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Re–Os isotopic composition of peridotitic sulphide inclusions in diamonds from Ellendale, Australia: Age constraints on Kimberley cratonic lithosphere

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Abstract

Sulphide-bearing diamonds recovered from the ~20 Ma Ellendale 4 and 9 lamproite pipes in north-western Australia were investigated to determine the nitrogen aggregation state of the diamonds and Re–Os isotope geochemistry of the sulphide inclusions. The majority of diamond studies have been based on diamonds formed in the sub-continental lithospheric mantle (SCLM) below stable cratons, whereas the Ellendale lamproites intrude the King Leopold Orogen, south of the Kimberley craton. The sulphide inclusions consist of pyrrhotite–pentlandite–chalcopyrite assemblages, and can be divided into peridotitic and eclogitic parageneses on the basis of their Ni and Os contents. A lherzolitic paragenesis for the high-Ni sulphide inclusions is suggested from their Re and Os concentrations. Regression analysis of the Re–Os isotope data for the lherzolitic sulphides yields an age of 1426 ± 130 Ma, with an initial $^{187}Os/^{188}Os$ ratio of 0.1042 ± 0.0034. The upper limit of the uncertainty on the $^{187}Os/^{188}Os$ initial ratio gives a Re depletion age of 2.96 Ga, indicating the presence of SCLM beneath Ellendale since at least the Mesoarchaean, with the lherzolitic diamond-forming event much younger and unrelated to the craton keel stabilisation. The nitrogen aggregation state of the diamonds and calculated mantle residence temperatures suggest an origin and storage of the Ellendale diamonds in a stable cratonic SCLM, consistent with the King Leopold Orogen being cratonised by about 1.8 Ga. The diamonds do not show evidence for pervasive deformation or platelet degradation, which suggests that the diamonds had a relatively undisturbed 1.4 billion year mantle storage history.

1. INTRODUCTION

The study of diamonds often allows insight into processes occurring within the sub-continental lithospheric mantle (SCLM) and has helped constrain whether diamond formation in the SCLM is continuous or episodic, with a number of studies contributing to the current understanding that diamonds form during discrete events. Moreover, Richardson et al. (1993) have shown that there are age differences between diamonds of different parageneses: harzburgitic diamonds typically yield Archaean ages, with eclogitic and lherzolitic diamonds giving younger Proterozoic ages.

Harzburgitic diamonds are considered to be related to early craton keel formation and subsequent metasomatism (Richardson et al., 2004, and references therein), whereas lherzolitic diamonds have been related not to craton keel development and stabilisation but to subsequent metasomatic processes and modification of the SCLM during the Proterozoic (Richardson et al., 1993, 2004, 2009; Shirey et al., 2002, 2004). Eclogitic diamond formation, in contrast, is thought to reflect craton stabilisation through Neoarchaean to Proterozoic accretionary events along the margins of cratonic nuclei with underplating and

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incorporation of oceanic crust into the SCLM (Schulze and Helmstaedt, 1988; Richardson et al., 1993, 2001, 2004; Carlson et al., 1999; Schmitz, 2002; Schmitz et al., 2004).

The majority of primary diamond deposits have diamonds that formed within the Archaean SCLM below stable cratons. Relatively few diamondiferous sources are found intrusive through Proterozoic mobile belts. Much of our understanding of diamond formation thus relates to early evolution of Archaean cratons. Examples of diamond localities in mobile belt/craton-margin settings include Ellendale (this study), Argyle in the Halls Creek Orogen (Richardson, 1986; Jaques et al., 1989; Viljoen, 2002); Venetia, River Ranch emplaced into the Limpopo Belt between the Zimbabwe and Kaapvaal cratons (Kopylova et al., 1997; Viljoen, 2002; Richardson et al., 2009); George Creek, Sloan and a number of kimberlites in the Colorado–Wyoming province (Otter, 1989; McCallum, 1991; Chinn, 1995) and the Prairie Creek lamproite province in Arkansas (Dunn, 2003). Of these, diamond-formation ages are only available for the eclogitic diamonds at Argyle (1580 ± 30 Ma; Richardson, 1986) and the harzburgitic to lherzolitic diamonds at Venetia ($\sim$2 Ga; Richardson et al., 2009).

Inclusion studies by Hall and Smith (1984), Griffin et al. (1988) and Jaques et al. (1989), as well as studies based on $\delta^{15}N$ and $\delta^{13}C$ of Ellendale diamonds (van Heerden et al., 1995a), have shown that the Ellendale lamproites host both lherzolitic and eclogitic diamond populations, in roughly equal proportions. Single harzburgitic pyrope inclusions were found at Argyle (CaO 5 wt%, Cr_2O_3 14.64 wt%; Jaques et al., 1989) and Ellendale (CaO 2.76 wt%, Cr_2O_3 6.84 wt%; Hall and Smith, 1984), however, an extensive harzburgitic diamond population has not been described at either locality. Nitrogen aggregation and geothermometry studies by Taylor et al. (1990) have shown that Ellendale and Argyle diamonds have distinct origins in both time and space, and suggest that the Ellendale diamond population is younger than at Argyle.

