



Quantifying lithological variability in the mantle



Oliver Shorttle^{a,*}, John Maclennan^a, Sarah Lambart^b

^a Department of Earth Sciences, University of Cambridge, Downing Street, Cambridge CB2 3EQ, UK

^b Division of Geological and Planetary Sciences, California Institute of Technology, Pasadena, CA 91125, USA

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ABSTRACT

We present a method that can be used to estimate the amount of recycled material present in the source region of mid-ocean ridge basalts by combining three key constraints: (1) the melting behaviour of the lithologies identified to be present in a mantle source, (2) the overall volume of melt production, and (3) the proportion of melt production attributable to melting of each lithology. These constraints are unified in a three-lithology melting model containing lherzolite, pyroxenite and harzburgite, representative products of mantle differentiation, to quantify their abundance in igneous source regions.

As a case study we apply this method to Iceland, a location with sufficient geochemical and geophysical data to meet the required observational constraints. We find that to generate the 20 km of igneous crustal thickness at Iceland's coasts, with $30 \pm 10\%$ of the crust produced from melting a pyroxenitic lithology, requires an excess mantle potential temperature (ΔT_p) of $\geq 130^\circ\text{C}$ ($T_p \geq 1460^\circ\text{C}$) and a source consisting of at least 5% recycled basalt. Therefore, the mantle beneath Iceland requires a significant excess temperature to match geophysical and geochemical observations: lithological variation alone cannot account for the high crustal thickness. Determining a unique source solution is only possible if mantle potential temperature is known precisely and independently, otherwise a family of possible lithology mixtures is obtained across the range of viable ΔT_p . For Iceland this uncertainty in ΔT_p means that the mantle could be $>20\%$ harzburgitic if $\Delta T_p > 150^\circ\text{C}$ ($T_p > 1480^\circ\text{C}$).

The consequences of lithological heterogeneity for plume dynamics in various geological contexts are also explored through thermodynamic modelling of the densities of lherzolite, basalt, and harzburgite mixtures in the mantle. All lithology solutions for Iceland are buoyant in the shallow mantle at the ΔT_p for which they are valid, however only lithology mixtures incorporating a significant harzburgite component are able to reproduce recent estimates of the Iceland plume's volume flux. Using the literature estimates of the amount of recycled basalt in the sources of Hawaiian and Siberian volcanism, we found that they are negatively buoyant in the upper mantle, even at the extremes of their expected ΔT_p . One solution to this problem is that low density refractory harzburgite is a more ubiquitous component in mantle plumes than previously acknowledged.

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1. Introduction

Plate tectonic motions have been cycling material from the Earth's surface into the deep mantle for several billion years, connecting the development of the atmosphere and oceans to the generation of chemical heterogeneity in the Earth's interior. The marble-cake mantle that we find today preserves a record of planetary differentiation (Allègre and Turcotte, 1986), which provides information about conditions early in Earth's history, and on the mantle dynamics driving planetary evolution.

The difficulty of sampling material from the Earth's deep interior poses a major obstacle to understanding its current and past states. One means of accessing this information is by studying the volcanic products erupted at mid-ocean ridges (MOR), arcs and intra-plate settings. Of these, MOR basalts (MORB) provide our best chance of obtaining information on the thermo-chemical state of the convecting upper mantle for a number of reasons. Firstly, there is only a thin layer of young igneous crust between source and surface, minimising the possibility of contamination from old radiogenic continental crust and lithosphere. Secondly, if MOR act as passive linear samplers of the upper mantle, then the compositional distribution of the material rising under MOR is the same as the global distribution of compositions in the uppermost convecting mantle. Thirdly, the coverage of the globe by MOR allows us to investigate global spatial patterns of mantle chemistry.

* Corresponding author.

E-mail addresses: os258@cam.ac.uk (O. Shorttle), jcm1004@cam.ac.uk (J. Maclennan), saral@ideo.columbia.edu (S. Lambart).

In order to understand the origin and dynamics of the mantle it is necessary to have knowledge of its composition. Although the long-held lherzolite model explains many features of mantle structure (Ringwood, 1962), a predicted ~10% of basaltic crust will have been returned to the mantle over Earth's history (Hofmann, 1997; Stracke et al., 1999). Given that basalts form by the depletion of some primary lherzolitic lithology, a large return flux of basalt to the Earth's interior necessitates a highly lithologically heterogeneous mantle, containing refractory harzburgitic and fusible pyroxenitic/eclogitic domains with a complete spectrum of lithologies of intermediate fertility in between. However, including such a wealth of mantle diversity in a melting model is currently beyond our ability, and in any case would be unconstrained by geochemical observations in most settings. Therefore, we reduce the spectrum of mantle lithological variability to a consideration of three representative lithologies, which between them encompass most of the expected range from recycling: (1) an aluminous lherzolite, representing depleted upper mantle and presumably the most abundant lithology in MORB genesis; (2) a pyroxenite, representing recycled basalt and an example of a high-productivity lithology; (3) a harzburgite, to represent the refractory residues left after melt extraction, which will have low productivity during any further melting. We develop a method that can be used to quantify the abundance of these three lithologies in basalt source regions.

