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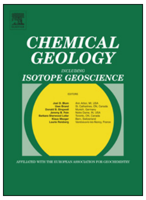

Petrographic and melt-inclusion constraints on the petrogenesis of a magmaclast from the Venetia kimberlite cluster, South Africa

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ABSTRACT

Kimberlitic magmaclasts are discrete ovoid magmatic fragments that formed prior to emplacement from disrupted kimberlite magma. To provide new constraints on the origin and evolution of the kimberlite melts, we document the mineralogy and petrography of a magmaclast recovered from one of the ca. 520 Ma Venetia kimberlites, South Africa. The sample (BI9883) has a sub-spherical shape and consists of a ~ 10 mm diameter central olivine macrocryst, surrounded by porphyritic kimberlite. The kimberlitic material consists of concentrically aligned, altered olivine phenocrysts, set in a crystalline groundmass of calcite, chromite, perovskite, phlogopite, apatite, ilmenite, titanite, sulphides, rutile and magnetite along with abundant alteration phases (i.e. serpentine, talc and secondary calcite). These features are typical of archetypal hypabyssal kimberlites.

We examined primary fluid/melt inclusions in chromite, perovskite and apatite containing a diversity of daughter phases. Chromite and perovskite host polycrystalline inclusions containing abundant alkali-carbonates (i.e. enriched in K, Na, Ba, Sr), phosphates, Na-K chlorides, sulphides and equal to lesser quantities of olivine, phlogopite and pleonaste. In contrast, apatite hosts polycrystalline assemblages with abundant alkali-carbonates and Na-K chlorides and lesser amounts of olivine, monticellite and phlogopite. Numerous solid inclusions of shortite ($Na_2Ca_2(CO_3)_3$), Na-Sr-carbonates and apatite occur in groundmass calcite along with fluid inclusions containing daughter crystals of Na-carbonates and Na-chlorides. The primary inclusions in chromite, perovskite and apatite are considered to represent remnants of fluid(s)/melt(s) trapped during crystallisation of the host minerals, whereas the fluid inclusions in calcite are probably secondary in origin. The component proportions of these primary fluid/melt inclusions were estimated in an effort to constrain the composition of the evolving kimberlite melt. These estimates suggest melt evolution from a silicate-carbonate kimberlite melt that became increasingly enriched in carbonates, phosphates, alkalis and chlorides, in response to the fractional crystallisation of constituent minerals (i.e. olivine to apatite).

The concentric alignment of crystals around the olivine kernel and ovoid shape of the magmaclast can be ascribed to the low viscosity of the kimberlite melt and rapid rotation whilst in a liquid or partial crystalline state, or to progressive layer-by-layer growth of the magmaclast. Although the mineralogy of our sample is similar to hypabyssal kimberlites worldwide, it differs from hypabyssal kimberlite units in the main Venetia pipes, which contain monticellite-phlogopite rich assemblages and segregationary matrix textures. Therefore magmaclast BI9883 probably originated from a batch of magma distinct from those that produced known hypabyssal units within the Venetia kimberlite cluster.

1. Introduction

Kimberlites are relatively rare, silica-poor, volatile-rich igneous rocks that originate from considerable mantle depths (>150–200 km; Dawson, 1980; Clement et al., 1984; Mitchell, 1986; Pearson et al., 2014). Kimberlites occur as sub-vertical pipes, sills and dykes and can be further divided into crater, diatreme and root zones (e.g., Dawson, 1971; Hawthorne, 1975; Mitchell, 1986; Sparks, 2013).

Some kimberlites contain unusual discrete spheroidal-to-ovoid fragments of kimberlite material, termed magmaclasts (Field and Scott Smith, 1998, 1999). Magmaclasts typically range in size from <1 mm up to 100 mm and are thought to have formed prior to emplacement from fragmentation/segregation of kimberlite magmas (Scott-Smith et al., 2013). However, the composition of the kimberlite magma responsible for the formation of magmaclasts and their relationship to the entraining kimberlite magma remains uncertain.

