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The ascent of kimberlite: Insights from olivine

R.C. Brett[a,b,*], J.K. Russell[a], G.D.M. Andrews[a,c], T.J. Jones[d]

[a] *Volcanology & Petrology Laboratory, Department of Earth & Ocean Sciences, The University of British Columbia, Vancouver, British Columbia, V6T 1Z4, Canada*
[b] *Rio Tinto Exploration Canada Inc., Vancouver, British Columbia, V6C 1S4, Canada*
[c] *Department of Geosciences, California State University Bakersfield, Bakersfield, CA, 93311, USA*
[d] *Department of Earth Sciences, Durham University, South Road, Durham, DH1 3LE, UK*

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ABSTRACT

Olivine xenocrysts are ubiquitous in kimberlite deposits worldwide and derive from the disaggregation of mantle-derived peridotitic xenoliths. Here, we provide descriptions of textural features in xenocrystic olivine from kimberlite deposits at the Diavik Diamond Mine, Canada and at Igwisi Hills volcano, Tanzania. We establish a relative sequence of textural events recorded by olivine during magma ascent through the cratonic mantle lithosphere, including: xenolith disaggregation, decompression fracturing expressed as mineral- and fluid-inclusion-rich sealed and healed cracks, grain size and shape modification by chemical dissolution and abrasion, late-stage crystallization of overgrowths on olivine xenocrysts, and lastly, mechanical milling and rounding of the olivine cargo prior to emplacement. Ascent through the lithosphere operates as a "*kimberlite factory*" wherein progressive upward dyke propagation of the initial carbonatitic melt fractures the overlying mantle to entrain and disaggregate mantle xenoliths. Preferential assimilation of orthopyroxene (Opx) xenocrysts by the silica-undersaturated carbonatitic melt leads to deep-seated exsolution of CO_2-rich fluid generating buoyancy and supporting rapid ascent. Concomitant dissolution of olivine produces irregular-shaped relict grains preserved as cores to most kimberlitic olivine. Multiple generations of decompression cracks in olivine provide evidence for a progression in ambient fluid compositions (e.g., from carbonatitic to silicic) during ascent. Numerical modelling predicts tensile failure of xenoliths (disaggregation) and olivine (cracks) over ascent distances of 2–7 km and 15–25 km, respectively, at velocities of 0.1 to $>4\ \mathrm{m\,s^{-1}}$. Efficient assimilation of Opx during ascent results in a silica-enriched, olivine-saturated *kimberlitic* melt (i.e. $SiO_2 > 20$ wt.%) that crystallizes overgrowths on partially digested and abraded olivine xenocrysts. Olivine saturation is constrained to occur at pressures <1 GPa; an absence of decompression cracks within olivine overgrowths suggests depths <25 km. Late stage (<25 km) resurfacing and reshaping of olivine by particle–particle milling is indicative of turbulent flow conditions within a fully fluidized, gas-charged, crystal-rich magma.

1. Introduction

Kimberlite magmas derive from deep (≥200 km) mantle sources and transport substantial loads (>25 vol.%) of dense, mantle-derived xenoliths and xenocrysts from the base of the mantle lithosphere to the Earth's surface. They are found almost exclusively within Archean cratons and are of particular interest because they are the deepest-sourced terrestrial magmas, are the major source rock of natural diamond, and carry xenoliths which inform on the petrology, structural state, and temperature of the deep cratonic mantle lithosphere.

The rapid transport of kimberlite through ~150–200 km of cool cratonic mantle lithosphere has been discussed by McGetchin and Ullrich (1973), Sparks et al. (2006), Sparks (2013), Wilson and Head (2007) and Kavanagh and Sparks (2009). Most kimberlite ascent models involve the propagation of a volatile-rich magma-filled crack upward through the mantle lithosphere. The exsolution and expansion of a fluid phase creates pressure gradients (100–300 MPa, Lensky et al., 2006; 70 MPa, Wilson and Head, 2007; Sparks, 2013) large enough to induce crack propagation within the mantle and the buoyancy needed to support continuous and rapid ascent. Russell et al. (2012, 2013) suggested a mechanism for the deep-seated exsolution of CO_2-rich fluids; carbonatitic magmas enter and ascend the cratonic mantle lithosphere and sample and disaggregate peridotite xenoliths. Orthopyroxene is assimilated preferentially over other mantle mineral phases (Mitchell, 1973) causing an increase in the melt's SiO_2 content, a drop in CO_2 solubility, and

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[*] Corresponding author at: Rio Tinto Exploration Canada Inc., Vancouver, British Columbia, V6C 1S4, Canada. Tel.: +1(604)762 6650; fax: +1(604)696 3401.
E-mail address: Curtis.Brett@riotinto.com (R.C. Brett).

