

Melt compositions and eruptive conditions inferred from the petrology of Dutoitspan kimberlite

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Introduction

The Dutoitspan kimberlite rocks, D2 Type 3, are relatively 'fresh' hypabyssal kimberlite rocks (Clement 1982). The D2 kimberlite contains fresh olivine that has undergone partial alteration along the margin of the crystals and in fractures. Olivine crystals are set in a fine-grained matrix that consists of abundant fresh monticellite, apatite, phlogopite, spinel, calcite, perovskite, and serpentine. The composition of the groundmass is an important factor in determining the compositions of the erupted melts, a major control on the properties of the erupting system.

Kimberlite magmas are explosive and travel to the surface at high speeds. Several processes occur during their ascent including: assimilation of the mantle and crustal minerals, decompression, degassing and crystallisation. The rate of eruption and modes of emplacement are influenced greatly by the volatile content of the kimberlite magma. The true contents and solubility of the volatiles are not well constrained, but the abundance of primary phlogopite, monticellite and probable igneous calcite in the D2 kimberlite indicates that these magmas contained significant volumes of water and CO₂ (Sparks et al. 2006, *references therein*).

Constraining the intensive variables (e.g. fO_2 and T) of kimberlite magmas can increase the understanding of mantle-derived processes and conditions. Oxygen fugacity (fO_2) determines the relative Fe^{3+}/Fe^{2+} ratio in coexisting melts so fO_2 can be used as a record for the oxidation levels of the terrestrial magma (Bellis and Canil 2007, *refs therein*). The variations in fO_2 of the magma can be recorded in perovskite, a common accessory phase. Fe^{3+} is preferentially partitioning into the perovskite structure under relatively low pressure. The fO_2 of the kimberlite is calculated by using an equation developed by Bellis and Canil (2007):

$$\Delta NNO = - [0.50(\pm 0.021) * Nb - Fe (\pm 0.031) + 0.030(\pm 0.001)] / 0.004(\pm 0.0002)$$

(Fe and Nb are in cation units per 3 oxygens; uncertainties are given at 2σ)

Methodology

Two standard thin sections of a relatively fresh character were used to study the mineralogy and petrology of the groundmass. 17 different

representative areas were selected. Each area was mapped out using an SEM to determine the volume percentage of each mineral present. Image analysis software was used to determine the modal proportions of each mineral present in the groundmass. The chemistry of each mineral was determined by electron microanalysis to help estimate the groundmass element composition for each individual area.

Groundmass Petrology

D2 kimberlite is a monticellite kimberlite that carries no diamonds. Monticellite is the most abundant groundmass phase, ~ 33% (Fig. 2), occurring mainly in segregations around large xenoliths. Monticellite inclusions (fresh and altered) are also enclosed in large poikilitic apatite. The euhedral to subhedral grains (15 μm - 50 μm) can reach up to 120 μm toward the edge of the segregations.

Phlogopite, ~ 24 vol% (Fig. 2), occurs as anhedral basal plates and groundmass stubby laths (10 μm - 300 μm). In some rare cases, larger phlogopite crystals can be seen forming around the outline of the olivine crystals, indicating phlogopite crystallised from the kimberlite magma.

Apatite, ~ 19 vol% (Fig. 2), is a late crystallising phase that occurs as either large poikilitic crystals (< 300 μm) or small (~25 μm) discrete crystals. Some poikilitic crystals stretch across the monticellite segregation areas and enclose Cr-spinel, perovskite and monticellite (both altered and fresh).

Calcite, ~11 vol% (Fig. 2), occurs in two different forms: euhedral and platy or irregular-shaped (blob-like), commonly surrounded by serpentine. The euhedral platy calcite crystals have sharper edges than the irregular elongated calcite crystals (< 6.4 mm diameter). Calcite tends to crystallise in areas that are monticellite-free along the edges of apatite.

Perovskite, ~4 vol% (Fig. 2), is an equant accessory mineral that occurs in two different parageneses: 1) within the groundmass of the kimberlite or 2) enclosed in poikilitic apatite. Perovskite crystals (< 75 μm) are zoned and range mainly between 15 μm to 30 μm . It is common for perovskite to be intergrown with spinel. The contact formed with spinel normally preserves the grain edge perfectly where the two minerals have crystallised simultaneously (Fig. 1).



