Deep mantle diamonds from South Australia: A record of Pacific subduction at the Gondwanan margin

Ralf Tappert[1], John Foden[1], Thomas Stachel[2], Karlis Muehlenbachs[2], Michelle Tappert[3], Kevin Wills[4]
[1]Geology and Geophysics, School of Earth and Environmental Sciences, University of Adelaide, 5005 South Australia, Australia
[2]Department of Earth and Atmospheric Sciences, University of Alberta, Edmonton, Alberta T6G 2E3, Canada
[3]Geology and Geophysics, School of Earth and Environmental Sciences, University of Adelaide, 5005 South Australia, Australia
[4]Flinders Mines Ltd., Norwood, 5067 South Australia, Australia

ABSTRACT

Diamonds from Jurassic kimberlites at Eurelia, South Australia, contain coexisting inclusions of ferropericlase and MgSi-perovskite that provide evidence for their deep (>670 km) lower mantle origin. Eurelia diamonds formed from mixed carbon sources, likely including subducted carbonate, as indicated by a trend toward isotopically heavy carbon compositions ($\delta^{13}C = 0‰$) and low nitrogen concentrations (<100 ppm) in highly aggregated states. The discovery of lower mantle diamonds at Eurelia extends the area of known Mesozoic kimberlites carrying sublithospheric diamonds within continental fragments of Gondwana. The alignment of the kimberlite localities with the former Gondwana subduction margin and the presence of crustal signatures in the composition of the sublithospheric diamonds provide evidence that deeply subducted remnants of the proto-Pacific plate are the ultimate source of the diamonds. The kimberlite magmatism and the widespread emplacement of Jurassic to Early Cretaceous large igneous provinces in southern Gondwana are also attributed to this subduction process.

INTRODUCTION

Diamonds of ultradeep, sublithospheric origin have been identified as minor components from a number of kimberlitic and alluvial diamond deposits worldwide. These diamonds and their mineral inclusions provide the only pristine samples of the sublithospheric mantle. Therefore, they are key evidence for large-scale processes and circulatory dynamics in the Earth's deep mantle, that fundamentally influence geological processes in the Earth's crust. They also give insights into the origin of deep carbon sources.

Unlike lithospheric diamonds that form at depths of ~140–250 km, sublithospheric diamonds originate in the asthenosphere (~250–410 km), the transition zone (410–670 km), and even the lower mantle (>670 km). Diamonds from the asthenosphere and the transition zone are characterized by inclusions of garnets with a majorite component (Stachel, 2001), which results from dissolution of pyroxene into garnet at high pressures (Ringwood, 1967). Diamonds from the lowermost part of the transition zone and the lower mantle typically contain inclusions of ferropericlase in combination with Mg or Ca silicates, which at lower mantle conditions have Mg-perovskite and Ca-perovskite structure (MgSiPvk, CaSiPvk). For the majority of deposits containing sublithospheric diamonds, characteristic inclusions are restricted to either majoritic garnet-bearing assemblages or to ferropericlase-MgSiPvk-CaSiPvk assemblages. Only a few deposits contain diamonds of both sublithospheric assemblages; these include the São Luiz–Juina area, Brazil (Harte et al., 1999), and Kankan, Guinea (Stachel et al., 2000a, 2000b).

The origin of sublithospheric diamonds and their connection to their lithospheric counterparts, as well as to their host kimberlites, are controversial. It has been noted that majorite-bearing diamonds from the asthenosphere and the transition zone are predominately eclogitic, i.e., mafic, whereas lower mantle diamonds predominately indicate an ultramafic, peridotite-like source composition. This observation has been interpreted as the result of a compositional stratification of the Earth's mantle (Gasparik, 2002), but such strong stratification is not supported by the nature of geochemical heterogeneities of the mantle (Hofmann, 2007) or dynamic models of mantle convection (Van Keken et al., 2007). It has also been suggested that the mafic paragenesis of inclusions in diamonds from the asthenosphere and transition zone reflect precipitation from alkaline melts, such as kimberlites, oceanic island basalts (Moore et al., 1991), or carbonatites (Walter et al., 2008). However, the discoveries of negative Eu-anomalies in silicate inclusions, in combination with crustal carbon isotope signatures of the host diamonds (Stachel et al., 2000a; Tappert et al., 2005a), provide strong evidence that sublithospheric diamonds formed in deeply subducted oceanic slabs.

