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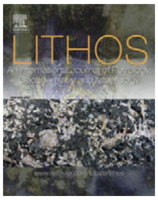

The olivine macrocryst problem: New insights from minor and trace element compositions of olivine from Lac de Gras kimberlites, Canada

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ABSTRACT

This study presents detailed petrographical and geochemical investigations on remarkably fresh olivines in kimberlites from the EKATI Diamond Mine™ located in the Tertiary/Cretaceous Lac de Gras kimberlite field within the Slave craton of Canada.

Olivine, constituting about 42 vol.% of the analyzed samples, can be divided into two textural groups: (i) *macrocrystic olivines*, >100 μm sub-rounded crystals and (ii) *groundmass olivines*, <100 μm subhedral crystals. Olivines from both populations define two distinct chemical trends; a "mantle trend" with angular cores, showing low Ca (<0.1 wt.% CaO) and high Ni (0.3–0.4 wt.% NiO) at varying Mg# (0.86–0.93), contrasts with a "melt trend" typified by thin (<100 μm) rims with increasing Ca (up to 1.0 wt.% CaO) and decreasing Ni (down to 0.1 wt.% NiO) contents at constant Mg# (~0.915). These findings are in agreement with recent studies suggesting that virtually all olivine is composed of xenocrystic (i.e. mantle-related) cores with phenocrystic (i.e. melt-related) overgrowths, thereby challenging the traditional view that the origin of kimberlitic olivine can be distinguished based on size and morphology.

The two main trends can be further resolved into sub-groups refining the crystallization history of olivine; the mantle trend indicates a multi-source origin that samples the layered lithosphere below the Slave craton, whereas the melt trend represents multi-stage crystallization comprising a differentiation trend starting at mantle conditions and a second trend controlled by the crystallization of additional phases (e.g. chromite) and changing magma conditions (e.g. oxidation). These trends are also seen in the concentrations of trace elements not routinely measured in olivine (e.g. Na, P, Ti, Co, Sc, Zr). Trace element mapping with LA-ICP-MS reveals the distribution of these elements within olivine grains. The trace element distribution between the two trends appears to be consistent with phenocrystic olivine overgrowths mainly originating from dissolved orthopyroxene, showing enrichment in Zr, Ga, Nb, Sc, V, P, Al, Ti, Cr, Ca and Mn in the melt trend.

In a sample of magmatic kimberlite from the Leslie pipe, the amount of xenocrystic and phenocrystic olivine is estimated to be around 23 vol.% and 19 vol.%, respectively. Subtraction of this xenocrystic olivine from the Leslie bulk composition, aimed at estimating the parental kimberlite melt, results in a minor decrease of Mg# (by about 0.01) and SiO_2 content (by about 3 wt.%), whereas CaO increases (by about 3 wt.%).

1. Introduction

Kimberlite is characterized by an inequigranular texture produced by the presence of larger crystals in a fine-grained matrix (Fig. 1) (Mitchell, 1986). As the origin of the larger crystals is unresolved, and could be either xenocrystic (i.e. mantle-derived) or phenocrystic (i.e. melt-derived), Clement et al. (1984) proposed the use of the non-genetic term "macrocrysts" for the larger crystal suite. Olivine constitutes by far the most abundant macrocryst phase (Clement et al., 1984). However, its genetic origin has proven difficult to determine, making the olivine macrocryst problem "one of the more controversial aspects of kimberlite petrology" (Mitchell, 1986).

The difficulty of unraveling the origin of olivine in kimberlite is in part due to its simple major element composition, which is mainly controlled by a solid solution between Mg-rich (forsterite) and Fe-rich (fayalite) end-members. Consequently, Mg# (Mg/(Mg + Fe)) is the single most efficient measure for the variation of olivine composition. Unfortunately, there is a large overlap in the Mg# for xenocrysts and presumed phenocrysts in kimberlites (Mitchell, 1986). This led to the assumption that olivine phenocrysts and xenocrysts in kimberlite can only be distinguished based on size and morphology of the crystals.

