



## THE PETROLOGY OF AK6, BOTSWANA: IMPLICATIONS OF VOLCANIC AND IGNEOUS PROCESSES

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### INTRODUCTION

In this study the three intrusive lobes of the AK6 kimberlite in Botswana (Figure 1) are studied and the mineralogy is used to try and understand the different processes that have occurred in each lobe e.g. magma mixing, as well as the textural features that indicate a volcanoclastic origin.

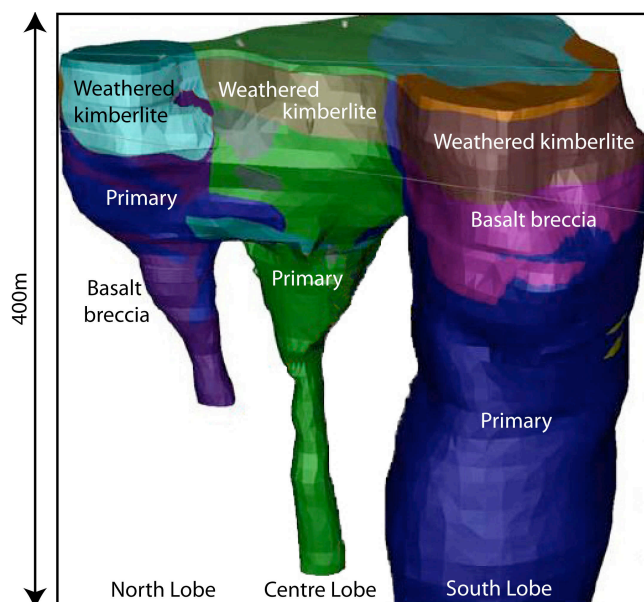


Figure 1. Diagram of AK6, adapted from McGeorge *et al.*, (2010), with the geological units are looking north-east. The AK6 tri-lobate kimberlite pipe forms part of the Orapa cluster kimberlites in Central Botswana.

The AK6 pipe has two distinct types of kimberlite: firstly a dark kimberlite in the South lobe and a green-grey, more obviously volcanoclastic kimberlite in the North and Centre lobe. The South Lobe is also significantly different from the North Lobe and Centre Lobe in terms of petrology, geochemistry, density, pipe shape and the diamond populations.

### PETROLOGY

#### South Lobe kimberlite

The South Lobe kimberlite is a poorly sorted, dark grey to black competent kimberlite that is olivine-rich, matrix- to clast-supported and contains country rock lithic clasts. Features that are considered characteristic of a coherent kimberlite include fresh olivine, monticellite and a highly crystallized interstitial matrix of groundmass material (Hayman *et al.*, 2008). This matrix is composed of small, euhedral olivine, zoned monticellite (up to 120  $\mu$ m), zoned perovskite, chromite spinel, Fe-Ti spinel, apatite, phlogopite and serpentine. There is little to no void filling material. However, it possesses some characteristics that are enigmatic to an intrusive rock. Lithic fragments from the deepest Archaean basement, basalt and Karoo sediments from the near surface are both evenly distributed throughout the whole pipe.

#### North and Centre Lobe kimberlite

The North and Centre Lobe kimberlites are poorly sorted, matrix-supported, green to grey coloured kimberlites that are much less competent than the South Lobe kimberlite. The olivine is partially to entirely serpenitised. Some olivine macrocrysts and highly altered xenoliths are surrounded by the initial stages of magmatic selvages (Figure 2). The groundmass of both these kimberlites contains an abundance of opaques, zoned perovskite, apatite, phlogopite  $\pm$  pseudomorphed monticellite,  $\pm$  hydrogarnets and a matrix consisting of serpentine with minor calcite or diopside or serpentine with pools of calcite. Chlorite and clay can also be a component of the matrix. The high abundance of interstitial carbonate in the Centre Lobe kimberlite is the main feature that distinguishes it from the North Lobe.



into two main categories. The first (Group 1) are iron-poor (6 wt% - 10 wt% FeO) and the second

