Partial melting of pyroxenite domains in peridotitic mantle - not all pyroxenites are born equal

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Discrete bodies of pyroxenite have been proposed in magma sources in intraplate and mid-ocean ridge settings [1]. The pyroxenite formed when recycled, mafic, oceanic crust (eclogite) in upwelling mantle partially melted at higher pressures than the host peridotite along an adiabat, produced siliceous liquids which are out of equilibrium with enclosing peridotite and reacted to form garnet pyroxenite at high pressures [2,3].

Several high pressure experimental studies attempted to test this model by partially melting a range of pyroxenite compositions and establishing solidus temperatures and partial melt compositions. However, many of these studies used inappropriate pyroxenite compositions. Pyroxenites formed as described above lie on the thermal divide in the normative high pressure eclogite projection [2]. They will be refractory, melting at a binary pseudo-eutectic on the Garnet-Orthopyroxene join (the thermal divide). Compositions explored experimentally to date, projected either on the Olivine-normative or Quartz-normative sides of the diagram, meaning they will melt at lower temperatures at pseudo-eutectics, at given pressure.

We predict the order of melting during adiabatic decompression of a hybrid mantle (peridotite enclosing discrete bodies of eclogite) will be as follows. Eclogite will melt first at the highest pressures. Extraction of that melt will form garnet pyroxenite on reaction with peridotite. Melting will next occur at boundaries between unreacted peridotite and the garnet pyroxenite at lower pressures, with further decompression melting normal peridotite and/or residual eclogite, depending on the solidus temperature of the latter. The garnet pyroxenite itself will melt at the shallowest pressures.

This scenario is consistent with a recent model [4] explaining the compositionally distinct double tracks of lavas on Hawaii (Loa and Kea) and other Pacific hotspot locations.

Intraplate volcanism is a widely studied but poorly understood phenomenon. In particular, Atlantic intra-oceanic volcanism near the African continental margin displays several characteristics that do not fully conform with classical plume theory. It has been suggested that Edge-Driven Convection (EDC) plays a major role in the generation of magmas beneath e.g. the Canaries, Cape Verde or the Cameroon volcanic line. To explore the roles of EDC vs. plume in the generation of Atlantic volcano chains, we have conducted a series of numerical models using the code CITCOM coupled with parameterizations for melting an assemblage of peridotites and pyroxenites. Our new parameterizations have been derived from experiments and pMELTS modelling, and can predict the extent and major-element composition of peridotite/pyroxenite melting as a function of the P-T path. We study the behavior of EDC alone, as well as the possible interactions of EDC with plumes. To better understand plume-EDC interaction, we explore a wide range of model parameters, focusing specifically on the effects of plate velocity, mantle viscosity, plume temperature, and plume position relative to the edge (i.e., African margin). Our results suggest that EDC alone is unable to sustain significant volcanism, unless the mantle is anomalously hydrous. In turn, plumes alone do not create the complex age progressions of e.g. the Canaries. However, we find that EDC can distort plume ascent and imprint characteristic properties on the related volcanism, resulting in irregular age progressions. In addition, our models predict that the chemical characteristics of primary magmas depend on mantle upwelling geometry, suggesting that the role of EDC on generating volcanism can be constrained by the geochemistry of primary magmas: for example, the pyroxenite signature decreases with decreasing plume temperature or as plume ascent becomes inhibited by EDC. Although EDC alone is not a suitable mechanism for extensive intraplate volcanism, it can have important effects on plume ascent, and thereby reconcile some previously poorly understood characteristics of eastern Atlantic volcano chains.
Source versus process: Peridotite constraints on magma genesis

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Abyssal peridotites, the residues of basalt crustal genesis, preserve lithologic, elemental, and isotopic evidence for source- and process-induced heterogeneities. For example, the larger isotopic range of abyssal peridotites relative to mid-ocean ridge basalts requires the presence of long-lived source heterogeneities that are smoothed out by melting and melt mixing.