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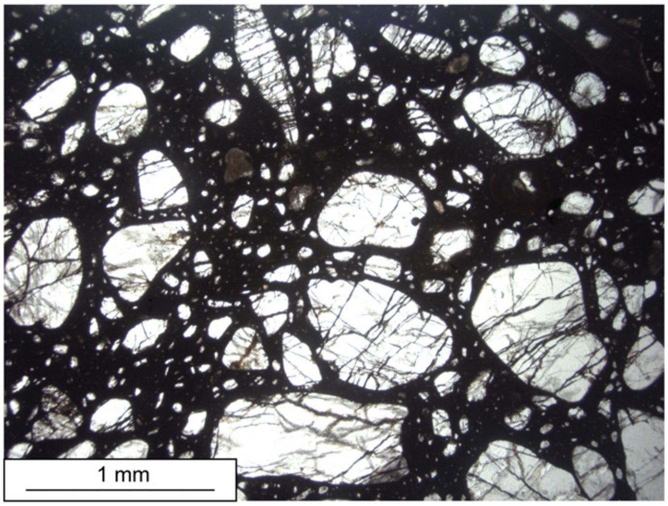

Fig. 1. Thin section photograph of magmatic kimberlite sample from Leslie, EKATI, displaying typical inequigranular texture produced by the presence of larger crystals (dominantly olivine, about 42 vol.%) in a fine-grained groundmass. Olivine occurs in different sizes and morphologies.

For over 30 years, a population of medium- to coarse-grained, subrounded to rounded olivine grains (macrocrysts) was ascribed a xenocrystic origin, whereas a second population of medium- to fine-grained (<500 μm), subhedral to euhedral olivine grains was believed to represent phenocrysts (Brett et al., 2009).

With the advance of new analytical technology, such as high-precision electron microprobe analysis (EPMA) using high sample currents, and laser-inductively coupled plasma-mass spectrometry (LA-ICP-MS), the minor and trace element composition of olivine became more accessible, and has resulted in a surge of new information on olivine geochemistry (Foley et al., 2013; Sobolev et al., 2005; Welsch et al., 2014). Due to its relatively simple mineral structure, olivine hosts a limited number of trace elements. Only few elements, predominantly the first row transition elements, have similar cation radii and/or charge to Mg^{2+} and Fe^{2+} allowing for the incorporation into olivine (Zanetti et al., 2004). However, the trace element geochemistry of olivine is also controlled by the extensive/intensive variables pressure, temperature and melt composition (P, T, and x) (De Hoog et al., 2010). This dependency on P, T, and x allows certain elements to be used as petrogenetic tracers. For instance, concentrations of Ni, Ca, Al, and Ti were found to be especially useful in the distinction of igneous from mantle olivines, with Mn and Cr being further potentially diagnostic elements (Foley et al., 2013; Prelevic and Foley, 2007; Sobolev et al., 2009).

The new analytical methods have prompted a series of new studies related to the olivine macrocryst problem (Arndt et al., 2006; Brett et al., 2009; Fedortchouk and Canil, 2004; Kamenetsky et al., 2008; Pilbeam et al., 2013). All of these studies reported the presence of melt-related overgrowths on olivines of both size populations, thereby challenging the traditional view that kimberlitic olivine can be distinguished into xenocrysts and phenocrysts based on size and morphology alone. Instead of a simple xenocrystic vs. phenocrystic distinction, a complex crystallization history involving entrainment of mantle olivine from different lithologies, resorption and recrystallization of such xenocrystic olivine, and heterogeneous crystallization onto the xenocrystic cores is envisaged. The discovery that virtually all olivines in kimberlite contain xenocrystic cores led to a drastic reduction of the estimated volume of olivine crystallized during transport, i.e. phenocrystic olivine, from about 25 vol.% to as low as ≤5 vol.% (Brett et al., 2009). Moreover, the inferred higher amount of xenocrystic olivine demanded a correction of previous estimates of primitive kimberlite melt compositions (Arndt et al., 2006; Brett et al., 2009).