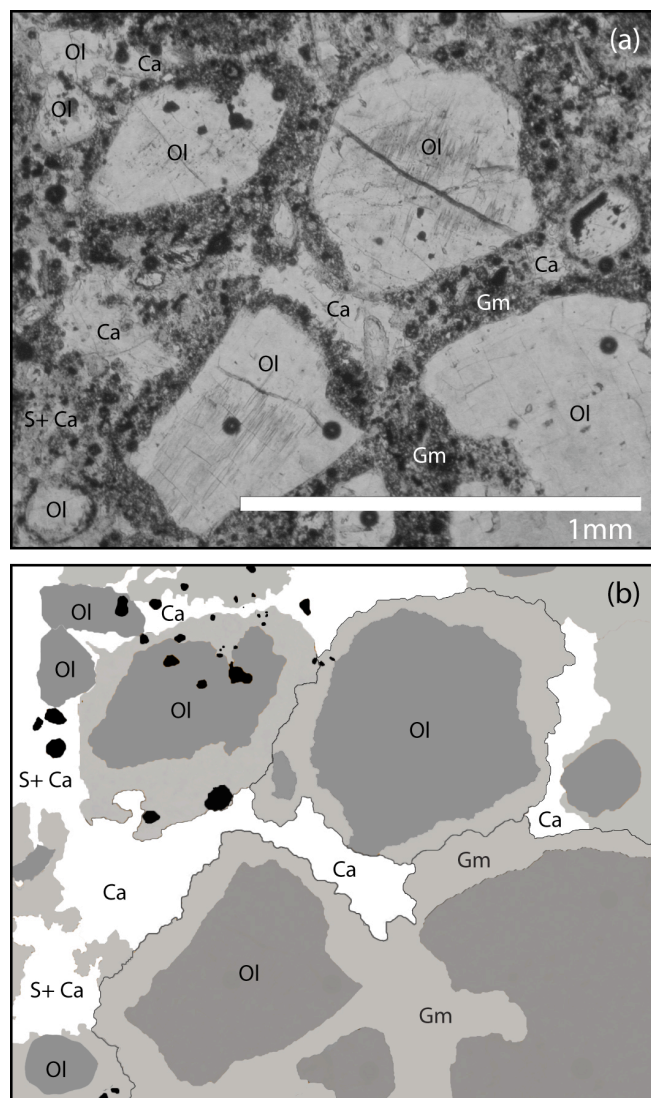


Figure 2. (a) Photomicrograph of the Centre Lobe kimberlite and (b) Cartoon of (a). Magmatic selvages full of oxides surround the pseudomorphed olivines. Irregularly shaped pools of oxide-free calcite and serpentine form the interstices between the olivine crystals. Ca = calcite; S = serpentine; Ol = olivine

## MINERAL COMPOSITIONS

### Olivine

The North and Centre Lobe olivines are rarely preserved, while fresh olivines in the South Lobe can be studied in detail. The olivine cores have variable forsterite (Fo) values ranging from Fo<sub>81</sub> to Fo<sub>93</sub>, whereas the Fo values remain fairly constant in the rims, between Fo<sub>86</sub> and Fo<sub>87</sub>. As shown in Figure 3, the olivine cores tend to fall

(Group 2) iron-rich (14 wt% to 18 wt% FeO). Both of these tend to be rimmed by olivine of a different composition, constantly between 12 wt% and 13 wt% FeO (Group 4). There is also an intermediate olivine composition (Group 3) that occurs in select olivines between the core and rim, which have FeO contents between 11 wt% and 12 wt%. The intermediate olivine composition occurs occasionally between the rims and both types of cores and as smaller euhedral groundmass olivines (< 500µm). These differences are also seen in the NiO contents, which range from 0.08 wt% to 0.43 wt%.