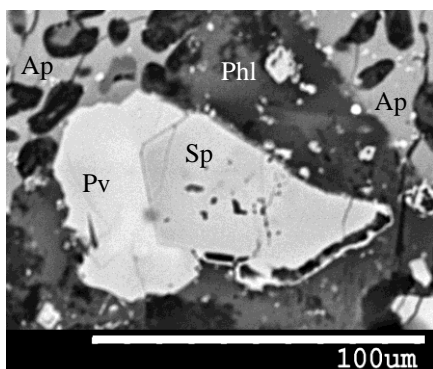


Fig. 1 Perfect contact preserved where the perovskite encloses the chrome spinel; an Fe-rich rim has formed where the (lower) edge of the spinel has been exposed to the kimberlite fluid; Pv – perovskite; Sp – spinel; Ap – Apatite; Phl – phlogopite

Spinel, ~7.7 vol% (Fig. 2), can be found enclosed within poikilitic apatites, the phlogopite and serpentine matrix or as a 'necklace' (with perovskite) around the edges of altered xenoliths. The spinel crystals are zoned and commonly have Cr-rich cores and Fe-rich rims (atoll texture). Crystals (< 65 μm) are typically 20 μm to 30 μm.

Mineral	(1)	(2)	(3)
Monticellite	11.48	23.50	33.25
Apatite	6.62	13.56	19.70
Calcite	3.70	7.58	10.83
Phlogopite	8.28	16.96	24.54
Cr spinel	0.98	2.00	2.83
Fe spinel	1.68	3.45	4.87
Perovskite	1.36	2.79	3.98
Serpentine	14.73	30.17	-
Alt Olivine*	20.84	-	-
Olivine	30.33	-	-

Fig. 2 Table showing the average volume percentages of each mineral in D2 kimberlite. (1) Vol % of minerals in the whole rock; (2) Vol % of the minerals in the groundmass including serpentine (only groundmass); (3) Vol % of the minerals in the groundmass excluding serpentine.

* Alt olivine - serpentine associated with olivine crystals

Modal proportions

The modal proportions of the kimberlite rocks were calculated using the average compositions and volume percentages of the minerals from the 17 different areas. These were calculated for 3 different scenarios: (1) the whole rock composition including serpentine (both associated with olivine alteration and the groundmass matrix), (2) the groundmass composition including serpentine (only associated with the groundmass matrix) and (3) the groundmass composition excluding all serpentine (Fig. 3).

The SiO₂ and MgO contents decrease notably when olivine and serpentine are removed from the rock composition. The CaO contents increase significantly (10.49 wt% to 28.62 wt%) due to the high contents of monticellite and apatite in the groundmass. The H₂O content decreases significantly when the groundmass composition is calculated without serpentine (6.02 wt% to 1.82 wt%) (Fig. 3).

Components	(1)	(2)	(3)
SiO ₂	32.23	25.26	20.58
MgO	34.11	21.90	15.18
CaO	10.49	20.51	28.62
Al ₂ O ₃	1.34	2.52	3.42
Cr ₂ O ₃	0.87	1.66	2.31
Fe ₂ O ₃	0.02	0.03	0.04
FeO	7.39	7.27	7.99
MnO	0.17	0.21	0.22
NiO	0.19	0.08	0.05
TiO ₂	1.34	2.62	3.67
Na ₂ O	0.08	0.10	0.08
Ce ₂ O ₃	0.05	0.10	0.14
La ₂ O ₃	0.02	0.04	0.06
Nd ₂ O ₃	0.02	0.05	0.07
Nb ₂ O ₃	0.01	0.02	0.03
Y ₂ O ₅	-	-	-
SmO	-	0.01	0.01
Pr ₂ O ₃	0.01	0.01	0.01
Ta ₂ O ₅	-	-	-
P ₂ O ₅	2.88	5.70	8.04
ThO ₂	0.01	0.02	0.03
F	0.19	0.38	0.54
Cl	-	-	-
SrO	0.25	0.49	0.69
BaO	0.14	0.27	0.39
ZnO	-	-	-
K ₂ O	0.68	1.35	1.90
CO ₂	1.47	2.90	4.10
H ₂ O	6.02	6.48	1.82
Total	100.00	100.00	100.00

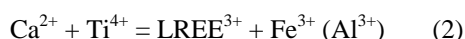
Fig. 3 Table showing the average of each element oxide wt%. (1) Wt% of each oxide in whole rock composition; (2) Wt% of each oxide in groundmass including serpentine (only groundmass); (3) Wt% of each oxide in groundmass excluding serpentine. (Marschall, H.R. and Miller, D.P. Personal Communication)

Perovskite geochemistry and oxygen fugacity

Perovskite crystallisation is controlled by the composition and temperature of the kimberlite liquid

(not the fO_2 of the magma) enabling the perovskite chemistry to provide insights into magmatic processes and the evolution of magma using *LREE*. The zoning patterns record compositional changes from the initial magma source and help constrain the modes of emplacement during ascent of kimberlite magma to the surface (Bellis and Canil 2007, *refs. there in*).

