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Eclogite formation beneath the northern Slave craton constrained by diamond inclusions: Oceanic lithosphere origin without a crustal signature

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ABSTRACT

We report the geochemical and oxygen isotope compositions for eclogitic mineral inclusions in diamonds hosted by high-MgO eclogite xenoliths from the Jericho kimberlite, Canada. These data are used to constrain the nature and evolution of the eclogite protolith. The garnet and clinopyroxene diamond inclusions (DIs) are compositionally different than their host eclogite counterparts. In particular, garnet DIs have much lower Mg-numbers (54 vs. 82) and Cr_2O_3 contents (0.1 vs. 0.6 wt.%) and higher CaO contents (7.6 vs. 4.3 wt.%) than host eclogite garnet. DI and host eclogite clinopyroxenes are more similar but differences include lower Mg-numbers (78–81 vs. 93) and higher Na_2O contents (2.3 vs. 1.8 wt.%) in the DIs. The DIs lack typical shallow oceanic crust signatures such as strong positive Eu and Sr anomalies, and oxygen isotope compositions that deviate significantly from the pristine mantle average. On the contrary, both the Jericho DIs and host eclogite garnets have small negative Eu and Sr anomalies, fractionated HREE patterns ($(Lu_N/Gd_N) \sim 3–5$) and pristine mantle-like $\delta^{18}O$ values of 5.2–6.0‰, indicating that shallow, plagioclase-rich oceanic crust protoliths are unlikely.

The eclogitic DI trace-element characteristics require that both garnet and plagioclase were present in the protolith, which likely crystallized in the shallow upper mantle. DI-based reconstructed whole-rock eclogite compositions have higher Mg-numbers and lower Al_2O_3 contents than found in typical basaltic or gabbroic oceanic crust, and are similar to pyroxenitic veins found in orogenic peridotite massifs. Due to the lack of clear oceanic crust signatures and the mantle-like $\delta^{18}O$ values of the studied DIs, we propose that the Jericho diamond eclogites originally crystallized as pyroxenite cumulates that formed veins within the oceanic mantle lithosphere. Following partial melt extraction, the eclogite protoliths were subducted into the diamond stability field beneath the evolving Slave craton. Hence, the Jericho DIs and host high-MgO eclogites may represent an example of eclogite formation in an oceanic setting without the diagnostic 'crustal signatures' that are typically observed in cratonic eclogite xenolith suites worldwide.

1. Introduction

Our knowledge of the composition of the cratonic mantle is largely based on information retrieved from mantle xenoliths. However, it is increasingly recognized that the majority of cratonic mantle xenoliths have been compositionally overprinted by melts and/or fluids (e.g. Harte, 1987; Simon et al., 2003). Mineral inclusions in diamonds, in contrast, appear to be more robust archives of the processes surrounding the early stages of cratonic mantle evolution (Ireland et al., 1994) as these inclusions represent the largely unmodified composition of the diamond source region (e.g., Stachel and Harris, 2008). Compositional data collected from both DIs and xenoliths have prompted debate on the origin of cratonic mantle, particularly on whether it formed at high-pressures by vertical, plume-related processes (e.g., Aulbach et al., 2007), or at low-pressures, as part of the oceanic lithosphere before subduction to diamond-stable depths (e.g., Helmstaedt and Schulze, 1989; Jacob et al., 1994; Stachel et al., 1998; Wittig et al., 2008).

