# Kimberlite: Magmas or Mixtures?

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**Introduction**

Although the exploration for diamonds has generated intense interest in kimberlites, their heterogeneous, brecciated and altered nature has discouraged the use of whole rock chemistry in diamond exploration and petrogenetic studies. Hypabyssal (i.e. coherent) kimberlites are, however, characterized by igneous textures and a low abundance of crustal xenoliths, and consequently offer insight into the compositions of kimberlite magmas and the nature of their mantle source. To pursue this avenue of research, we have undertaken a systematic analysis of hypabyssal kimberlite dykes from the Foxtrot Kimberlite Field in Northern Quebec, Canada. The results of this study confirm that the whole rock compositions of hypabyssal kimberlite not only provides constraints on the nature of kimberlite magma and their mantle source, but also provide information on the diamond potential of that source.

**Results**

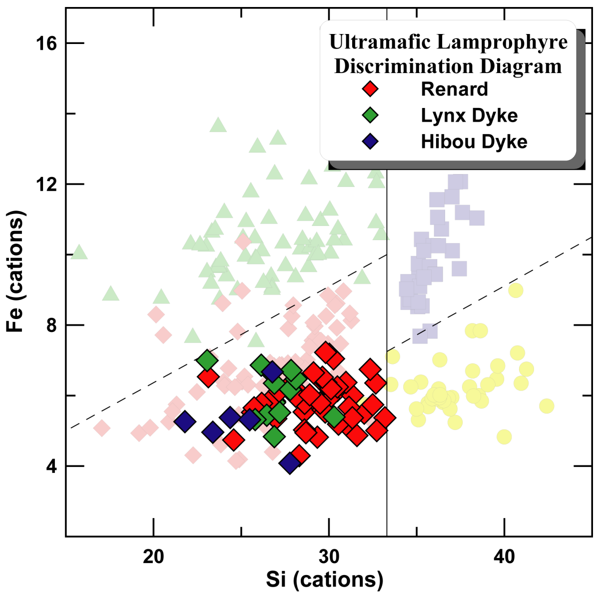


**Figure 1: Foxtrot kimberlite superimposed over global dataset of ultra-mafic lamprophyres. (green triangle – aillikites; blue squares – meimechite; yellow circles – olivine lamproite; red triangles – group I kimberlite).**

The Foxtrot kimberlites include the Renard kimberlite pipes that extend ~2 km along a north-west trend, and contain coherent dykes whose composition and petrology correspond to Group I kimberlites. Kimberlite dyke systems also occur in the Foxtrot Field, intruding the country rock surrounding the Renard pipes. The Lynx dyke system is ~2.5 km to the west of the Renard cluster, with a similar orientation and has been encountered discontinuously in drill core for ~4 km. The Hibou dyke system has a west-north-west strike and is situated north of the Renard cluster. Geochemical analyses of these dykes indicate that they also correspond to Group I kimberlite. A trench

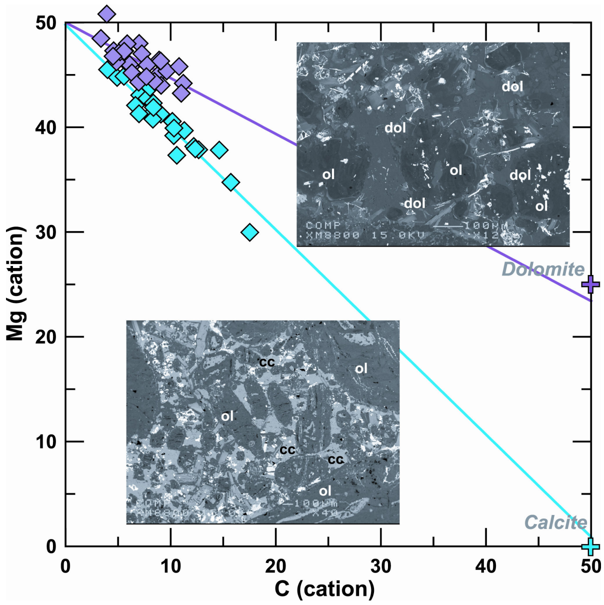


**Figure 2: Dolomite and calcite trends, backscatter images showing typical morphologies of carbonates in their respective trends.**

