resources and personnel, much greater insight should be obtainable within the next decade or two.

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Additional information

Supplementary information accompanies this paper on www.nature.com/nature-geoscience. Correspondence and requests for materials should be addressed to K.H.R.