The cores of the zoned perovskite contain the highest amount of $LREE^{3+}$ (particularly Ce^{3+}) and Na^+ , while the rims show a large increase in Fe^{3+} and Al^{3+} and a decrease in $LREE^{3+}$ (Fig. 4). This is due to coupled substitutions influenced by fO_2 on to the perovskite A-site, Ca^{2+} , and the B-site, Ti^{4+} .



Wt%	(1)	(2)	(3)	(4)
CaO	34.53	36.02	36.80	37.63
TiO ₂	53.97	54.68	54.93	54.46
Fe ₂ O ₃ *	0.70	0.87	1.15	1.63
Ce ₂ O ₃	2.96	2.71	2.22	1.86
La ₂ O ₃	0.84	0.87	0.84	0.88
Nb ₂ O ₅	0.68	0.67	0.66	0.90
Nd ₂ O ₃	1.57	1.36	1.03	0.77
Na ₂ O	0.88	0.66	0.45	0.36
Al ₂ O ₃	0.09	0.10	0.15	0.21
SrO	0.26	0.25	0.30	0.27
Pr ₂ O ₃	0.34	0.32	0.29	0.13
ThO ₂	1.54	0.39	0.01	0.00
SmO	0.20	0.18	0.15	0.13
Ta ₂ O ₅	0.21	0.13	0.05	0.03
Y ₂ O ₃	0.00	0.01	0.01	0.02
SiO ₂	0.01	0.02	0.03	0.01
MnO	0.00	0.00	0.00	0.01
MgO	0.03	0.02	0.03	0.04
Total	98.84	99.27	99.11	99.32
ΔNNO	-5.24	-4.55	-3.29	-1.52

Fig. 4 Representative compositional data for the zoned perovskite. (1) and (2) represent the cores of the perovskite; (3) and (4) represent the rims of the perovskite.

*Total Fe calculate as Fe_2O_3

Due to the correlation of Na^+ and Ce^{3+} , Na^+ decreases from the core to the rim (Fig. 5). The amount of Fe^{3+} and Nb^{5+} within the cores remains constant as Na^+ decreases. There is a sudden increase in Fe^{3+} in the rims as Na^+ continues to decrease, whereas the Nb^{5+} levels undergo very little change or remain constant.

The barren kimberlite shows evidence of bi-modal cores and a wide range of fO_2 , signifying the occurrence of magma mixing and different episodes of emplacement. The cores of the zoned perovskite are the most enriched and reduced part of the crystal. The

rims are the most depleted and oxidised part of the zoned perovskite, proving to be more evolved than the (primitive) cores (Fig. 6).

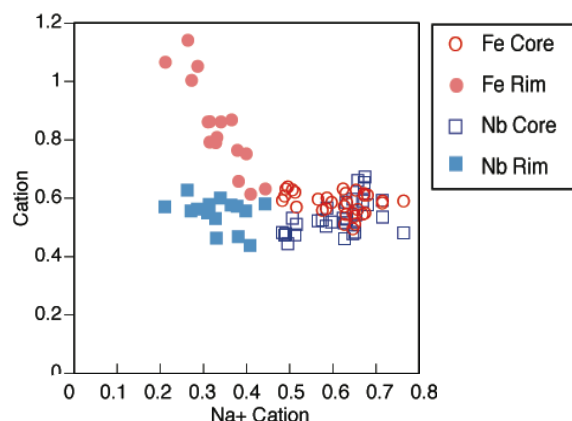


Fig. 5 Fe^{3+} and Nb^{5+} vs. Na^+ . Hollow symbols are the cores and solid symbols are the rims. Fe^{3+} and Nb^{5+} are constant in the cores as Na^+ decreases. Fe^{3+} increases significantly in the rims, Nb^{5+} remains constant. There is some evidence of bi-modal cores.

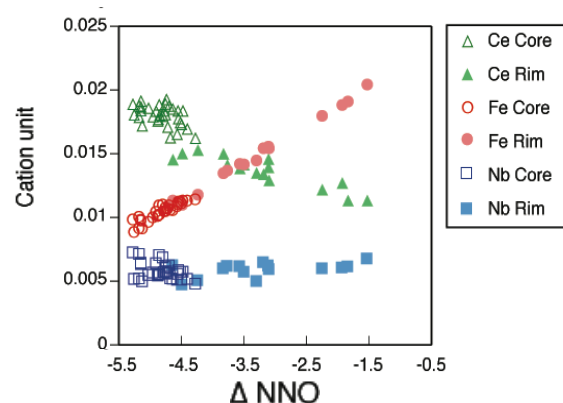


Fig. 6 Fe, Nb and Ce are in cations units per 3 oxygen vs. fO_2 . The data is split into the cores (hollow symbols) and rims (solid symbols) from the zoned perovskites. The cores are the most oxidised and the rims are the most reduced.

References

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