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THE CARBONATITIC CHARACTER OF KIMBERLITE MAGMA

Patterson*, M.V. and Francis, D.

McGill University, Montreal, Quebec, Canada

ABSTRACT

Although the composition of primary kimberlite magma has been the subject of much debate, their true nature remains enigmatic. Recent research on kimberlite has shown that carbonate is an essential component in kimberlite magmas and that although olivine is an ubiquitous phase in kimberlite, the vast majority of it is sourced from disaggregated cratonic mantle and therefore xenocrystic. If olivine in kimberlite is considered mainly xenocrystic, the composition of kimberlite magma can be estimated by the removal of a cratonic mantle component based on the modal abundance of olivine. Such estimates for the Nikos kimberlite result in magma compositions that are carbonate rich (~30 wt% CO_2) and have low Mg# (~73.5). Olivine in kimberlite can also exhibit rare phenocrystic rims on xenocrystic cores that have Fe-rich compositions (Fo_{87-89}), variable Ni content. Using Fe/Mg partitioning coefficients between liquid and olivine for carbonate rich magma the Mg# from which the phenocrystic rims crystallized is ~ 73.5, this agreement indicates that the removal of a cratonic mantle component from kimberlite results in good estimates of kimberlite magma.

INTRODUCTION

Francis and Patterson (2009) demonstrated that magmatic carbonate plays an essential role in the petrogenesis of alkaline ultramafic rocks. Although these magmas owe their origin to carbonate rich melts rising from the asthenosphere, their compositions reflect the lithospheric mantle they have consumed. Patterson et al. (2009) demonstrated that the compositional variation in the Foxtrot kimberlites in Quebec is best explained by mixing between a carbonate rich liquid and harzburgite mantle in the form of xenocrystic olivine and assimilated orthopyroxene. The xenocrystic nature of olivine in the Slave kimberlite province has been demonstrated (Brett et

al., 2009) with Ni- and Mg-poor phenocrystic rims account for only 10% of the 50-70% olivine in the Lac de Gras kimberlites. Olivine in West Greenland kimberlite has also been ascribed to the entrainment from lithospheric mantle (Arndt et al., 2010). Tappe et al. (2011) concluded that the compositional variation observed in carbonatite/aillikite/kimberlite rocks of West Greenland is not simply a result of varying degrees of partial melting, but reflects the interaction of a carbonate rich parental magma derived from the sublithospheric mantle with cratonic lithosphere. The foregoing demonstrates that studies of many kimberlite suites all indicate that the majority of olivine in kimberlite is xenocrystic and therefore has little relationship to kimberlite primary magmas. If olivine is viewed as xenocrystic, estimates of primary kimberlite magma compositions have much lower Mg and Si contents and are much more carbonate rich than previous estimates. The existence of phenocrystic overgrowths on xenocrystic olivine, however, provides further constraints on the carbonate rich primary kimberlite magma. In this paper, we use the composition of the phenocrystic rims on olivine to constrain the Fe/Mg systematics of the carbonate rich magmas for producing kimberlite.

RESULTS

Although olivine in kimberlite is primarily xenocrystic, rare over growths of phenocrystic olivine have been observed on cores that exhibit similar compositions to that of the xenocrystic olivine (i.e. Lac de Gras kimberlite – Brett et al., 2009). Similar rims of phenocrystic olivine are observed in a suite of kimberlite samples from the Nikos kimberlite from Somerset Island. Although much of the phenocrystic olivine rim is altered, the phenocrystic habit of the olivine can still be observed and varies from euhedral to subhedral. The xenocrystic core shape are variably rounded or irregular and the shape exhibited by
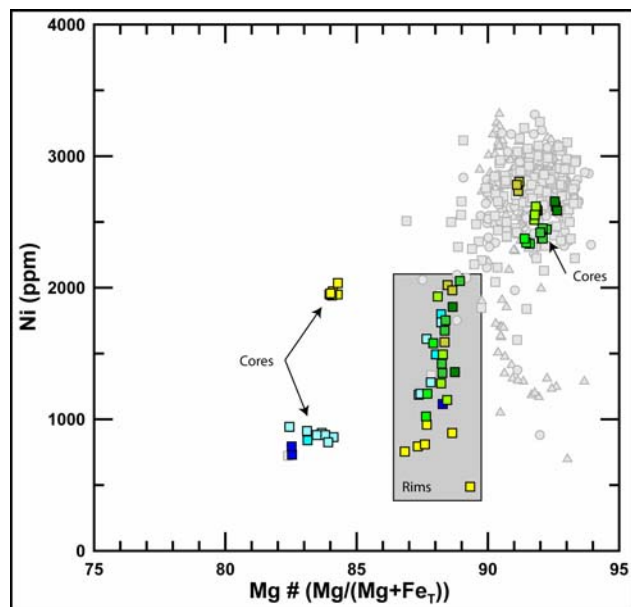
Figure 1: Ni versus Mg# plot of olivine xenocrystic core and phenocrystic rim compositions (colored squares, cores and rims as labeled). Light grey symbols are representative olivine analyses typically found in kimberlite.

