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Invited review article

Insights into kimberlite petrogenesis and mantle metasomatism from a review of the compositional zoning of olivine in kimberlites worldwide

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ABSTRACT

Olivine is the dominant component in kimberlites (~40–60 vol%), where it occurs as individual grains of variable size (>1 cm to <100 μm) of xenocrystic and magmatic origin. Understanding the processes governing its compositional variations will provide unique insights into the genesis and evolution of kimberlites. The results reviewed here include >2700 major and minor element analyses of olivine from 17 kimberlite localities from southern Africa, Canada, Greenland and Russia. These data show that the large majority of olivine grains in coherent kimberlites are compositionally zoned regardless of size and shape. The zonation typically includes a core of variable composition (e.g., $Mg\# = 100 \times Mg/(Mg + Fe) = 78–95$) that is overgrown by a rim characterised by relatively restricted Mg# (typically ≤1 “unit”; predominantly 88–92), decreasing Ni and Cr, and increasing Mn, Ca and Ti contents. One or more internal zones of variable composition occur between core and rim of some grains. The internal zones can be euhedral, diffuse or partially resorbed (i.e. embayments). Low-Ni, high Mg-Ca rinds (Mg# up to 96–98) commonly fringe olivine rims in fresh (i.e. minimally serpentinised) kimberlites.

A comparison between the compositions of olivine cores and olivine from mantle xenoliths (including megacrysts) entrained by kimberlites, demonstrates that olivine cores are xenocrysts derived from disaggregation of mantle wall-rocks. This interpretation is consistent with the inclusion of mantle phases (i.e., orthopyroxene, clinopyroxene, garnet and Cr-spinel) in olivine cores, and evidence of resorption (i.e. embayments) and abrasion (e.g., rounded shapes) of these cores. A variable proportion of olivine cores is sourced from the products of kimberlite metasomatism at mantle depths (e.g., sheared peridotites, megacrysts, ‘defertilised dunites’), which implies variable extent of kimberlite activity in the mantle before kimberlite emplacement at surface.

Olivine rims host inclusions of groundmass minerals (e.g., spinel, Mg-ilmenite, rutile), which requires a magmatic origin for the rims. With few exceptions (i.e., Benfontein; Udachnaya-East), olivine rims in each kimberlite locality, cluster (e.g., Kimberley) and, potentially field (e.g., Lac de Gras), form a single compositional trend. This suggests that kimberlites within the same cluster derive from similar parental melts and therefore sources, which is consistent with available radiogenic isotope results, and undergo similar crystallisation processes. Indistinguishable compositions of olivine rims in kimberlites from Lac de Gras that were emplaced as hypabyssal root-zones, dykes and volcaniclastic units, indicate that olivine crystallised during ascent, i.e. before different emplacement processes modified magma compositions. The implication is that the composition of (near-primitive) melt parental to olivine has minimal influence on kimberlite emplacement mechanism. Variations on the compositions of olivine rims in kimberlites from different areas suggest contribution from a range of local processes, such as variable source composition, olivine and spinel fractionation, assimilation of mantle material, CO_2 loss, melt oxidation, changing pressure and temperature conditions of crystallisation.

Based on their compositional and textural features, three types of internal zones can be distinguished: 1) euhedral early liquidus olivine with higher Mg# and Ni than rims and hosting inclusions of magmatic chromite; 2) diffusional zones with compositions intermediate between those of cores and rims; 3) zones exhibiting resorption features that may be products of earlier kimberlite metasomatism at mantle depths.

Olivine grains represent unique capsules that provide a potentially complete record of the evolution of kimberlite systems. Olivine cores store information on the mantle column entrained by kimberlites, including clues to early kimberlite metasomatism. Internal zones can show the effects of mantle metasomatism and/or record early kimberlite crystallisation at mantle depths. Rims (and rinds) testify to the complex interplay of different processes during ascent and emplacement of kimberlite magmas.