Here, we demonstrate that peridotites also record a greater range of oxygen fugacity ($f_{O_2}$) than their basalt counterparts. We have determined the $f_{O_2}$ of basalts and peridotites from the same ridge segment using μ-XANES and spinel oxybarometry, respectively [1]. Both lithologies reflect source mantle very near the quartz-fayalite-magnetite (QFM) buffer, and basalt $f_{O_2}$ is within error of the global basalt average. While basalt $f_{O_2}$ spans less than one log unit, peridotite $f_{O_2}$ spans almost three log units, from $<$QFM-1.5 to $-$QFM+1. Some peridotite dredges vary by over two log units, indicating relatively small length-scale (<1 km) variability. The peridotites record a diversity of features, including evidence of melt addition and a subset that suggest an ancient refractory component.

Constraining the relative contributions of source and process requires an understanding of the thermodynamic and petrologic controls on the chemical evolution of melts and residues during melting and reactive melt transport. We explore the use of numerical models for identifying which elements can serve as tracers of different parts of the system, through the incorporation of trace element transport into reactive melt transport models [2]. Source heterogeneity is not preserved in the melt when it occurs at small length-scales, but is preserved in the residue for elements that are moderately incompatible ($D$≈0.1). These elements – such as heavy rare earth elements – may be key to tracing source variability in peridotites, whereas highly incompatible elements are more process influenced.

Markov Chain Monte Carlo Inversion of Mantle Temperature and Composition Beneath Iceland

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Basaltic magmatism is a fundamental consequence of convection within the earth’s interior. Basalts are generated by adiabatic decompression melting of the upper mantle, and thus provide spatial and temporal records of the thermal, compositional, and dynamical conditions of their source regions. Uniquely constraining these factors through the lens of melting is challenging, however, given that primary basalts are variable mixtures of melts derived from compositionally heterogeneous mantle sources consisting of a range of lithologies with different melting behaviors (e.g. peridotite vs. pyroxenite). To overcome these challenges, we have combined the Metropolis-Hastings Markov chain Monte Carlo sampling method with the forward melting model REEBOX PRO [1], which simulates adiabatic decompression melting of lithologically heterogeneous sources containing peridotite and pyroxenite. This coupling allows us to invert for key mantle source parameters (and their uncertainties), including mantle potential temperature ($T_P$), lithologic abundances and their initial trace element and isotopic compositions, by identifying optimal models that produce the best fits to the observations. We have applied this combined methodology to magmatism along Reykjanes Peninsula in Iceland, exploring melting of depleted peridotite and an enriched peridotite/pyroxenite lithology (either KG1 peridotite or G2 pyroxenite). Best-fit model sources have ~92% depleted peridotite and ~8% pyroxenite with $T_P$ ~148 ± 4 °C above ambient mantle. The enriched lithology has an EMORB-like trace element composition but was not likely produced by melting at a mid-ocean ridge. The depleted peridotite lithology is similar to DMM [2] in terms of its trace element and Nd isotopic compositions. We discuss these results with regard to existing Iceland source models and reconcile our results with arguments against the depleted Iceland source being derived from DMM [3].

Mantle source and magma evolution of the dying spreading ridge in the South China Sea

