Constraining Kimberlite Magma Composition using Kimberlite Pelletal Lapilli Compositions

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Summary

Lapilli have long been recognized as droplets of magma formed during the eruption of a variety of volcanic suites, including pelletal lapilli in kimberlites. The compositions of kimberlite lapilli have received little attention due to the difficulty of analyzing such small volumes of rock. We have analyzed the compositions of several pelletal lapilli from various kimberlite occurrences using broad beam electron microprobe analysis in conjunction with x-ray fluorescence analysis. The compositional trends of lapilli differ systematically from those of kimberlite whole-rock; however, the two trends converge in several bivariate plots. The intersection composition of these two trends is interpreted to represent the composition of the kimberlite parental magma and is significantly lower I Si and Mg than many previous estimates.

Introduction

The composition of kimberlite parental magma has been debated for many years with no clear consensus. Although xenocrystic material (principally disaggregated harzburgite) is considered a fundamental component of kimberlite, by definition it cannot be included in the composition of the parental liquid. However, excluding the xenocrystic chemical component in kimberlite during analysis is very difficult, if not impossible, due to millimeter scale of xenocrysts and xenoliths. Compounding this difficulty is the hybrid, contaminated (both mantle or crustal), and altered nature of kimberlite. Therefore, we are left with an absence of kimberlite samples that can be truly considered as representative of primary melts, and estimates of its composition are largely theoretical and/or calculated.

In an effort to approach this problem from a fresh perspective, we utilize the compositions of fine-grain pelletal lapilli. Pelletal lapilli are ovoid shaped inclusions that have outer rims of fine-grained material, and commonly nuclei consisting of single xenocrysts or rarely a lithic fragment (Mitchell, 1986, 1997). Lloyd and Stoppa (2003) further define pelletal lapilli as a juvenile component of ultrabasic, ultramafic and/or carbonatitic diatremes that represent the interface between the erupting magma and the volatile component, which is dominated by CO_2. The xenocrystic nuclei of pelletal lapilli are typically olivine $Fo_{>90}$. The rarity of crustal lithic nuclei, despite the abundance of crustal lithic fragments in the host kimberlite breccias, suggests they initially formed at mantle depths. Thus, the compositions of lapilli rims likely represent that of kimberlite liquids.

Materials and Methods

The pelletal lapilli in this study are taken from several kimberlite intrusions (i.e. Buffalo Head Hills (BHH) kimberlite cluster in Northern Alberta, Foxtrot kimberlite field (FKF) in Northern

Quebec, Nikos kimberlite from Somerset Island in Northern Canada). The lapilli vary in size from 1 to 10's of mm and are set in a fine grain serpentine/carbonate matrix of macrocrystic brecciated kimberlite often with relatively fresh olivine xenocrysts. The ovoid shapes of pelletal lapilli do not reflect the shape of the nuclei when present, which is often angular. The lapilli exhibit a concentric rims of fine-grained serpentine (<200 µm) in a finer grained carbonate (<10 µm), with rare olivine, chlorite, perovskite, illmenite, magnetite and apatite (<10 µm). The width of the lapilli rims can vary from very thin (<0.25 mm) to 10 mm with no correlation with the size of the lapilli. Carbonate composes 30-45% of the lapilli rim, whereas serpentine composes 65 - 50% and accessory oxides ~ 5% (illmenite, magnetite, perovskite, rutile, apatite). The carbonate is primarily calcite that occurs both as irregular shaped aggregates composed of subhedral to euhedral crystals and tends to occur as single, anhedral crystals in the matrix. Serpentine occurs as anhedral to euhedral grains that often exhibit zoning and rims in backscatter images.

The compositions of lapilli rims were analyzed by both electron microprobe (EMP) and x-ray fluorescence (XRF) techniques for major elements. EMP analysis was conducted on a 500 µm area using a 20 kV and $2x10^{-8}$ nA defocused broad beam. At least five areas were analyzed per lapillus and then averaged to construct a composition for the entire lapillus rim. Wavelength-dispersive spectroscopy (WDS) analyses of major elements result in totals between 75 and 85 wt % with the deficit assumed to be CO_2 and H_2O, present in carbonates and hydrous minerals (serpentine and chlorite). Serpentine in the lapilli rims was analyzed to estimate the water content by allocating the mass balance deficit of these minerals as H_2O. Using both petrographic observation and image analysis to estimate the modal abundance of serpentine in the lapilli rims, a proportionate amount of the lapilli mass balance deficit can be assumed as H_2O, with the remaining difference being assigned to CO_2.

