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Fluid-induced transition from banded kyanite- to bimineralic eclogite and implications for the evolution of cratons

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Abstract

Heterogeneous, modally banded kyanite-bearing and bimineralic eclogites from the lithospheric mantle, collected at the Roberts Victor Diamond mine (South Africa), show a reaction texture in which kyanite is consumed. Geothermobarometric calculations using measured mineral compositions in Perple_X allowed the construction of a *P-T* path showing a steep, cool prograde metamorphic gradient of 2 °C/km to reach peak conditions of 5.8 GPa and 890 °C for the kyanite eclogite. The kyanite-out reaction formed bimineralic eclogite and is probably an integral part of the mineralogical evolution of most archetypal bimineralic eclogites at Roberts Victor and potentially elsewhere. The kyanite-out reaction occured at close to peak pressure (5.3 GPa) and was associated with a rise in temperature to 1380 °C. Mass balance calculations show that upon breakdown, the kyanite component is fully accommodated in garnet and omphacite via a reaction system with low water fugacity that required restricted fluid influx from metasomatic sources. The $\delta^{18}O$ values of garnets are consistently higher than normal mantle values. Each sample has its characteristic trend of $\delta^{18}O$ variance between garnets in the kyanite-bearing sections and those in the bimineralic parts covering a range between 5.1‰ and 6.8‰. No systematic change in O-isotope signature exists across the sample population. Differences in garnet trace element signatures between differing lithologies in the eclogites are significant. Grossular-rich garnets coexisting with kyanite have strong positive Eu-anomalies and low Gd/Yb ratios, while more pyrope-rich garnets in the bimineralic sections have lost their positive Eu-anomaly, have higher Gd/Yb ratios and generally higher heavy rare earth element contents. Garnets in the original kyanite-bearing portions thus reflect the provenance of the rocks as metamorphosed gabbros/troctolites. The kyanite-out reaction was most likely triggered by a heating event in the subcratonic lithosphere. As kyanite contains around 100 ppm of H_2O it is suggested that the kyanite-out reaction, once initiated by heating and restricted metasomatic influx, was promoted by the release of water contained in the kyanite. The steep (high-P low-T) prograde *P-T* path defining rapid compression at low heating rates is atypical for subduction transport of eclogites into the lithospheric mantle. Such a trajectory is best explained in a model where strong lateral compression forces eclogites downward to higher pressures, supporting models of cratonic lithosphere formation by lateral collision and compression.
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Keywords: Kaapvaal craton; Cratonic lithosphere; Perple_X; Kyanite; Oxygen isotopes; Eclogite

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1. INTRODUCTION

Many eclogite xenoliths brought up by kimberlites are subducted oceanic crustal rocks with an often complex history of melting and metasomatic re-enrichment in the mantle (Shervais et al., 1988; Taylor and Neal, 1989; Jacob et al., 1994; Viljoen et al., 1994; Snyder et al., 1997; Barth et al., 2001; Shirey et al., 2001; Usui et al., 2006; Nikitina et al., 2014; Dongre et al., 2015). Some eclogite xenolith suites are interpreted as subducted residues of tonalitic melt removal (Ireland et al., 1994; Rollinson, 1997; Jacob and Foley, 1999; Barth et al., 2002; Rapp et al., 2003; Tappe et al., 2011; Pernet-Fisher et al., 2014; Smit et al., 2014) and more rarely, some are interpreted to represent high-pressure magmatic cumulates (e.g. MacGregor and Carter, 1970; Snyder et al., 1997; Taylor et al., 2003; Greau et al., 2011; Huang et al., 2012). Radiogenic ages of eclogite xenoliths reach well back into the Archaean (Pearson et al., 1995; Jacob and Foley, 1999; Shirey et al., 2001; Tappe et al., 2011; Aulbach and Viljoen, 2015) and are interpreted to represent the age of metamorphism/subduction. These rocks are thus amongst the oldest high-grade metamorphic rocks on Earth and may represent some of the best preserved samples of Archaean oceanic crust.

