

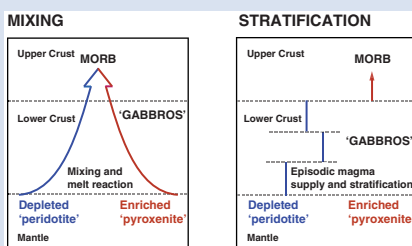
# Mantle depletion recorded by olivine and plagioclase megacrysts in oceanic basalts

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## Abstract



Earth's oceanic crust is largely formed by melting of the upper mantle where it upwells beneath mid-ocean ridges, providing a geographically widespread elemental and isotopic 'sample' of Earth's interior. Radiogenic isotope variations in oceanic basalts are commonly attributed to compositional heterogeneity in Earth's upper mantle, albeit reduced by mixing and reaction during melt ascent. Nevertheless, many mid-ocean ridge basalts are biased towards incompatible element enriched radiogenic isotope compositions, and questions remain as to whether their chemistry is indeed representative of the underlying mantle. Here we present Pb isotope data for plagioclase megacrysts (and olivine-megacryst hosted inclusions) from oceanic

basalts that crystallised in the lower oceanic crust or mantle, from incompatible element depleted melts. Our data show that the plagioclase megacrysts and olivine grew from melts with substantially less radiogenic Pb compositions than their host lava. High Ca plagioclase megacrysts are common in oceanic basalts, suggesting that depleted melts in the lower crust or mantle may also be widespread, acting to balance the enriched isotope compositions seen in many erupted basalts.

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## Introduction

Earth's silicate mantle is largely inaccessible to direct sampling yet bears the imprint of planetary formation and core segregation, melting to form the crust, and the recycling of crustal material through plate tectonics. Oceanic basalts form by partial melting of Earth's upper mantle, and their concentration ratios of incompatible elements or radiogenic isotope compositions are considered to relate directly to that of the mantle source. The fundamental tenet underlying the use of radiogenic isotopes in such mantle-derived basalts is that they are in equilibrium with their mantle source (e.g., Hofmann and Hart, 1978; Zindler and Hart, 1986). Thus, the composition of the long lived isotopes of heavy elements in basalts and their upper mantle source should be the same.

For the most part the radiogenic isotope composition of Mid-Ocean Ridge Basalts (MORB) points to the depletion of incompatible elements (that is, those that preferentially partition into a silicate melt) in the mantle over much of Earth's history (e.g., Hofmann, 2022). Variations in the radiogenic isotope composition of MORB, however, indicate that there must be some degree of chemical heterogeneity in the mantle (Zindler and Hart, 1986; Salters and Dick, 2002; Warren, 2016; Hofmann, 2022). These radiogenic isotope variations may be due to the presence of mantle material of either differing age, or differing concentrations of incompatible elements, resulting in variable radiogenic isotope compositions over time (or some combination of both factors). Furthermore, these chemical variations are often

ascribed to the presence of discrete rock types in the mantle. Clinopyroxene is the dominant host of incompatible elements in the upper mantle, therefore, any mantle lithology relatively rich in clinopyroxene, such as pyroxenite, is likely to be enriched in incompatible elements relative to typical depleted mantle peridotite. Indeed, pyroxenites from orogenic peridotites often possess radiogenic isotope compositions that are distinct from peridotites from the same bodies (e.g., Warren, 2016).

Evidence for mixing of magmas from both depleted and enriched sources in the mantle is seen in elemental variations (e.g., Rhodes *et al.*, 1979), and radiogenic isotopes in erupted basalts (e.g., Stracke *et al.*, 2003). Moreover, pioneering work showed how olivine-megacryst hosted melt inclusions preserve significantly greater chemical variability than their host lava, and that mixing must occur during crystallisation in the crust or shallow mantle (e.g., Sobolev, 1996). More recently spatial variations in radiogenic isotopes preserved by magmatic minerals in both ancient and modern oceanic crust have been taken to indicate mixing and melt reaction (e.g., Jansen *et al.*, 2018; Lambart *et al.*, 2019), dramatically reducing the chemical variability seen in erupted basalts. Nevertheless, that radiogenic isotope variations are still preserved, both globally and at the scale of individual ridge segments, indicates that magma mixing is incomplete.

