Magmas trapped at the continental lithosphere–asthenosphere boundary

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ABSTRACT

The lithosphere–asthenosphere boundary (LAB) beneath the continents is a key interface in plate tectonics, yet its nature remains elusive. A partial melt layer has been advocated to explain its geophysical characteristics. However, the main counter-argument is that such a layer cannot be stable as melts should rise through the lithosphere. Density measurements of volatile-containing alkali basalts taken as a proxy for LAB melts show that they are neutrally buoyant at the pressure (P)–temperature (T) conditions of the LAB under continents. Complementary X-ray diffraction and Raman data provide structural insights on melt compaction mechanisms. Basalts generated below the lithosphere may thus be gravitationally trapped and accumulate over time. Their presence provides answers to key questions on continental lithosphere geodynamics, and in particular on cratonic keels stability. This buoyancy trap would cease to exist at higher mantle T such as those relevant of the Archean, and as such, could be linked to the onset of plate tectonics.

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1. Introduction

Several geophysical observables define the continental LAB: 1) the Lehmann discontinuity at constant depth (200–250 km) across the Archean and proterozoic units in North America (Yu and Romanowicz, 2010); 2) the low velocity zone in global tomographic models of shear-wave velocity (Cammarano and Romanowicz, 2007); 3) a shear wave radial anisotropy with horizontally polarized shear waves traveling faster than those that are vertically polarized, anomaly present under most cratons in the depth range 250–400 km (Yu and Romanowicz, 2010) with East–West flow in the convective mantle, and North–South fast direction in the LAB; 4) an electrical resistivity drop (Jones, 1999; Jones et al., 2010). Only observable 2 is common to oceanic and continental LAB, the former being significantly shallower (circa 90 km). It has long been suggested that all characteristics given

above for the continental LAB may be caused by small amounts of partial melt (Eaton et al., 2009; Anderson and Sammis, 1970). Petrological models of the continental lithosphere describe its lowest part as enriched by melts from below (Foley, 2008), consistently with melts having ponded in the asthenosphere (O'Reilly and Griffin, 2010). Magnetotelluric observations suggest that the partial melt layer is of finite thickness, which implies that partial melting ceases at greater depths (Jones, 1999), and/or that melts are trapped at this particular depth as suggested by Agee (1998) and Chen et al. (2002). A stable partial melt layer in the LAB would have major geodynamical consequences such as lithosphere–asthenosphere decoupling (Doglioni et al., 2011) and explain why cratonic roots survive so long while numerical models predict that they should be eroded (King, 2005) by shielding them from the mantle stress field. However, this suggestion requires the presence of materials that will: 1) melt at the P–T conditions of the LAB, and 2) be retained at that depth by some mechanism.

2. Why the choice of an alkali basalt?

There has been a strong focus on carbonatites as candidates for LAB melts, essentially as they can be generated as deep as

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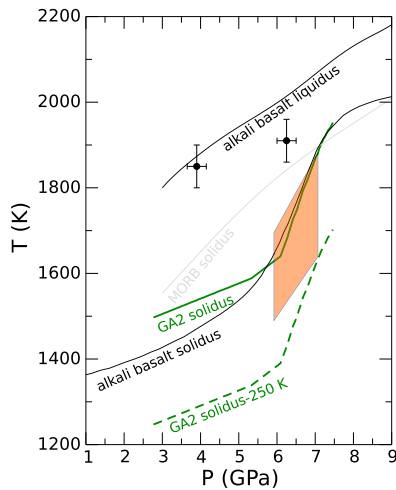
Fig. 1. Experimental P–T conditions compared to melting relationships for alkali basalt (Tsuruta and Takahashi, 1998), mid-oceanic ridge basalts (MORB) (Yasuda et al., 1994), GA2 eclogite (Spandler et al., 2004), and geotherm estimates covered by the shading (James et al., 2004). The effect of added K_2O (+1.5 wt%), CO_2 and H_2O on the solidus of the GA2 eclogite is shown (−250 K). N.B.: alkali basalt and MORB have a very similar liquidus curve.

250 km from partial melting of carbonated peridotite, and have been proposed to explain the oceanic low-velocity zone (Gaillard et al., 2008; Dasgupta et al., 2013). However, their low density (2.2–2.3 g/cc) discards them for the continental LAB as they would not be retained at depth. Instead, alkali basalts combine a higher density with a relatively low melting point. The solidus of an alkali basalt is lower than that of a typical mid-ocean ridge basalt (MORB) at depth with a maximum depression of 200 K at 6 GPa (Tsuruta and Takahashi, 1998), and in contrast to the MORB solidus, the alkali basalt solidus becomes very steep around 6–7 GPa (Fig. 1), i.e. at or around the conditions of the continental LAB.