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Abstract

The South China Sea developed a seamount chain along the fossil ridge shortly after cessation of spreading. However, it remains enigmatic on the mantle source and magmatic evolution of the dying spreading ridge. IODP Expedition 349 has recovered a shallow volcanic breccia layer with carbonatite clasts and two deeper (upper and lower sections) basalt layers, inter-bedded with hemipelagic sediments, at Site U1431 near the fossil ridge of the South China Sea. Here we show the results of whole-rock major and trace elements and Sr-Nd-Pb-Hf isotopes and high-precision olivine trace element compositions of these basalts. The upper section basalts with unusually high whole-rock MgO contents (up to $\sim$20 wt%) can be attributed to olivine accumulation during off-ridge/intraplate volcanism with lack of a stable magma chamber. The lower and upper basalt sections show distinct geochemical compositions that indicate a compositional change in sub-ridge mantle source. The isotopic compositions of upper section basalts can be explained by mixing between the lower section basalts and the uppermost volcanic clasts with an EM2 type mantle source at Site U1431. A CO$_2$-rich EM2-type mantle source has likely played a fundamental role in the genesis of the upper section basalts. The MORB type basalts at Site U1431 have bulk-rock low CaO and Hawaii-like high olivine Ni and Fe/Mn and low olivine Ca and Mn that are distinctly different from the normal global MORBs, which we attribute to melting of pyroxenite-rich sub-ridge mantle. We propose that the Hainan plume with a pyroxenitic component has played a fundamental role in the volcanism of the dying spreading ridge of the South China Sea.

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Water content of abyssal peridotites: implications for melt transports beneath mid-oceanic ridges

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Melt generated by upwelling mantle is fundamental to the creation of oceanic crust at mid-oceanic ridges (MORs). A major question has been how melt is transported from the melt production in the board melting region to the narrow axis that still remains challenging for geophysical observations. Such melt flow through the shallow mantle has been evidenced readily by vein lithologies and metasomatism in peridotites exposed at MORs. It is suggested to also occur in a more cryptic way, leaving depleted residual peridotites with enrichment of water, a highly incompatible and fast-diffusing component. However, origin and distribution of the secrete melt at the shallow mantle beneath the axis remain puzzles. Here, we determined H2O content of clinopyroxene (cpx) and orthopyroxene (opx) in depleted mantle peridotites from a continuous lithospheric section created at a segment of the Mid-Atlantic ridge (MAR), showing an “equilibration” hydration by late-stage melt in the mantle. The retrieved melt H2O content is from 2.5 to 7.4 wt%, and from 1.8 to 5.8 wt% beyond Vema[1][2], suggesting a global existence of the “ghost” mantle melt, with an average of 4.1±1.4 wt% H2O, beneath the axis. Therefore, divergent melt transports is proposed that small volumes of low-degree melts, produced off-axis by incipient melting, are channeled along the base of the sloping thermal lithosphere to the axis, segregated from melt transport by dunite conduits to the axis occurring in the molten region. Our findings argue against melts produced in the vicinity of MORs as lateral supply for the Lithosphere and Asthenosphere Boundary melts observed away from ridges.

Extreme mantle heterogeneity preserved in Earth’s oceanic crust

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Earth’s oceanic crust, produced by melting of the upper mantle where it upwells beneath mid-ocean ridges, provides a geographically widespread elemental and isotopic ‘sample’ of Earth’s mantle, preserving key information on planetary differentiation. The problem remains that mixing and reaction during melt ascent act to homogenise the chemical variations that Mid-Ocean-Ridge-Basalts (MORB) acquire. Primitive minerals in MORB and their trapped melt inclusions point to substantial heterogeneity in the mantle source, implying that the lower oceanic crust is also heterogeneous. This study presents radiogenic (Pb, Nd and Os) and stable isotope (Fe, Zn) data for primitive crystals in MORB, and gabbroic minerals from the lower oceanic crust.

Primitive minerals hosted by MORB glass, from the FAMOUS segment on the mid Atlantic ridge, yield Pb, Nd and Os isotope compositions indicating the presence of an extremely depleted mantle source (ɛNd ≈ +12; 206Pb/204Pb ≈ 17.40; 187Os/188Os ≈ 0.12), not evident in the host glass. While Fe and Zn stable isotopes for the same minerals yield compositions closer to those of the depleted mantle (δ⁵⁶Fe ≈ +0.02; δ⁶⁶Zn ≈ +0.15) than typical MORB. Melt inclusions indicate that these phases must have crystallised in the lower oceanic crust. The radiogenic isotope composition of minerals from lower crustal gabbros and troctolites, from the Atlantis Bank, south the SW Indian ridge, indicate an even greater heterogeneity than that seen in primitive minerals in MORB, while Fe and Zn isotopes reflect both source variations and the effects of fractional crystallisation.