The problem that remains is that the range of radiogenic isotope variations seen in erupted basalts appears to be biased towards enriched compositions. It is now well established that many MORB possess radiogenic isotope compositions that must be derived from a mantle rock type that is more enriched than

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typical depleted peridotite, likely pyroxenite (*e.g.*, [Salters and Dick, 2002](#); [Warren, 2016](#)). As the mantle upwells beneath mid-ocean ridges it is inevitable that enriched, more fusible rock types, such as pyroxenites will melt first (*e.g.*, [Pertermann and Hirschmann, 2003](#)). Although the abundance of pyroxenites in the mantle is thought to be low, around 2–5 % (*e.g.*, [Pertermann and Hirschmann, 2003](#)), they appear to make a disproportionate contribution to melts forming the oceanic crust, perhaps because of their lower solidus temperature, higher melt productivity and higher elemental abundance (*e.g.*, [Shorttle \*et al.\*, 2014](#)).

An alternative possibility is that melt transport and crystallisation is controlled by the magma chemistry itself. Recent experiments indicate that magmas from enriched mantle rocks retain a higher melt fraction during cooling and ascent, largely because plagioclase crystallisation is suppressed to lower temperatures in the Na- and H<sub>2</sub>O-rich, but Ca- and Al-poor, liquids derived from enriched source lithologies ([Neave \*et al.\*, 2019](#)). The preferential survival of enriched melts during cooling and crystallisation biases the compositions of erupted basalts towards those from enriched mantle sources ([Neave \*et al.\*, 2019](#)). In contrast, melts from depleted mantle peridotite will start to crystallise at higher temperatures in the lower crust (or mantle). If depleted melts crystallise at greater depths in the lower oceanic crust or mantle then this raises the intriguing possibility that their radiogenic isotope signatures are not simply erased by mixing but rather are not represented by the melts that arrive at the surface.

## Rationale

What is needed is a radiogenic isotope system that is highly susceptible to differing degrees of incompatible element enrichment in the mantle, and magmatic minerals that preserve a robust record of the chemistry of magmas that crystallised in the lower oceanic crust,

The lead (Pb) isotope system, involving the decay of uranium (U) and thorium (Th) to the isotopes of Pb, provides an extremely sensitive tracer of chemical variability in the mantle. Uranium and Th are highly incompatible (relative to Pb) and therefore likely to be depleted in mantle rocks that have experienced melting. Depleted mantle rocks will, consequently, possess low U/Pb and Th/Pb ratios and evolve to relatively unradiogenic Pb isotope compositions over time. In contrast, enriched mantle rock types, such as enriched melts from prior melting trapped in the mantle, or recycled crustal material, with high U-Th/Pb ratios, acquire relatively radiogenic Pb isotope compositions over time that can be readily traced in the melts that form the oceanic crust.

Mid-Ocean Ridge Basalts (MORB) commonly contain calcic plagioclase and magnesian olivine crystals that are physically entrained in more evolved and enriched host lavas from which they cannot have crystallised (*e.g.*, [Rhodes \*et al.\*, 1979](#)). Recent work, using the volatile contents of olivine- and plagioclase-hosted melt inclusions, indicates that crystallisation of plagioclase megacrysts often occurs in the lithospheric mantle ([Drignon \*et al.\*, 2018](#); [Bennett \*et al.\*, 2019](#)), while crystallisation of olivine may occur at shallower levels ([Bennett \*et al.\*, 2019](#)), in the lower oceanic crust. For both the plagioclase and olivine megacrysts, their major element chemistry points to crystallisation from incompatible element depleted magmas ([Sobolev \*et al.\*, 2007](#); [Neave and Namur, 2022](#)) typical of those expected from the melting of depleted mantle peridotite.

## Methods

Here we present high precision Pb isotope data ([Table 1](#)) for sulfide and melt inclusions trapped in an olivine megacryst in a single MORB sample from the FAMOUS ridge segment, and for plagioclase megacrysts and host basaltic glass from several localities in the Pacific and Atlantic oceans (most of which are thought to have crystallised in the lower crust or mantle) (see [Supplementary Information](#) for a full description of the methods used, and major element data for all phases; [Table S-1](#)). Plagioclase and sulfide have relatively high Pb concentrations and are amenable to precise isotope measurement. Additionally, they possess low U/Pb ratios, so there is little ingrowth of Pb subsequent to crystallisation. Furthermore, for plagioclase, diffusion rates of Pb are often sufficiently low that the isotope composition is not significantly modified at magmatic temperatures ([Cherniak, 1995](#)).

