

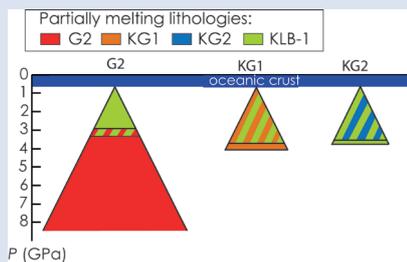
## No direct contribution of recycled crust in Icelandic basalts

S. Lambart<sup>1,2\*</sup>



doi: 10.7185/geochemlet.1728

### Abstract



Using Melt-PX to model the decompression melting of a heterogeneous mantle, I investigated the role of major-element composition of the lithologies present in the source on magmatic productivity, and trace element and isotopic melt compositions, independently of the bulk mantle composition. My calculations demonstrate that the volume of magma produced is not significantly affected by the nature of the lithological heterogeneity, but depends on the bulk mantle composition. However, an isochemical bulk mantle can produce contrasting trace element and isotopic melt compositions depending on the major-element compositions of the lithologies present in the source. Results show that the observed crust thickness of the Icelandic rift zones is consistent with about 10 % of recycled crust in

the source, but also demonstrate there is no need to involve the contribution of melts derived from a recycled basalt component to explain the compositional variability of the Icelandic basalts in rift zones, and rather advance the contribution of olivine-bearing hybrid lithologies formed by solid-state reactions between the recycled crust and the peridotite.

Received 2 April 2017 | Accepted 6 June 2017 | Published 12 July 2017

### Introduction

It is widely accepted that the compositional spectrum of Icelandic lavas requires the presence of at least two components in the mantle source (e.g., Thirlwall *et al.*, 2004, 2006; Sobolev *et al.*, 2007; Brown and Leshner, 2014). However, the nature of these components is still debated and two end-member models have been suggested: while trace element and isotopic analyses of Icelandic lavas seem to suggest the presence of two distinct lithologies in the form of pyroxenite and peridotite (e.g., Kokfelt *et al.*, 2006; Koornneef *et al.*, 2012; Brown and Leshner, 2014), major-element compositions and olivine chemistry suggest a peridotite mantle composed of more or less re-fertilised domains by reaction with the recycling material (Shorttle and MacLennan, 2011; Herzberg *et al.*, 2016). Using a quantitative melting model for the adiabatic decompression of a multi-lithological source, I show that trace element and isotopic compositions of the Icelandic basalt suite can be reproduced without involving the contribution of melts derived from the recycled basalt component in the mantle source.

the specific lithologies that are present and make up the bulk composition. To test this hypothesis, I considered a bulk mantle composition corresponding to 10 % recycled oceanic crust G2 + 90 % peridotite KLB-1 (Bulk1 in Table S-1) and compared the melting behaviour during adiabatic decompression at  $T_p = 1480$  °C of three different heterogeneity distributions in the mantle: G2-, KG1- and KG2-configurations. In the “G2-configuration”, the two distinct lithologies are the MORB-like type eclogite G2 (Pertermann and Hirschmann, 2002) and the peridotite KLB-1 (Hirose and Kushiro, 1993). To model the KG1- and KG2-configurations, I considered a mantle containing 20 % lithology KG1 and 80 % peridotite KLB-1, and a mantle containing 30 % lithology KG2 and 70 % peridotite KLB-1, respectively. Because KG1 and KG2 (Kogiso *et al.*, 1998) are two compositions produced by mixing 1/2 G2 and 1/2 KLB-1, and 1/3 G2 and 2/3 KLB-1, respectively, all three mantle configurations are isochemical (Bulk 1 in Table S-1). In the three configurations, the two lithologies present in the source are chemically isolated but in thermal equilibrium.