Alkali basalts have been dragged in the Japanese sea and interpreted as originating from the asthenosphere (Hirano et al., 2006), with a high vesicularity suggesting high CO_2 content in the pre-eruptive melt. The contribution of high pressure eclogites, the crystallized high pressure equivalent of an alkali basalt, to the source of mafic magmatism has been recognized from the isotopic and geochemical characteristics of some basalts, in particular of ocean island basalts (Hofmann, 2003; Pertermann and Hirschmann, 2003; Sobolev et al., 2005, 2007). The importance of volatile-rich alkali basalts in the asthenosphere may however not be limited to the oceanic contexts. Silica enrichment of some cratonic peridotites compared to what would be expected for simple partial melt residues (Carlson et al., 2005) has been interpreted by percolation of Si-rich melts derived from subducted slabs (Rudnick et al., 1994; Kelemen et al., 1998). Similarly, eclogitic melts may have lead to the refertilization of the lithosphere at depths of circa 170–220 km beneath cratons (O'Reilly and Griffin, 2010). Finally, diamond inclusions originating from the asthenosphere are of metabasite (i.e. eclogitic) affinity (Harte, 2010), and the genesis of diamondites, polycristalline diamonds, has been linked to the presence of volatile saturated eclogitic melts in the sub-cratonic mantle (Mikhail et al., 2013).

The presence of eclogite in the cratonic mantle as a whole has been quantified from seismology to about 1%, and locally to as much as 15% (Schultze, 1989), as mafic magmatic rocks may be returned to the mantle via plate subduction or through delamination of the lower crust after contributing to the formation of cratonic roots (Lee, 2006). This motivated the investigation of the eclogite dry solidus up to 5 GPa (Spandler et al., 2008). The composition used in this study, a primary alkali basalt (Pichavant et

al., 2009), contains 1.5 wt% more K_2O than the GA2 composition used by Spandler et al. (2008). The eclogite dry solidus can be depressed by circa 250 K for our alkali- and volatile-rich composition (0.9 wt% CO_2–1.04 wt% H_2O), accounting for the effect of dissolved carbonate ions and water observed on altered MORB at high pressure – respectively circa −25 K per wt% CO_2 (Gerbode and Dasgupta, 2010) and −150 K for 0.87 wt% H_2O in the glass (Kiseeva et al., 2012) – and for the effect of excess K_2O assuming a similar effect to that observed for a hydrated and carbonated peridotite in the 4–6 GPa range (Foley et al., 2009).

T estimates at the LAB under cratons range from 1573 K to 1773 K at 200 km (∼6.6 GPa) from the study of xenoliths in the Kaapvaal craton in South Africa (James et al., 2004). The solidus of our composition will thus be about 200 K below petrological T estimates for the LAB, which corresponds to 70–85% of melt fraction (Pertermann and Hirschmann, 2003; Spandler et al., 2008) as required to generate an alkali basaltic melt. Consistently, a melt with a similar composition to ours was obtained by bringing an eclogite + 3 wt% (H_2O–CO_2) + 3 wt% KCl at 5 GPa and 1573 K (Butvina et al., 2009). The high alkali content is thus efficient in both lowering the melting point and increasing melt productivity, and it is important in that respect that alkalis are not leached out of the subducted slabs, as supported by examination of eclogites from paleo-subduction zones (Spandler et al., 2004).

A few studies have investigated the reactivity of eclogite-derived melts with peridotite, some finding that all melt is consumed (Yaxley and Green, 1998), others that once a reaction band of pyroxene is produced, it will prevent further contact between melt and mantle, thereby trapping melt in peridotite/pyroxenite reaction zones (Kogiso et al., 2004). Latest reaction experiments between peridotite (KLB-1) and MORB-eclogite-derived carbonated melts (2.6 wt% CO_2) (Malik and Dasgupta, 2013) produced between 11 and 24% sustainable melt at near equilibrium conditions, while melt composition spanned the range of most alkali basalts. Malik and Dasgupta (2013) noted that their experiments are relevant beneath continental lithosphere as generation of the first carbonated-eclogite melt might be triggered by conversion of graphite to carbonate at the redox front, constrained to occur at 250 km depth (Rohrbach et al., 2007, 2011).

Volatile-containing alkali basalts can thus thermally be present in the LAB but the physical mechanism for retention is still to be discovered as magmas are expected to percolate through the silicate matrix after formation. Wetting experiments at high P suggest that, in contrast to low P conditions, very little amounts are needed for the melt to totally wet olivine crystals and hence have a large influence on the electrical conductivity of the upper mantle (Yoshino et al., 2009). But another consequence of this high melt connectivity is that it will be even harder to prevent it from moving through the mantle. An alternative to mechanical retention of melts at depth is gravitational trapping. This idea was suggested (Agee, 1998) based on shock-wave density data on basalts (Rowan, 1993). However, the scatter in the shock-wave data was too large to be conclusive and an ex situ sink–float density measurement on molten MORB at 6 GPa did not confirm it either (Agee, 1998). Additional sink–float data have been collected on molten MORB with and without water in the 15–20 GPa/2573 K–2673 K range (Sakamaki et al., 2006), but these conditions are largely above the estimates for the LAB discussed above, especially for T, and that makes extrapolations back difficult.

3. Experimental procedures

3.1. Generation of high P–T conditions

High pressure conditions were generated by a VX5 Paris–Edinburgh press. The cell-assembly used is detailed in van Kan