transect that the dyke is laterally zoned, with a distinct increase in both modal olivine and in the maximum olivine grain size from the margins towards the center. Modal olivine abundance is positively correlated with whole rock Mg# in the Foxtrot dykes in general (Figure 5 – inset). The Group I kimberlite affinity of these dykes is best demonstrated in a cation plot of Fe versus Si, in which they cluster with a larger global data set of Group I kimberlites (Figure 1). The Foxtrot Group I kimberlite dykes can be further subdivided into calcitic and dolomitic subtypes on the basis of their dominant groundmass carbonate mineral. The two kimberlite subtypes can also be recognized in cation plots of Mg versus C, in which two trends are apparent, one toward calcite and the other toward dolomite (Figure 2).

Olivine and carbonate together comprise 60 to 95% of the Foxtrot hypabyssal kimberlite dykes and the variation in their relative abundance is responsible for the anti-correlation between MgO (35-20 wt %) and $CO_2$ (1-16 wt %) in the whole rock chemistry of the kimberlites. Olivine is a ubiquitous phase in the Foxtrot hypabyssal dyke rocks (35 to 75%), occurring as ovoid to subhedral, variably serpentinized crystals ranging from 0.1 mm to 10 mm in grain size. Although the grain size distribution of olivine in the Foxtrot dyke rocks at first appears to be bimodal, a grain size analysis of over 800 olivine crystals indicates a normal distribution, best fit with an exponential curve. The compositional range of the olivine is relatively restricted, but distinctly bimodal with prominent modes at Mg#'s (Mg ×100/(Mg + ∑Fe) of 91.1±0.9 and

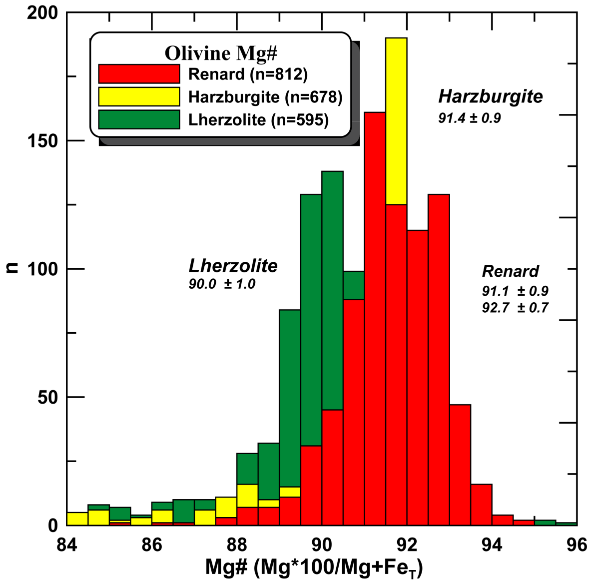


**Figure 3: Histogram of kimberlite olivine with modes as indicated on diagram. Background histograms for harzburgite and lherzolite with modes, data from GEOROC website.**

92.7±0.7, independent of grain size (Figure 3). The majority of the olivine (95%) has nickel contents ranging from 3400 to 2100 ppm, with the remaining 5% ranging down to 500 ppm (Figure 4). The calcium content of the Foxtrot olivine is uniformly low, ranging from less than detection limit (0.03) to 0.28 cations (Figure 4 - inset).