Using Melt-PX (Lambart *et al.*, 2016), I modelled the decompression melting of these three mantle configurations for a potential temperature  $T_p = 1480$  °C and calculated the trace element and isotopic compositions of the accumulated melts for complete mixing of melts from the two mantle components integrated over the melting column (Supplementary Information). Similar heterogeneous melting models have been described in the literature but, unlike those presented here, the melting behaviours of the different components were

### Strategy

Lambart *et al.* (2016) demonstrated that the final extent of melting and the mean melting pressure of the potential lithologies present in the mantle sources are strong functions of their major element composition. Hence, the same mantle bulk composition may melt differently and produce different trace element and isotopic melt compositions depending on

1. Department of Earth and Planetary Sciences, University of California Davis, One Shields Avenue, Davis, California 95616, USA

2. School of Earth and Ocean Sciences, Cardiff University, CF10 3AT Cardiff, UK

\* Corresponding author (email: sarahlambart@yahoo.fr)



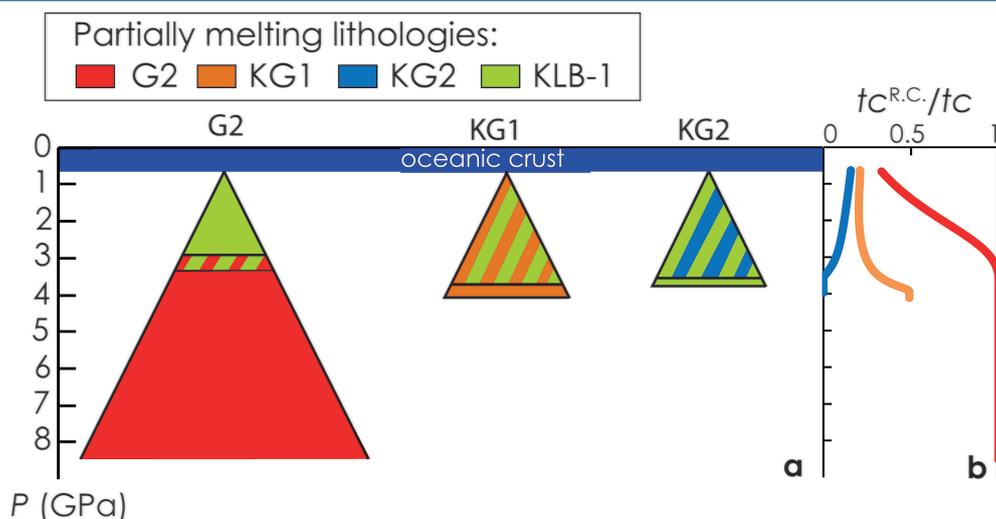
arbitrarily chosen (e.g., Ito and Mahoney, 2005; Stracke and Bourdon, 2009; Waters *et al.*, 2011), the  $F$  versus  $T$  relationships were calculated with pMELTS (e.g., Rudge *et al.*, 2013; Sims *et al.*, 2013) that strongly overestimates the size of melting interval of mantle lithologies and especially pyroxenites, by both overestimating the liquidus temperature and underestimating the solidus temperature (Lambart *et al.*, 2016), and/or the thermal interactions between components were not taken into account (e.g., Koornneef *et al.*, 2012). This study presents the first quantitative calculations taking into account the effect of the major element composition on the melting behaviours of the lithologies present in the source and on trace element and isotopic compositions of the magmas produced.