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the spontaneous exsolution of a CO_2-dominated fluid phase (Brey and Ryabchikov, 1994; Brooker et al., 2011; Russell et al., 2012; Sparks, 2013; Moussallam et al., 2014). This provides a continuous decrease in density, an increase in buoyancy and an accelerating ascent even with increasing loads of dense mantle cargo. Despite these recent advances in our understanding of kimberlite origins and transport (Wilson and Head, 2007; Sparks et al., 2006; Kavanagh and Sparks, 2009; Russell et al., 2012, 2013), many physical aspects of kimberlite ascent, and their time scales, remain unresolved.

Olivine is ubiquitous and volumetrically the most important constituent in kimberlite; it mainly derives from disaggregated mantle-derived peridotite or dunite (Clement et al., 1984; Mitchell, 1986; Arndt et al., 2006, 2010; Moss et al., 2010). Here, we describe a diverse array of textural features in kimberlitic olivine and build on previous studies of sizes, shapes and surfaces of kimberlitic olivine (e.g., Brett et al., 2009; Jones et al., 2014; Moss et al., 2009; Jerram et al., 2009). The majority of features within xenocrystic olivine result from syn- to post-entrainment processes operating during magma ascent, including: grain size and shape modification, healed and sealed fractures, late-stage crystallization of overgrowths, and very-late resurfacing and reshaping (rounding) of the olivine cargo by mechanical milling.

We establish the relative timing of each textural element and relate the individual textural features to specific physical and chemical processes attending kimberlite ascent. These observations, combined with modelling of the decompression-driven, tensile failure of xenoliths and olivine crystals, lead to an integrated model for the physical transport of kimberlite magmas. We propose that ascent via upward dyke propagation through cratonic mantle lithosphere operates as a *kimberlite factory*, whereby parental carbonatitic magmas are progressively converted to kimberlite (e.g., Russell et al., 2012, 2013; Bussweiler et al., 2015). The sequence of textural elements recorded by kimberlite-hosted olivine inform directly on the physical mechanisms, chemical conditions, and timescales of kimberlite ascent.

2. Previous studies of kimberlitic olivine

Olivine has been used as a means to constrain the origins, composition, transport, and eruption of kimberlite in numerous studies (Fedortchouk and Canil, 2004; Arndt et al., 2006, 2010; Kamenetsky et al., 2008; Brett et al., 2009; Jerram et al., 2009; Moss et al., 2010; Pilbeam et al., 2013; Jones et al., 2014; Bussweiler et al., 2015). Arndt et al. (2010) propose a three-fold classification of kimberlitic olivine, which we adopt here: (1) a dominant population of medium to coarse-grained (>1 mm), rounded to sub-rounded grains (Fig. 1A, B); (2) fine-grained (<1 mm) euhedral to subhedral olivine crystals (Fig. 1C, D); and (3) faceted, strain-free tablets (<0.01–1 mm) of olivine or neoblasts (Fig. 1E, F). Recent work has established that olivine in kimberlite has a continuous grain size distribution spanning <0.01 mm to 5 cm in diameter (e.g., Jerram et al., 2009; Moss et al., 2010). Olivine grain morphology gradually changes with grain size from euhedral (fine grained) to anhedral or rounded (coarse grained) (e.g., Sobolev et al., 2015).

