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Garnet in cratonic and non-cratonic mantle and lower crustal xenoliths from southern Africa: Composition, water incorporation and geodynamic constraints

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ABSTRACT

Garnets from kimberlite-hosted mantle and a few xenoliths from the lower crust were investigated for water, major, minor, and trace elements. Xenoliths from the mantle comprise pyroxenite, eclogite, alkremite, and peridotite, and crustal xenoliths are mafic high-pressure granulites. Samples from South Africa, Lesotho, and Namibia comprise two principal settings, Kaapvaal Craton ('on craton') and Rehoboth terrane ('off craton').

The composition of garnet depends on rock type but is unrelated to the setting, except for Ti and Cr. In garnets from 'off craton' mantle xenoliths, Ti positively correlates with Cr whereas those from 'on craton' samples reveal a negative correlation between both elements. Rare earth element patterns indicative of a metasomatic overprint are observed in garnets from both settings, especially in eclogitic garnet.

Water contents in garnet are low and range from <1 to about 40 ppm. No setting-related difference occurs, but a weak correlation between water and rock type exists. Water contents in garnets from eclogite and mafic granulite are lower than those in pyroxenite, alkremite, and peridotite. All garnets are water under-saturated, i.e. they do not contain the maximum amount of water that can be accommodated in the mineral structure. Cratonic and non-cratonic samples also show the same characteristics in the infrared (IR) absorption spectra. An absorption band at 3650 cm^{-1} is typical for most mantle garnets. Bands at $3520 \text{ and } 3570 \text{ cm}^{-1}$ are present only in TiO₂-rich garnets from the Rehoboth terrane and are ascribed to a Ti-related hydrogen substitution.

A number of garnets, especially from the Kaapvaal Craton, contain molecular water in addition to structural water. Molecular water is inhomogeneously distributed at grain scale pointing to local interaction with fluid and to disequilibrium at grain scale. These garnets consistently reveal either submicroscopic hydrous phases or additional IR bands at 3630 and 3610–3600 cm⁻¹ caused by structural water. Both features do not occur in garnets in which molecular water is absent. The observations imply (i) relatively late introduction of fluid, at least in cases where hydrous phases formed, and (ii) a relatively dry environment because only water-deficient garnets are able to incorporate additional structural water. Most importantly, they imply (iii) that the low water contents are primary and not due to water loss during upward transport. This late water influx is not responsible for the metasomatic overprint indicated by garnet REE patterns.

The results of this study suggest dry conditions in the lithosphere, including mantle and crustal sections of both the Kaapvaal Craton ('on craton') and the Rehoboth terrane ('off craton'). If the low water contents contributed to the stabilization of the Kaapvaal cratonic root (Peslier et al., 2010) the same should apply to the Rehoboth lithosphere where the same variety of rock types occurs. The extremely low water contents in eclogite relative to pyroxenite may be explained by an oceanic crust origin of the eclogites. Subduction and partial melting would cause depletion of water and incompatible elements. The pyroxenites formed

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by crystal accumulation in the mantle and did not suffer melt depletion. Such a difference in origin can be reconciled with the low Ti contents in eclogitic garnet and the high Ti contents in pyroxenitic garnet. © 2015 Elsevier B.V. All rights reserved.

1. Introduction

Significant amounts of water can be dissolved in nominally anhydrous minerals such as garnet, pyroxene, and olivine (e.g. Miller et al., 1987; Bell and Rossman, 1992). Water or, more precisely, hydrogen can be incorporated in the mineral structure by various coupled substitutions as demonstrated in a number of studies, particularly for olivine and pyroxene (e.g. Libowitzky and Beran, 1995; Rauch and Keppler, 2002; Lemaire et al., 2004; Stalder, 2004; Berry et al., 2005; Gose et al., 2008, 2009; Schmädicke et al., 2013). Structural water in mantle minerals behaves as an incompatible trace element that modifies the physical properties and the dynamic behavior of the Earth's mantle (e.g. Karato, 1990; Hirth and Kohlstedt, 1996) and facilitates the generation of partial melts (Asimow and Langmuir, 2003). Water is specifically important for mantle convection because it reduces the viscosity of mantle minerals and enhances deformation (e.g. Bercovici and Karato, 2003; Dixon et al., 2004).

Moreover, the influence of water on mantle rheology affects the position of the lithosphere-asthenosphere boundary and the stabilization of cratons (Green et al., 2010; Peslier et al., 2010). Cratonic roots - and with them the continental crust - owe their long-term survival to buoyancy and mechanical strength (e.g. Jordan, 1988). Buoyancy results from the strongly depleted Mg-rich composition of the cratonic mantle showing a lower density compared to the underlying more Fe-rich asthenosphere (e.g. Boyd and McAllister, 1976; Boyd, 1989). A recent study of kimberlite-hosted mantle xenoliths from the Kaapvaal Craton has shown that very low water contents are a typical feature of the cratonic mantle (Peslier et al., 2010). The authors concluded that low water contents in olivine lead to stronger resistance against deformation and prevent the cratonic roots to be incorporated in the convecting asthenosphere. This suggests that water may play a much greater role for the stabilization and longevity of cratons than considered before.