## Results

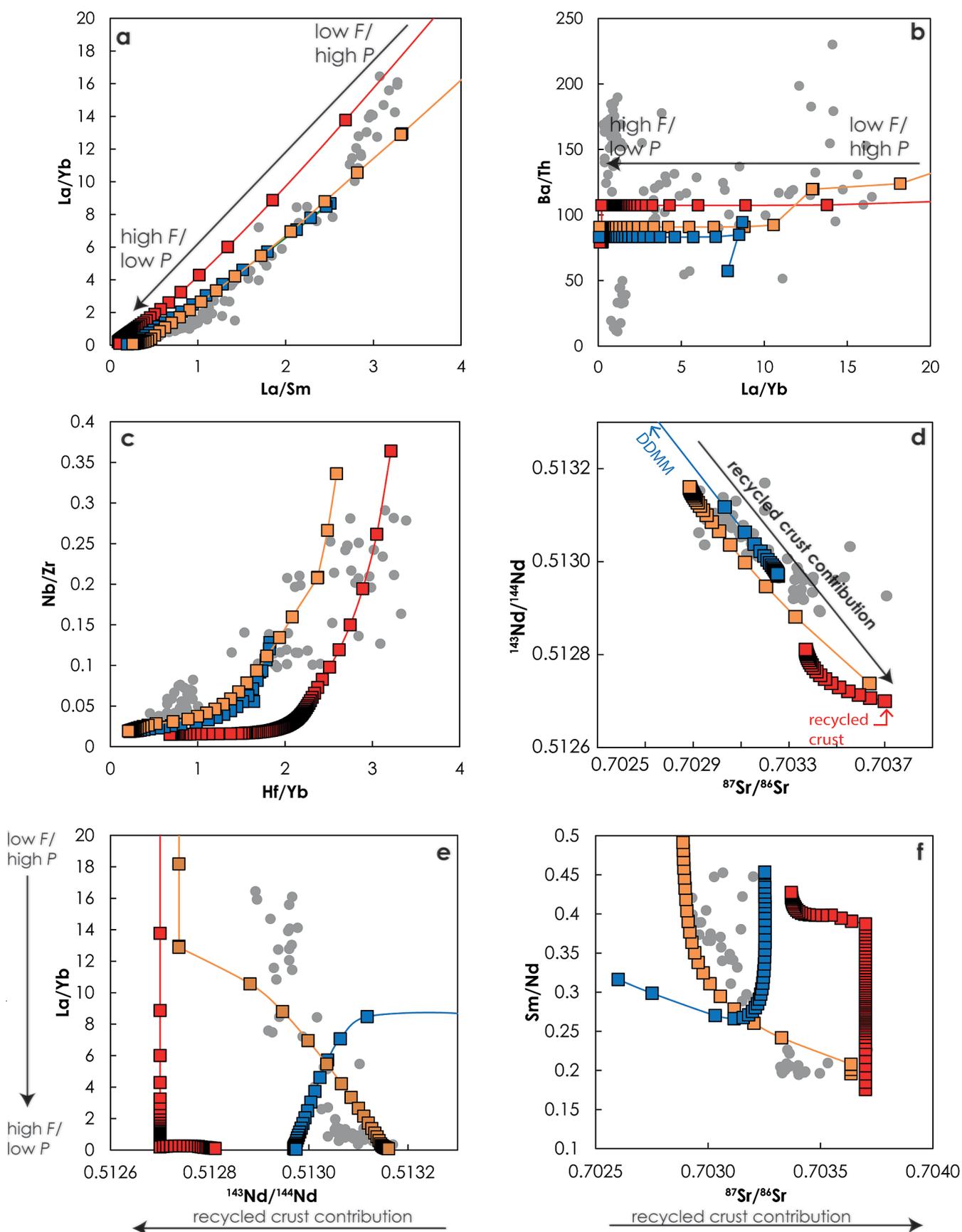
Results of the calculations with Melt-PX are illustrated in Figure 1. The mantle melting behaviour is much contrasted between the three configurations. In the G2-configuration, the pyroxenite component starts to melt at very high pressure (~8.7 GPa), but rapidly stops soon after the peridotite crosses its solidus (Fig. 1a). This phenomenon occurs because the adiabatic melting path is steeper than the solidus of G2 residue once the peridotite solidus is crossed (Fig. S-1; Lambart *et al.*, 2016). Hence, partial melts generated along the adiabatic path are initially derived from the pyroxenite alone; once the peridotite starts to melt, the fraction of G2-derived melt in the aggregated liquid decreases by dilution with decreasing pressure (Fig. 1b). Unlike G2, lithology KG1 starts to melt just before the peridotite and, despite a drop of melt productivity when the peridotite solidus is crossed (Fig. S-2), both KG1 and KLB-1 continue to melt simultaneously. Finally, KG2 starts to melt after the peridotite but the melt productivity of KG2 is higher than the one of KLB-1 (Fig. S-3) and the fraction of KG2-derived liquid in the aggregated partial melt progressively increases with decreasing pressure (Fig. 1b). Despite these contrasting behaviours, the magmatic productivity and

consequently the oceanic crust thickness produced in the three configurations are very similar with 21.8, 22.3 and 22.0 km for G2-, KG1- and KG2-configuration, respectively.

