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SUB-VOLCANIC DEVELOPMENT OF EMBRYONIC KIMBERLITE PIPES: EVIDENCE FROM THE LACE AND VOORSPOED GROUP II KIMBERLITES, SOUTH AFRICA

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Introduction

The sub-volcanic development of embryonic kimberlite pipes is a controversial topic in current kimberlite literature and was first described by Clement (1982). Recently this theory has been further developed by Skinner and Marsh (2004) and Skinner (2008); in particular for the emplacement of South African kimberlites. Distinct globular segregationary textured kimberlite within a transitional zone between coherent and tuffisitic kimberlite has been interpreted to result from the segregation of kimberlite magma and volatile phases in a sub-volcanic environment during en masse crystallisation of the magma (Skinner and Marsh, 2004; Skinner, 2008) or as frozen de-gassing fronts in the root zone of the kimberlite (Hetman et al. 2004). Alternatively, Sparks et al. (2006) suggest that these distinct globular segregationary kimberlites form much later after vent clearing eruptions as a result of pyroclastic welding deep within the vent. The main objective of this study is to provide detailed descriptions of globular segregationary kimberlites observed at the Lace and Voorspoed Group II kimberlites in order to constrain the development of globular segregationary textures. Furthermore a model for the development of sub-volcanic embryonic pipes at the Lace and Voorspoed pipes is presented.

The Lace and Voorspoed kimberlites form part of the Kroonstad kimberlite cluster located on the Kaapvaal Craton, South Africa, approximately 200 km south west of Johannesburg. The Voorspoed volcaniclastic infill in distinctly different from typical South African tuffisitic kimberlites and has been compared with kimberlite pipes infilled with dominantly reworked tephra, such as the Jwaneng pipe (Howarth and Skinner, in review). The Lace volcaniclastic kimberlite is very similar (Howarth, 2010) and is likely formed through similar processes to that described for the Voorspoed volcaniclastic kimberlite. These pipes are classified as Class 3 type pipes; as described by Skinner and Marsh (2004). The Kroonstad kimberlites have undergone extensive post-emplacement erosion of ~1600 m (Hanson, 2006; Howarth and Skinner in review) and current exposures are deep within the original pipe.

Lace Kimberlite

The Lace kimberlite is comprised of two kimberlite pipes: a) main pipe of ~2 ha in size and b) a satellite blind pipe of ~0.5 ha. Three distinct globular segregationary kimberlites are described. Firstly, within the main pipe at depths between 250-600 m a column of incipient and variably textured globular segregationary to coherent kimberlite, which was sampled from core intersections. At the base of this column the kimberlite is typical coherent hypabyssal kimberlite. The mineralogy is described in detail in Howarth et al. (2011) and is classified as a pyroxenitised phlogopite kimberlite with low proportions of country rock xenoliths (CRX; 1 vol. %). Diopside is observed replacing the primary groundmass mineralogy, which includes: monticellite, melilite and apatite. Replacement by diopside is not pervasive and has a variable/patchy distribution throughout the groundmass. Altered CRX xenoliths typically are rimmed by diopside. It must be noted that serpentine is a rare constituent and the interstitial matrix is dominated by calcite. Olivine macrocrysts and phenocrysts are highly altered by a combination of calcite and clay minerals. Phlogopite is highly poikilitic and contains inclusions of spinel and perovskite. An incipient development of globular segregations gradually develops upward in the column and the first occurrence of the texture is observed at 595 m depth. Minor development of distinct globular structures are observed, where olivine macrocrysts or phenocrysts form central kernels with rims of groundmass kimberlite with a typical coherent hypabyssal texture. The proportion of CRX also increases gradually with decreasing depth. The kimberlite is characterized by variable development of incipient globular structures with patchy diopside distribution, observed from 600-550 m depth. A distinct zone with very high abundance of CRX is observed from 550-534 m. This zone is characterised by a