Geochemical signatures of a 'shallow' oceanic lithosphere origin are found in many mantle eclogite xenolith suites and eclogitic diamonds. These include Eu and Sr anomalies in eclogite trace-element patterns indicating involvement of plagioclase during protolith formation (e.g., Barth et al., 2001; Jacob, 2004), oxygen isotope compositions of eclogitic minerals distinct from the mantle average indicating hydrothermal alteration of shallow oceanic crust by seawater (Jacob et al., 1994; MacGregor and Manton, 1986; Muehlenbachs and Clayton, 1972), and ^{13}C-depleted carbon isotope compositions

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($\delta^{13}C < -15$‰) of some eclogitic diamonds indicating derivation from subducted organic matter (e.g. Tappert et al., 2005). Such diamonds with isotopically light carbon are reported from other Slave craton kimberlites (e.g., Davies et al., 2004) and the Jericho kimberlite itself (De Stefano et al., 2009; Smart et al., 2011). Interestingly, Shilobreeva et al. (2011) reported a mean $\delta^{13}C$ value of altered oceanic crust of −4.7‰, and thus diamonds with apparently 'mantle-like' $\delta^{13}C$ values of ~−5‰ may actually be derived from carbon associated with subducted oceanic crust. Although the subduction paradigm provides an elegant solution to the existence of crustal signatures at great depths, there is eclogitic material within the cratonic mantle without 'crustal' signatures. These eclogites are typically interpreted to have formed via mantle magmatism without subduction-related processes (e.g., Barth et al., 2002; Schmickler et al., 2004; Taylor and Neal, 1989).

Here we discuss new secondary ion mass spectrometry (SIMS) trace-element and oxygen isotope data for garnet and clinopyroxene inclusions from diamonds hosted in a high-MgO eclogite xenolith from the Jericho kimberlite, located in the northern Slave craton, Canada. In contrast to most diamond inclusion studies, we have the exceptional opportunity to investigate both the diamond inclusions and the host eclogite. This is an essential prerequisite to decipher the complex multi-stage evolution of the Jericho diamondiferous high-MgO eclogite suite, as inclusions and host eclogite minerals have markedly different compositions (Smart et al., 2009a). Rare comparative studies of DIs and host xenolith minerals not only demonstrate the importance of secondary processes in altering the cratonic mantle, but also the potential pitfalls of building petrogenetic models solely on xenolithic material that may be overprinted by later-stage processes. Our approach of using both diamond inclusions and the host xenolith enables us to gain a deeper understanding of the formation and evolution of these exceptionally diamond-rich eclogitic components within the northern Slave cratonic mantle.

2. Samples and methods

Full details of the analytical methods can be found in Electronic Appendix A.

Six garnet and two clinopyroxene inclusions were extracted from diamonds derived from a high-MgO eclogite xenolith (JDE 02) from the Jericho kimberlite. Major- and minor-element compositions were determined with a JEOL-8900 electron microprobe using a 20 kV accelerating voltage and a 20 nA beam current for most elements. Ten spots per grain were analyzed, and analyses and X-ray counts were converted to concentrations using natural garnet and clinopyroxene standards. Trace-element data were obtained at the Edinburgh Ion Microprobe Facility (EIMF, University of Edinburgh) using a Cameca IMS-4f instrument. Minerals were analyzed in Au-coated epoxy mounts with a 5 nA primary beam of $^{16}O^-$ ions and net impact energy of 15.2 kV. Counting times were between 2 and 8 s (element dependent) per cycle and a total of 16 cycles (8 cycles of heavy and light element analyses) were performed per spot. Ions were counted using an electron multiplier collector. Molecular interferences were reduced using energy filtering techniques, including a 400 nominal mass resolution, 75 eV offset and a 40 eV window. Corrections for the overlap of BaO and LREE-oxides on Eu and HREEs were made using tabulated values for secondary ion energies, known from experimentally determined patterns of REE oxides to REEs relative to CeO/Ce in doped garnet and clinopyroxene. In clinopyroxene, the REE oxide/REE correction is checked at mass 156 using CeO/Ce (after correction for ^{156}Gd), and contribution of BaO at mass 154 (after correction for Sm and Gd) and applying these values to correct for Eu (mass 151). For garnet, the overlap of LREE on HREE and BaO on Eu was corrected in the same way as for clinopyroxene, although the magnitude of the corrections was generally much smaller due to low LREE to HREE ratios and very low Ba abundances. Ion yields were calibrated using the NIST SRM610 glass and Si (determined via EMPA) was used as an internal standard. Garnet (KP1; Irving and Frey, 1978) and clinopyroxene (KH1; Irving and Frey, 1984) secondary standards were analyzed at the beginning of each analytical session and yielded trace element values within 20% of reported values. Duplicate analyses of one garnet inclusion yielded results within 15%, excluding elements of ultra-low abundance (Rb, La, Ta, Pb, Th, and U). All data were reduced offline using an in-house program. The uncertainty of the analyses is element-dependent, but in general is <1% for elements with concentrations >100 ppm, <10% for elements between 1 and 10 ppm, and >15% for elements <1 ppm. Uncertainties exceeding 50% are common for elements with concentrations <0.01 ppm and, therefore, such ultra-low concentrations are not reported here. In addition to the SIMS analyses, the trace-element composition of two garnet DIs was also determined by LA-ICP-MS at the Geological Survey of Canada, using an Analyte193 excimer laser ($\lambda = 193$ nm) coupled to an Agilent 7700× quadrupole ICP-MS. An elliptical spot size of 34×50 μm was used and each analysis consisted of ca. 45 s blank measurement followed by ca. 75 s of analysis. Energy density was between 4.4 and 7.0 J/cm^2. Data was reduced by GLITTER™ (Griffin et al., 2008). The 2-sigma standard errors for the DI garnet analyses are <10%, except for Nb, La, Hf and Ta, which are <20%. Unknown analyses were bracketed by analyses of glasses (GSD1G, BCR-2G) and garnet (MON34) standards, which differed from accepted values from <1 to 13%.