The trace element and isotopic compositions of the pooled melts for the three configurations along the adiabatic path are presented in Figure 2. Stracke and Bourdon (2009) demonstrated that trace element ratios involving a moderately incompatible element (e.g., La/Sm, La/Yb, Hf/Yb) are dominantly influenced by the melting process. In fact La/Sm *vs.* La/Yb variations (Fig. 2a) show similar trends in the three configurations. On the contrary, highly incompatible element ratios, such as Ba/Th (Fig. 2b), do not vary significantly with progressive melting and differences between the ratios reflect differences in the source components. The three configurations show contrasting trends in the Sr-Nd isotopic space (Fig. 2d). Both G2- and KG1-configurations produced melts that become progressively less radiogenic due to the decrease of the recycled component contribution in the pooled melt along the adiabatic path (Fig. 1b). Interestingly, the range of isotopic compositions produced in G2-configuration is much smaller than the one produced in KG1-configuration. KG2-configuration produces melts that become increasingly radiogenic with decreasing pressure due to the increase of recycled crust contribution along the adiabatic path (Fig. 1b). Finally, correlations between trace element ratios and isotopic ratios show very distinctive trends for the three configurations (Fig. 2e-f). In the G2-configuration, the  $^{143}\text{Nd}/^{144}\text{Nd}$  of the pooled melt stays constant as long as only G2 is melting, while the La/Yb ratio decreases with increasing  $F$ . When the peridotite starts to melt, G2 has reached 57 wt. % melting and the accumulated melt is much depleted in incompatible trace elements. The addition of an isotopically depleted peridotite partial melt results in a shift of the pooled liquid isotopic composition, while the La/Yb ratio stays relatively constant (Fig. 2e). In the KG1-configuration, KG1 only reached 13 wt. % melting at the onset of the peridotite melting. Hence, the La/Yb ratio continues to decrease with the increasing melting degree of KG1 while the addition



**Figure 1** (a) Representation of the melting column in the three configurations. Colours show the lithologies that are partially melting at a given pressure. (b) Contribution of the recycled crust ( $tc^{R.C.}/tc$ ) to the melt production as functions of the pressure along the adiabatic path in G2- (red), KG1- (orange) and KG2- (blue) configurations. The contribution of the recycled crust is assumed to be equal to the contribution of G2, to half of the contribution of KG1 and to one third of the contribution of KG2, in the respective configurations.



**Figure 2** Compositions of the aggregated melts produced over the melting column in G2- (red), KG1- (orange) and KG2- (blue) configurations. Grey dots are the compositions of Icelandic basalts with MgO contents between 9.5 and 17 wt. % from the Northern Volcanic zone, the Reykjanes Peninsula, the Snaefellsnes area and the South Eastern Volcanic Zone (GEOROC). Detailed explanations of the calculations are given in the Supplementary Information.



of peridotite melt increases the isotopic ratio  $^{143}\text{Nd}/^{144}\text{Nd}$  of the pooled melt. Finally, in the KG2-configuration, the peridotite starts to melt before KG2 and the first degree melt is a peridotite liquid at 3.6 GPa (Figs. 1, S-5). Soon after, the solidus of KG2 is crossed and the aggregated melt becomes more isotopically enriched due to the addition of KG2-derived melt (the  $^{143}\text{Nd}/^{144}\text{Nd}$  ratio decreases and the  $^{86}\text{Sr}/^{87}\text{Sr}$  ratio increases with decreasing pressure; Fig. 2e-f).

