

Origins of Olivine in Kimberlite: Phenocryst or Imposter?

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Introduction

Kimberlite is generally understood to host two populations of olivine that are distinguished on the basis of grain size and morphology (e.g. Mitchell, 1970); the populations are described genetically as xenocrysts and phenocrysts. Olivine xenocrysts have been ascribed to disaggregated mantle rocks (e.g. Boyd, 1967) whereas the smaller, euhedral olivine crystals are presumed entirely cognate to the kimberlite melt (e.g. Mitchell, 1986). There have been several recent studies on zoning patterns in phenocystic olivine in kimberlite that have thrown doubt on the actual origins of the smaller olivine crystals (e.g. Kamenetsky et al., 2008). These authors proposed the terms olivine-I for macrocystic (large, rounded) and olivine-II for small euhedral crystals in order to avoid genetic connotations.

Here, we report on petrographic and geochemical studies of olivine in kimberlite from the Diavik Diamond Mine, N.W.T, Canada, with the intent of clarifying the origins of kimberlitic olivine. For the purposes of our investigation we have adopted the Kamenetsky et al. (2008) terminology. Our study elucidates the nature and origins of the textural and chemical zonation that characterize *both* populations of olivine: macrocrysts (olivine-I) and euhedral crystals (olivine-II). Specifically, we find that both olivine-I and olivine-II feature chemically distinct overgrowths resulting from magmatic crystallization on pre-existing olivine xenocrysts. These results suggest that the total volume of olivine crystallized during transport is substantially lower (<5%) than previously proposed (~25%) (e.g. Clement, 1982). These relationships have implications for: i) the time-scales and heat budgets of kimberlite during transport and eruption, ii) the relationship between olivine crystallization and orthopyroxene dissolution (e.g. Mitchell, 1986), iii) the transport properties of kimberlite, and iv) the composition of the kimberlite melt (e.g. Price et al., 2001).

Sample suite

Data for this study focuses on olivine from coherent intrusive kimberlite dykes (HK) associated with three kimberlite pipes (A154 north, A154 south and A21) and two volcanioclastic kimberlite units from the A154 north pipe, Diavik Diamond Mine, N.W.T. Canada. The electron microprobe study consisted of analyses of olivine-I cores (N=84), olivine-I rims (N=35), olivine-II cores (N=98) and olivine-II rims (N=103) for a total of 182 crystals analysed.

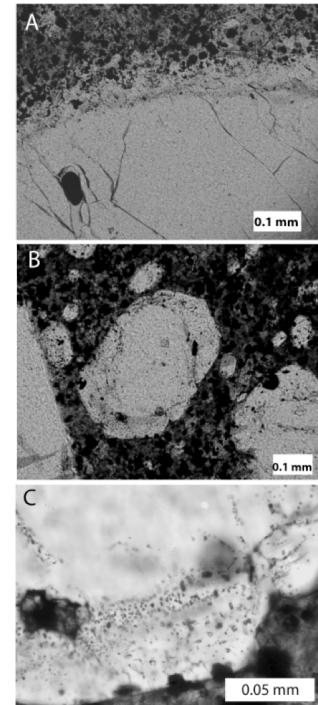


Figure 1. Photomicrographs of olivine in kimberlite from Diavik pipes, showing: a) overgrowth on olivine macrocryst (olivine-I) defined by increase in concentration of inclusions, b) phenocryst-like olivine (olivine-II) showing euhedral overgrowth on rounded core, c) detailed view of overgrowth olivine showing abundant fluid and mineral inclusions.

Petrographic & geochemical description of olivine

Crystallization overgrowths are identified petrographically on both olivine-I (Fig. 1a) and olivine-II (Fig. 1b) on the basis of mineral and/or fluid inclusions. Cores of both types of olivine are homogeneous and do not contain inclusions. However, numerous, small (< 5 µm) spherical fluid inclusions often mark the interface between the core-overgrowth boundaries. The fluid inclusions occur as dark bands at the core-overgrowth boundary (Fig. 1a,b) and commonly define discrete planes of inclusions (Fig. 1c). Mineral inclusions are smaller at the interface and increase in size towards the edge of the crystal. Mineral inclusions include Mg-chromites, rutile and perovskite.

The chemical compositions of the cores of olivine-I and olivine-II are within analytical error. Core compositions have an average forsterite content of 91.3 and average NiO content of 3450 ppm (Fig. 2). Similarly, the overgrowths (Olivine-I and - II) have identical ranges in chemical composition but are chemically distinct from their cores (Fig. 2). Nickel is the best chemical discriminator between mineral cores

and overgrowths. The cores of all olivine grains have NiO contents that are generally >3000 ppm, whereas the olivine overgrowths feature substantially lower nickel contents (<2400 ppm NiO).