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Quantifying the composition of magmaclasts and host kimberlite rocks is hampered by several factors, including: i) kimberlites are inherently hybrid rocks that include xenolithic and magmatic components (e.g., Dawson, 1980; Brett et al., 2009; Arndt et al., 2010; Giuliani et al., 2016); ii) kimberlite melts commonly entrain and assimilate mantle and crustal xenoliths and xenocrysts (e.g., Hunter and Taylor, 1982; Kamenetsky and Yaxley, 2015; Soltys et al., 2016), iii) the magmas degas volatiles (CO_2 and H_2O) *en route* to the surface and upon emplacement; iv) kimberlite rocks are often extensively altered by post-emplacement meteoric or hydrothermal fluids (e.g., Sparks et al., 2006, 2009; Giuliani et al., 2014b, this issue). To circumvent these problems, analyses of melt/fluid inclusions trapped within magmatic minerals can provide alternative insights into the kimberlite melt composition prior to post-magmatic alteration (e.g., Kamenetsky et al., 2014).

To provide constraints on the origin and composition of the kimberlite melts that produce kimberlite magmaclasts, we present a detailed study of the petrography and mineralogy of a single magmaclast (BI9883) recovered from a mine dump in the Venetia cluster of kimberlites in north-eastern South Africa. Our petrographic results show that this magmaclast hosts a mineral assemblage typical of Group-I (or archetypal) hypabyssal kimberlites (Smith, 1983; Mitchell, 1986, 2008; Skinner, 1989). Additionally, our analyses of melt/fluid and solid inclusions hosted in a variety of groundmass minerals (chromite, perovskite, apatite and calcite) reveal a systematic change in inclusion compositions, which is broadly related to the relative timing of host mineral crystallisation from the kimberlite melt.

2. Geological setting

The Venetia kimberlite cluster comprises 14 kimberlite pipes and dykes emplaced within an area of 4 km^2 in the north-eastern Limpopo Province of South Africa (Seggie et al., 1999; Kurszlaukis and Barnett, 2003). These kimberlites have intruded Precambrian metamorphic rocks (3.3–2.0 Ga) of the Limpopo Mobile Belt (Barton et al., 2003), which probably developed from the collision between the Kaapvaal and Zimbabwe cratons (Barton et al., 1983; Van Reenen et al., 1987). The Venetia country-rocks include amphibolite gneisses, biotite schists, metaquartzites and marbles (Van Reenen et al., 1987; Allsopp et al., 1995; Fontana et al., 2011). These kimberlites have been classified as Group-I (or archetypal) kimberlites, based on their monticellite-phlogopite mineralogy and major trace element and isotope geochemistry (Seggie et al., 1999). Rb-Sr dating of phlogopite from pipe K1 produced an isochron age of 510 ± 16 Ma (2σ; Allsopp et al., 1995), and ^{40}Ar-^{39}Ar dating of groundmass phlogopite provided an age of 519.2 ± 1.2 Ma (2σ; Phillips et al., 1999). The Venetia kimberlites form pipes of irregular shape, sometimes associated with thin kimberlite dykes occurring around the pipe margins (Brown et al., 2008). The main pipes (i.e. K1, K2) contain a variety of mantle and crustal xenoliths (up to 20–30% vol.%; Walters et al., 2006) and are currently mined for diamonds with an average grade of 122 cpht (Field et al., 2008).

3. Sample description

Sample BI9883 was derived from the Venetia mine dumps and is therefore likely derived from either the K1 or K2 kimberlite pipes. The studied sample represents a coherent kimberlite magmaclast that is sub-spherical in shape and approximately 60 mm in maximum diameter. The sample has a porphyritic texture defined by concentrically aligned olivine phenocrysts (1–5 mm in length) around a central core formed by a single olivine macrocryst (~10 mm; Fig. 1a). The edges of the magmaclast are defined by distorted groundmass textures and extensive mineral alteration (i.e. olivine and phlogopite) to admixtures of serpentine and talc, along with deformation of larger (>100 μm) phlogopite grains. In this sample, olivine is extensively serpentinised, in common with olivine in other samples from the Venetia kimberlites (Allsopp et al., 1995; Stripp et al., 2006; Kurszlaukis and Barnett, 2003). Altered olivine phenocrysts are set in a groundmass of (in order of decreasing abundance) calcite, chromite, perovskite, phlogopite, apatite, ilmenite, titanite, sulphides, rutile and magnetite along with abundant alteration phases (i.e. serpentine, talc and secondary calcite).

