ELSEVIER

Available online at www.sciencedirect.com

ScienceDirect

Geochimica et Cosmochimica Acta 213 (2017) 574–592

Geochimica et Cosmochimica Acta

www.elsevier.com/locate/gca

Eclogite xenoliths from Orapa: Ocean crust recycling, mantle metasomatism and carbon cycling at the western Zimbabwe craton margin

S. Aulbach [a,*], D.E. Jacob [b], P. Cartigny [c,d], R.A. Stern [e], S.S. Simonetti [f], G. Wörner [c], K.S. Viljoen [g]

[a] *Inst. Geosciences, Goethe-Universität, Altenhöferallee 1, Frankfurt am Main, Germany*
[b] *Australian Research Council Centre of Excellence for Core to Crust Fluid Systems and Department of Earth and Planetary Sciences, Macquarie University, North Ryde, New South Wales 2109, Australia*
[c] *Abteilung Geochemie, Geowissenschaftliches Zentrum (GZG), Universität Göttingen, Goldschmidtstr. 1, 37077 Göttingen, Germany*
[d] *Laboratoire de Géochimie des Isotopes Stables, Institut de Physique du Globe de Paris, Université Paris Diderot, Centre National de la Reserche Scientifique, UMR 7154, Sorbonne Paris-Cité, 75005 Paris, France*
[e] *Canadian Centre for Isotopic Microanalysis, Department of Earth and Atmospheric Sciences, University of Alberta, Edmonton, AB T6G 2E3, Canada*
[f] *Department of Civil & Environmental Engineering & Earth Sciences, University of Notre Dame, IN 11 46556, USA*
[g] *Department of Geology, University of Johannesburg, PO Box 524, Auckland Park, 2006 Johannesburg, South Africa*

Received 9 November 2016; accepted in revised form 21 June 2017; available online 1 July 2017

Abstract

Major- and trace-element compositions of garnet and clinopyroxene, as well as $^{87}Sr/^{86}Sr$ in clinopyroxene and $\delta^{18}O$ in garnet in eclogite and pyroxenite xenoliths from Orapa, at the western margin of the Zimbabwe craton (central Botswana), were investigated in order to trace their origin and evolution in the mantle lithosphere. Two groups of eclogites are distinguished with respect to $^{87}Sr/^{86}Sr$: One with moderate ratios (0.7026–0.7046) and another with $^{87}Sr/^{86}Sr$ >0.7048 to 0.7091. In the former group, heavy $\delta^{18}O$ attests to low-temperature alteration on the ocean floor, while $^{87}Sr/^{86}Sr$ correlates with indices of low-pressure igneous processes (Eu/Eu*, Mg#, Sr/Y). This suggests relatively undisturbed long-term ingrowth of ^{87}Sr at near-igneous Rb/Sr after metamorphism, despite the exposed craton margin setting. The high-$^{87}Sr/^{86}Sr$ group has mainly mantle-like $\delta^{18}O$ and is suggested to have interacted with a small-volume melt derived from an aged phlogopite-rich metasome.

The overlap of diamondiferous and graphite-bearing eclogites and pyroxenites over a pressure interval of ~3.2 to 4.9 GPa is interpreted as reflecting a mantle parcel beneath Orapa that has moved out of the diamond stability field, due to a change in geotherm and/or decompression. Diamondiferous eclogites record lower median $^{87}Sr/^{86}Sr$ (0.7039) than graphite-bearing samples (0.7064) and carbon-free samples (0.7051), suggesting that interaction with the – possibly oxidising – metasome-derived melt caused carbon removal in some eclogites, while catalysing the conversion of diamond to graphite in others. This highlights the role of small-volume melts in modulating the lithospheric carbon cycle. Compared to diamondiferous eclogites, eclogitic inclusions in diamonds are restricted to high FeO and low SiO_2, CaO and Na_2O contents, they record higher

---

* Corresponding author.
E-mail address: s.aulbach@em.uni-frankfurt.de (S. Aulbach).

http://dx.doi.org/10.1016/j.gca.2017.06.038

equilibrium temperatures and garnets have mostly mantle-like O isotopic composition. We suggest that this signature was imparted by a sublithospheric melt with contributions from a clinopyroxene-rich source, possibly related to the ca. 2.0 Ga Bushveld event.

