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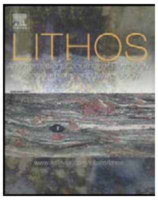

Trace element chemistry of mineral inclusions in eclogitic diamonds from the Premier (Cullinan) and Finsch kimberlites, South Africa: Implications for the evolution of their mantle source

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ABSTRACT

Although diamonds of eclogitic paragenesis are commonly encountered in the productions of many Southern Africa kimberlites, the nature and evolution of the protolith to eclogitic diamonds are still poorly understood. There is some evidence that these protoliths (and possibly also the diamonds) may be related to subduction of oceanic crust, although this is not a universally accepted view. In order to further investigate the protolith/diamond relationship, garnets and (in some cases) clinopyroxene inclusions in 23 diamonds from Premier mine and 16 diamonds from Finsch were analysed for their trace element composition.

From both mines a strong correlation between the garnet Ca content and the chondrite-normalised rare earth element (REE) pattern is evident. Garnets with comparatively low Ca content are characterised by REE patterns which show a steady increase in abundance from light rare earths (LREE) to heavy rare earths (HREE). With increasing Ca content in garnet, the abundance of LREE (La, Ce, Pr, and Nd) as well as the middle rare earths (MREE; Sm, Eu, Gd, and Tb) progressively increases, ultimately giving the trace element pattern a distinct 'humped' appearance.

Bulk-rock trace element abundance patterns have been reconstructed from measured trace element contents in garnet as well as calculated trace element concentrations in clinopyroxene, based on known clinopyroxene–garnet partition coefficients (Harte and Kirkley, 1997). At both Premier and Finsch, the low-Ca group samples (2.6 to 5.0 wt.% CaO in garnet) are LREE depleted, and have relatively flat calculated bulk-rock trace element abundance patterns at approximately 10 times chondrite concentrations, but with marked positive Sr and negative Zr anomalies. The intermediate-Ca group samples (5.2 to ~9 wt.% CaO in garnet) are LREE depleted, show Sr and Zr anomalies, have somewhat higher concentrations of Zr and MREE, and have HREE contents that overlap with the low-Ca group (Fig. 6). High-Ca group samples (~9 to 14.8 wt.% CaO in garnet) are LREE depleted, show Sr and Zr anomalies, are MREE-enriched, and have HREE contents that are slightly less than the low- and intermediate-Ca group samples.

Based on both the calculated bulk eclogite trace element abundances and their patterns, as well as previously published radiogenic isotope data, our preferred model of protolith evolution for the eclogitic diamonds from Premier and Finsch is one in which both the major and trace element chemistry of the inclusions are ultimately inherited from low-pressure oceanic protoliths, consisting of varying mixtures of oceanic basalt + cumulate gabbro for diamonds from both Premier and Finsch. Of particular importance in the current data are the presence of marked negative Zr anomalies, marked positive Sr anomalies, and a general absence of Eu anomalies in all compositional groupings. The Zr anomaly can arise in reconstructed bulk eclogite trace element abundance patterns if rutile is not included in the calculations, but the Sr anomalies (coupled with an absence of Eu anomalies) can only be explained through the mixing of oceanic gabbro and mid-ocean ridge basalt. The averaged eclogite bulk trace element compositions for Premier and Finsch are also markedly similar to that of clinopyroxene in a typical cumulate gabbro, and a role for cumulate clinopyroxene in protolith evolution may therefore also be inferred.

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It is likely that prior to and during diamond crystallisation, the major and particularly the trace element compositions of the high-pressure eclogite source rock to these diamonds may have been slightly modified by metasomatic fluids and melts. However large-scale fluid- or melt-related metasomatic processes are not indicated.

1. Introduction

Due to the chemically inert nature of diamonds, minerals occurring as inclusions record conditions of protolith evolution and diamond crystallisation up to the time of encapsulation (Gurney, 1991), being thereafter isolated from any later metasomatic modification of the high-pressure diamond host rock by transiting melts, fluids, and the carrier kimberlite (Ireland et al., 1994). This situation markedly contrasts with xenoliths (including diamondiferous ones), of peridotite and eclogite found in kimberlite, which may have been extensively and repeatedly modified in the mantle until sampled by the host kimberlite. Hence inclusions represent pristine micro-samples of the deep lithosphere.

The two dominant parageneses of mineral inclusions are termed peridotitic and eclogitic (Stachel and Harris, 2008). Peridotitic inclusion assemblages typically consist of olivine, chromite, orthopyroxene and purple (chrome pyrope) garnet whereas eclogitic assemblages predominantly comprise orange pyrope–almandine garnet and pale green omphacitic clinopyroxene. A websteritic paragenesis and an ultrahigh-pressure sub-lithospheric paragenesis are also recognised, but these diamonds are rare at most localities (Stachel and Harris, 2008).

Diamonds of eclogitic paragenesis vary widely in abundance in the productions from kimberlite mines in Southern Africa. For example, in diamonds of about 2 mm in maximum dimension they range from <5% at Finsch (Phillips et al., 2004) to >60% in the case of Orapa in Botswana (Gurney et al., 1984). The abundance at Premier in this size range is 28% and for both Premier and Finsch the proportion of eclogitic diamonds steadily increases with size so that with ~4 mm diamonds at Premier abundance is 72% whilst at Finsch for ~3 mm diamonds the abundance is 15.9% (Stachel and Harris, 2008).