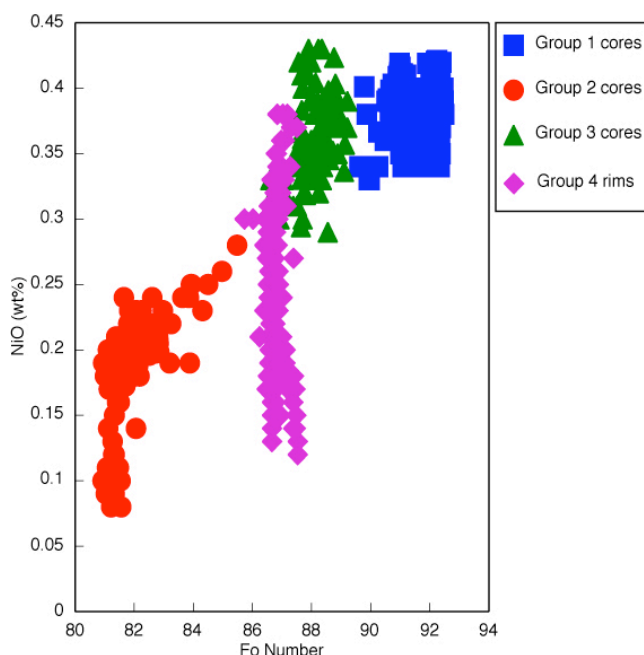


Figure 3. Plot showing the Fo number vs. NiO (wt%). This plot shows four different olivine compositions: (i) Group 1, low FeO, (ii) Group 2, high FeO, (iii) Group 3, intermediate FeO and (iv) Group 4, rim composition.

### Monticellite

The compositions of the South Lobe monticellite are discussed below as monticellite is rarely preserved in the North and Centre Lobes.

The monticellite tends to have Fe-rich cores and Fe-poor margins, with FeO contents ranging from 2.6 – 10.6 wt%. However, normal zoning is also evident, where the cores are less enriched in Fe than the outer rim. The Ca/(Ca+Mg+Fe) ratio ranges from 0.45 – 0.5 and Fe/(Fe+Mg) ranges from 0.06 – 0.24. Some monticellites with high Fe correlate with data from monticellite found in the Polino monticellite-calciocarbonatite (Stoppa and Lupini, 2004).



## Spinel

The North and Centre Lobe spinels differ from the South Lobe spinels (Figure 4). The South Lobe has two groups of spinels. Whilst both groups show  $\text{Fe}^{3+}$  increasing with increasing  $\text{Fe}^{2+}/(\text{Mg}+\text{Fe}^{2+})$  up towards magnetite, the Group 2 spinels are more Fe-rich compared to Group 1. The difference is seen in  $\text{Fe}^{2+}/(\text{Fe}^{2+}+\text{Mg})$ , which is between 0.4 and 0.6 at low concentrations of  $\text{Fe}^{3+}/(\text{Fe}^{3+}+\text{Al}+\text{Cr})$ .