Cores of olivine macrocrysts show intense internal microfracturing, undulose extinction, deformation bands, and commonly contain mineral inclusions (e.g., garnet, clinopyroxene) indicative of lower lithospheric mantle conditions (Reid et al., 1975; Kamenetsky et al., 2008; Bussweiler et al., 2015). The compositions of the cores also indicate a peridotitic mantle origin; they have high Ni contents (3000–4000 ppm NiO), low CaO (<1000 ppm) and varying Mg# (0.88–0.93; Griffin et al., 2003; Kamenetsky et al., 2008; Brett et al., 2009). Bussweiler et al. (2015) argue, on the basis of detailed chemical study of olivine cores, and the ubiquitous presence of peridotitic minerals (garnet, spinel, clinopyroxene), that kimberlites have traversed and sampled peridotitic mantle at all depths. Elevated Mg-rich (i.e. shallower, depleted mantle) core compositions tend to be more angular relative to more rounded, higher Fe content cores (i.e. deeper, fertile mantle). They ascribed these differences in xenocrystic olivine core shape to longer transit times offering greater opportunities for mineral dissolution.

The cores to all kimberlitic olivine commonly have thin (<150 μm), chemically distinct rims; the core-rim interface can also be marked by abundant mineral and fluid inclusions (Fig. 1; Kamenetsky et al., 2008; Brett et al., 2009; Arndt et al., 2010; Pilbeam et al., 2013). The rims are characterized by lower NiO, higher CaO contents and, commonly, a lower and narrower range of Mg# (Fedortchouk and Canil, 2004; Arndt et al., 2006; Kamenetsky et al., 2008; Brett et al., 2009; Bussweiler et al., 2015). The core to rim zoning suggests the rims are overgrowths representing new crystallization of the melt onto pre-existing xenocrystic cores of olivine (Fedortchouk and Canil, 2004; Arndt et al., 2006; Kamenetsky et al., 2008; Brett et al., 2009; Sobolev et al., 2015). The exterior margins of the olivine overgrowths commonly have an even thinner rim (~2 μm) characterized by higher forsterite (Fo_{96}) and CaO (<2 wt.%) contents and lower NiO (<1000–1500 ppm; Fedortchouk and Canil, 2004; Brett et al., 2009; Bussweiler et al., 2015). These compositions have been ascribed to changing oxidation conditions, perhaps due to elevated H_2O contents or co-crystallization of additional phases (e.g. chromite; Bussweiler et al., 2015).

Smaller (<50 μm), euhedral olivine crystals within the groundmass have similar compositions to the overgrowths suggesting that overgrowths and phenocrysts represent concomitant crystallization of the kimberlite melt (Fedortchouk and Canil, 2004; Arndt et al., 2006; Kamenetsky et al., 2008; Brett et al., 2009). The total volume of olivine crystallized during ascent is thought to vary between ~5–20% (Brett et al., 2009; Patterson et al., 2009; Arndt et al., 2010; Bussweiler et al., 2015) which is lower than original estimates (e.g., ~25%; Mitchell, 1986). Trace element compositions reported for olivine overgrowths and olivine phenocrysts show enrichment in Ca, Mn, Cr, Ti, Al, P, V, Sc, Nb, Ga and Zr, which is consistent with simultaneous olivine crystallization and orthopyroxene (Opx) dissolution (Bussweiler et al., 2015).

Deformation bands (Fig. 1E), undulose extinction, and sub-grain development (Fig. 1E, F) characterize many olivine xenocrysts. These strain indicators populate cores of olivine xenocrysts but are absent in olivine overgrowths and phenocrysts; this suggests that deformation predates xenolith entrainment (Arndt et al., 2010). At high temperature and in low stress environments, the highly strained portions of olivine will recrystallize or anneal on relatively short timescales (Mercier, 1979) to form tablet-shaped neoblasts. In kimberlite, the olivine neoblasts typically have compositions similar to peridotitic olivine, indicating they represent recrystallization of originally highly-strained xenocrysts (e.g., Arndt et al., 2006, 2010; Brett et al., 2009).

3. Sample suite

Our samples derive from hypabyssal kimberlite dykes from four pipes (A154N, A154S, A418, A21) at Diavik Diamond Mine (DDM), N.W.T, Canada (Brett et al., 2009; Moss et al., 2009) and from the Quaternary Igwisi Hills kimberlite volcanoes (IHV) in Tanzania (Reid et al., 1975; Dawson, 1994; Brown et al., 2012; Jones et al., 2014). Samples were selected on the basis of their young ages (54 Ma and 10 ka, respectively), their high olivine contents, and the relative absence of post-emplacement alteration (see Figs. 1–4). Diavik samples contain 40–50 vol.% olivine and have a groundmass of monticellite, apatite and oxides (perovskite, spinel-