## Results

Sample ARP1973-010-003 is a porphyritic, picritic basalt from the FAMOUS segment (36° 50' N) on the mid-Atlantic ridge, with abundant (>20 %) olivine megacrysts (Fo<sub>89-91</sub>) in a glassy to crystalline groundmass. Chromium spinel and sulfide occur as inclusions in olivine and groundmass. Spinel is thought to be a relict high pressure phase ([Sigurdsson and Schilling, 1976](#)), and volatile contents of melt inclusions in olivine indicate crystallisation in the lower crust ([Laubier, pers. comm](#)). Melt inclusions themselves possess both depleted and enriched trace element compositions ([Laubier \*et al.\*, 2012](#)). The Pb isotope composition of the glass and crystalline matrix (blue circles) is in the range of other enriched MORB samples typical of this ridge segment (green circles) ([Fig. 1](#)). However, spinel, sulfide and melt inclusions in olivine (an aggregate of hand picked inclusions) possess Pb isotope compositions that are substantially less radiogenic than the host glass, indicating that these phases crystallised from a depleted melt in the lower crust. The question then is to what extent these unradiogenic Pb compositions are typical in the lower crust?

Plagioclase megacrysts from samples from FAMOUS, Garrett fracture zone, South Atlantic and Iceland, all possess Pb isotope compositions that are less radiogenic than their host lava ([Table 1, Fig. 2a,b](#)). For plagioclase from the North Atlantic substantially so, but even for the Garrett fracture zone lavas (amongst the least radiogenic MORB globally) the Pb isotope composition of plagioclase is less radiogenic than the host lava, and close to the composition expected for the bulk silicate Earth.

## Pb Isotopes in Oceanic Basalts

The results here are consistent with previously reported Pb isotope data for plagioclase and host lava from a single sample on the Mid-Atlantic Ridge ([Bryce and DePaolo, 2004](#)). Although <sup>204</sup>Pb data are not reported in that study, differences in <sup>206</sup>Pb/<sup>207</sup>Pb and <sup>238</sup>U/<sup>207</sup>Pb are consistent with the plagioclase having crystallised from a melt with a low U/Pb ratio (relative to the host lava) ([Bryce and DePaolo, 2004](#)). Likewise, strontium isotope data for plagioclase crystals in MORB shows that the plagioclase often possesses a less radiogenic <sup>87</sup>Sr/<sup>86</sup>Sr isotope composition relative to host glass ([Lange \*et al.\*, 2013](#)). This indicates that the plagioclase crystallised from a melt with a mantle source with a low Rb/Sr ratio, and therefore, like Pb, a source that has experienced ancient depletion of incompatible elements. Taken together, the results here, and elsewhere, indicate that both plagioclase and olivine megacrysts crystallise from melts sourced by depleted mantle material with an unradiogenic Pb isotope composition that is



**Table 1** Pb isotope data: oceanic basalts and minerals.

			$^{206}\text{Pb}/^{204}\text{Pb}$	+/- (2 s.d.)	$^{207}\text{Pb}/^{204}\text{Pb}$	+/- (2 s.d.)	$^{208}\text{Pb}/^{204}\text{Pb}$	+/- (2 s.d.)	[Pb], ppm	An, %
<b>FAMOUS, North Atlantic</b>										
<b>ARP1973-010-003</b>	36° 83.7' N	33° 24.8' W								
matrix			18.514	0.002	15.506	0.003	38.090	0.008	0.231	
glass 1			18.669	0.004	15.523	0.004	38.173	0.010	0.175	
glass 2			18.581	0.005	15.528	0.003	38.198	0.008		
melt inclusions in olivine			17.447	0.030	15.381	0.033	37.094	0.008	0.240	
sulfide 1			17.595	0.024	15.404	0.023	37.258	0.052		
sulfide 2			17.748	0.027	15.431	0.029	37.429	0.058		
spinel			17.345	0.002	15.375	0.005	36.968	0.012	0.355	
plagioclase			18.054	0.002	15.433	0.003	38.038	0.008	0.244	82
<b>CH31 DR01-76</b>										
matrix	36.50° N	33.16° W	18.446	0.008	15.462	0.010	38.033	0.032	0.346	
plagioclase			18.041	0.002	15.414	0.003	37.604	0.008	0.150	
<b>ARP1974-014-013</b>										
plagioclase	36.85° N	33.25° W	18.257	0.006	15.427	0.006	37.797	0.019	0.104	87
<b>ALV 518-3-1</b>										
glass	36.82° N	33.26° W	18.786	0.002	15.538	0.003	38.351	0.008	0.368	
plagioclase			17.649	0.005	15.408	0.004	37.430	0.016	0.223	91
<b>South Atlantic</b>										
<b>EW9309 12D</b>										
glass	49.76° S	8.03° W	18.348	0.002	15.504	0.003	37.828	0.008	0.344	
plagioclase			17.606	0.002	15.362	0.003	37.250	0.008	0.213	81
<b>Garrett fracture zone, East Pacific</b>										
<b>GN4-11</b>										
glass*	13° 26.9' S	111° 29.5' W	17.903	0.014	15.444	0.018	37.327	0.040	0.271	
plagioclase			17.493	0.011	15.320	0.010	36.994	0.028	0.024	94
<b>GN12-10</b>										
glass*	13° 24.2' S	111° 56.5' W	17.655	0.014	15.363	0.018	37.004	0.040	0.294	
plagioclase			17.480	0.002	15.325	0.003	36.899	0.008	0.093	94
<b>Iceland, Central rift zone</b>										
<b>Borgarhraun</b>										
matrix	65° 50.35' N	17° 1.07' W	18.085	0.002	15.438	0.005	37.663	0.008	0.246	
plagioclase			17.458	0.005	15.337	0.005	37.119	0.008	0.137	85

