Constraints on kimberlite ascent mechanisms revealed by phlogopite compositions in kimberlites and mantle xenoliths

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ABSTRACT

Kimberlite magmas are of economic and scientific importance because they represent the major host to diamonds and are probably the deepest magmas from continental regions. In addition, kimberlite magmas transport abundant mantle and crustal xenoliths, thus providing fundamental information on the composition of the subcontinental lithosphere. Despite their importance, the composition and ascent mechanism(s) of kimberlite melts remain poorly constrained. Phlogopite is one of the few minerals that preserves a history of fluid migration and magmatism in the mantle and crust and is therefore an invaluable petrogenetic indicator of kimberlite magma evolution.

Here we present major and trace element compositional data for phlogopite from the Bultfontein kimberlite (Kimberley, South Africa; i.e. the kimberlite type-locality) and from entrained mantle xenoliths. Phlogopite macrocrysts (~ > 0.3–0.5 mm) and microcrysts (between ~0.1 and 0.3 mm) in the Bultfontein kimberlite display concentric compositional zoning patterns. The cores of these phlogopite grains exhibit compositions typical of phlogopite contained in peridotite mantle xenoliths. However, the rims of some grains show compositions analogous to kimberlite groundmass phlogopite (i.e. high Ti, Al and Ba; low Cr), whereas other rims and intermediate zones (between cores and rims) exhibit unusually elevated Cr and lower Al and Ba concentrations. The latter compositions are indistinguishable from matrix phlogopite in polymict breccia xenoliths (considered to represent failed kimberlite intrusions) and from Ti-rich overgrowth rims on phlogopite in other mantle xenoliths. Consequently, it is likely that these phlogopite grains crystallized from kimberlite melts and that the high Ti-Cr zones originated from earlier kimberlite melts at mantle depths.

We postulate that successive pulses of ascending kimberlite magma progressively metasomatised the conduit along which later kimberlite pulses ascended, producing progressively decreasing interaction with the surrounding mantle rocks. In our view, these processes represent the fundamental mechanism of kimberlite magma ascent. Our study also indicates that, in addition to xenoliths/xenocrysts and magmatic phases, kimberlite rocks incorporate material crystallized at various mantle depths by previous kimberlite intrusions (mantle-derived 'antecrysts').

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1. Introduction

Kimberlites are of great economic and scientific value because they are the major hosts to diamonds, entrain abundant mantle and crustal xenoliths and represent the deepest magmas (>150–200 km) produced in the mantle that we may observe at the Earth's surface. At the surface, kimberlites occur as diatremes, sills and dykes. Mapping indicates that kimberlite diatremes typically comprise multiple units that originated from discrete magma batches, whereas sills and dykes represent one or more discrete magma pulses at surface (e.g., Clement, 1982; Dawson and Hawthorne, 1970; Field and Scott Smith, 1999; Mitchell, 1986, 1995; Nowicki et al., 2004; Sparks, 2013).

Despite the importance of kimberlites, and at least 40–50 years of dedicated studies, several unresolved issues remain in relation to different aspects of kimberlite petrology, geochemistry, mineralogy and volcanology. These include, but are not limited to:

1) The composition of kimberlite melts upon formation in the deep Earth and at the time of emplacement in the upper crust (e.g., see contrasting views of Kopylova et al., 2013 and Kamenetsky et al., 2014) and the extent to which kimberlite melts are modified by interaction with, and assimilation of, wall-rock material (e.g., Donnelly et al., 2012; Kamenetsky and Yaxley, 2015; Kirkley

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et al., 1989; Malarkey et al., 2010; Mitchell, 2008; Patterson et al., 2009; Pilbeam et al., 2013).

2) The depth of kimberlite melt formation, i.e. the asthenosphere (e.g., Griffin et al., 2014; Haggerty, 1994; Paton et al., 2009; Ringwood et al., 1992; Smith, 1983; Tappe et al., 2011, 2013) *vs* the lithosphere (e.g., Becker and le Roex, 2006; Gaffney et al., 2007; le Roex et al., 2003; Tainton and McKenzie, 1992).

