Delineation of kimberlite lithofacies at the D/K1 Pipe, Letlhakane, Botswana

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Introduction

Kimberlite pipes frequently host several texturally distinct types of volcaniclastic kimberlite or kimberlite lithofacies (Trofimov, 1970; Hawthorne, 1975; Dawson, 1980; and Clement and Reid, 1989). Characterization of individual lithofacies is not always easy and therefore there is a high level of uncertainty in geological models of producing mines. We investigated a number of ways to facilitate the identification and delineation of kimberlite lithofacies at the D/K1 pipe, Letlhakane, Botswana.

Geology

The D/K1 pipe is the larger of two kimberlite pipes at the Letlhakane Mine that erupted through the Zimbabwe Craton ~93 Ma (Siefenhofer et al., 1997; Denies and Harris, 2004). The Letlhakane Mine is ~200 km west of Francistown in the Boteti District of Central Botswana. The host rock geology is a simple, layer-cake sequence comprised of Archaen basement granites and gneisses overlain by Karoo mudstones, silts, coal and sands with an uppermost unit of Stormberg flood basalt. 4-10 m of Cretaceous to recent Kalahari sediments and calcrete overlay the basalt.

The D/K1 kimberlite pipe was divided into four kimberlite lithofacies based on diamond grade and geological observation during the mid-1990s (Figure 1). Differentiation between the lithofacies became increasingly difficult over time, indicating a revision of the model was required. The revised pipe model was proposed after detailed drill core logging supported by petrographic study. Six major volcaniclastic kimberlite units were identified some comprising of sub-units or lithofacies associations that were believed to have related emplacement histories. A summary of each major unit is given in Table 1.

	VK1	DVK	PVK	SVK	BBR	CK
Colour	Dark grey	Very dark grey	Pale-dark grey	Pale grey-brown	Light brown-grey	Very dark grey-black
Ol Content (vol%)	30-40	50	30	30	10-20	60
Av. ol size (mm)	3	2	4	5	3	3
Ol alt.	Completely serpentinised	Fresh-serpentinised	Completely serpentinised	Completely serpentinised	Completely serpentinised	Fresh with Ca-rich rims
Av. lithic content (vol%)	12	10	8	15	60-≥90	7
Lithic fragment size; max. av.	10 mm, 2 mm	20 mm, 2 m	300 mm, 10 mm	20 mm, 2 m	200 mm, 10 m	100 mm, 10 mm
Lithic Alt.	Few alteration haloes	Metamorphosed and alteration haloes	Metamorphosed (?)	Unaltered	Unaltered-oxidised	Metamorphosed
Texture	Ghost lapilli, pseudo-pelletal	Ghost lapilli, pseudo-pelletal	Pelletal and juvenile lapilli	Pelletal and juvenile lapilli	Ghost lapilli and rare pelletal lapilli	Coherent, non-fragmental
IM or GM phase	Fine microlites and serpentine	Coarser microlites, serpentine and rare calcite	V. fine-grained microlites and serpentine	V. fine-grained microlites, serpentine, calcite and phlogopite	Serpentine and microlites	calcite, serpentine, oxides and phlogopite
Structure	Massive to crudely layered	Massive to crudely layered	Massive to crudely layered	Massive to crudely layered	Massive to crudely layered	Massive

Table 1: Summary table of the main characteristics of the major D/K1 lithofacies; VK1, DVK, PVK, SVK, BBR and CK. (Ol - olivine; IM - interclast matrix; GM - groundmass; Alt - alteration; Av. average; Max. - maximum; v – very; microlites – diopside).