## Implications for the Nature of the Mantle Heterogeneity Beneath Iceland

Several studies have questioned the necessity to involve the direct contribution of melts from the recycled component to the magmatic production beneath Iceland (Shorttle and MacLennan, 2011; Herzberg *et al.*, 2016). On Figure 2, I compared the calculated trends with the observed variation in Icelandic basalts produced in the rift zones at the coasts (GEOROC database). Consistent with the calculations, magma production in this context is thought to reflect a passive plate spreading alone (Brown and Leshner, 2014, Shorttle *et al.*, 2014) and  $T_P = 1480$  °C is in agreement with the most recent estimated potential mantle temperature beneath Iceland (Matthews *et al.*, 2016). Calculated crust thicknesses are in fact similar to the estimated crustal thicknesses in Iceland's rift zones (Darbyshire *et al.*, 2000). In addition, these calculations suggest that in the context of passive melting regime, the volume of magma produced is relatively independent of the nature of the lithological heterogeneity, but is mainly controlled by the mantle potential temperature (Lambart *et al.*, 2016) and the bulk mantle composition. Calculations show that the trace element – isotope systematics are mostly controlled by the pressure difference between the onset of melting of the lithologies present in the source (Stracke and Bourdon, 2009). Overall, the trace element and isotopic systematics of Icelandic basalts are well reproduced by the melting of a mantle containing 20 % KG1. In detail, the trace element compositions of Icelandic basalts become more depleted with increasing  $^{143}\text{Nd}/^{144}\text{Nd}$  ratios (Fig. 2e) and decreasing  $^{87}\text{Sr}/^{86}\text{Sr}$  (Fig. 2f). In other words, the progressive depletion of the Icelandic melts with increasing extent of melting indicates that the enriched component becomes progressively diluted with the peridotite component. This is only possible if the enriched component has a lower solidus temperature compared to the depleted component, in agreement with Sims *et al.* (2013). Moreover, Figure 2 suggests that a small difference in solidus temperature of the enriched and depleted components is required to reproduce the co-variations between trace element and isotopic ratios, especially those involving highly incompatible elements over moderately incompatible elements (Fig. 2e-f). Otherwise, for large solidus temperature differences between the two components, such as in G2-configuration, the enriched component will undergo large degree of melting before onset of the peridotite melting resulting in insufficient enrichment of melts in highly incompatible elements. Hence, by using Melt-PX to model the melting behaviour of the mantle components, this study provides quantitative constraints on the melting behaviour, and consequently on the major-element composition, of the lithologies present in the source.

It could be argued that the absolute positions of the compositional trends along the isotopic ratio axes in Figure 2e-f depend on the isotopic compositions chosen for the peridotite and the recycled components (Table S-1). For the peridotite component, I chose the isotopic composition of the most depleted end of the MORB field reported by Salters and Stracke (2004). In fact, unradiogenic Pb isotopic compositions, Nd and Hf isotope systems and trace element systematics of

Icelandic basalts have all been used to validate the presence of a distinct depleted endmember for the Iceland plume (*e.g.*, Thirlwall *et al.*, 2004, 2006; Shorttle *et al.*, 2014 and references therein). For the recycled crustal component, I chose a 2 Ga recycled crust (*e.g.*, Chauvel and Hémond, 2000; Kokfelt *et al.*, 2006). However, the age of the recycled component in the basalt source of Iceland is highly debated and could be younger by up to an order of magnitude (Halldórsson *et al.*, 2016). A younger recycled material will have a lower content of radiogenic isotopes and consequently trends in Figure 2e-f will be shifted toward higher  $^{143}\text{Nd}/^{144}\text{Nd}$  ratios and lower the  $^{87}\text{Sr}/^{86}\text{Sr}$  ratios. For instance, the range of Nd isotopic compositions displayed by the Icelandic basalt (Fig. 2d) could be reproduced in the G2-configuration by varying the age of the recycled component from 1.7 to 0.5 Ga, but would not explain the co-variations between trace element and isotopic ratios (Fig. 2e). In the following section I provide additional constraints on the nature of the mantle heterogeneity beneath Iceland by looking at the implications of these observations for melt extraction mechanisms.