3) The causes of the very fast ascent (several m/s; Canil and Fedortchouk, 1999; Kelley and Wartho, 2000; Peslier et al., 2008) of kimberlite magmas (cf. Brett et al., 2015, and Russell et al., 2012 *vs* Kamenetsky and Yaxley, 2015; Wilson and Head, 2007 *vs* Sparks et al., 2007; Gregoire et al., 2006).

4) The extent to which kimberlite rocks are modified by syn- and post-emplacement processes including alteration by ground waters (e.g., see contrasting views of Mitchell, 2008, 2013 and Afanasyev et al., 2014; Giuliani et al., 2014b; Sparks, 2013; Stripp et al., 2006).

The purpose of this contribution is to provide new insights into two of the above controversies, namely, the ascent mechanism(s) of kimberlite magmas and the evolution of kimberlite melts during ascent through the lithospheric mantle. We leave the remaining questions to future studies.

The driving forces that promote the rapid ascent of kimberlite magmas are poorly constrained. For example, Russell et al. (2012) proposed that exsolution of a CO_2-rich vapour phase at mantle depths provides the main propellant for kimberlite melt ascent. However, this hypothesis is at odds with the carbonate-rich nature of kimberlite matrices and, hence, the parental magma(s) (e.g., Brooker et al., 2011; Kamenetsky et al., 2004, 2014; Nielsen and Sand, 2008; Patterson et al., 2009), as well as the non-explosive emplacement of many kimberlite magmas (e.g., magmatic dykes several km in length) (e.g., Andrews and Emeleus, 1975; Mitchell, 1986; Nielsen and Sand, 2008). Conversely, if magma ascent is not driven by volatile exsolution as proposed by Gregoire et al. (2006), we might expect the highly reactive kimberlite melts to be entirely consumed through reaction with mantle wall rocks. In fact, experiments using bulk kimberlite rock (Canil and Fedortchouk, 1999; Chepurov et al., 2013) and Na-carbonate compositions (Kamenetsky and Yaxley, 2015) as proxies for kimberlite melts have shown that orthopyroxene, clinopyroxene, garnet and, to a lesser extent, olivine in mantle peridotites are unstable and dissolve in kimberlite magmas at mantle pressure and temperature conditions. Petrographic observations of resorbed orthopyroxene, clinopyroxene and garnet in kimberlite rocks (Hunter and Taylor, 1982; Kamenetsky et al., 2009; Mitchell, 2008; Shee et al., 1994) confirm the instability of these minerals in kimberlite magmas. The experimental and petrographic evidence for assimilation of entrained mantle material by kimberlite melts implies that (1) the composition of kimberlite melts must vary during their rise to surface; and (2) the ascent of kimberlite magmas to the Earth's surface requires unique conditions, such as partial shielding from the wall rocks lining the magma conduit (Giuliani et al., 2014a).

Investigations of the evolution of kimberlite magmas require phases that preserve geochemical signatures of magma interaction during transport through both the crust and the mantle. One such phase is phlogopite. Phlogopite is a common mineral in kimberlites where it spans a range of size from macrocryst (~>0.5 mm) to groundmass phase (~<0.1 mm), and preserves large compositional variations, thus providing a useful repository of information on the evolution of kimberlite and related melts (Beard et al., 2000; Downes et al., 2006; Fritschle et al., 2013; Hunter et al., 1984; Mitchell, 1986, 1995; O'Brien et al., 1988; Reguir et al., 2009). Phlogopite is also a common mineral in metasomatised mantle rocks (Boettcher and O'Neil, 1980; Carswell, 1975; Dawson and Smith, 1977; Erlank et al., 1987; Grégoire et al., 2002; Jacob et al., 2009; Jones et al., 1982; Konzett et al., 2000; Rehfeldt et al., 2008; Waters, 1987), including those preserving evidence of interaction with kimberlite-related melts immediately prior

to kimberlite eruption (e.g., Boyd et al., 1983; Dawson et al., 2001; Farmer and Boettcher, 1981; Giuliani et al., 2012, 2013a, 2014b).