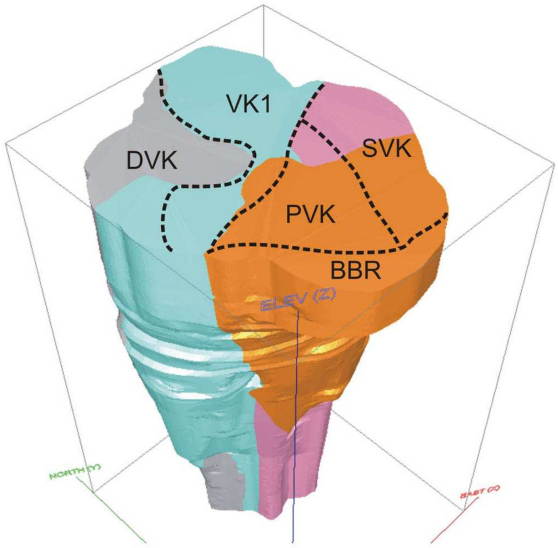

Figure 1: Model of the D/K1 kimberlite pipe with new facies overlying the old model

Spinel petrography

Groundmass spinel compositions were analyzed to determine how well they could fingerprint the lithofacies identified from field and thin section study. In addition, we wanted to understand how their compositional and textural variations related to petrogenetic and physiochemical processes.

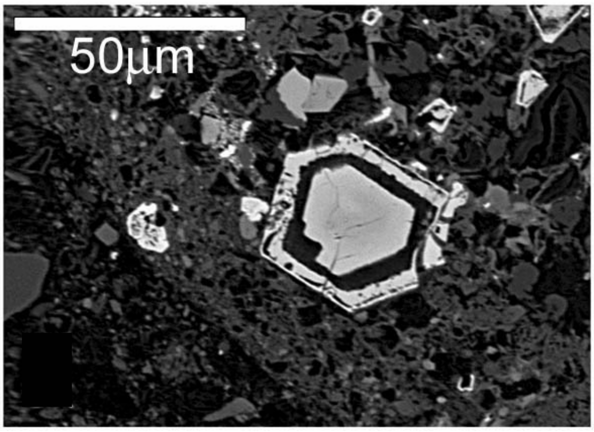

Figure 2 - Back scattered electron image of atoll spinel within a juvenile lapillus.

D/K1 groundmass spinels define a compositional trend of decreasing Cr and Al with increasing Ti and Fe^{3+} (Figure 3). This is consistent with the 'kimberlite trend' of Barnes & Roeder (2001) and Magmatic Trend 1 of Mitchell (1986). It is interpreted as the effect of co-crystallization of chromite with olivine at a constant composition and constant temperature (Irvine 1967). The Letlhakane D/K1 groundmass spinels are notably Ti-rich and very few analyses have <5 wt% TiO_2. The groundmass assemblage was dominated by perovksite which also suggests a strong influence of Ti on the kimberlite. However, pure magnetite was only found in one grain out of >700 analyses. It is possible that the liquidus phases were continually saturated in Ti and therefore Ti-free magnetite never stabilized on the liquidus. This is probably a direct result of a Ti-enriched melt.

We were looking for lithofacies-specific trends. Although there was a degree of overlap in compositions from all lithofacies, the locus of each analyzed set was subtly set apart. Core compositions were shifted along the Fe^{2+}/Fe^{2+}+Mg axis by lithofacies; compositions from PVK were the most Mg-rich, followed by SVK, VK1, BBr1* and spinels from the DVK were the most Fe-rich. The subtle distinction in Fe^{2+}/Fe^{2+}+Mg ratios between lithofacies is significant because it reflects the primitive composition of the melt and may show that spinels crystallized from melts with different starting compositions. This was also demonstrated in hypabyssal kimberlite within the root zone at the De Beers pipe by Pasteris (1983) and the Wesselton pipe by Shee (1985).