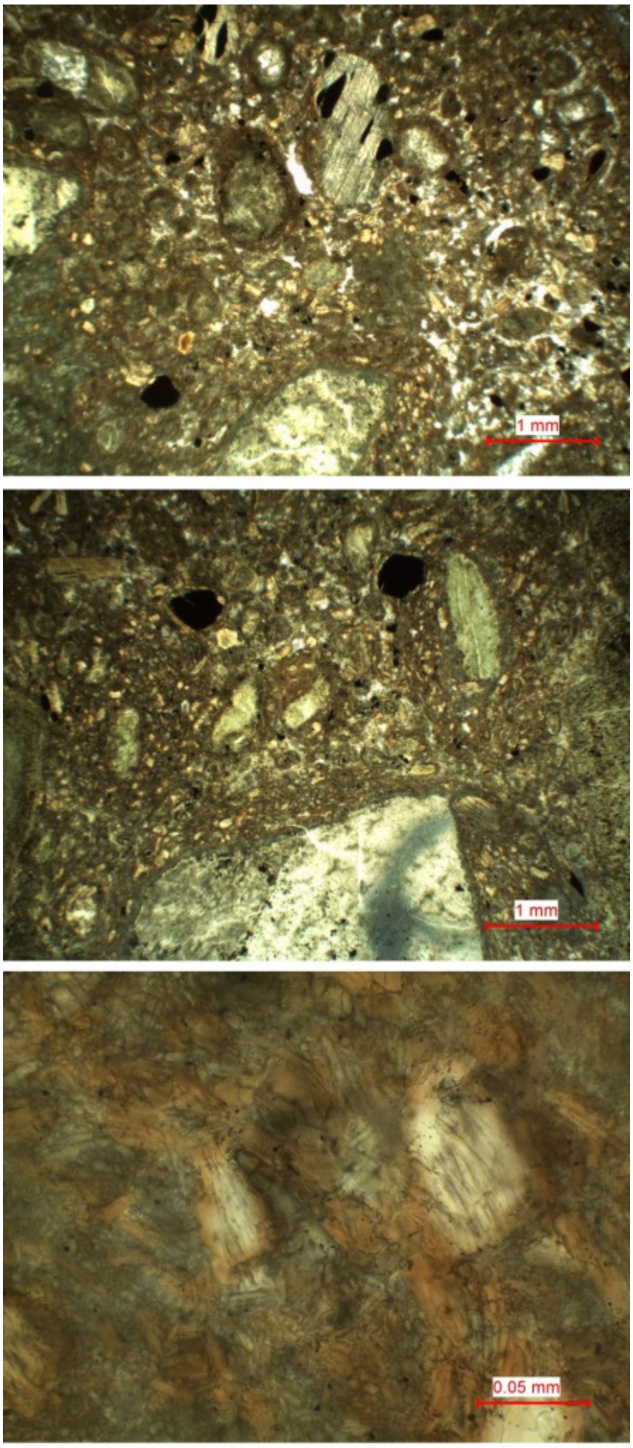

Figure 1. Incipient globular segregationary kimberlite from the Lace kimberlite (530 m depth). Top: incipient development of globules and segregations of calcite. Middle: Incipient development of globules with central kernels of altered olivine. Bottom: High power image showing pervasive alteration by diopside.

high proportion of CRX (~60 vol. %), a high degree of globular segregationary texture development and the absence of diopside replacement. Globular structures are similar to that described above and segregations in the groundmass are typically calcite. Due to the high CRX abundance, these rocks are classified as kimberlite breccias. Above this kimberlite breccia at depths of between 534-519 m the CRX proportions become far less (20 vol. %) however the globular segregationary texture is still well developed (figure 1). This rock is characterised by pervasive diopside alteration of the groundmass (figure 1). Minor development of tangential alignment is observed for the elongate phlogopite and melilite laths within globules. Above this the kimberlite is dominated by kimberlite breccia similar to that described above.

The second occurrence of globular segregationary textured kimberlite is observed from a late stage post-eruptive intrusive plug, mineralogy described by Phillips et al. (1999). The kimberlite is characterised by a typical coherent texture and is comprised of abundant altered olivine macrocrysts and phenocrysts in a groundmass of highly poikilitic phlogopite, altered monticellite, altered melilite, spinel, perovskite and apatite set in a base of calcite and serpentine. Samples from this kimberlite could only be collected from old dump sites as the open pit is no longer accessible due to the highly unstable nature of the sidewalls. In this case only very rare development of globular segregationary textures is observed and is always incipient. The globular structures are similar to those described above with central kernels of altered olivine with a rim of coherent textured kimberlite.