## Constraints from Melt Extraction

It was shown in the preceding section that (1) the compositional variability of Icelandic basalt requires at least two different mantle components with different radiogenic isotopic compositions, (2) the most radiogenic component should have the lowest solidus temperature (as in G2- or KG1-configurations), and equally importantly (3) the pooled melts need to be extracted at different depths along the adiabatic path, in agreement with the conclusions of Stracke and Bourdon (2009). This last observation implies an efficient melt extraction mechanism capable of sampling relatively low degree partial melts without significant interaction with the mantle. In the G2-configuration, the peridotite mostly stays subsolidus during the melting of the pyroxenite (Fig. 1a) and the highest La/Yb (>12) and La/Sm (>3) ratios displayed by the Icelandic basalts (Fig. 2a) are produced at  $P > 8.3$  GPa (Fig. S-6). Hence, the G2-configuration requires the unlikely scenario of the circulation of a very silica-rich (Fig. S-7) low-degree melt into a subsolidus peridotite mantle from 8.3 GPa to 3.1 GPa (the onset of peridotite melting) and without significant melt-rock interaction. In the KG1-configuration, the peridotite starts to melt soon after the enriched component (Fig. 1a) and the highest La/Yb and La/Sm ratios are produced at  $P > 3.4$  GPa, *i.e.* by the melting of the KG1 component only. However, unlike G2, KG1 produces melts with major element compositions very similar to peridotite melts (Fig. S-7). This small compositional contrast will result in limited reactivity between KG1-derived melt and peridotite, favourable to the preservation of their trace element signature (Lambart *et al.*, 2012). Finally, it should be noted that, in the G2-configuration, the entire range of trace element compositions observed in Icelandic basalts is produced by the melting of the pyroxenite G2 while the peridotite component stays subsolidus. Lambart *et al.* (2012) showed that migration of melts in a subsolidus mantle results in a strong consumption of the melt. On the contrary, melt extraction is facilitated when the surrounding mantle is partially melted, as in the KG1-configuration in which, with the exception of the most enriched basalt compositions (La/Yb > 12 and La/Sm > 3), both KG1 and KLB-1 are contributing to the pooled melts (Fig. S-6).



## Solid-State Reaction Versus Melt–Rock Reaction

Calculations presented above resolve an ambiguity that has arisen in the literature, between the need for the direct contribution of melts from recycled basaltic lithologies, *versus* the manifestation of their presence through re-fertilised hybrid lithologies, and demonstrate that hybrid lithologies can be an important contributor to lithological diversity in the mantle. However, these hybrid lithologies could be formed either by solid-state reaction (*i.e.* homogeneous mixing and phase equilibration between the solid recycled crust and the solid peridotite) or by melt-rock reaction, in which melts derived from the recycled crust react with the peridotite to form an olivine-free secondary pyroxenite, such as Px-1 (Sobolev *et al.*, 2007). Because KG1 and Px-1 have similar solidus and melting curves (Fig. S-8; Lambart *et al.*, 2016), the trace element – isotope systematics that would be produced by an isochemical bulk mantle containing Px-1 would be very similar to the one produced by the KG1-configuration and would not lead to the discrimination between both models. Similarly, both models can reproduce the high nickel content of primitive Icelandic olivine (Fig. S-9). However, one major difference between these two models, is the major-element composition of the hybrid lithology and consequently, of the derived melts produced by these lithologies. In fact, olivine-free secondary pyroxenites produced melts with similar silica content to G2-derived melts (Fig. S-7). As mentioned above, such melts are likely to react with the surrounding peridotite to produce pyroxenes and dissolve olivine and, consequently, are less likely to preserve their compositional signature.