All errors are 2 s.d. mean. Concentrations in ppm weight.

Pb isotopic ratios relative to NBS 981 Pb standard which yields an external precision of  $^{206}\text{Pb}/^{204}\text{Pb} = 16.9428 \pm 24$ ,  $^{207}\text{Pb}/^{204}\text{Pb} = 15.5007 \pm 28$  and  $^{208}\text{Pb}/^{204}\text{Pb}$  ratio of  $36.7276 \pm 75$  (2 s.d., n = 59).

\* Pb isotope data for glass samples from [Wendt et al. \(1999\)](#).

potentially widespread in the upper mantle and lower oceanic crust.

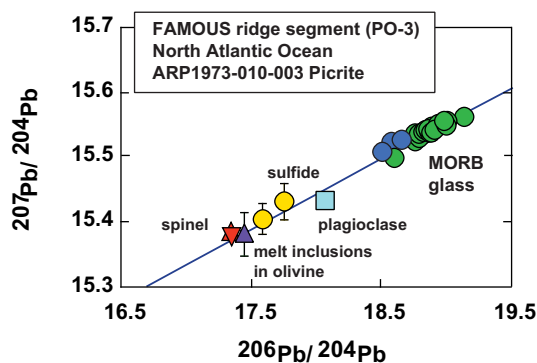
## The Pb Isotope Composition of the Silicate Earth and Ocean Crust Formation

Our data indicate that both plagioclase and olivine megacrysts in oceanic basalts commonly crystallise from melts sourced by depleted mantle material with an unradiogenic Pb isotope composition that is complementary to the radiogenic Pb isotope compositions seen in erupted basalts. In the past, the radiogenic Pb isotope composition of many oceanic basalts, the so called 'Pb paradox', has been attributed to segregation of Pb into Earth's metallic core (e.g., [Allègre, 1969](#)) or loss as a volatile element ([Albarède, 2009](#)). While the results here do not preclude Pb

removal to the core, or volatile loss, they do show that a substantial proportion of Earth's unradiogenic Pb is potentially present in the mantle, and that Pb is simply not sampled by erupted basalts.

Spatial variations in radiogenic isotopes through the oceanic crust potentially reveal how melts are delivered to the surface, and the nature of oceanic crust formation. From an elemental and isotopic perspective it is generally thought that mantle melts from diverse sources (both incompatible element depleted and enriched) are delivered to the base of the crust, from where mixing and crystallisation during ascent act to reduce the primary chemical variability (e.g., [Maclennan, 2008](#); [Lambart et al., 2019](#)). Thus, the actual extent of isotope heterogeneity in the mantle is lost in the final melts erupted as MORB, the composition of which represents some average of those different mantle melts. However, if melts from depleted mantle rocks tend to crystallise in the lower crust, then that crust may, at least in





**Figure 1**  $^{207}\text{Pb}$ - $^{206}\text{Pb}$  isotope diagram for constituent minerals from a picritic basalt from the FAMOUS ridge segment. The Pb isotope composition of the glass and crystalline matrix (blue circles) is in the range of other enriched MORB samples typical of this ridge segment (green circles; Gale *et al.*, 2013). However, spinel (red star), sulfide (yellow circle) and melt inclusions in olivine (purple triangle) possess Pb isotope compositions that are substantially less radiogenic than the host glass, indicating that these phases crystallised from a depleted melt that crystallised in the lower crust. Much of the plagioclase in this sample (blue square) crystallised late accounting for the more radiogenic composition (relative to the spinel, sulfide and melt inclusions).

some circumstances, be isotopically stratified. With MORB and gabbro from the shallowest part of the oceanic crust being derived from enriched mantle sources, while intrusive rocks deeper in the crust originate from depleted mantle lithologies. In this case, not only are the melts delivered to the oceanic crust derived from isotopically distinct sources, but those melts can also traverse the crust while maintaining a high degree of chemical integrity.