In this study, a parcel of 69 diamonds recovered from the Ellendale 4 and 9 lamproite pipes is characterised, with a focus on those containing sulphide inclusions. Cathodoluminescence techniques (CL) and Fourier transform infrared spectroscopy (FTIR) are used to determine the internal structure and nitrogen aggregation state of the diamonds and to infer diamond storage temperatures and residence times in the SCLM. Re–Os isotopic analysis of the sulphide inclusions allows the formation age of the sulphide-bearing diamonds to be constrained. The age of diamond growth episode/s has been compared to the geological processes in the region, such as stabilisation of the Kimberley craton and later continent-margin accretion along the King Leopold Orogen. Comparison of the results to published work on other mobile belt diamond localities provides an improved understanding of mantle conditions in mobile belt/craton-margin settings.

2. REGIONAL GEOLOGY

Ellendale is one of only two currently producing volcanic sources of diamonds in Australia. Both are located in Proterozoic mobile belts adjacent to the Kimberley craton and are atypical diamond deposits, as most primary deposits worldwide occur within the boundaries of stable cratons. The Ellendale lamproites (West Kimberley province) intrude into the King Leopold Orogen to the south of the Kimberley craton. The Argyle lamproite (East Kimberley province) occurs in the Halls Creek Orogen to the south-east of the Kimberley craton. The Kimberley craton lies within the boundaries of the larger North Australian craton (Plumb, 1979) and is bounded to the east and south by the intracratonic Halls Creek and King Leopold Orogens, respectively (Fig. 1). The Halls Creek Orogeny (1830–1800 Ma) to the south-east of the Kimberley craton represents the suture zone between the Kimberley craton and the North Australian craton (Tyler and Page, 1996).

The West Kimberley province is a suite of more than 100 lamproites that occur at the north-eastern margin of the Canning Basin and the southern margin of the King Leopold Orogen (Jaques et al., 1986). The main fields that comprise the West Kimberley province are, from North to South, the Ellendale, Calwynyardah and Noonkabah lamproites. These lamproite fields are emplaced in the hanging wall of the Oscar Shear system, which forms the contact between the King Leopold Orogen and the Lennard Shelf (White et al., 1995), and has been traced into the upper mantle by deep seismics (Drummond et al., 1989). There are 48 intrusions in the Ellendale lamproite field that are Miocene in age (24–19 Ma; Wellman, 1973; Jaques et al., 1986; Pidgeon et al., 1989), of which 34 are diamond-bearing (Jaques et al., 1986). The two largest olivine lamproites are Ellendale 4 and Ellendale 9 (Jaques et al., 1986). Ellendale has a much lower diamond grade (<1 carat per tonne) than the higher grade Argyle deposit (5–6 carats per tonne) (compilation in Gurney et al., 2005), though are considered economic due the high quality of the diamonds.

Seismic tomography (van der Hilst et al., 1998; Kennett, 2003; Fishwick et al., 2005) confirms that the Kimberley craton is underlain by a high seismic velocity zone, which has been interpreted to represent cold lithospheric mantle to depths of at least 150 km (Fig. 1). This zone extends much further than is suggested by the surface cratonic edge, and underlies both the Halls Creek and King Leopold Orogens. Preservation of the lithospheric mantle keel beneath these two orogens suggests that they could represent shallow crustal features thrust over older lithosphere, as modelled for the Slave craton. Complementing the seismic evidence, cool cratonic geotherms have been established for the West Kimberley (Griffin and Ryan, 1995), East Kimberley (Jaques et al., 1990) and North Kimberley provinces (Griffin and Ryan, 1995; Wyatt et al., 1999). Xenolith studies from the Kimberley area (including Argyle as well the Seppelt kimberlite intruded into the northern Kimberley craton) have shown that the SCLM is largely lherzolitic in composition (with minor harzburgite component) and was stabilised in the Archaean (Jaques et al., 1986, 1989, 1990; Lucas et al., 1989; Ramsay et al., 1994; Smith et al., 1994; Griffin and Ryan, 1995; Graham et al., 1999; Wyatt et al., 1999; Downes et al., 2007; Luguet et al., 2009).

3. SAMPLES

Sixty-nine Ellendale diamonds, ranging in size from 0.26 to 0.92 carats, were selected from run-of-mine production