In summary, this study supports the fact that two distinct mantle components are required to explain the compositional diversity of Icelandic basalts with the most radiogenic component being the most fusible, but also demonstrates that the direct contribution of the melts derived from the recycled crust cannot explain the trace element – isotope systematics of Icelandic basalt, and rather advances the polybaric melting of various olivine-bearing lithologies, likely produced by solid-state interactions between the recycled crust and the peridotite.

## Acknowledgements

This study has benefited from discussions with Mike Baker and Ed Stolper. This work was supported by the National Science Foundation grant EAR-1551442 and the European Union's Horizon 2020 research and innovation programme under the Marie Skłodowska-Curie grant agreement No. 663830. Two anonymous reviewers are thanked for their helpful suggestions.

Editor: Graham Pearson

## Additional Information

**Supplementary Information** accompanies this letter at [www.geochemicalperspectivesletters.org/article1728](http://www.geochemicalperspectivesletters.org/article1728)

**Reprints and permission information** are available online at <http://www.geochemicalperspectivesletters.org/copyright-and-permissions>

**Cite this letter as:** Lambart, S. (2017) No direct contribution of recycled crust in Icelandic basalts. *Geochem. Persp. Let.* 4, 7-12.

## References

- BROWN, E.L., LESHER, C.E. (2014) North Atlantic magmatism controlled by temperature, mantle composition and buoyancy. *Nature Geoscience* 7, 820–824.
- CHAUVEL, C., HÉMOND, C. (2000) Melting of a complete section of recycled oceanic crust: Trace element and Pb isotopic evidence from Iceland. *Geochemistry, Geophysics, Geosystems* 1, 1001.
- DARBYSHIRE, F.A., WHITE, R.S., PRIESTLEY, K.F. (2000) Structure of the crust and uppermost mantle of Iceland from a combined seismic and gravity study. *Earth and Planetary Science Letters* 181, 409–428.
- HALLDÓRSSON, S.A., HILTON, D.R., BARRY, P.H., FÜRI, E., GRÖNVOLD, K. (2016) Recycling of crustal material by the Iceland mantle plume: New evidence from nitrogen elemental and isotope systematics of subglacial basalts. *Geochimica et Cosmochimica Acta* 176, 206–226.
- HERZBERG, C., VIDITO, C., STARKEY, N.A. (2016) Nickel-cobalt contents of olivine record origins of mantle peridotite and related rocks. *American Mineralogist* 101, 1952–1966.
- HIROSE, K., KUSHIRO, I. (1993) Partial melting of dry peridotites at high pressures: Determination of compositions of melts segregated from peridotite using aggregates of diamond. *Earth and Planetary Science Letters* 114, 477–489.
- ITO, G., MAHONEY, J.J. (2005) Flow and melting of a heterogeneous mantle: 1. Method and importance to the geochemistry of ocean island and mid-ocean ridge basalts. *Earth and Planetary Science Letters* 230, 29–46.
- KOGISO, T., HIROSE, K., TAKAHASHI, E. (1998) Melting experiments on homogeneous mixtures of peridotite and basalt: application to the genesis of ocean island basalts. *Earth and Planetary Science Letters* 162, 45–61.
- KOKFELT, T.F., HOERNLE, K., HAUFF, F., FIEBIG, J., WERNER R., GARBE-SCHÖNBERG, D. (2006) Combined Trace Element and Pb–Nd–Sr–O Isotope Evidence for Recycled Oceanic Crust (Upper and Lower) in the Iceland Mantle Plume. *Journal of Petrology* 47, 1705–1749.