The question remains as to what extent depleted melts with unradiogenic Pb isotope compositions contribute to the formation of the oceanic crust, rather than just the deep roots of oceanic magmatism in the mantle. Indeed, are the samples here more widely representative? Gabbroic plagioclase from the upper ~500 m of oceanic crust at the Atlantis Bank on the Southwest Indian Ridge (ODP Hole 735B) preserves a relatively uniform Pb isotope composition (Kempton *et al.*, 1991) that is indistinguishable from nearby MORB. The work of Holm *et al.* (2002) however, suggests that, at greater depths in this crustal section, gabbroic plagioclase possesses a systematically less radiogenic Pb isotope composition, consistent with the observations

here. The presence of plagioclase-bearing depleted gabbros in the lower crust or mantle might also explain, at least in part, the so called “ghost plagioclase” signature seen in many oceanic basalts (*e.g.*, Sobolev *et al.*, 2000). Basalts and melt inclusions characterised by Sr, Ba and Eu anomalies, have been attributed by some, to the presence of plagioclase-rich cumulates in the oceanic crust, through which these melts have percolated (*e.g.*, MacLennan, 2008). Finally, some erupted MORB do show unradiogenic Pb isotope compositions akin to those seen here (*e.g.*, Wendt *et al.*, 1999), attributed to the preferential melting of depleted mantle stripped of enriched rock types by previous melting. Elsewhere, however, this unradiogenic signal appears to be lost either by mixing during ascent through the crust, or else by the tendency of melts from depleted sources to crystallise in the lower crust. In either case the actual composition of the depleted mantle is concealed.

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### Additional Information

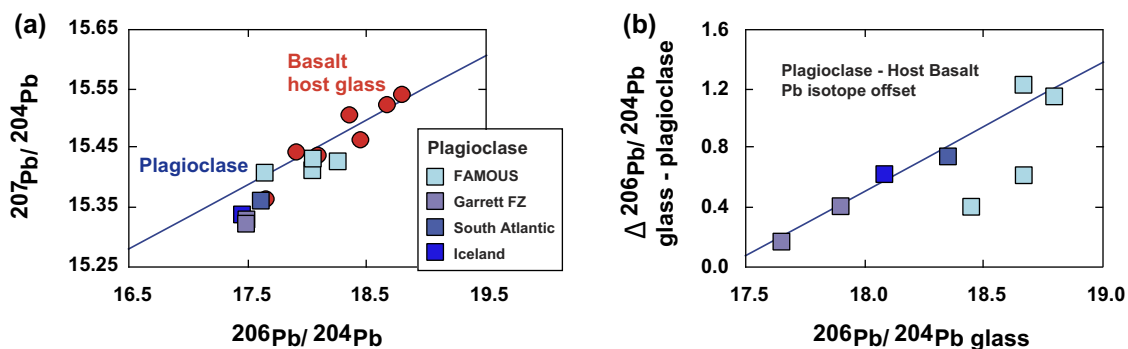
Supplementary Information accompanies this letter at <https://www.geochemicalperspectivesletters.org/article2405>.



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**Figure 2** (a)  $^{207}\text{Pb}$ - $^{206}\text{Pb}$  isotope diagram for plagioclase crystals and their host basalts. Plagioclase crystals (blue squares) and host basalt (red circles) from samples from FAMOUS, Garrett fracture zone, South Atlantic and Iceland, in all cases the Pb isotope composition of plagioclase is less radiogenic than the host lava (Table 1). (b) Difference ( $\Delta$ ) in  $^{206}\text{Pb}/^{204}\text{Pb}$  between the plagioclase/olivine and host basalt vs. the Pb isotope composition of the host basalt. These data show that in general the more radiogenic the host basalt composition, the greater is the difference in Pb isotope composition between the plagioclase/olivine and the basalt host.



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