The occurrence of sublithospheric diamonds is commonly associated with Mesozoic to early Cenozoic kimberlite magmatism. Many of the kimberlites that produce sublithospheric diamonds are located on continental fragments that, at the time of kimberlite emplacement, were part of Gondwana. To evaluate whether the Mesozoic to early Cenozoic kimberlite magmatism, which produced sublithospheric diamonds in Africa and South America, extended as far east as Australia, and to reconstruct the processes that lead to the formation of those diamonds, we present compositional data for diamonds and their inclusions from three kimberlites (K2, K3, and K7) near Eurelia, Orroroo district, South Australia.

METHODS

The concentration and aggregation state of nitrogen impurities in diamond were determined by Fourier transform infrared (FTIR) spectroscopy, using a Thermo Nicolet Nexus 470 FTIR spectrometer with infrared microscope (University of Alberta; see Tappert et al., 2005b).

The carbon stable isotope composition of the diamonds was determined with a Finnigan MAT 252 mass spectrometer (University of Alberta) after combusting ~1 mg of inclusion free diamond cleavage chips at 1000 °C for ~12 h.

Mineral inclusions in the diamonds were released from the host diamonds by crushing. The major and minor element compositions of the inclusions were determined with a CAMECA SX-51 electron microprobe (University of Adelaide).

RESULTS

Within the set of 43 diamonds from kimberlites at Eurelia, 1 diamond (FBS5–11) from the K7 kimberlite dike was found to contain 6 coexisting inclusions of ferropericlase (MgO) and one magnesium silicate ($MgSiO_3$ stoichiometry). Because ferropericlase and $MgSiO_3$ at pressures lower than ~24.5 GPa would react to form an olivine polymorph (Mg_2SiO_4), their coexistence places the origin of this diamond into the lower mantle, to depths in excess of 670 km (e.g., Ito and Takahashi, 1989). At this pressure, $MgSiO_3$ is stable in the perovskite structure (MgSiPvk). The only other inclusion-bearing diamond (FBS5–12), which was also recovered from the K7 kimberlite, was found to contain a single inclusion of olivine stoichiometry. The remaining 41 diamonds were inclusion free.

The carbon stable isotope composition ($\delta^{13}C$) of the bulk of the diamonds ranges from −1.9‰ to −9.4‰ versus Peedee belemnite (Fig. 1). Within this group, the distribution of isotope