Keywords: Kimberlite-borne xenoliths; Archaean oceanic crust; Diamond stability; Mantle metasomatism; Strontium isotopes; Oxygen isotopes; Mantle heterogeneities

1. INTRODUCTION

Kimberlite-borne mantle eclogite xenoliths with oceanic crustal protoliths have been the subject of intense investigation (reviews in Jacob, 2004; Aulbach and Jacob, 2016), as their presence in the cratonic lithosphere is thought to support the operation of some form of plate tectonic process: Cratons may have widened and thickened by accretion of oceanic lithosphere, while loss of silicic partial melt, similar to tonalite-trondhjemite-granodiorites (TTGs) typically found in Archaean granite-greenstone belts, from subducting basalt may have contributed to growth of continental crust (Ireland et al., 1994; Rollinson, 1997; Shirey et al., 2001; Foley et al., 2002a; Rapp et al., 2003; Lee, 2006; Shirey and Richardson, 2011; Pearson and Wittig, 2008, 2014). In addition, mantle eclogites host a disproportionate amount of gem-quality diamonds relative to their subordinate abundance in the cratonic mantle (Stachel and Luth, 2015). Finally, eclogite xenoliths potentially represent our only samples of ancient oceanic crust (Helmstaedt and Doig, 1975; MacGregor and Manton, 1986; Jacob and Foley, 1999; Foley, 2011) and as such may hold clues to the thermal, redox and chemical state of the ambient convecting mantle, from which their protoliths are ultimately derived (Aulbach and Viljoen, 2015).

Amongst mantle eclogite localities, the Orapa kimberlite cluster is noteworthy for several reasons: (1) It is one of the few kimberlites yielding predominantly eclogitic xenoliths, other examples being Jwaneng (also in Botswana) as well as Premier, Roberts Victor and Kaalvallei in the Kaapvaal craton (Viljoen et al., 1996, 2005; Shirey et al., 2002) and Koidu in the West African craton (Hills and Haggerty, 1989). (2) The kimberlites also yielded predominantly eclogitic inclusion-bearing diamonds (~85%; Gurney et al., 1984) and eclogitic minerals occurring along with polycrystalline diamond (framesite; Jacob et al., 2011), all of which have been extensively studied, as detailed in Appendix A. (3) Orapa is located in a Palaeoproterozoic fold belt at the western margin of the craton, which has been strongly affected by Palaeo- to Midproterozoic accretionary processes (Jacobs et al., 2008).

Geochronology of inclusions in diamond has revealed the presence of multiple generations of eclogitic diamond (Richardson et al., 1990; Shirey et al., 2008; Timmerman et al., 2017). The western margin of the Zimbabwe craton was exposed to a multiplicity of processes ranging from crustal accretions to rifting in the Proterozoic (Jacobs et al., 2008), and at least four compositionally distinct groups of eclogite xenoliths have been recognised (Viljoen et al., 1996). Thus, the question arises whether the different diamond generations and eclogite groups recognised at Orapa relate to tectonic events affecting the western Zimbabwe craton. The exact nature of the relationship between the origin(s) and evolution of mantle eclogites and diamond genesis at Orapa has not been addressed in detail since early work (Viljoen et al., 1996). In the meantime, more data-sets have been produced in studies focussing on specific aspects of eclogitic diamond formation.

This study combines new data (garnet and clinopyroxene major, minor and trace elements, garnet and clinopyroxene $\delta^{18}O$ and clinopyroxene $^{87}Sr/^{86}Sr$) with published data with the aims to (1) decipher the origin(s) and chemical evolution of the mantle eclogite reservoir, (2) investigate the overprint of mantle eclogites from Orapa in the context of its proximity to the craton margin and (3) establish a link to multiple diamond formation events recognised at this locality.

2. CRUST AND MANTLE GEOLOGY

The Orapa kimberlite cluster in central Botswana (Fig. 1) was emplaced into the Palaeoproterozoic Magondi

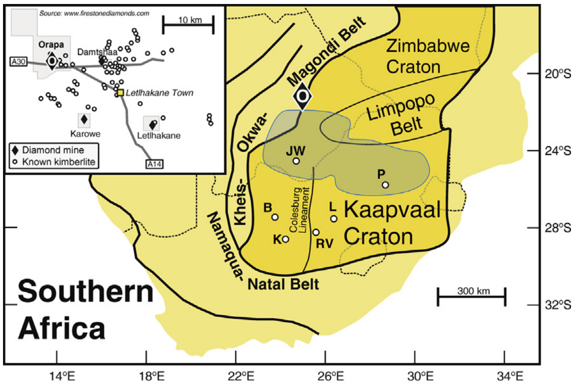

Fig. 1. Map of southern Africa (after Pearson et al., 1998; Shirey et al., 2002) showing the outline of the Kaapvaal and Zimbabwe cratons, separated by the Limpopo Belt, and approximate locations of kimberlites that have yielded abundant eclogite materials (O Orapa, B Bellsbank, JW Jwaneng, K Kimberley, L Lace, RV Roberts Victor, P Premier). The highlighted area south and west of the Limpopo belt encompasses lithosphere affected by the ca. 2 Ga Bushveld large igneous event. Proterozoic mobile belts (Kheis-Okwa-Magondi, Namaqua-Natal) and political boundaries (fine stipples) are also shown. Inset indicates known kimberlites and diamond mines forming part of the Orapa kimberlite field, including the main Orapa pipe, Damtshaa and Letlhakane, all of which have yielded xenoliths and/or inclusion-bearing diamonds that have been studied.