In this contribution, we compare the major and trace element compositions of phlogopite macrocrysts, microcrysts and groundmass grains in the Bultfontein kimberlite (Kimberley, South Africa (Fig. 1); i.e. the kimberlite type-locality) with phlogopite crystals in mantle xenoliths entrained by the Kimberley kimberlites. Phlogopite grains in the Bultfontein kimberlite exhibit multiple concentric zoning patterns that record a complex history of crystal growth episodes and interaction with mantle wall rocks. These zoning profiles reveal that individual kimberlite units in diatremes, sills and dykes are not necessarily the product of a single pulse of kimberlite melt, but can result from complex, multi-stage emplacement and interaction mechanisms that are often obscured by the very complexity of these rocks. Outcomes of this work also support our previous inference that kimberlite magmas probably only reach the surface if they ascend along conduits that have already been metasomatised by previous pulses of kimberlite melt (Giuliani et al., 2014a).

1.1. Phlogopite in the Kimberley kimberlites and entrained mantle xenoliths

Limited petrographic and compositional data exists for phlogopite hosted in the Kimberley kimberlites. Clement (1982) reported that phlogopite occurs as megacrysts (>10 mm), macrocrysts (0.3–10 mm), phenocrysts and groundmass grains in these kimberlites. Macrocrysts, phenocrysts and groundmass grains display complex, multiple zoning; in particular dark-coloured overgrowths often rim partially resorbed cores of macrocrysts. Shee (1985) provided additional details on the compositions of phlogopite in the Wesselton kimberlite, which is part of the Kimberley cluster (see Section 2). He reported that macrocryst cores have compositions analogous to phlogopite in metasomatised mantle rocks from the Kimberley area. In addition, phlogopite macrocrysts display deformation features (e.g., kink-banding, undulose extinction) attributed to transport from mantle depths. Shee (1985) and Clement (1982) suggested that most phlogopite macrocrysts probably originated from disaggregation of metasomatised mantle rocks as previously proposed for some phlogopite megacrysts from southern African kimberlites (Dawson and Smith, 1975). Interestingly, Shee (1985) reported high Ti-Cr compositions for some macrocryst rims, which are distinct from the compositions of groundmass mica in the Wesselton kimberlite; these rims host inclusions of spinel of undefined composition.

Apart from the detailed work of Clement (1982) and Shee (1985), Dawson and Smith (1975) and Boettcher and O'Neil (1980) reported the major element compositions of megacrysts from the Kimberley kimberlites. Allsopp and Barrett (1975) reported the Rb-Sr isotope systematics of phlogopite from some of the Kimberley kimberlites and Fitch and Miller (1983) analysed the K-Ar isotope composition of mica from the De Beers pipe, also part of the Kimberley cluster.

Several studies have documented the petrography and geochemistry of mica in mantle xenoliths from the Kimberley kimberlites (e.g., Boettcher and O'Neil, 1980; Boyd et al., 1983; Carswell, 1975; Dawson and Smith, 1977; Delaney et al., 1980; Erlank et al., 1987; Farmer and Boettcher, 1981; Giuliani et al., 2013a,c, 2014a,b,c; Grégoire et al., 2002; Jacob et al., 2009; Jones et al., 1982; Konzett et al., 2000; Matson et al., 1986; Rehfeldt et al., 2008; Rosenbaum, 1993; Shee, 1985; Simon et al., 2007; Waters, 1987). Phlogopite in mantle xenoliths commonly occurs as laths of variable size (rarely exceeding 1 cm in size) associated with other metasomatic minerals such as clinopyroxene, K-richterite, ilmenite, rutile, titanates, sulphides, etc. The composition of these phlogopite laths is usually homogeneous, but, in some xenoliths, darker rims enriched in Ti are observed (Delaney et al., 1980; Farmer and Boettcher, 1981; Giuliani et al., 2014a; Jones et al., 1982; Rosenbaum, 1993). Irrespective of the presence of large phlogopite laths, several mantle xenoliths host a second generation of phlogopite, which occurs as interstitial, fine-grained, dark-coloured