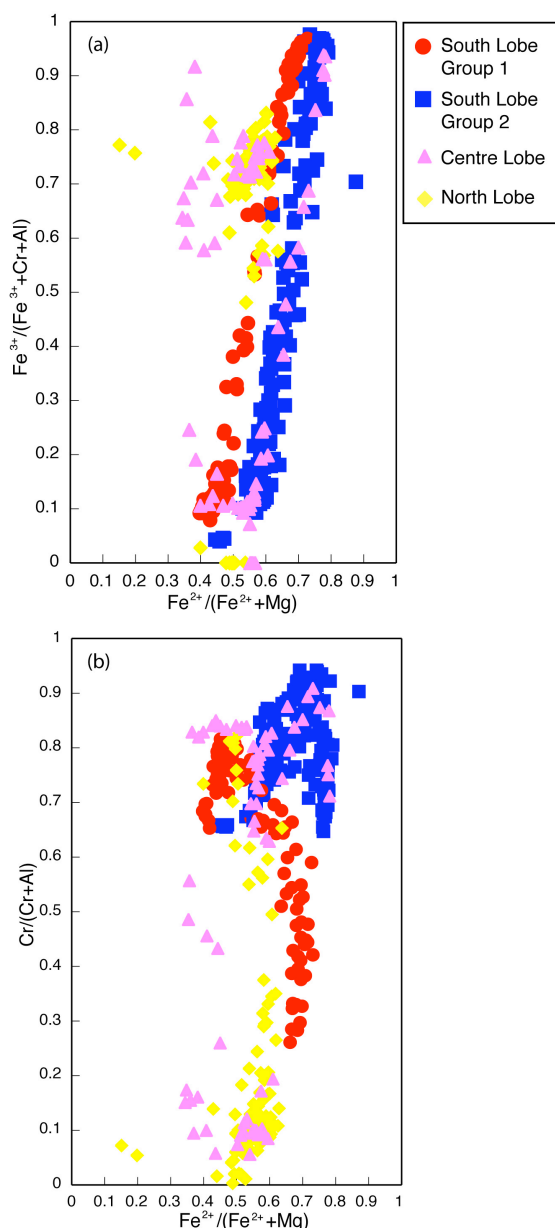


Figure 4.  $\text{Fe}^{2+}/(\text{Fe}^{2+}+\text{Mg})$  vs (a)  $\text{Fe}^{3+}/(\text{Fe}^{3+}+\text{Al}+\text{Cr})$  and (b)  $\text{Cr}/(\text{Cr}+\text{Al})$  for spinel in the AK6 kimberlite

$\text{Cr}/(\text{Cr}+\text{Al})$  is also significantly different between these two groups. In Group 1, Cr decreases significantly as Fe increases, from 0.8 to 0.2. However, the change in Group 2 is not as extensive, over the  $\text{Cr}/(\text{Cr}+\text{Al})$  ranges from 0.6 – 0.95. Group 2 spinels compositions are intermittently found crystallized on the edge of the Group 1 crystals.

Most of the spinel in the North and Centre Lobe are titanomagnetites; some are partially altered to hydro-garnets (mainly in the Centre Lobe). Occasionally, rare large Cr spinels can be found that have similar compositions to both Group 1 and Group 2 in the South Lobe.

## Perovskite

Perovskites in the South Lobe are significantly different from the North Lobe and Centre Lobes (Figure 5), which have very similar compositions. The Centre and North Lobe perovskites have significantly higher Ce (1.8 – 3.3 wt%  $\text{Ce}_2\text{O}_3$ ) and Nb (0.7 – 1.7 wt%  $\text{Nb}_2\text{O}_5$ ) compared to the South Lobe (0.1 – 2.4 wt%  $\text{Ce}_2\text{O}_3$  and 0.3 – 0.9 wt%  $\text{Nb}_2\text{O}_5$ ), although the rim Ce and Na content are must closer in value compared to the North and Centre lobes.

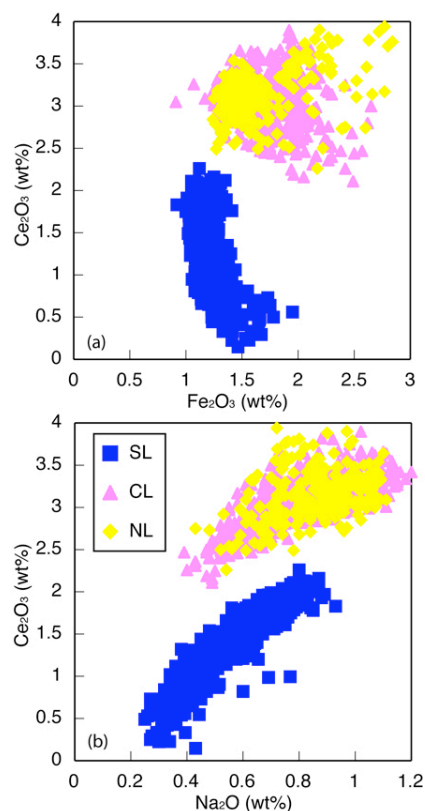


Figure 5. Plot showing (a)  $\text{Fe}_2\text{O}_3$  (wt%) and (b)  $\text{Na}_2\text{O}$  vs  $\text{Ce}_2\text{O}_3$  (wt%) in perovskite. The South Lobe is significantly different to the North and Centre lobes, which are indistinguishable from each other and more



## DISCUSSION

The South Lobe is characterised by: (1) fresh zoned olivine with two distinct core compositions with rims of a similar composition; (2) abundant groundmass monticellite (generally unaltered); (3) high-Cr and low-Ti primitive spinels; (4) REE-poor, F-rich apatite; (5) REE- and Nb-poor perovskite; (6) little to no void filling material e.g. microlites or diopside; (7) comparatively little groundmass serpentine.