1.1. Previous estimates of the lithological character of the mantle

Recycled oceanic crust was first invoked as a mantle component to explain the high trace element concentrations and radiogenic isotopic compositions of ocean island volcanics (Chase, 1981; Hofmann and White, 1982). Following the 'marble-cake' mantle model of Allègre and Turcotte (1986), Prinzhofer et al. (1989) explored the role of a mixed peridotite–pyroxenite source in generating the local variation in trace element and isotopic compositions of basalts from the East Pacific Rise. Hirschmann and Stolper (1996) extended this logic to MORB globally, suggesting a mixed lherzolite–garnet pyroxenite source as the cause of the signature of garnet in MORB. The crucial methodological insight of Hirschmann and Stolper (1996) was to couple the geochemical constraints with a requirement to match typical MOR crustal thickness (~7 km, White et al., 1992), combining these chemical and physical observations with a model of mantle melting. This model allowed for the higher productivity of pyroxenite compared with lherzolite lithologies to be accounted for when estimating the abundance of source pyroxenite. With these observational and model constraints, Hirschmann and Stolper (1996) estimated that 5% of MORB mantle-source could be formed of pyroxenite.

A number of authors have recently attempted to estimate the proportion of pyroxenite in various settings using olivine compositions or the trace and major element compositions of basalts (e.g., Sobolev et al., 2005, 2007, 2008; Lambart et al., 2009; Pietruszka et al., 2013). By combining Os isotopes and olivine compositions, Sobolev et al. (2008) concluded that ~40% of the mass of some Icelandic melts were derived from pyroxenite melting. However, this estimation does not formally include the requirement to match melt volumes with source composition, nor do the authors perform an investigation into how productivity differences affect the estimates of source lithology. Shorttle and MacLennan (2011) identified lithological heterogeneity beneath Iceland using basalt major element compositions and produced a melting model to explore pyroxenite's effect on melt production. However, they did not use geochemical constraints to define the fraction of melt production derived from pyroxenite melting, nor did they rigorously constrain source composition.

A separate issue overlooked by the above methods is the role and abundance of refractory material in the mantle. The unradiogenic Pb isotopic compositions found in North Atlantic basalts associated with the Iceland plume, and their offset from depleted MORB mantle values, led Thirlwall (1995) and Kerr et al. (1995) to infer the presence of refractory domains in plume sources. Subsequent to these studies Fitton et al. (1997) used the Nb–Zr–Y trace element systematics of Icelandic basalts to identify a distinct depleted endmember for the Iceland plume. Nd and Hf isotope systems have been used to validate this result for Icelandic basalts (Kempton et al., 2000; Fitton et al., 2003), and also compiled from MORB globally to highlight the importance of depleted domains (Salters et al., 2011). Abyssal peridotites provide an independent line of evidence for the presence of highly depleted domains in the mantle. Stracke et al. (2011) showed that clinopyroxenes from Gakkal Ridge abyssal peridotites contain extremely radiogenic Nd and Hf isotopic compositions, extending beyond the values observed in MORB. Importantly for the issue of melt generation and mantle dynamics, Stracke et al. (2011) also found that the Hf isotopes correlated with major and trace element indices of depletion, meaning these domains with radiogenic Hf are also refractory. These results suggest that refractory domains could be a ubiquitous upper mantle component. However, identifying the role of refractory domains in basalt genesis remains challenging and we are lacking in tools to quantify the combined effect of refractory and fusible heterogeneity on melt production.

As the earlier Hirschmann and Stolper (1996) analysis showed, neither geochemical nor geophysical constraints alone are sufficient to quantify mantle lithological variability. The abundant observational evidence for both depleted and enriched mantle domains, forces us to develop a method to formally quantify the involvement of both of these sources in the melting process, even if the refractory domain contributes little melt. Here we demonstrate how geochemical and geophysical observations can be combined with a model of three lithology melting to quantify the thermochemical state of the mantle.

1.2. Approach

This contribution is split into three sections, each exploring constraints on source lithology.

Section 2 contains a description of a method for estimating the mass fraction of pyroxenite derived melts forming the average Icelandic crust (F_{px}^{melt}). Using the geochemistry of Icelandic basalts we form a mass budget of enriched and depleted melts and find that $F_{px}^{melt} = 0.3 \pm 0.1$.

In Section 3 we project the calculated value of F_{px}^{melt} back into a mass fraction of solid mantle material. We develop a melting model that includes lherzolite, pyroxenite and harzburgite lithologies to resolve the influence of their different productivities on F_{px}^{melt} . Coupling observational constraints on F_{px}^{melt} and melt production allows a single source lithology mixture to be identified. However, the abundance of lherzolite and harzburgite lithologies in the source is strongly dependent on having knowledge of mantle potential temperature (T_p).

We next investigate the dynamical implications of lithological heterogeneity as a possible additional constraint on source. In Section 4 we model the densities of lherzolite–pyroxenite–harzburgite mixtures to assess their buoyancy in the upper mantle and consequences for plume volume flux. All our valid source solutions for Iceland are buoyant. However, we show that some previous literature estimates for Hawaiian and Siberian trap volcanism, which involve >15% pyroxenite in the source, are not likely to be buoyant even in mantle plumes with large ΔT_p .

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