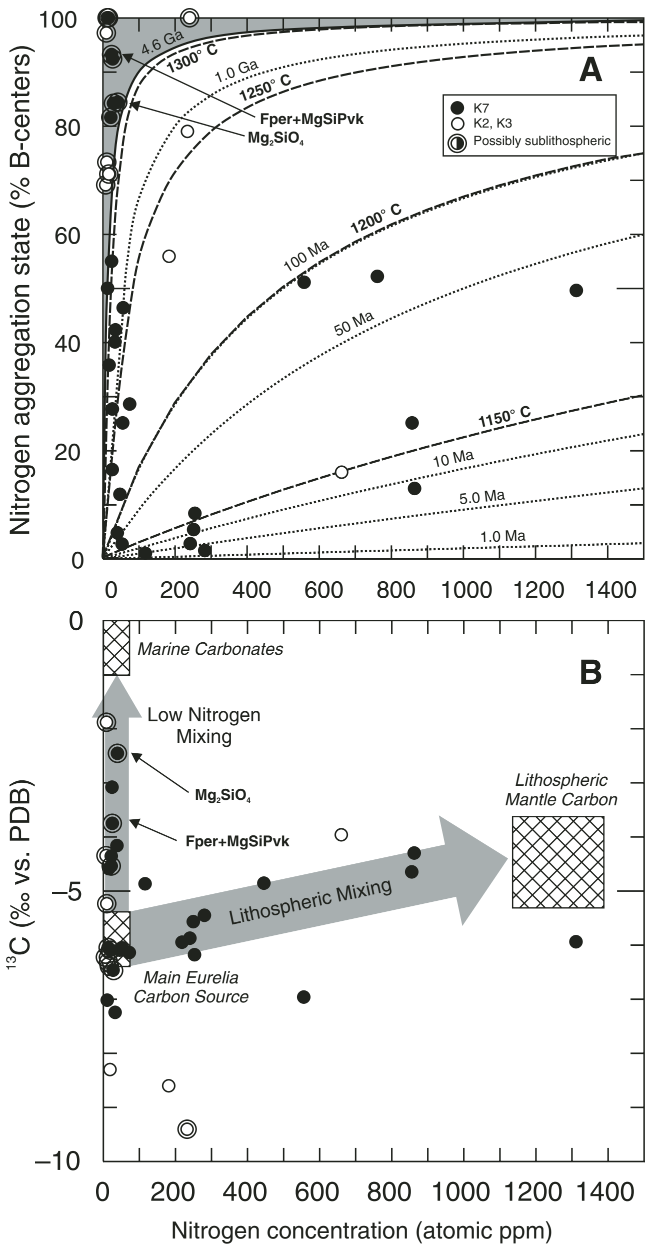

Figure 1. A: Nitrogen concentration versus nitrogen aggregation state in Eurelia diamonds. Aggregation state of nitrogen is given as percentage of nitrogen in higher aggregated B center relative to the A center. Isochrones (dotted) are calculated for temperature of 1200 °C; isotherms (dashed) are calculated for mantle residence time of 100 m.y. Gray field encloses diamonds with calculated ages older than 4.6 Ga. Fper+MgSiPvk—ferropericlase and MgSi-perovskite. B: Nitrogen concentrations versus $\delta^{13}C$ of Eurelia diamonds. Cross-hachured boxes represent composition of carbon sources that define mixing lines (arrows). Note that one diamond with nitrogen concentration of 2568 ppm exceeds the scale of plots A and B. Two diamonds with $\delta^{13}C$ of −15.7‰ fall outside plot B. PDB—Peedee belemnite.

values is bimodal, with modes at −6.0‰ and −4.5‰ (0.5‰ bin size). Two diamonds were found to be isotopically much lighter, with almost identical $\delta^{13}C$ values of −15.7‰.

Despite the large range of nitrogen concentrations (5–2568 atomic ppm), most of the diamonds from Eurelia (>60%) have <100 ppm of nitrogen impurities. The aggregation states of nitrogen are variable, ranging from 0% to 100% of fully aggregated B centers.

DISCUSSION

The presence of coexisting inclusions of ferropericlase and MgSiPvk in diamond FBS5–11 supports the notion of Scott-Smith et al. (1984) that part of the diamond population at Eurelia may be derived from the lower mantle. Additional support for a lower mantle origin for diamond FBS5–11 comes from the low concentrations (25 ppm) of nitrogen impurities, which are present in highly aggregated states (92% B centers). Only at temperatures significantly higher than those determined for the base of the lithosphere in the Eurelia area (~1200 °C; Tappert et al., 2007) can these small amounts of nitrogen impurities fully transform into highly aggregated B centers over geologically reasonable time spans (Fig. 1A). This implies a mantle residence at significantly higher temperatures (>1300 ºC for an assumed mantle residence and/or recycling time of 100 m.y.; Fig. 1A), which is consistent with the inferred sublithospheric origin for this diamond. The low nitrogen concentration of diamond FBS5–11 is also consistent with observations on other sublithospheric diamonds from deposits worldwide, which have either low nitrogen concentrations or no detectable nitrogen (Hutchison et al., 1999; Stachel, 2001; Stachel et al., 2002). The olivine-bearing diamond FBS5–12, which also has low nitrogen concentrations (39 ppm) and high aggregation states (84% B centers) may also be of sublithospheric origin, which implies that the olivine was incorporated as ringwoodite or wadsleyite.

Because the bulk of the diamonds from Eurelia contain no inclusions, it is not possible to assess the proportion of sublithospheric to lithospheric diamonds directly from their inclusion assemblages. However, from the evidence of low nitrogen concentrations (<100 ppm) in combination with high nitrogen aggregation states (>70% B centers), there is an indirect indication of a sublithospheric origin for an additional 10 of the inclusion-free diamonds (Fig. 1A). In contrast, most of the nitrogen-rich diamonds from Eurelia (>100 ppm nitrogen) have low aggregation states of <60% B centers (Fig. 1A), which indicates that they formed within relatively cool lithospheric mantle.

The nitrogen and carbon isotopic characteristics of the Eurelia diamonds are consistent with simple mixing trends originating from a low-nitrogen carbon source with a $\delta^{13}C$ of −6‰ (Fig. 1B). One trend can be defined by mixing of carbon from this reservoir with a typical lithospheric mantle carbon source, which ranges in $\delta^{13}C$ from ~−4‰ to −5‰ (Cartigny et al., 1998), and is associated with high concentrations of nitrogen (>1000 ppm). This first mixing trend is attributed to a lithospheric diamond population (lithospheric mixing; Fig. 1B). A second mixing trend is characterized by nitrogen-poor diamonds extending from $\delta^{13}C$ of −6‰ toward a 0‰ end member (low-nitrogen mixing; Fig. 1B). This trend is consistent with simple mixing of the −6‰ carbon source with marine carbonates, which have a $\delta^{13}C$ of 0‰. The fact that all potential sublithospheric diamonds fall into this trend may indicate that deeply subducted carbonates were involved in the formation of the sublithospheric diamonds from Eurelia.