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Contents

1. Introduction

Olivine is the most abundant mineral constituent of the upper mantle and a liquidus phase in the vast majority of mantle-derived magmas. Coherent kimberlites(as defined in Scott Smith et al., 2013) typically comprise between ~40 and 60 vol% olivine (Brett et al., 2009; Kamenetsky et al., 2008; Mitchell, 1986; Moss et al., 2010; Soltys et al., 2018a). Kimberlites are rare, small-volume igneous rocks poor in silica and rich in volatiles ($CO_2 \pm H_2O$) that originate within the diamond stability field (>150 km). They occur as volcanic pipes and hypabyssal intrusions. Kimberlites are hybrid rocks that comprise abundant mantle and deep crustal fragments, including large olivine grains, in a groundmass of carbonates (calcite ± dolomite), serpentine, olivine, monticellite, spinel, perovskite, Mg-ilmenite, apatite and phlogopite.

High Mg contents and inclusions of various groundmass phases in olivine rims indicate that olivine is a primary liquidus phase in kimberlite melts that crystallises (or re-equilibrates) throughout most of the crystallisation sequence of kimberlites (e.g., Bussweiler et al., 2015; Kamenetsky et al., 2008; Mitchell, 2008). This implies that olivine can provide unique insights into the genesis and evolution of kimberlites during ascent from the mantle to emplacement in the crust. In addition, olivine has similar specific gravity and hydrodynamic behaviour to diamonds and, due to its abundance, can be employed to estimate diamond distribution in kimberlites (e.g., Harvey et al., 2013; Scott-Smith and Smith, 2009).

Improved micro-analytical techniques and detailed studies of olivine in worldwide kimberlites in recent years have provided a wealth of information on olivine compositions and generated new ideas pertaining to its genesis, with profound implications for kimberlite petrogenesis. For example, recognition that a larger component of kimberlite rocks is composed of olivine xenocrysts has resulted in new models that describe parental kimberlite melts as carbonate to silico carbonate in composition rather than ultramafic magmas, as previously thought (Abersteiner et al., 2017; Brett et al., 2015; Giuliani et al., 2017; Kamenetsky et al., 2008, 2014a, 2014b; Nielsen and Sand, 2008; Patterson et al., 2009; Pilbeam et al., 2013; Russell et al., 2012; Soltys et al., 2018). However, geochemical studies of olivine in kimberlites have so far concentrated on individual localities, with limited comparisons of olivine in kimberlites on a regional and global scale.

This contribution reviews the major and minor element compositional variations of olivine in kimberlites worldwide (Fig. 1), with a specific focus on the origin of its mineral chemical zoning (i.e. occurrence of discrete zones within the same grain, which are compositionally distinct; Fig. 2). Kimberlitic olivine in each locality typically includes a *core* of variable composition and a *rim* characterised by relatively homogeneous Mg# [i.e. $= 100 \times Mg/(Mg + Fe)$] and variable minor element composition. Additional discrete layers intermediate between core and rim have been increasingly identified (e.g., Cordier et al., 2015; Howarth and Taylor, 2016; Sobolev et al., 2015). After a concise summary of the early (i.e. 70's and 80's) studies of kimberlitic olivine, I provide an overview of the textural features of olivine garnered primarily from scanning electron microscope (SEM), back-scattered electron (BSE) observations. These results combined with those from selected electron microprobe (EMP) studies, are then employed to generate a filter to discriminate between analyses of olivine cores and rims that have been incompletely reported or labelled differently in the original studies. This approach permits comparison of different datasets and assemblage of a unifying global database. The review includes compositional results for olivine in 17 kimberlite localities from southern Africa, Canada, Greenland and Russia (Table 1; Fig. 1), including multiple samples from the same kimberlite body (e.g., Benfontein), cluster (e.g., Kimberley) or field (i.e., Lac de Gras). This extensive dataset (>2700 analyses) is utilised to address the formation of olivine cores, constrain factors controlling the compositional evolution of rims, and help understand the origin of small olivine grains in the kimberlite groundmass, thus improving kimberlite petrogenetic models.

2. Olivine in kimberlites

Although the crystal size distribution of olivine in kimberlites is continuous (Moore, 1988; Moss et al., 2010), two types of olivine are generally identified based on size and texture. *Macrocrysts* include relatively large grains (>0.5 mm; more commonly >1.0 mm) with anhedral or rounded shapes, which exhibit evidence of significant strain (e.g., undulose extinction, kink banding) and are pervasively fractured (Fig. 3a, b) (e.g., Mitchell, 1986; Moore, 1988). *Phenocrysts* (and *micro-phenocrysts*) show euhedral to subhedral shapes, less common undulose extinction, and size ranges from ~1.0 mm to <100 μm (i.e. similar size