The final occurrence of globular segregationary kimberlite observed at the Lace kimberlite is from within the satellite blind pipe. Samples were obtained from drill core at a depth of 240-300 m depth from the surface. The kimberlite in this case is very similar to the kimberlite breccias observed from the main pipe occurrence. The kimberlite is characterised by a high proportion of CRX (35 vol. %), well developed globular segregationary texture and the absence of diopside replacement. It must be noted that within both the main pipe and blind pipe the CRX are all sourced from local sidewall lithologies, i.e. dominantly shales from the Transvaal Supergroup.

Voorspoed Kimberlite

One distinct globular segregationary kimberlite has been identified at depth within the Voorspoed pipe. This kimberlite occurs at depth (295 m) along the south western margin of the pipe. The kimberlite is characterised by a high but variable CRX proportion (20-70 vol. %). CRXs are highly angular and are all sourced from local sidewall lithologies; Transvaal Supergroup shales dominate (figure 2). The kimberlite is typically coherent textured with

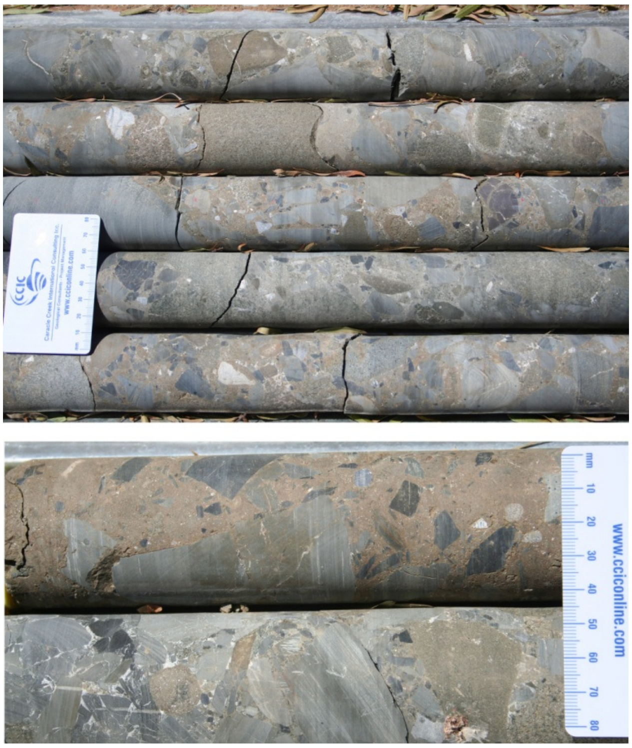

Figure 2. Photographs of borehole core from the Voorspoed coherent to globular segregationary textured kimberlite. Top: Coherent kimberlite with high abundance of CRX derived from local sidewall lithologies. Bottom: Incipient developed globular segregationary texture is evident of the lower core.

incipient development of a globular segregationary texture. Olivine occurs as phenocrysts only and no macrocrysts are observed. Olivine phenocrysts are typically euhedral to subhedral and highly altered by clay minerals and lesser calcite. The groundmass is dominated by phlogopite with lesser primary diopside and spinel. The base of the kimberlite is comprised of calcite, clay minerals and ultra fine (< 0.01mm) grains of phlogopite. Calcite also forms distinct segregations in the groundmass. The globular segregationary textures are variably developed and no distinct gradational development is observed. Globular structures are different from those described at Lace in that they typically do not contain a central kernel or tangentially aligned phlogopite laths.

Contact breccias are observed at the sidewall contacts along the northern and north-western margins of the pipe at depths of 230 m and 164 m respectively. These contact breccias are characterised by typical jigsaw fit textures where fragments are highly angular. A minor degree of rotation of the fragments is observed at the pipe margins, however away from the pipe the degree of fragmentation and rotation decreases and at ~ 20 m from the pipe only fractures are observed. The fractures are infilled with calcite only. Contact breccias typically transgress country rock lithologies. In these cases there is no mixing of fragments of different lithologies.

Discussion

Formation of Globular Segregationary Textured Kimberlite

We interpret the formation of globular segregationary textured kimberlite at the Lace and Voorspoed kimberlites to occur at depth in a sub-volcanic environment. Compelling evidence in support of this interpretation is the presence of well developed globular segregationary textured kimberlite within the satellite blind pipe at Lace. Globular segregationary kimberlite has also been described from blind intrusions at the B/K44 and A/K15 occurrences in Botswana (Field and Scott Smith, 1999) and the 5034 blind intrusion at Gahcho Kue in Canada (Hetman et al. 2004). Furthermore globular segregationary kimberlite has been described from intrusive dykes associated with the Aries kimberlite, Australia (Downes et al. 2007) as well as at the Finsch, Dutoitspan and Jagersfontein kimberlites (Clement and Skinner, 1985). The development of globular segregationary textured kimberlite, within known hypabyssal environments, has been repeated in space and time at numerous localities around the world.