The Centre and North lobes are characterised by: (1) partially-to-completely serpentinised olivine, with some Fe-hydroxide alteration; (2) groundmass monticellite, typically pseudomorphed by serpentine; (3) titanomagnetite spinel partially altered to hydrogarnet; (4) REE-, Nb- and Fe-rich perovskite; (5) oxide-free calcite and/or serpentine segregations (occasionally containing microlites or radiating diopside); (6) REE-rich and F-poor (relative to the South Lobe) apatite; (7) groundmass containing common serpentine.

### Multiple magma batches and magma mixing

The AK6 kimberlite shows evidence for multiple batches of magma by: i) the presence of the two distinct kimberlite types within one pipe and ii) range of mineral compositions within the South Lobe kimberlite.

The South Lobe olivine, monticellite and spinel each have distinct groupings defined by different compositions (see Figure 3 and 4). This is most apparent in the case of the olivines (and to some extent monticellite), which have two defined groups of cores (high Fe and low Fe), all enclosed with the same rim compositions. Such features are commonly attributed to magma mixing (e.g. Luhr and Carmichael, 1980). Unfortunately, primary minerals, such as olivine and monticellite, have been highly altered within the North and Centre Lobes and therefore cannot be used for comparison.

Spinel in the South Lobe also shows two distinct groupings. Roeder and Schulze (2008) suggest that the different compositions of different batches of kimberlite magma can cause a variation in spinel compositions. Spinel from Group 1 are not as common as Group 2 and occasionally are mantled by spinels with compositions of Group 2, but not vice versa. This infers that Group 1 spinels crystallized prior to the crystallisation of Group 2 from a different magma.

While the South Lobe kimberlite crystallizes spinels that have a Cr-rich core and Fe-rich rims, the North and Centre lobe spinels are predominantly small discrete Mum crystals. Large zoned crystals with Cr-rich cores as seen in the South Lobe are uncommon. This is most likely a growth feature

Perovskite also differs significantly between the South Lobe and the North and Centre Lobes. The North and Centre Lobes are more enriched in LREE and Fe<sup>3+</sup> compared to the South Lobe. Chakhmouradian and Mitchell (2000) observed that high contents of LREE, Th and Nb in perovskite was not exclusive to any specific type of kimberlite but a merely the result of a kimberlitic magmas becoming enriched in such elements. The clear difference in perovskite composition and LREE, Nb and Fe<sup>3+</sup> contents indicate a different magma source for the perovskite to crystallize from.

### Welding

The South Lobe groundmass is devoid of calcite-serpentine filled interstices, because the pelletal clasts have completely coalesced forming patches of igneous-textured material. These textural criteria suggest that the South Lobe should be interpreted as a densely welded rock due to its uniformly dense nature. Such welded rocks have been recognized in other kimberlites that are also part of the Orapa cluster (e.g. B/K9) and at Venetia (Brown *et al.*, 2008; Buse *et al.*, 2011). The hot clasts sinter together at the point contacts and then deform to reduce pore space (Brown *et al.*, 2008). Compared with the other lobes, a greater depth in the South Lobe results in a more dense kimberlite becomes with a higher amount of preserved primary minerals i.e. monticellite. Magma deeper in the conduit can experience more compaction from a heavier overburden causing the minerals to be squashed together removing any void space and therefore.

The North and Centre Lobes are interpreted as incipiently welded kimberlites. The pelletal clasts have thin envelopes of earlier melt inferring different eruption dynamics between the South Lobe and the North and Centre Lobes. The hot clasts sinter together at the point clasts. However, there is minimal deformation of the pelletal clasts, creating pore space. The irregular calcite and serpentine patches (Figure 2) represent the infilled pore space (Brown *et al.*, 2008). This also allows later fluids to alter primary minerals such as olivine.

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