- KOORNNEEF, J.M., STRACKE, A., BOURDON, B., MEIER, M.A., JOCHUM, K.P., STOLL, B., GRÖNVOLD, K. (2012) Melting of a Two-component Source beneath Iceland. *Journal of Petrology* 53, 127–157.
- LAMBART, S., LAPORTE, D., PROVOST, A., SCHIANO, P. (2012) Fate of pyroxenite-derived melts in the peridotitic mantle: Thermodynamical and experimental constraints. *Journal of Petrology* 53, 451–476.
- LAMBART, S., BAKER, M.B., STOLPER, E.M. (2016) The role of pyroxenite in basalt genesis: Melt-PX, a melting parameterization for mantle pyroxenites between 0.9 and 5GPa. *Journal of Geophysical Research: Solid Earth* 121, doi:10.1002/2015JB012762.
- MATTHEWS, S., SHORTLE, O., MACLENNAN, J. (2016) The temperature of the Icelandic mantle from olivine–spinel aluminum exchange thermometry. *Geochemistry, Geophysics, Geosystems* 17, 4725–4752.
- PERTERMANN, M., HIRSCHMANN, M.M. (2003) Anhydrous Partial Melting Experiments on MORB-like Eclogite: Phase Relations, Phase Compositions and Mineral–Melt Partitioning of Major Elements at 2–3 GPa. *Journal of Petrology* 44, 2173–2201.
- RUDGE, J.F., MACLENNAN, J., STRACKE, A. (2013) The geochemical consequences of mixing melts from a heterogeneous mantle. *Geochimica et Cosmochimica Acta* 114, 112–143.
- SALTERS, V.J.M., STRACKE, A. (2004) Composition of the depleted mantle. *Geochemistry, Geophysics, Geosystems* 5, Q05004, doi:10.1029/2003GC000597.
- SHORTLE, O., MACLENNAN, J. (2011) Compositional trends of Icelandic basalts: Implications for short-length scale lithological heterogeneity in mantle plumes. *Geochemistry, Geophysics, Geosystems* 12, Q11008, doi:10.1029/2011GC003748.
- SHORTLE, O., MACLENNAN, J., LAMBART, S. (2014) Quantifying lithological variability in the mantle. *Earth and Planetary Science Letters* 395, 24–40.
- SIMS, K.W.W., MACLENNAN, J., Blichert-Toft, J., MERVINE, E.M., BLUSZTAJN, J., GRÖNVOLD, K. (2013) Short length scale mantle heterogeneity beneath Iceland probed by glacial modulation of melting. *Earth and Planetary Science Letters* 379, 146–157.
- SOBOLEV, A.V., HOFMANN, A.W., KUZMIN, D.V., YAXLEY, G.M., ARNDT, N.T., CHUNG, S.L., DANYUSHEVSKY, L.V., ELLIOTT, T., FREY, F.A., GARCIA, M.O., GURENKO, A.A., KAMENETSKY, V.S., KERR, A.C., KRIVOLUTSKAYA, N.A., MATVIENKOV, V.V., NIKOGOSIAN, I.K., ROCHOLL, A., SIGURDSSON, I.A., SUSHCHEVSKAYA, N.M., TEKLAY, M. (2007) The amount of recycled crust in sources of mantle-derived melts. *Science* 316, 412–417.
- STRACKE, A., BOURDON, B. (2009) The importance of melt extraction for tracing mantle heterogeneity. *Geochimica et Cosmochimica Acta* 73, 218–238.



- THIRLWALL, M.F., GEE, M.A.M., TAYLOR, R.N., MURTON, B.J. (2004) Mantle components in Iceland and adjacent ridges investigated using double-spike Pb isotope ratios. *Geochimica et Cosmochimica Acta* 68, 361–386.
- THIRLWALL, M.F., GEE, M.A.M., LOWRY, D., MATTEY, D.P., MURTON, B.J., TAYLOR, R.N. (2006) Low  $^{18}\text{O}$  in the Icelandic mantle and its origins: evidence from Reykjanes ridge and Icelandic lavas. *Geochimica et Cosmochimica Acta* 70, 993–1019.
- WATERS, C.L., SIMS, K.W.W., PERFIT, M.R., Blichert-Toft, J., Blusztajn, J. (2011) Perspective on the Genesis of E-MORB from Chemical and Isotopic Heterogeneity at 9–10°N East Pacific Rise. *Journal of Petrology* 52, 565–602.