the overgrowth does not appear to reflect the shape of the core, however, alteration makes it difficult to compare the two with certainty. Although fresh olivine in the rims are typically <100 µm wide, the altered portion was likely phenocrystic as well, thus the rims may be 100's of µm.

EMP analysis of kimberlite olivine rims and cores reveal that there are at least three different varieties of olivine cores (Figure 1). The majority of olivine cores fall within the field of xenocrystic olivine found in kimberlite (Ni ~ 2800±400 ppm and ~Fo_{90-94}). There is variation between different xenocrystic cores, however, individual cores have homogenous compositions. Although rare, the other two varieties of olivine cores both have much lower forsterite contents (82-84) than the predominant xenocrystics, but are distinct in terms of Ni(~ 2000 and <1000 ppm respectively). The phenocrystic rims have similar Fo contents (87-89), regardless of their respective core composition (Figure 2), but have exhibit considerable variation in Ni contents (<1000-2000 ppm). Despite this variability, Ni systematically decreases outward in the phenocrystic rims on xenocrystic cores, however the systematics of Ni contents in rims on the low Fo cores is uncertain (Figure 2).

DISCUSSION

The observed rims are interpreted to be phenocrystic over growths on xenocrystic olivine, thus providing information on the composition of kimberlite liquids. Although the rims are rare and grow on chemically varied cores, they exhibit remarkable homogeneity in terms of Fe and Mg, typically Fo_{88}. The $K_{D(Fe/Mg)}$ partitioning coefficient for magmatic olivine is robust for basaltic magmatic systems, however, its value in carbonate rich magmas is less well constrained. A KD 0.3±0.3 (Roeder & Emslie, 1970) implies that the phenocrystic rims crystallized from a magma whose Mg# ranged from 67-71 (assuming total ferrous Fe). Estimates for Fe/Mg partitioning between olivine and carbonate rich magmas, however, range from 0.4 for kimberlite melts to 0.6 for carbonate melts (Girnis et al., 2005). Assuming $K_{D(Fe/Mg)}$ of 0.4, the Fo_{87-89} rims could crystallize from Mg# 73-77 magma. The partitioning of Ni between carbonate rich magmas and olivine has been estimated to be ~20 at 1100-1200 °C (Sweeney et al., 1995), therefore the 1000-2000 ppm range in Ni in the olivine phenocrystic rims indicates a magma with a low Ni content, ~ 50-100 ppm.

The rims investigated in this study come from the Nikos kimberlite and therefore the estimated magma composition for the Nikos is used in comparison to the phenocrystic rims. The composition of kimberlite parental magma can be estimated by the mathematical removal of a harzburgite mantle component from kimberlite whole-rock compositions. Although the amount of harzburgite composition removed must be constrained by the modal abundance of olivine because the associated orthopyroxene has apparently been assimilated. The composition estimated by this method for the Nikos kimberlite is; SiO_2 ~ 12 wt%, FeO ~ 8 wt% MgO ~ 12 wt%, CaO ~ 31 wt%, CO_2 ~ 30 wt%, and Mg# ~ 73.5. Assuming an average composition of the rims (Fo_{88}), a $K_{D(Fe/Mg)}$ of 0.37 would satisfy a magma composition of Mg# ~ 73.5.