XRF analysis was also performed on pelletal lapilli of sufficient mass (>3 g) suitable for XRF. The individual lapilli were ground out using a micro drill ensuring the olivine nucleus was first completely removed. The samples were dried at 60 °C, pulverized to 150 µm using an alumina ring-and-puck grinder, and analyzed for whole-rock geochemistry by X-ray fluorescence using fused bead (major elements) and thermo-combustion for CO_2 at McGill University. The advantage of the EMP technique is the ability to analyze very thin lapilli rims that could not otherwise be considered. The disadvantage is that the CO_2 contents must be estimated by means of image analysis and subsequent calculation. XRF and thermo-combustion analysis has the advantage of robust major element and CO_2 results, but is limited to only larger, less common lapilli.

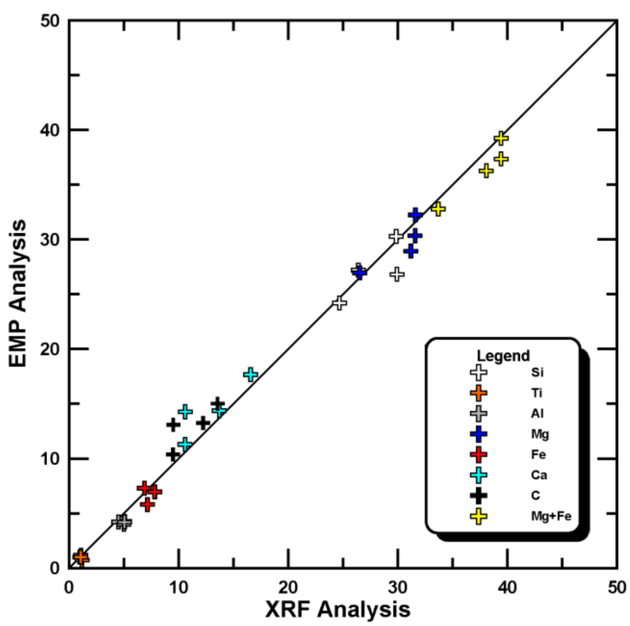

Figure 1: Comparison of EMP and XRF analyses for individual lapilli

Results

EMP analysis of each lapillus was conducted on between five and ten spots and results in a wide variation for individual elements, for example, one lapillus has Ca contents that range ~ 15 wt %. These same analyses however, have a range of Si contents of ~ 12 wt % and form a negative co-linear relationship with Ca and Mg forms a positive correlation with Ca over the same content range. Although the ranges in individual lapilli differ, the correlations and trends are identical. The large range in between individual spot analysis appears to reflect the differing amounts of serpentine and carbonate within each analyzed spot. Thus, the composition that best represents an individual lapillus rim is the average of all the analyses for that lapillus. The averaged EMP analyses and the XRF analyses are similar for individual pelletal lapilli in terms of major elements (figure 1), however, the CO_2 content for the EMP analysis was over estimated by 1-2 wt%. The good agreement between the results from both methods indicates that EMP analyses of smaller lapilli will approximate the bulk lapilli composition.

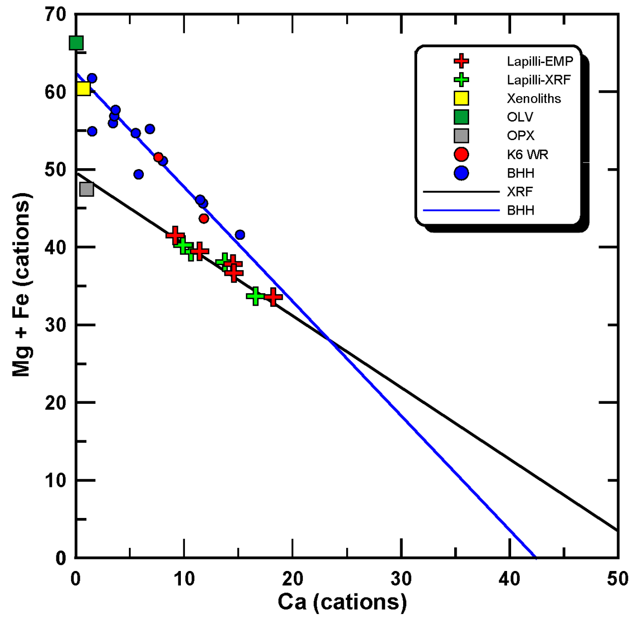

Figure 2: Mg+Fe vs Ca plot illustrating trends observed for pelletal lapilli and whole-rock data

Pelletal lapilli compositions are similar to that of the published whole rock compositions of the host BHH kimberlites (Eccles et al., 2004) in terms of Si (~ 28) and have slightly higher Fe contents (~ 8) compared to (~ 6) for the BHH, but are significantly lower in Mg (~ 30) than the BHH kimberlites (~ 45). Although there is a good correlation between the lapilli analyses and the host kimberlite in terms of Fe/Si compositions, there are significant deviations in other major elements; Al, Ti, K, and Ca are all enriched whereas Mg, Cr, and Ni are depleted. The Ca contents range in the lapilli is ~ 13 cations, whereas the whole rock compositions have slightly lower Ca contents of ~ 8 cations. Although the carbon contents of the lapilli (8-15 cations) is similar to those of the kimberlite whole rock chemistry (3-17 cations), the lapilli have on average higher contents.