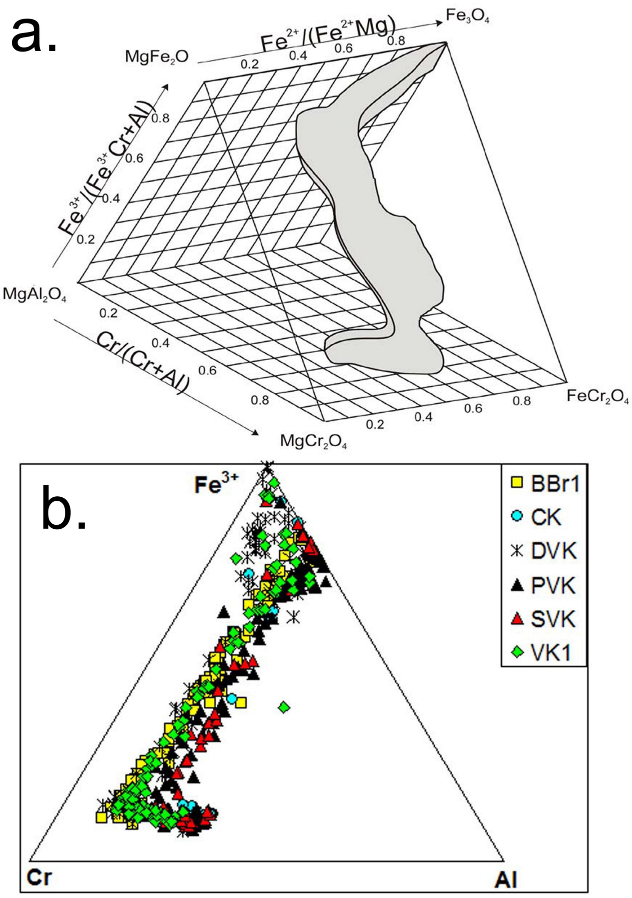

Figure 3: (a) Oxidised spinel prism illustrating the locus (~90% of analyses) of all D/K1 spinel compositions. (b) Triangular plot of Fe^{3+}, Cr^{3+} and Al^{3+}.

Atoll spinels (Figure 2) were most developed and well preserved in juvenile lapilli. One sample from the PVK lithofacies contained atoll spinels with different compositional trends from two separate lapilli. We believe this suggests that the lithofacies contains spinels that were derived from at least two batches of erupted magma, implying multiple eruptive phases.

* BBr1 is a subset of the VK1 lithofacies

Bulk rock geochemistry

The bulk rock geochemistry of a wide range of samples from the D/K1 pipe was analyzed by XRF. Our aim was to test whether the geochemistry of volcaniclastic kimberlite could be used to delineate the D/K1 lithofacies. Previous work by Nowicki (1993) showed that this method had succeeded in the past; we wanted to extend this study to the entire pipe and examine the results using multivariate statistics to group the data into distinct clusters.

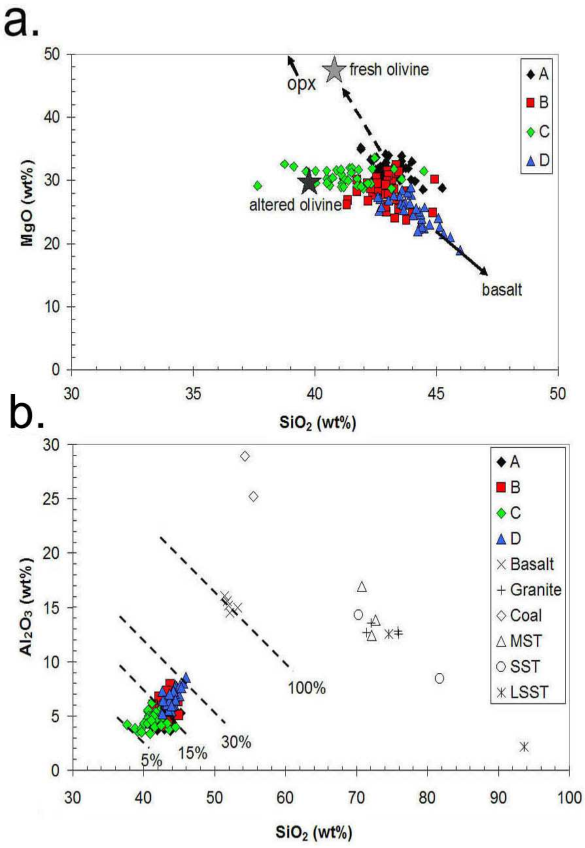

Figure 4: Geochemistry results (a) MgO and (b) Al_2O_4 versus SiO_2 with fresh and altered olivine and basalt compositions in (a) and percentage of country rock waste indicated in (b).