Comparison of the mineral chemistries of diamond-bearing eclogites with that of eclogitic minerals occurring as inclusions in diamonds, clearly indicates a genetic relationship (Gurney, 1991). The petrogenesis of cratonic eclogite xenoliths remains controversial with a crustal origin (the subduction hypothesis) as well as a mantle origin (ponding of asthenosphere-derived melts) being proposed by various authors (see Jacob, 2004 and references therein). Although not a universally accepted view (Griffin and O'Reilly, 2007), the majority of eclogites from the subcratonic lithosphere are probably best explained as samples of subducted oceanic crust (Jacob, 2004). This view is also held by those who have studied eclogitic inclusions in diamond (Stachel and Harris, 2008; references therein). Within this framework, Ireland et al. (1994) suggested that some eclogitic inclusions in diamond may derive from an eclogite protolith consisting of Archean basalt depleted by the extraction of tonalitic–trondhjemitic melts at high pressure during subduction, a hypothesis considered likely in the case of eclogitic inclusion-bearing diamonds from Mwadui (Stachel et al., 1999) and Venetia (Aulbach et al., 2002).

The proposed models for the nature and timing of diamond crystallisation in the eclogite host rock, range from the syngenetic crystallisation of inclusions and the diamond host (Navon, 1999) to models advocating diamond formation from subducted organic matter through the direct conversion of graphite to diamond (Tappert et al., 2005a,b), or through a metasomatic origin of diamond in which protolith formation and diamond crystallisation may be completely separate events (Cartigny et al., 1998a,b; Stachel and Harris, 2008; references therein).

The trace element geochemistry of eclogitic garnet and clinopyroxene inclusions in 'normal' lithospheric diamonds (as opposed to eclogitic deep sublithospheric diamonds) have been studied at many localities world-wide. For information from a) Udachnaya, Mir and Aikhal in Siberia see Ireland et al. (1994); Taylor and Anand (2004); b) Jagersfontein, Monastery and Venetia in South Africa see Moore et al. (1991); Aulbach et al. (2002); Tappert et al. (2005a,b); c) Mwadui in Tanzania see Stachel et al. (1999); d) KanKan in Guinea see Stachel et al. (2000); e) DO27, Snap Lake, A154 South, Buffalo Hills and Jericho in Canada see Davies et al. (2004a,b); Promprated et al. (2004); Donnelly et al. (2007); De Stefano et al. (2009); f) Guaniamo in Venezuela see Kaminsky et al. (2000); g) and placer deposits in Namibia and Brazil see Stachel et al. (2004) and Tappert et al. (2006), respectively. In most cases these studies comprise up to five eclogitic diamonds per locality, but at Guaniamo, Jericho, Jagersfontein, and Namibia more substantial sample suites were examined.

Comprehensive geochemical studies of diamond-bearing eclogite xenoliths in kimberlites are not numerous, but have been completed for Mir and Udachnaya in Siberia (Jacob et al., 1994; Snyder et al., 1997), Kaalvallei and Newlands in South Africa (Menzies et al., 2003; Viljoen et al., 2005), and Jericho in Canada (Smart et al., 2009).

The purpose of the present paper, therefore, is to report on an investigation into the nature and genesis of the protolith to eclogitic diamonds, through the study of compositional trends amongst a large and chemically diverse suite of eclogitic minerals occurring as inclusions in diamonds from the Premier and Finsch kimberlites in South Africa. For this study, 22 garnets and 4 clinopyroxenes in 23 eclogitic diamonds from the Premier mine and 15 garnets and 4 clinopyroxene inclusions in 16 eclogitic diamonds from the Finsch diamond mine, were analysed for their major and trace element composition (Tables 1–3).

2. Samples and methods

The Premier kimberlite (Field et al., 2008) is of the Group I variety (Smith, 1983) and has a preferred emplacement age of 1180 Ma ± 30 Ma (Richardson et al., 1993). From Sm–Nd studies on the garnets and clinopyroxenes of the lherzolitic component of the peridotitic inclusion suite, a genesis isochron age of 1930 ± 60 Ma was obtained, but with the harzburgitic component Sm/Nd and ^{143}Nd/^{144}Nd ratios were not sufficiently different from each other to yield either a genesis isochron age, or a meaningful model age (Richardson et al., 1993). Similar inclusion studies on garnets and clinopyroxenes of the eclogitic paragenesis yielded a genesis isochron age of 1150 ± 60 Ma. Considering the errors of the analytical methods (see above), the eclogite isochron age allows the crystallisation of eclogitic diamonds at Premier to be contemporaneous with the age of pipe emplacement (Richardson, 1986). However the level of nitrogen aggregation within the Type I (nitrogen-bearing) eclogitic diamond population clearly indicates a residence time within the upper mantle (Richardson, 1986) making these diamond xenocrysts within this kimberlite, as is the case world-wide.

The Finsch kimberlite (Field et al., 2008) is of the Group II variety (Smith, 1983), with an estimated Rb–Sr pipe emplacement age of 118 ± 3 Ma (Smith et al., 1985). As previously noted, the inclusion suite of small diamonds at Finsch is dominated by inclusions of the peridotitic (harzburgitic) paragenesis (Harris and Gurney, 1979) from which an Archean Sm–Nd model age of 3.3 ± 0.1 Ga was obtained (Richardson et al., 1984). Similar studies on eclogitic