In order to assess the source of the sublithospheric diamonds from Eurelia and especially the validity of their origin by subduction, it is useful to consider the tectonic environment. The Eurelia kimberlites were emplaced in the Jurassic, ca. 170 Ma (Scott-Smith et al., 1984), in the southeastern part of Gondwana (Fig. 2). At that time, the southern margin of Gondwana was defined by an active subduction zone. This margin extended from South America and southern Africa to Australia (Fig. 2). Marginal accretion and subduction along this zone started after the assembly of Gondwana in the Early to Middle Cambrian (Cawood, 2005; Foden et al., 2006) and continued at least until the Jurassic. To the east of Australia, subduction still occurs beneath New Zealand. The southern part of

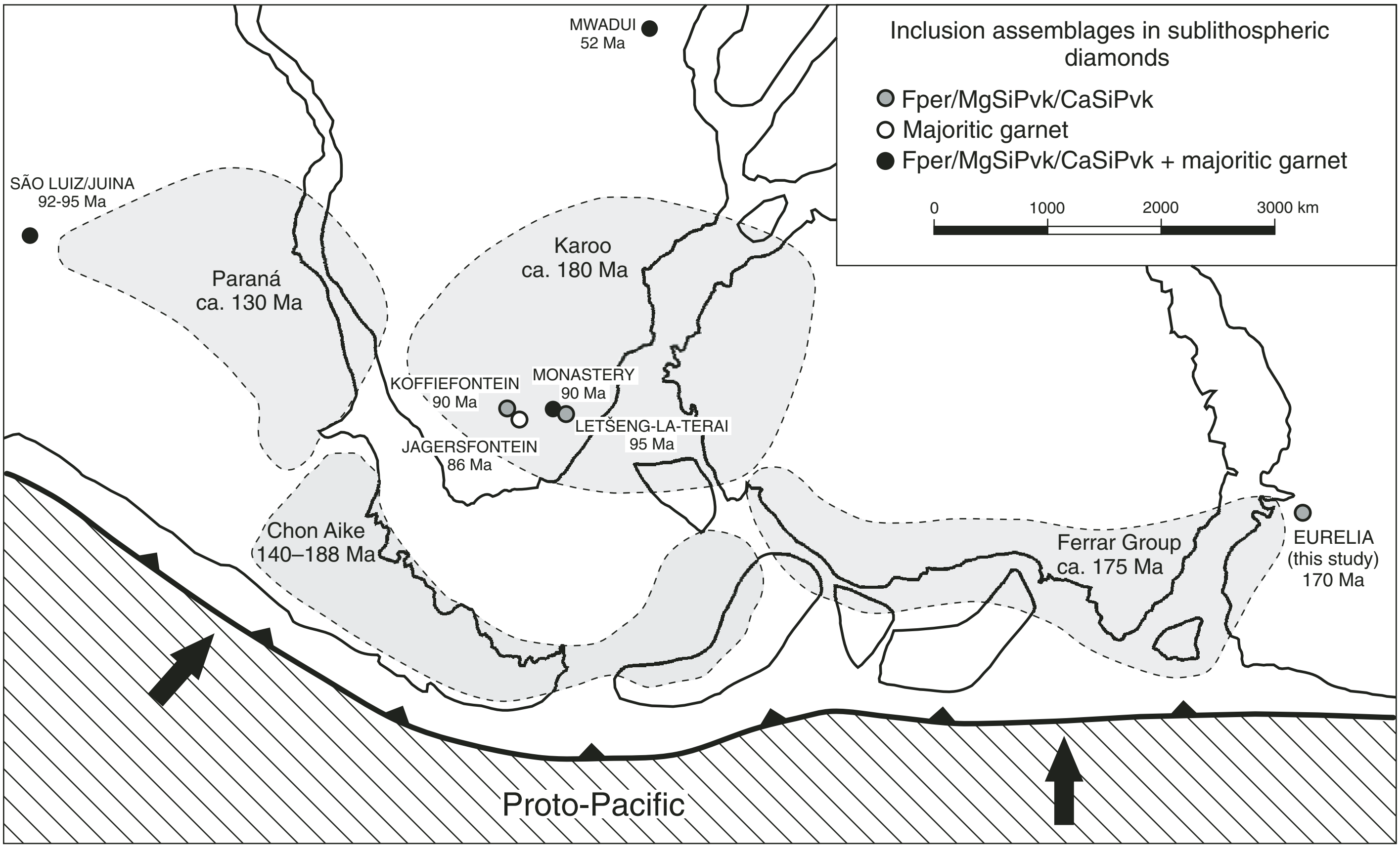

Figure 2. Reconstruction of southern Gondwana before breakup showing locations of Mesozoic and early Cenozoic kimberlites with sublithospheric diamonds. Simplified inclusion parageneses for sublithospheric diamond population at each locality are given. Emplacement ages for southern African kimberlites are based on Allsopp and Barrett (1975), Smith (1983), Allsopp et al. (1989), Rickard et al. (1989), and Stiefenhofer and Farrow (2004). Ages of kimberlitic sources for alluvial diamonds in São Luiz–Juina area, Brazil, are based on Heaman et al. (1998). Areal extent of Mesozoic large igneous provinces (gray shaded) and ranges for their eruption ages are based on Hergt et al. (1991) and Pankhurst et al. (1998). Fper—ferropericlase; Pvk—perovskite.

Gondwana in the Jurassic and the Early Cretaceous was characterized by widespread basaltic and silicic magmatism in the Karoo, Ferrar, Paraná, and Chon Aike provinces (Cox, 1978; Riley et al., 2006) that resulted in the formation of an elongated, semicontinuous large igneous province (LIP) (Fig. 2). The eastern termination of this large igneous province is located immediately to the southwest of Eurelia.

At the time of the kimberlite emplacement, the Eurelia area was located >1000 km away from the active continental margin (Fig. 2). Assuming a nearby subduction-related origin for the diamonds and the kimberlite magmatism at Eurelia, deep subduction of slab material must have predated the kimberlite emplacement by at least 100 m.y. At typical subduction rates, this would be the approximate time required to transfer oceanic lithosphere from the subduction margin to the lower mantle boundary beneath Eurelia. In this case, the subducted lithosphere beneath Eurelia would have been Permian or older. A similar scenario and timing have been suggested for kimberlites with sublithospheric diamonds in South Africa (Tappert et al., 2005b). Evidence for the existence of a Permian arc system at the margin of East Gondwana is now preserved in form of arc volcanics and ophiolites in the Brook Street and Dun Mountain terranes in New Zealand (Mortimer, 2004), and in the New England orogen of Australia (Cawood, 1984).