The analyzed samples were clustered into four major groups and subgroups by statistical processing. The major geochemical influences that clustered the samples were from (i) mantle-derived components, predominantly Ni and MgO consistent with olivine accumulation, and Cr from chrome-spinel accumulation (ii) magma-derived components, predominantly incompatible trace elements, CaO, K_2O and TiO_2 representing the last phases to crystallize from the magma, and (iii) crustal-derived Al_2O_3, Na_2O and to some extent SiO_2 (Figure 4b). This illustrated how shallow-level and eruptive processes, including those taking place during the eruption, can geochemically fingerprint the D/K1 kimberlite. This is potentially a quick and powerful tool in delineating kimberlite lithofacies elsewhere.

Conclusion

The underlying question throughout this study was how well certain geological, mineralogical, petrographic and geochemical indicators could delineate lithofacies at the D/K1 kimberlite pipe. By analyzing the relationship between groundmass spinel and perovskite we also proposed a groundmass crystallization sequence. We have shown from groundmass spinel compositions, core logging, petrographic study, and bulk rock geochemistry that the D/K1 kimberlite pipe is comprised of multiple, distinct kimberlite lithofacies. These were produced by a dynamic eruptive event that involved repeated episodes of activity which, in some cases, quarried out and mixed with older deposits.

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References

Barnes, S. J. & Roeder, P. L. (2001). The range of spinel compositions in terrestrial mafic and ultramafic rocks. Journal of Petrology, 42(12), 2279–2302.

Clement, C. R. & Reid, A. M. (1989). In Kimberlite and Related Rocks, Proceedings of the Fourth International Kimberlite Conference Blackwell Scientific Publications. pp. 634–646.

Dawson, J. (1980). Kimberlites and their Xenoliths. Springer Verlag.

Deines, P. & Harris, J. W. (2004). New insights into the occurrence of ^{13}C-depleted carbon in the mantle from two closely associated kimberlites: Letlhakane and Orapa, Botswana. Lithos, 77, 125–142.

Hawthorne, J. B. (1975). Model of a kimberlite pipe. Physics and Chemistry of the Earth, 9, 1–15.

Irvine, T. (1967). Chromian spinel as a petrogenetic indicator. part 2. Canadian Journal of Earth Sciences, 4, 71–103.

Mitchell, R. H. (1986b). Kimberlites: Mineralogy, Geochemistry and Petrology. Plenum Press, New York.

Nowicki, T. (1993). The HMA and geochemistry of boreholes LFD3, LFD5 and LFD6 , Letlhakane Mine, Botswana. Technical Report R/93/075, Anglo American Research Laboratories.

Pasteris, J. D. (1983). Spinel zonation in the De Beers kimberlite, South Africa: possible role of phlogopite. Canadian Mineralogist, 21, 41–58.

Shee, S. R. (1985). The petrogenesis of the Wessleton Mine Kimberlite, Kimberly, Cape Province, R.S.A. PhD thesis, University of Cape Town.

Stiefenhofer, J., Viljoen, K., & Marsh, J. (1997). Petrology and geochemistry of peridotite xenoliths from the Letlhakane kimberlites, Botswana. Contributions to Mineralogy and Petrology, 127, 147–158.

Trofimov, V. S. (1970). On the origin of diamantiferous diatremes. Bulletin of Volcanology, 34, 767–776.