Carbonate is also a ubiquitous phase in the Foxtrot hypabyssal dykes, accounting for 8 to 35% of the rock and dominates the interstitial matrix (35-80%). The best magmatic textures are observed in the Lynx dyke, where the carbonate exhibits dramatic millimeter scale calcite oikocrysts that encompass small olivine and other matrix minerals (e.g. chromite). The dolomitic kimberlite samples also contain micron scale euhedral dolomite rhombs forming larger clusters. This carbonate paragenesis is also observed in fresh samples of the Hibou dyke and the Renard dykes. Although

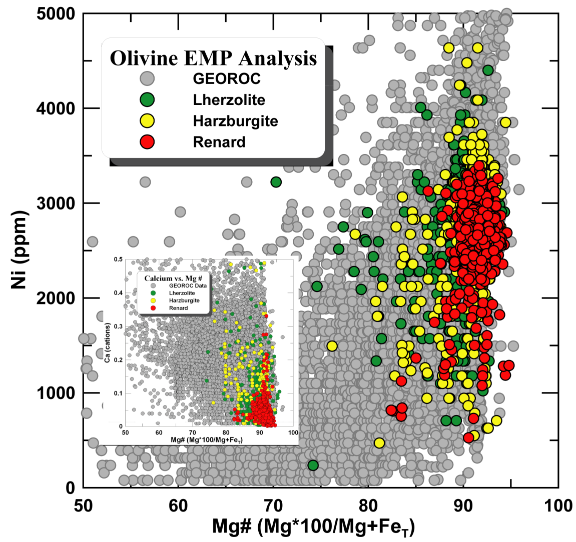


**Figure 4: Nickel content correlation with Mg# for olivine data from GEOROC website as background. Kimberlite, harzburgite and lherzolite data same as in Figure 3. Inset showing calcium correlation with Mg#.**

both dolomite and calcite are present in all samples, one type typically dominates resulting in the dolomitic and calcitic kimberlite subtypes.

## Discussion

Mantle $\delta^{13}C$ values (-5‰) and magmatic textures indicate that carbonate is commonly a magmatic phase in kimberlites (Francis and Patterson, 2008, Wilson et al., 2007; Armstrong et al., 2004; Clarke et al., 1991; Deines & Gold, 1973). The remarkable poikilitic texture of carbonate in the Foxtrot hypabyssal kimberlites is interpreted to be a primary magmatic feature and thus it is essential to include $CO_2$ when deciphering their whole rock compositional variations.

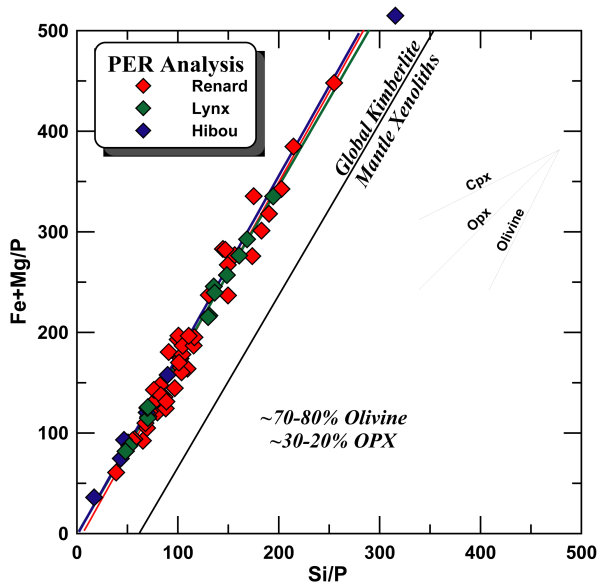


**Figure 5: Pearce Element Ratio analysis and calculated olivine and orthopyroxene ratios (xenolith data included showing identical slope).**

The olivine content of kimberlite is more enigmatic. The overlap of the Mg number and Ni content of Foxtrot olivine with mantle-derived lherzolite and harzburgite suggests that most of the olivine in the Foxtrot dykes is xenocrystic (Figure 3 and 4). This interpretation is supported by the fact that the compositions of Foxtrot hypabyssal kimberlite define a linear array in a Pearce element ratio plot (Figure 5), using P as a conserved element, that can be explained by variable amounts of olivine and orthopyroxene in proportions of ~75/25, similar to those of cratonic mantle xenoliths. The olivine is present as xenocrysts in hypabyssal kimberlites, but the associated orthopyroxene is occult, since it is not a phase in kimberlite, and has presumably been assimilated. Orthopyroxene is not stable in the presence of a hydrous carbonate-rich rich fluid (Eggler, 1973) and is presumably replaced by magmatic carbonate in kimberlite.