The constant forsterite content of the rims over a 1000 ppm variation in Ni, is difficult to explain with simple crystal fractionation models. Although Ni behavior in the phenocrystic rims on low Fo cores is uncertain, Ni contents systematically decrease toward the outer edges
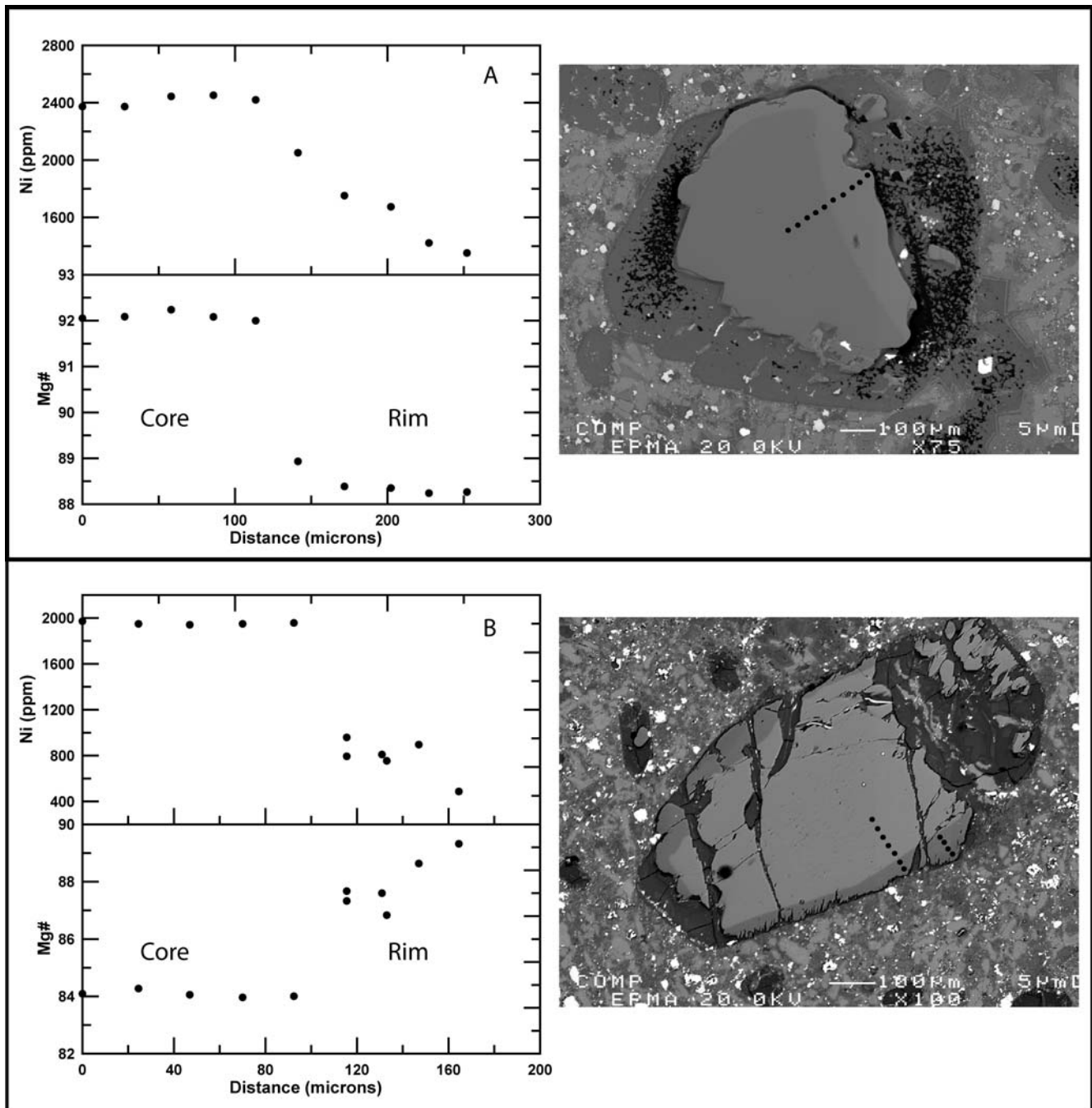
Figure 2: Plot of Ni and Mg# in profile across phenocrystic rim with backscatter image for comparision. A: normally zoned phenocrystic rim with high Ni and Mg# values in core, whereas rims have low Ni and Mg# values. B: reversed zoned phenocrystic rim that exhibit higher Ni and lower Mg# cores compared to phenocrystic rims.