Despite these recent findings, opinions on the origin of olivine in kimberlite still diverge. For example, Moore (2012) argues for a cognate, i.e. purely phenocrystic, origin of kimberlitic olivine, demonstrating that the olivine macrocryst problem is not yet resolved. Moreover, these recent findings are still to be satisfactorily reconciled with current models of kimberlite formation.

Our study comprises detailed petrographical and geochemical investigations on olivines from magmatic and volcaniclastic kimberlites from the EKATI Diamond Mine™ located in the Lac de Gras kimberlite field within the Slave Province, Northwest Territories, Canada. Major and minor element analyses by electron microprobe, and trace element analyses with LA-ICP-MS, including trace element mapping, reveal new insights into the complex crystallization history of olivine in Canadian kimberlites. Our results support a hybrid character of virtually all kimberlitic olivine and point to a genetic history that may be applicable to kimberlites worldwide.

2. Geological setting

The Slave craton is located in northwestern Canada, partially occupying the provinces Nunavut and the Northwest Territories, covering an elliptical area 510 km wide by 710 km long (Padgham, 1990). As an Archean craton, the Slave Province forms the northwestern part of the Canadian Shield (Kusky, 1989). In the west, south and east, the Slave craton is bounded by Proterozoic belts, these are the Wopmay Orogen, the Taltson Magmatic Zone, and the Thelon Front, respectively. To the north, the Slave craton is covered by younger sediments (Isachsen and Bowring, 1994). Current models describe the Slave Province as an Archean granite-greenstone formation which grew by tectonic accretion of a pre-3 Ga nucleus in the west with a Neoarchean juvenile arc in the east (Davis et al., 1996; Nowicki et al., 2004). Cratonization is assumed to have been completed by 2.5 Ga, and was followed by collisional events that formed the Paleoproterozoic Thelon–Taltson and Wopmay orogens. The Slave Province is classified as a type-3 kimberlite province as defined by Mitchell (1986) and hosts multiple kimberlite fields with various emplacement ages which span a large range from the Cambrian to the Eocene (Creaser et al., 2004; Heaman et al., 2003).

Studies on peridotitic mantle xenoliths from kimberlites have revealed a layered structure of the lithosphere below the central Slave craton (Gaul et al., 2000; Griffin et al., 1999; Helmstaedt, 2009; Menzies et al., 2004). A shallow (<145 km) ultra-depleted layer, consisting mainly of harzburgite, and a deeper (145–200 km) layer, dominated by lherzolite, were inferred. The shallow ultra-depleted layer is interpreted as an ancient oceanic or sub-arc mantle formed during terrane accretion, whereas the deeper layer is interpreted as a fossil plume head that rose from the lower mantle and underplated the existing ultra-depleted lithosphere, probably near 2.6 Ga (Griffin et al., 1999).

The Lac de Gras kimberlite field constitutes the central Tertiary/Cretaceous domain within the Slave Province, and occurs east of the inferred suture as a ca. 100 km by 200 km northwest-trending zone (Lockhart et al., 2004). The kimberlites occur as pipes, generally small features (2–12 ha) that rarely crop out at the surface (Fedortchouk and Canil, 2004). These pipes intrude the metamorphosed Archean sedimentary, volcanic, and plutonic rocks of the Slave craton, and are overlain by Quaternary glacial deposits associated with the Late Wisconsinan Ice Age (Nowicki et al., 2004). Up to the year 2004, more than 270 kimberlites have been discovered in the Lac de Gras kimberlite field (Lockhart et al., 2004). Kimberlite magmatism at Lac de Gras was potentially triggered by fast and complex subduction processes along the western margin of North America in the Late Cretaceous (Tappe et al., 2013).

The EKATI Diamond Mine™ (short: EKATI) is located within the Lac de Gras kimberlite field in the east-central portion of the Slave Province (Dyck et al., 2004). EKATI comprises a claim block of approximately 1800 km^2 including about 150 kimberlite occurrences (Nowicki et al., 2004). According to their petrographic and geochemical characteristics, EKATI kimberlites classify as Group 1 kimberlites, as typified by Smith