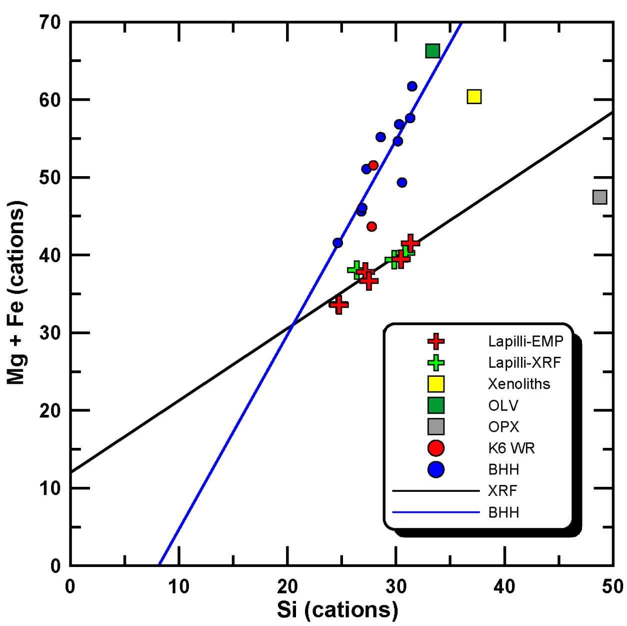

Figure 3: Mg+Fe vs Si plot illustrating trends observed for pelletal lapilli and whole-rock data

The pelletal lapilli and kimberlite whole-rock compositional arrays form two distinctive trends in a plot of Mg + Fe versus Ca that converge at Mg + Fe ~29 and Ca ~23 cations (figure 2). Similar trends are observed in a diagram of Mg + Fe versus Si that converge at Mg + Fe ~29 and Si ~19 cations (figure 3). Distinctive trends are also observed in a plot of Mg + Fe versus C that converge at Mg + Fe ~21 and C ~27 cations. Pearce element ratio (PER) analysis of the pelletal lapilli chemistry (using P as the conserved element), indicates that their compositional variation can be explained by variable amounts of olivine (~20) and orthopyroxene (~80). Although the lapilli data forms a trend roughly between

	This Study	Patterson et al., 2009
SiO_2	19.0	22.1
TiO_2	0.0	2.7
Al_2O_3	4.0	5.4
FeO	11.0	8.1
MgO	14.0	13.8
MnO	0.0	0.2
CaO	22.0	20.2
Na_2O	0.0	0.1
K_2O	0.0	1.8
P_2O_5	0.0	0.9
CO_2	20.0	15.7
H_2O	9.0	9.0
Total	**99.0**	**100.0**
normative mineralogy		
Al_2O_3	4.0	3.3
OPX	25.0	9.1
Olivine	17.0	24.7
Calcite	39.0	33.9
Magnesite	6.0	1.5
Total	**91.0**	**72.5**

Table 1: Kimberlite liquid composition

orthopyroxene and carbonate in both Mg + Fe versus Ca and C diagrams, the Ca and C poor end-member has compositions that can be defined by an olivine/orthopyroxene ratio of ~ 20/80% using the lever rule. The Ca and C rich end-member is rich in calcite, but has a ferro-magnesian component of ~ 5%. The lapilli trend in the Mg + Fe versus Si plot can also be defined by similar end-members, although this trend appears to have a smaller orthopyroxene component (~70%) and a larger ferro-magnesian Si-poor end-member (~12%).

The compositional variation of the pelletal lapilli, whether individual EMP spot analysis or whole lapilli compositions, all plot to the carbonate poor side of the intersection point with the whole-rock trend, suggesting that this trend is due to contamination of the intersection composition by variable amounts of orthopyroxene. The whole-rock trend has a similar configuration, however this trend represent the contamination of the intersection composition by olivine and orthopyroxene. Thus, the intersection point represents kimberlite liquid that has not been contaminated by the mantle and is carbonate rich. Kimberlite parental magma composition calculated by the mathematical removal of olivine and orthopyroxene from kimberlite whole-rock composition (Patterson et al., 2009) is virtually identical to the intersection composition (table 1).

Conclusions

Although pelletal lapilli are often too small for conventional XRF analysis, comparing the results of EMP and XRF (plus thermo-combustion) analysis of the same lapilli indicates that representative compositions of small lapilli can be obtained using averaged EMP analyses. The compositional variation in pelletal lapilli reflect the assimilation of variable amounts of orthopyroxene by a carbonate rich fluid, however, the intersection point represents the composition of the kimberlite liquid before mantle contamination. The estimate of kimberlite parental magma composition here is much poorer in MgO (~14 wt%) and much richer in CO_2 (~20 wt%) than previous estimates.

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