3. Results for Jericho diamond inclusions

The diamond inclusions (DIs) discussed here were derived from five diamonds from a single eclogite xenolith (JDE02). JDE02 represents a high-MgO eclogite from a suite of thirteen compositionally indistinguishable diamond eclogites reported by Smart et al. (2009a). The eclogites from Smart et al. (2009a) overlap compositionally with the ten Jericho high-MgO diamond eclogites described in Heaman et al. (2006), and we therefore consider eclogite JDE02 to be representative of the diamond-bearing high-MgO eclogite component of the northern Slave cratonic mantle. Table 1 contains major- and trace-element and oxygen isotope data for both garnet and clinopyroxene DIs and mineral separates from the host eclogite JDE02. Eclogitic DIs for Jericho were previously reported in De Stefano et al. (2009) and were derived from forty-two loose diamond xenocrysts (i.e. diamonds that have no constraints on the exact composition of their mantle sources).

3.1. Major- and trace-element compositions

Although extracted from separate diamonds, the six studied garnet DIs are compositionally indistinguishable. The garnets have approximately equal proportions of pyrope and almandine components and 20% grossular component, classifying as Group B (Fig. 1), in the geochemical classification of Coleman et al. (1965). The two clinopyroxene DIs have diopside-rich compositions with low Na_2O (2.1–2.4 wt.%) and Al_2O_3 (3.6–3.9 wt.%) contents (Fig. 2). Chondrite normalized rare-Earth element patterns for the DIs are shown in Fig. 3. Garnet DIs (Fig. 3a) have LREE-depleted ($La_N/Sm_N < 0.05$), but enriched and fractionated HREE ($Lu_N = 51.5$–56.6; $Lu_N/Gd_N = 2.7$–4.2) and exhibit subtle negative Eu anomalies (Eu/Eu* 0.7–0.9). There is no difference between the SIMS and ICP-MS trace-element analyses for garnets (Fig. 3; Table 1). The clinopyroxene DIs are LREE-enriched ($La_N/Sm_N = 1.4$) and HREE-depleted, yet they show slight depletions in La relative to other LREEs such as Ce (Fig. 3b). Clinopyroxene DIs also have negative Eu anomalies ranging from 0.7 to 0.8 and negative Sr anomalies of 0.7, calculated