of the phenocrystic rims on the xenocrystic cores. Furthermore, the relatively constant Fo of the phenocrystic rims over the systematically decreasing range of Ni presents a dilemma. This dilemma may simply be the result of a boundary layer being generated as the phenocrystic rims are crystallizing, however the rarity of the phenocrystic rims and turbulent nature of kimberlite magmas suggests that this is unlikely to occur. Ni diffusion from the high Ni cores into the phenocrystic rims is also a possible process to produce this profile,

however recent studies indicate that Fe/Mg and Ni have similar diffusion rates (Qian et al., 2010). The elemental profiles exhibited by the phenocrystic rims likely represents a combination of the above process, however, suggests that Ni and Fe/Mg are not diffusing at equal rates.

Orthopyroxene is largely absent from kimberlite petrology, assimilation of orthopyroxene in kimberlite magmas has long been proposed as the mechanism to account for its absents. Assimilation of orthopyroxene at first glance is at odds with the xenocrystic nature of olivine in kimberlite, since the assimilation of orthopyroxene by a carbonate rich magma under mantle conditions should facilitate olivine crystallization:

$$MgSiO_3 \text{ (s)} + MgCa(CO_3)_2 \text{ (m)}$$
$$\Leftrightarrow Mg_2SiO_4 \text{ (s)} + CaCO_3 \text{ (m)} + CO_2 \text{ (v)}$$
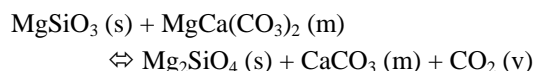
This reaction may explain many of the attributes of kimberlite; the lack of orthopyroxene in kimberlite, the dominance of calcite in kimberlite groundmass mineralogy, the assumed disaggregation of cratonic mantle and the volatile phase that is thought to drive the rapid eruption of kimberlite. Mantle-derived xenoliths in kimberlite are primarily harzburgite, therefore the macrocryst suite should contain significant amounts (~20%) of orthopyroxene if the olivine xenocrysts are derived from such xenoliths. This missing orthopyroxene was likely preferentially dissolved since experimental studies have determined that orthopyroxene stability is much reduced in hydrous CO_2 rich magmas (Eggler, 1973). Preferential dissolution of orthopyroxene also provides a process for the disaggregation of cratonic mantle and the crystallization of phenocrystic olivine.

The Ni contents of the calculated Nikos magma are virtually zero, however, caution must be used when interpreting this result given the mathematical technique used. Harzburgitic orthopyroxene (GEOROC database) have an average Ni content of ~ 700 ppm, much lower than that of coexisting olivine. The assimilation of orthopyroxene by a carbonate rich liquid would essentially assimilate all of the Ni and dilute that content depending on ratio of liquid to orthopyroxene. To produce

the very low Ni contents estimated by the $K_{D(Ni)}$ between carbonate rich liquids and olivine (50-100 ppm), the ratio of liquid must be high compared to orthopyroxene.

CONCLUSIONS

Constraining the composition of primary kimberlite magma is difficult due to kimberlite being mixtures of asthenospheric liquids and cratonic mantle, however, the carbonate rich nature of the asthenospheric liquid has been demonstrated from several suites of kimberlite. The xenocrystic nature of olivine in kimberlite allows a first order estimate of the primary magma by removal of a cratonic mantle component. For the Nikos kimberlite, the composition of the parental magma is CO_2 rich (~30 wt%), very poor in MgO and SiO_2 (12 wt% respectively), and has a Mg# ~73.5. The phenocrystic overgrowths on olivine provide robust compositional constraints on the Fe/Mg characteristics of primary kimberlite magma and result in a similar Mg# of 73 for the Nikos kimberlite. Although the importance of carbonate in the petrogenesis of kimberlite has been previously demonstrated, the assimilation of orthopyroxene is dependant on the carbonate rich asthenospheric liquid. The similarity between the Mg# of the calculated magma composition and the Mg# result utilizing the Fe/Mg partitioning of carbonate rich mantle melts from the phenocrystic rims on olivine, indicates that the calculated magma composition is a good constraint on primary kimberlite magma.

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