Overall, these results indicate that primitive minerals in MORB and the lower oceanic crust, preserve a record of depletion and enrichment that is largely erased in erupted MORB glass, moreover this signal is biased towards the composition of more fusible rock types [1]. Offsets in the stable isotope composition of MORB, relative to mantle rocks largely reflect these different sources, rather than processes such as partial melting or redox/polymerization in magmas.

The effects of two-lithology mantle melting on U-series in basalts

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Melting in a lithologically heterogeneous mantle is expected to impact magma supply, crustal thickness, and magma transport. Oceanic basalts are products of mantle melting and thus potential indicators of such heterogeneity, but basalts record complex histories that can be difficult to uniquely interpret. Uranium-series isotopes are well-suited to fingerprinting diverse lithologies due to variations in 1) source mineralogy and U-Th-Pa-Ra partitioning, and 2) lithologic melt fertility and the series’ particular sensitivity to melting rates. However, such interpretations to-date have been hampered by a lack of constraints on the melting behavior of mafic rocks under mantle conditions.

Recent, experimentally-based parameterizations for pyroxenite melting, and the application of those new calibrations to two-lithology melting calculations [Lambart et al., 2016, JGR, 10.1002/2015JB012762; Lambart, 2017, GPL, 10.7185/geochemlet.1728], constitute significant improvements to our predictions for pyroxenite melting. Here we use the outcomes of those parameterizations and of energy-constrained two-lithology melting calculations to produce a refined set of melt fractions and mineral modes during adiabatic melting. We tested the effects of melting upper mantle containing 10% pyroxenite for a range of mantle potential temperatures. In agreement with recent work [Lambart, 2017], we find that productivity variations for two-lithology melting regimes have a significant impact on resulting melt mixtures, with particular dependence on pyroxenite compositions and resulting solidus temperatures.

The resulting melt fractions and partition coefficients will next be used to determine U-series disequilibria for pyroxenite- and peridotite-derived partial melts and mixtures thereof. We will consider 1D, continuous numerical solutions for both dynamic melting and reactive porous flow scenarios, allowing both the degree of melting and the mineral/melt partition coefficients to vary non-linearly. We expect the resulting predicted basalt compositions to better approach the effects of heterogeneous mantle melting on U-series isotope disequilibria in basalts.
Deciphering the geochemistry of lithospheric mantle in the melt source of the Payenia volcanic province, Argentina

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The Payenia volcanic province (central Argentina, 34.5-38° S) comprises a region of voluminous Plio-Quaternary back-arc basaltic volcanism, a substantial portion of which bears an intraplate geochemical signature. Some previous workers have attributed this signature to convecting asthenosphere [1,2], while others suggested the involvement of the subcontinental lithospheric mantle (SCLM) [3,4,5]. To better resolve the mantle source of Payenia volcanism, we report whole rock major and trace element concentrations and Sr-, Nd-, Hf-, and Pb-isotope ratios and high-precision oxygen-isotope ratios of olivine phenocrysts in a set of 35 Payenia back arc basalts and basaltic andesites. The δ18O VSMOW values of olivine phenocrysts from Payenia basalts vary from 4.84 to 5.39‰, a range that covers and extends below the range of normal mantle δ18O ol values (5.0-5.4‰) [5,6]. A subset of Payenia lavas with an intraplate signature have δ18O ol≈5.0‰ and exhibit Hf and Nd isotope ratios that diverge from the Hf-Nd mantle array (i.e., ΔεHf values reaching -2.8). The low δ18O ol and the trace element composition of these lavas preclude contribution from the continental crust. Instead, we suggest such isotopic fractionation may occur during metasomatism of the SCLM. We developed a simple forward model of melting magmatic cumulates within the SCLM, which predicts the isotopic variations and trace element compositions observed in the erupted melts. Model results represent the first quantitative indication of a SCLM-derived melt source in Payenia.