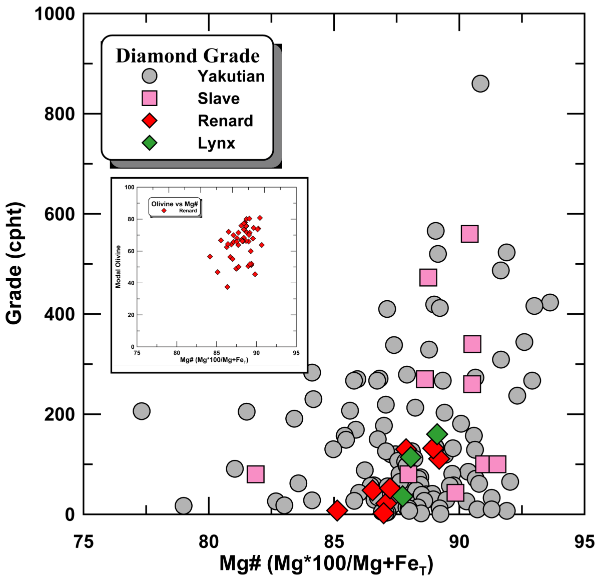


**Figure 6: Positive correlation between kimberlite whole rock Mg# and diamond grade indicating a positive correlation between modal olivine content and diamond grade. (hypabyssal dyke composition averaged for each pipe and sample trench in Lynx dyke). Background data set from Vasilenko, 2002. Inset showing positive correlation between olivine content and Mg#.**

A comparison of kimberlite whole rock Mg# and diamond grade in kimberlites from the Foxtrot Field, and the Yakutian and Slave Provinces indicates that the highest grades are found in kimberlites with the highest Mg# (Figure 5). This is consistent with a previous observation that high diamond grades correlate with low Ti content (Francis and Patterson, 2008) and may simply reflect the fact that the diamonds are also xenocrystic and are most abundant in kimberlite with the highest refractory harzburgite load. Although phlogopite in cratonic mantle harzburgite may contribute elements such as Ti, Al and K to kimberlite, the bulk of these elements are likely carried in the fluid phase, and largely diluted by mantle xenoliths.

## Conclusions

The whole rock compositions of the Foxtrot hypabyssal kimberlites are best explained by a model in which a hydrous carbonate-rich fluid interacts with and entrains refractory cratonic mantle. This carbonate-rich fluid is saturated relative to olivine and thus much of the cratonic mantle remains as rounded olivine xenocrysts, whereas the mantle orthopyroxene is assimilated by the carbonate-rich fluid. Evident magmatic carbonate in the Foxtrot kimberlites indicates that carbonate plays an essential role and must be included in petrogenetic models for the origin of their magmas. A carbonate-rich fluid also provides a simple explanation for the distinctive compositional characteristic of kimberlite in general; that of being highly enriched in incompatible trace elements, but highly refractory in terms of both major elements, such as Mg, and compatible trace elements, such as Cr and Ni. The carbonate-rich fluid provides the highly incompatible elements, whereas the major elements are determined by the entrained mantle. The association of the highest diamond grades in kimberlites with the highest Mg# and lowest Ti contents is thought to reflect the greater abundance of highly refractory harzburgite in such kimberlites, coupled with the preferential development of diamonds in highly refractory mantle lithosphere.

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