In southern Gondwana, Mesozoic kimberlites carrying sublithospheric diamonds of possible subduction origin were emplaced in the vicinity of the Jurassic and the Early Cretaceous LIPs (Fig. 2). The kimberlites either postdate the emplacement of the LIPs by tens of millions of years, as in the case of the southern African kimberlites, or by only a few million years, as in the case of Eurelia. Their close spatial and temporal connections suggest that the emplacements of the kimberlites and the LIPs are directly linked. The presence of subduction-related sublithospheric diamonds within the kimberlites suggests that the kimberlite and LIP magmatism was caused by subduction processes (e.g., slab breakoff, slab rollback, slab accumulation and melting) in the asthenosphere, transition zone, or uppermost part of the lower mantle, rather than by plumes from the core-mantle boundary. In this scenario, the subducted oceanic crust of the proto-Pacific may be the direct source material of the sublithospheric diamonds. The observed compositional distinction between sublithospheric diamonds of eclogitic and peridotitic affinity may purely be a reflection of their growth environment within the subducting slab. Diamonds with eclogitic majorite inclusions, in this case, may reflect the basaltic crustal portion of the slab, whereas diamonds with ferropericlase and MgSi-perovskite or CaSi-perovskite inclusions may reflect the peridotitic mantle portion.

CONCLUSIONS

Part of the diamond population from Jurassic kimberlites at Eurelia, South Australia, is of sublithospheric origin, i.e., the diamonds formed in the lowermost asthenosphere or the lower mantle. The presence of such deep diamonds links the Eurelia kimberlites with similar aged (Mesozoic) sublithospheric diamond–bearing kimberlites on other continental fragments of Gondwana, including southern Africa and South America. A subduction-related origin of the sublithospheric diamond population has been established for some of these kimberlites, based on crustal signatures in the composition of the diamonds and their associated mineral inclusions. The combination of nitrogen characteristics and carbon isotope composition suggests that crustal sources were also involved in the formation of the sublithospheric diamond population at Eurelia. The fact that the locations of Mesozoic kimberlites with known sublithospheric diamond populations align with the convergent southern margin of Gondwana suggests that subducted oceanic lithosphere of the proto-Pacific plate is the ultimate source of the sublithospheric diamonds. The emplacement of LIPs in the southern part of Gondwana during the Mesozoic and the subsequent kimberlite magmatism are also considered to be directly related to this subduction process.

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