Overgrowths on the rounded macrocrystic olivine crystals (olivine-I) are present as thin rims (typically < 50 µm) and do not appreciably change the overall shape of the individual grain (Fig. 1a). In contrast, the subhedral to euhedral shape of the smaller olivine grains (i.e., olivine-II) is largely due to the overgrowths; in this case the rims are thick enough (100 µm) to change the shape of the originally rounded grain to euhedral (Fig. 1b).

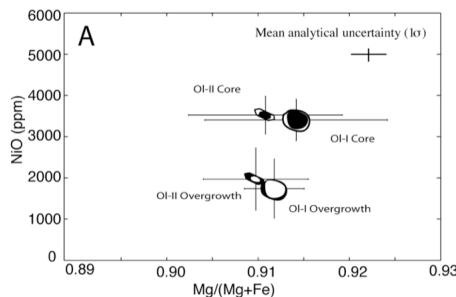


Figure 2. Electron microprobe analyses of olivine from Diavik kimberlite plotted as mean NiO content (ppm) vs. mean Fo-content for olivine-I and olivine-II cores and rims (see text). Crosses show variance in each sample set (1s) and are compared to mean analytical uncertainty (1s; upper right).

Origin of olivine

The concentration of nickel in olivine in the upper mantle is considered to be relatively constant (e.g. Griffin et al., 1992). Most studies of mantle olivine report NiO contents in excess of 3000 ppm; there are no studies reporting mantle olivine with nickel contents less than 2400 ppm (e.g. Arndt et al., 2006). As discussed above, the cores of olivine-I and II grains in our kimberlite have identical major and trace element compositions (Fig. 2). The trace element contents, especially NiO, of the olivine-I and II cores closely resemble concentrations observed in olivine from mantle xenoliths. The simplest interpretation of these data is that cores of all olivine grains have the same origin, that is, they derive from mantle peridotite.

In contrast, overgrowths on olivine-I and olivine-II are marked by the presence of mineral/fluid inclusions and associated with a major drop in NiO content. Kamenetsky et al.'s (2008) study of euhedral olivine in kimberlite also showed a marked decrease in NiO contents in the rims of olivine grains relative to their cores. In our study, overgrowths on olivine-I and olivine-II have the same major and trace element signatures and we take this as evidence that they have the same origin. Furthermore, the low NiO contents (< 2400 ppm) in the olivine overgrowths are inconsistent with a mantle source suggesting that they result from magmatic crystallization of olivine onto pre-existing xenocrystic olivine.

In summary, we observe texturally and chemically distinct overgrowths on olivine-I (i.e. macrocrysts) and olivine-II (i.e. phenocrysts). The larger grains remain rounded in shape (Fig. 1a) because

the overgrowths are thin relative to the diameter of the original olivine crystal. The smaller olivine grains are commonly subhedral to euhedral in shape (i.e. idiomorphic) because the thickness of the overgrowths is sufficient to change the shape of the original grain (Fig. 1b). The cores of most olivine grains having discernible overgrowths are rounded to sub-rounded regardless of the size of the present olivine grain. Our analysis shows that overgrowths exist on all morphologies and sizes of olivine in kimberlite; there is little evidence to support homogeneous nucleation of olivine in kimberlite (i.e. true phenocrysts). Rather the smaller idiomorphic olivine population found in kimberlite results from heterogeneous crystallization of olivine onto activated surfaces offered by pre-existing, rounded, smaller (< 1 mm) xenocrysts of olivine. If all olivine crystallization is heterogeneous, then the amount of olivine that crystallized during transport and eruption has been greatly overestimated. Below we model the volumetric consequences of heterogeneous crystallization of olivine in kimberlite.

Heterogeneous crystallization model

We consider the growth of spherical crystals from a melt. The advantage of heterogeneous crystallization of olivine onto pre-existing surfaces is that the surface energies are small relative to the energetics driving new crystallization in response to changes in temperature, pressure or fluid content. Once crystals reach a critical size, essentially all of the Gibbs free energy behind crystallization (i.e. Affinity) is reduced by continued crystallization on the available surfaces rather than dissipated through new nucleation. In such regimes, the long term growth rate for crystal i can be treated as proportional to the inverse of its radius square root ($r_i^{-0.5}$, Tiller, 1991). This implies that the final (observed) crystal size (r_i^f) can be related to the original crystal size (r_i^o) by:

$$r_i^f = r_i^o + \frac{\kappa}{\sqrt{r_i^o}} \quad (1)$$

where κ is an unknown constant for that system and r_i^o is the unknown initial radius (xenocryst). The total volume of magmatic olivine (V^x) for a system is found by integration from the initial surface (xenocryst radius) to the final surface area of the crystal:

$$V^x = \int_{r_i^o}^{r_i^f} 4\pi \sum r^2 dr \quad (2)$$

Mass balance relationships between melt, olivine and the rock (assuming negligible ΔV of crystallization) for the system requires:

$$V^x = M^x \cdot (V^f - V^o + \frac{(1-F)V^f}{F}) \quad (3)$$

where M^x is the melt fraction of the original melt that crystallizes olivine, and F is the fraction of olivine in the final system. The superscripts on V denote the volumes of: original olivine xenocrysts (o), crystallization as overgrowths (x), and the observed olivine (f ; final). Equations 1-3 comprise a determined system of non-linear equations, which can be solved



for estimates of the constant, κ , and the original radius of each crystal before crystallization.

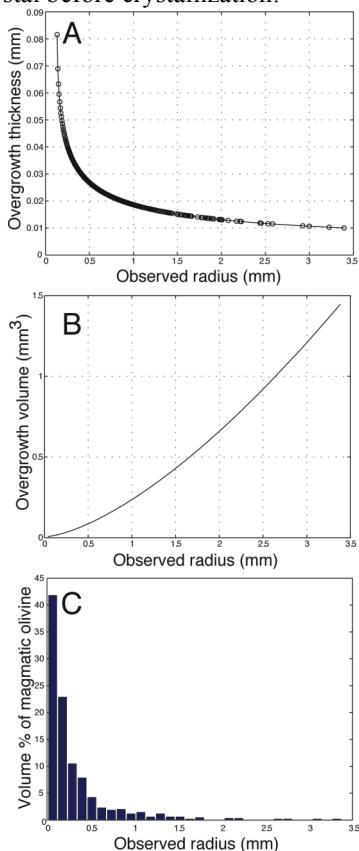


Figure 3. Model for heterogeneous crystallization of olivine on pre-existing olivine xenocrysts in kimberlite and showing: a) model crystallization plotted as observed crystal size vs. thickness of overgrowth; b) observed crystal size vs. calculated overgrowth volume; and c) a histogram of volume % of new crystallization vs. observed crystal size.

Results and Discussion

As input for the problem we used the olivine grain size distribution for a sample of kimberlite from the Diavik pipes, NWT (A154N_01; Moss et al., *this volume*). Results presented here are for data collected from a polished slab of kimberlite and include all olivines in the size range 0.1 to 3.4 mm radius. The sample comprises 37% olivine by volume, where 13 % of the observed olivine crystals are less than 1mm, 60 % of the rock is unresolved matrix, and 2 % are other xenocrysts and xenoliths (e.g. garnet). A model grain size distribution was created by converting the area of each measured particle ($n=718$) to a circle of equivalent area. Model results depend on the melt fraction (M^x) used. We match the observed thicknesses of overgrowths best using a value of $M^x \sim 0.02$; values of $M^x > 0.05$ predict overgrowths $> 100 \mu\text{m}$ which is inconsistent with observation.

These results indicate that there is much less olivine crystallization than previously documented. Olivine crystallization volumes calculated using this model imply 1.3% of the whole rock (matrix + olivine) is magmatic olivine, and that the original macrocryst population initially comprises 35% of the system verses 36.3 %. This is in contrast to previous estimates of modal magmatic olivine, that are on the order of

~25% (Scott-Smith 1996). Smaller crystals ($< 0.5 \text{ mm}$) are predicted to have rims of up to $90 \mu\text{m}$ thickness; whereas larger macrocrysts have very thin ($< 10 \mu\text{m}$) overgrowths (Fig. 3a). Although individual large crystals have larger volumes of magmatic olivine than do smaller crystals (Fig. 3b), magmatic olivine is volumetrically concentrated on small crystal sizes (Fig. 3c) because there are many more small crystals ($N > 618$) than large crystals ($N < 100$). The calculated κ value is $1.84E-2$.

Our model suggests there is little olivine crystallization during transport. This result has consequences for heat budgets in kimberlite because the heats of crystallization from olivine are significantly reduced. This will affect the capacity of kimberlite to assimilate other mantle xenocrysts (i.e. opx, garnet). Xenocrystic olivine is increased in total volume, changing the transport properties of kimberlite by increasing the systems bulk viscosity. Lastly, if the objective is to use the properties of *phenocrystic* olivine to constrain kimberlite melt chemistry then care must be taken to recognize, isolate and analyse true magmatic overgrowths rather than xenocrystic material.

Acknowledgements

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