Different varieties of magmaclasts have been reported from the Venetia kimberlites, including accretionary (armoured) lapilli (Kurszlaukis and Barnett, 2003), pyroclasts (Medlin, 2005) and pelletal lapilli (Stripp et al., 2006; Gernon et al., 2012). Sample BI9883 bears broad petrographic and mineralogical similarities to descriptions of pelletal lapilli from a pyroclastic intrusion in the Venetia pipe K1, which contains abundant pelletal lapilli and bomb-sized clasts (up to 90 vol.%; Tait and Brown, 2008; Gernon et al., 2012). The pelletal lapilli described by Gernon et al. (2012) commonly contain a sub-angular lithic clast or olivine macrocryst nucleus that is coated by olivine, phlogopite and spinel-bearing kimberlite material, commonly with concentrically aligned crystals around the core. Although mineralogically similar, our sample is considerably larger (~60 mm) than the pelletal lapilli reported by Gernon et al. (2012), which show an average diameter of 9.4 mm, and size range of 0.03–32 mm. Kimberlite samples with similar features have also been described as nucleated autoliths (Ferguson et al., 1973; Danchin et al., 1975); however Clement (1982) and Mitchell (1986, 1995) subsequently described these magmaclasts as varieties of larger pelletal lapilli. Given the ambiguity of these definitions, we prefer the term magmaclast for our current sample.

4. Analytical methods

Polished thin sections of sample BI9883 were prepared using kerosene as a lubricant rather than water to avoid dissolution of any soluble minerals present. Initial mineralogical and textural investigations were undertaken using a petrographic microscope and a Philips (FEI) XL30 ESEM TMP, equipped with an OXFORD INCA energy-dispersive X-ray spectrometer (EDS) at the University of Melbourne.

More detailed examinations of the inclusions in mineral phases were carried out using a Hitachi SU-70 field emission SEM equipped with an Oxford INCA Energy XMax 80 detector at the Central Science Laboratory, University of Tasmania. A beam accelerating voltage of 15 kV was employed to produce high-resolution backscattered electron (BSE) images of minerals and energy-dispersive X-ray spectroscopy (EDS) semi-quantitative analyses and elemental maps of minerals and inclusions. In addition, the inclusions in calcite were characterised using a Renishaw inVia Raman microscope equipped with a 532 nm laser, operated at 225 μW, with 1 s exposure and 10 accumulations, a 1800 l/mm grating and a 50× objective microscope.

The major oxide compositions of chromite and ilmenite were measured at the Central Science Laboratory, University of Tasmania, using a Cameca SX100 electron microprobe with a beam accelerating voltage of 20 kV, beam current of 15 nA and beam size of 2 μm. Detection limits (99% confidence) were 0.01 wt.% for Si, Ti, Al and Ca, 0.02 wt.% for Nb, V, Ni and Mg, and 0.03 wt.% for Zn, Cr, Fe and Mn. Analytical precision (1σ) was 0.01 wt.% for Nb, Si, Zn, V, Ni and Ca, 0.03 wt.% for Ti and Al, 0.04 wt.% for Mn and Mg, and 0.06 wt.% for Cr and Fe.

5. Petrography

Magmaclast sample BI9883 contains a central olivine macrocryst core as well as phenocrysts, micro-phenocrysts and/or xenocrysts of olivine and rare phlogopite microcrysts, set in a fine-grained groundmass. The groundmass (Fig. 1b and c) consists primarily of fine-grained interstitial serpentine and calcite, including aggregates of coarser calcite, with subordinate amounts of (in order of decreasing abundance) chromite, perovskite, phlogopite, apatite, ilmenite, titanite, sulphides, rutile and magnetite. This assemblage is typical of archetypal hypabyssal kimberlites (e.g., Mitchell, 1995, 2008).

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