In the case of the Lace main pipe there is a distinct gradational development from typical coherent hypabyssal kimberlite to globular segregationary kimberlite. This distinct gradational development has been observed at numerous tuffisitic (Class 1) kimberlite pipes; e.g. numerous South African kimberlites (Skinner and Marsh, 2004), Gahcho Kue kimberlites, Canada (Hetman et al. 2004) and the Pimenta Bueno kimberlites, Brazil (Masun and Scott Smith, 2008). In these cases coherent hypabyssal kimberlite shows a continuous gradational change to tuffisitic kimberlite. This is not the case at Lace and Voorspoed as there is no tuffisitic kimberlite present within the pipes. The pipes are infilled with re-worked tuff ring and side-wall material.

The gradational development of the globular segregationary textures at the Lace kimberlite reflects in situ formation through magmatic processes. Numerous authors (Clement, 1982; Field and Scott Smith, 1999; Skinner and Marsh, 2004 and Hetman et al. 2004) have suggested the exsolution of volatile phases as the driving mechanism for the formation of globular segregationary textures. The coherent kimberlite at depth within the Lace kimberlite resembles typical hypabyssal kimberlite described from numerous localities worldwide apart from the variable replacement of the primary mineralogy by diopside. While some of the diopside is clearly forming as a result of CRX alteration it seems unlikely that the minor proportions of CRX observed within the coherent kimberlite at the base of the Lace column can account for the patchy distribution of diopside throughout the groundmass. The complete absence of diopside alteration within the late-stage coherent kimberlite plug suggests that diopside is not forming as a result of post-emplacement alteration. Diopside forms as a result of alteration by internal hydrothermal-like fluids as suggested by Mitchell et al. (2009). The presence of diopside indicates the onset of extensive exsolution, which results in the development of globular segregationary textures in the kimberlite column above.

Model for the development of a Sub-volcanic Embryonic Pipe

A model for the development of an embryonic kimberlite pipe is presented here based on the observations from the Lace and Voorspoed kimberlites but may be applied to kimberlite pipes worldwide where similar root zones are observed. 1) Intrusion of kimberlite magma reaches 1-3 km from the surface. 2) En masse crystallisation ensues with resultant exsolution of volatile phases as a result of 2nd boiling. 3) Initial crystallisation begins with the nucleation of crystallising phases on pre-existing solid components (e.g. olivine, CRX). 4) Extensive exsolution results in the production of hydrothermal-like fluids and resultant alteration of primary groundmass mineralogy. 5) Exsolved volatile phases migrate to the head of the column where they occupy much of the interstitial spaces. 6) At depth continued crystallisation of the magma results in typical coherent textures. At the head of the column high volatile contents inhibit further crystallisation of the magma and the original nucleated globules remain intact. 7) The exsolution of volatile phases is accompanied by an increase in volume of the magma column and results in the formation of sub-volcanic breccias as a result of hydraulic fracturing of the sidewalls. 8) Decompression associated by hydraulic fracturing leads to further exsolution through 1st boiling and this quickly becomes a runaway process, as described by Burnham (1985). 9) Cracking through to the surface results in large scale decompression and resultant large scale eruption. This large scale eruption would incorporate much of the original magma column into resultant volcaniclastic kimberlite deposits.

In the case of the Voorspoed pipe globular segregationary kimberlite has been preserved within the sidewall of the pipe where it has intruded earlier formed contact breccias. At Lace the large scale decompression related eruption incorporated much of the original kimberlite column and the very base of the embryonic pipe is observed in this study at ~ 2-2.5 km (see erosion estimate for the Kroonstad cluster discussed in Howarth, 2010) from the original land surface. At this level globular segregationary textures are incipient however were likely better developed higher up in the original column.

Conclusion

The development of globular segregationary textures at the Kroonstad kimberlites is clearly occurring in a sub-volcanic environment and more specifically an embryonic pipe. Extensive exsolution of volatile phases is occurring through 1st and 2nd boiling processes resulting in significant pre-conditioning of the country rock through extensive hydraulic fracturing. We believe that the development of embryonic pipes is fundamental in understanding kimberlite emplacement.

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