He, CO$_2$, and $\delta^{13}$C variations during a mid-ocean ridge eruptive event

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We report $^3$He/$^4$He, He and CO$_2$ concentrations for the dissolved (glass) and vapor (vesicle) phase of basalts, plus $\delta^{13}$C of vesicles, for a suite of 23 lavas from the 2005-2006 eruption on the East Pacific Rise. This sample suite provides a rare opportunity to study magma recharge along the mid-ocean ridge system and to quantify degassing prior to and during a single eruptive event. Our study covers the spatial and temporal extent of the months-long eruption (ages from $^{210}$Po-$^{206}$Pb dating). $^3$He/$^4$He is in isotopic equilibrium between vesicles and glass (mean = 8.51±0.04(1σ) $R_A$). Vesicle He and CO$_2$ concentrations vary by factors of 17 and 230, respectively. Nearly all samples lie in a narrow range of 280-370 ppm for total CO$_2$ (vesicles+glass), suggesting volatile saturation at ~1.5 km depth in the crust, similar to depths of the seismically imaged magma lenses. Vapor phase CO$_2$/He co-varies positively with the fraction of CO$_2$ contained in vesicles ($r^2=0.94$) due to kinetic fractionation between He and CO$_2$ during vesiculation. There is no evidence for kinetic fractionation of $^{13}$C from $^{12}$C. Vesicle $\delta^{13}$C varies negatively with fraction of CO$_2$ in vesicles ($r^2=0.83$), ranging from -2.6 to -5.0‰, and straddles the isotope composition of EPR vent fluids. The $^{13}$C-enrichment during CO$_2$ exsolution from the basaltic melt is similar to experimentally determined fractionation factors. Collectively the observations are explained by quasi-closed-system degassing, where melt ascent from the magma lens was sufficiently rapid that minimal bubble loss occurred during the eruption and flow of lava onto the seafloor.
Phase equilibria and geochemical constraints on the petrogenesis of high-Ti picrite from the Paleogene East Greenland flood basalt province

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Phase equilibrium experiments have been performed on an extremely high-Ti (5.4 wt.% TiO₂) near-primitive picrite from the base of the Paleogene (~55 Ma) East Greenland Flood Basalt Province. This sample has a low An content, a steep REE profile and is enriched in incompatible trace elements. Near-liquidus phase relations were determined over the pressure range of 1 atm, 1 to 1.5 GPa and at temperatures from 1094 to 1400°C. They provide an important constraint on the petrogenesis of these lavas. High-Ti picritic glasses are multi-saturated with respect to olivine (Ol) + orthopyroxene (Opx) at pressures about 1 GPa but have only Ol or Opx on the liquidus at lower and higher pressures, respectively. This indicates the primitive melt was last equilibrated with its mantle source at relatively shallow pressure (~1 GPa). Melting probably started at 2-3 GPa and the picritic melt was produced by 15-30% melting of the mantle source. Such a degree of partial melting requires a mantle with a high potential temperature (1480-1530°C). Relatively low CaO content and high FeO/MnO ratios of the most primitive East Greenland picrites, the high Ni content of olivine phenocrysts and the presence of low-Ca pyroxene (i.e., pigeonite) at high pressure in experiments all suggest a major component of garnet pyroxenite in the mantle source. The high degree of enrichment in incompatible elements is suggested to result from melting of a metasomatized mantle. Based on geochemical modelling, we propose that the mantle source contains 5% Ti-enriched amphibole and that moderate partial melting (15-20%) of this source can produce the high Ti picritic lavas of East Greenland.