In contrast to the study by Peslier et al. (2010) that was concentrated on olivine in peridotite xenoliths from the cratonic mantle, the present study focuses on non-peridotitic mantle lithologies from spatially related cratonic and non-cratonic settings in southern Africa. The mantle xenoliths include garnet pyroxenite, eclogite, and alkremite. A few peridotite and mafic lower crustal xenoliths are included for comparison. The 'off-craton' samples are derived from Namibia, and 'on-craton' samples are from the Kaapvaal Craton and include localities in South Africa and Lesotho. Garnet is the only suited mineral that can be used to compare all rock types and is chosen here as a proxy for the water content in these rocks. Garnet is well preserved and common to all rock types, and in eclogite and alkremite it is the most abundant mineral.

The aim of this study is to compare the incorporation of water in garnet in different types of mantle rocks as well as to compare samples from non-cratonic and cratonic settings. For this, the water contents in garnet were determined by IR spectroscopy. Additionally, the same garnet grains were measured for major, minor, and trace element composition. In detail, the following questions are addressed:

- (1) Is there a systematic difference in water concentration between cratonic and non-cratonic rocks?
- (2) Do different xenolith types from the same setting have different water contents?

- (3) Is the water content in garnet related to garnet major and/or trace element composition?
- (4) Are there any characteristics in the IR absorption spectrum that can be related to garnet composition and/or rock type and/or setting?

2. Geological setting and samples

The investigated kimberlite-hosted mantle and crustal xenoliths are derived from kimberlite pipes in Namibia, South Africa, and Lesotho. The localities in South Africa and Lesotho are situated on the Archean Kaapvaal Craton. Samples from Namibia are derived from the Gibeon kimberlite field that is situated in the Palaeo-Proterozoic Rehoboth terrane. The latter was accreted to the western margin of the Kaapvaal Craton in the time span between 2.1 and 1.7 Ga (e.g. Jacobs et al., 2008; Janney et al., 2010). The suture between the Rehoboth terrane in the W and the Kaapvaal Craton in the E most probably coincides with the Kalahari Lineament, an unexposed but magnetically distinct north–south trending structure (Muller et al., 2009).

The investigated samples represent both cratonic and noncratonic lithosphere or 'on craton' and 'off craton' settings, respectively. For sample localities see Table 1. All investigated xenoliths are garnet-bearing. The mantle xenoliths include pyroxenite, eclogite, alkremite, and peridotite. Xenoliths from the lower continental crust are mafic high-pressure granulites.

Pyroxenites comprise orthopyroxene-bearing types as well as bimineralic types consisting only of garnet and diopsidic clinopyroxene. The latter have also been classified as 'eclogite type II', particularly in the literature dealing with southern African occurrences (e.g. Viljoen et al., 2005; Appleyard et al., 2007). This, presumably, is due to the fact that in thin sections bimineralic garnet clinopyroxenite is nearly indistinguishable from eclogite. In this study, bimineralic xenoliths with garnet and non-omphacitic clinopyroxene are termed pyroxenite.

Mantle xenoliths from the Gibeon kimberlite province were subject to a recent study that focused on thermobarometry (Table 1, Schmädicke et al., 2011). The same samples used in this study are included in the present investigation. Mantle xenoliths from South Africa and Lesotho were studied previously in numerous investigations, and for most of them mantle equilibrium conditions were estimated (Table 1). For a straightforward comparison of the various rock types the given temperatures are all based on garnet-clinopyroxene thermometry, whenever possible. For the Rehoboth terrane (Schmädicke et al., 2011), the calibrations by Ellis and Green (1979) and Powell (1985) were applied. The values in Table 1 are averages from both calibrations. The difference between both is commonly ≤ 20 °C. Thermometry for alkremite is not possible because clinopyroxene is a secondary phase that does not coexist with garnet. Equilibrium pressures are only well defined for orthopyroxene-bearing samples, i.e. peridotite and orthopyroxene-bearing pyroxenite. For the Rehoboth terrane (Schmädicke et al. (2011), the orthopyroxene barometer by Harley (1984) was used. In the case of orthopyroxene-free samples, pressure estimates are deduced from the equilibrium temperature in combination with the model mantle geotherm (Carswell and Gibb, 1987). For a few samples, the presence or inferred pre-existence of coesite or diamond defines a minimum pressure.

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