Most eclogite xenoliths in kimberlites are bimineralic in nature and are likely to have been modified by melt extraction, metasomatism, or both. In contrast, kyanite-bearing eclogites occur in the xenolith suites of a number of kimberlite localities worldwide and probably represent a more pristine sample of the eclogite assemblage judging from the reaction textures observed in some of them (Lappin and Dawson, 1975). At the Roberts Victors Mine on the Kaapvaal craton in South Africa, kyanite eclogites are relatively common where particularly large specimens of kyanite-bearing eclogite have been found, often interlayered with bimineralic lithologies. Kyanite is a prograde metamorphic mineral that forms by the breakdown of plagioclase in gabbroic rocks of the oceanic crust (Shu et al., 2016). Its occurrence in eclogite xenoliths is key evidence of their crustal origin, because the high Al_2O_3 content of kyanite excludes equilibrium with the peridotitic mantle, and high-pressure mantle melts cannot precipitate kyanite (Jacob et al., 1998). In the absence of a fluid or melt to facilitate diffusion and melting (Wayte et al., 1989), kyanite can persist in metastable form at basal lithospheric temperatures and pressures (ca. 1300 °C, 5.5 GPa, Mather et al., 2011). Upon breakdown, the aluminum from kyanite can be accommodated in the extensive solid-solution series of garnet and clinopyroxene. Petrographic evidence for kyanite resorption and breakdown is common in the eclogite xenolith record (e.g. Lappin and Dawson 1975; Dongre et al., 2015). The layered kyanite eclogites from Roberts Victor provide perhaps the most spectacular examples of this process.

This study presents a detailed quantitative geochemical and mass balance study of five large kyanite-bearing eclogites from the Roberts Victor Mine. We show that the kyanite-bearing portions of these composite xenoliths represent relict low-pressure assemblages developed in a prograde *P-T* path, while the associated bimineralic parts are fluid-assisted subsolidus reaction products of a kyanite-out reaction that occurred at mantle pressures and temperatures.

2. THE ROBERTS VICTOR KIMBERLITE AND ITS ECLOGITE SUITE

The Roberts Victor Mine is situated in the Kaapvaal craton, RSA in close vicinity to the Colesberg lineament (Silver et al., 2004). The mine consists of two small pipes that intrude the Beaufort Sandstone and Karoo Basalts (Field et al., 2008). The kimberlite is classified as a mica-rich Group-2 kimberlite and is dated at ~128 Ma using Rb–Sr on phlogopites (Smith et al., 1985). It is extraordinarily rich in mantle xenoliths, especially in eclogites, which make up 80–90% of the fresher xenoliths in this pipe (MacGregor and Carter, 1970). The age of the eclogite xenolith suite is 2700 ± 100 Ma using Sm-Nd (Jagoutz et al., 1984). In contrast to the xenoliths, the heavy mineral concentrate in Roberts Victor is dominated by peridotitic material (Schulze, 1989); the few peridotitic xenoliths found at Roberts Victor are diamondiferous (Viljoen et al., 1994) but highly altered.

A combined textural-compositional classification based of bimineralic eclogites differentiates diamondiferous Group I eclogites as equilibrated at high *P-T* (4.5–7.0 GPa, 980–1550 °C), displaying subhedral garnets with high Na_2O concentration >0.09 wt%, and Group II eclogites, which are non-diamondiferous, equilibrated at lower *P-T* (1.7–4.5 GPa, 730–1100 °C), with interlocking angular mineral fabric and lower Na_2O contents in garnet (MacGregor and Carter, 1970; McCandless and Gurney, 1989). Group I eclogites make up the majority of the suite at Roberts Victor and can be strongly metasomatized (e.g., Greau et al., 2011), while Group II eclogites are generally very fresh, but are much rarer. Kyanite-bearing eclogites, such as the samples in this study, are interlayered with bimineralic Group I eclogites and are thus affiliated with this group, although other classifications distinguish them as a separate group (Huang et al., 2012). Some kyanite-bearing eclogites are grospydites (**gros**sular–**py**roxene–**dis**thene rocks; Sobolev, 1977), distinguished by very Al-rich bulk compositions and garnets with >50 mol% grossular component.

3. MATERIALS AND METHODS

3.1. Samples and petrography

Five kyanite-bearing layered eclogites were chosen from a large suite: three are previously unstudied (RV1570, DEJ1, BD1987) and two have been worked on before (RV124: Jacob and Jagoutz, 1994; BD1168: named 'sample 6913' in Lappin and Dawson, 1975). All samples show modal and compositional layering and either contain a kyanite-bearing part as a layer irregularly sandwiched between bimineralic layers (Fig. 1) or more diffuse layers with kyanites irregularly distributed throughout the rock (DEJ1). The kyanite-bearing areas in each sample except for DEJ1 contain a reaction zone towards the bimineralic sections, in

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