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DIAMOND FORMATION IN THE SLAB AND MANTLE WEDGE: EXAMPLES FROM THE SLAVE CRATON

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INTRODUCTION

The formation of diamonds requires redox reactions (Stachel and Harris, 2009). Strong redox gradients are encountered in subduction zones (Foley, 2011), providing favourable conditions for the formation of eclogitic and mantle wedge diamonds (e.g. Kesson and Ringwood, 1989; Westerlund et al., 2006). In the central Slave craton, two pipes (Diavik and Ekati) have yielded abundant eclogitic, pyroxenitic and peridotitic xenoliths, xenocrysts, diamonds and their inclusions. Trace-element and multiple isotope studies of inclusions in eclogitic diamonds and of eclogite xenoliths from the central Slave craton have revealed that they have crustal protoliths that were emplaced during Paleoproterozoic subduction at the western craton margin (Davies et al., 2004; Schmidberger et al., 2007). Here, we review constraints from inferred subduction-related diamondiferous xenoliths and sulphide-bearing diamonds from the central Slave craton on the nature and origin of the diamond-forming fluids. This type of sample material allows utilisation of the information contained in diamonds (nitrogen concentration and aggregation state, expressed as the percentage of N occurring in the B centre, carbon isotope compositions), sulphide inclusions (major element composition, Re-Os isotope systematics) as well as diamond host rocks (major and trace elements).

CHARACTERISTICS OF SUBDUCTION-RELATED DIAMONDS, INCLUSIONS AND HOST ROCKS

Sulphide inclusions in eclogitic diamonds from the central Slave craton form an array in the Re-Os isochron diagram, with a slope corresponding to a ca 1.86 Ga age and a radiogenic initial Os isotope composition ($\gamma_{Os(i)}$ = +12). The host diamonds have high average N abundance of 670 ppm, yet low N aggregation state of 6% N as B, and mantle-like $\delta^{13}C$ of –5.1‰ (Aulbach et al., 2009a). Abundances of highly siderophile elements in eclogitic sulphide inclusions in diamonds are similar to those of modern-day MORB sulphide, indicating conservative behaviour during subduction-zone processing (Aulbach et al., under review). Peculiar stepped REE-patterns, with average NMORB-normalised Dy/La >23, of a group of diamondiferous reconstructed whole-rock eclogites from Ekati are similar to recent eclogites that have been metasomatised along fluid conduits in subduction zones. Associated diamonds have average N contents and aggregation states of 540 at.ppm and 12 %N as B, similar to sulphide-inclusion-bearing eclogitic diamonds (Aulbach et al., 2011).

A distinct group of sulphide inclusions in diamond from Diavik, with mantle-like $\delta^{13}C$ (average –5.0‰) and Ni content (14 at.%) similar to peridotitic inclusions, but ~60 times lower Os contents, yields an unradiogenic $\gamma_{Os(i)}$ of –6 and a Re-Os isochron age of 1.70±0.26 Ga, within error of the age of accretion at the craton margin (Aulbach et al., in prep.). Their N contents and aggregation states are similar to those of eclogitic diamonds.

Silicic melts derived from subducting slabs react with mantle wedge peridotite to form pyroxenite (Rapp et al., 1999). A low-temperature pyroxenite xenolith from the central Slave craton has an age of 1.84 Ga and radiogenic $\gamma_{Os(i)}$ of +38, that is identical to eclogitic inclusions in diamond within the uncertainty (Aulbach et al., 2009b).

The characteristics of these different sample suites are summarized in Table 1.

Table 1 Summary of compositions for average sulphide inclusion and host diamond compositions for inferred Paleoproterozoic subduction-related samples from the central Slave craton; data for older peridotitic diamonds are shown for comparison. References in text

Lithology	n	Ni (at.%)	Re (ppb)	Os (ppb)	initial γ_{Os}
Eclogitic	12	3.5	482	226	+12
"Wedge"	7	14	730	4090	-6
Pyroxenitic	5	7.1	43	59	+38
Peridotitic	43	17.3	485	248000	3
		Re-Os age	$\delta^{13}C$ (‰)	N (at.ppm)	%N as B
Eclogitic		1.84 Ga	-5.1	670	6
Wedge		1.70 Ga	-5.0	590	11
Pyroxenitic		1.86 Ga	na	na	na
Peridotitic		3.3+3.5 Ga	-5	340	11

DISCUSSON

Armed with the information summarised in the previous section, we can now attempt a synthesis of the redox reactions and fluids involved in diamond formation in various source rocks inferred to be related to a Palaeoproterozoic subduction zone. We emphasize that the following discussion and conclusions pertain to the central Slave craton and cannot necessarily be extrapolated to other cratons or even the northern Slave craton, where, for example, diamondiferous high-Mg eclogites with characteristics very different from those described here are common and require a different origin (e.g. Smart et al., 2011).

Eclogitic Diamond Formation

Re-Os dating of sulphide inclusions in eclogitic diamonds from the central Slave craton indicates formation ca 1.85 Ga ago, penecontemporaneously with subduction beneath the western craton margin and with eclogitisation of basaltic protoliths. The radiogenic initial $^{187}Os/^{188}Os$ is consistent with derivation of the Os – and probably sulphur – from matured, high Re/Os oceanic basaltic crust (Aulbach et al., 2009a).

Based on their similarity to modern eclogites that were metasomatised along fluid conduits in subduction zones (Beinlich et al., 2010), the markedly stepped REE-patterns of the majority of diamondiferous eclogites from Ekati were suggested to result from interaction with a high volume of fluids derived from serpentinised oceanic mantle underlying the oceanic crust. This is consistent with mantle-like $\delta^{13}C$ of eclogitic diamonds in the central Slave craton (Aulbach et al., 2011). The very low N aggregation states of eclogitic sulphide-bearing diamonds, despite their high N contents, suggest a cool time-averaged mantle residence temperature and hence derivation from the relatively shallow lithospheric mantle.

Abundances of highly siderophile elements in eclogitic sulphide inclusions in diamonds are similar to those of modern-day MORB sulphide, indicating that these elements were not mobilised in the fluid (Aulbach et al., under review). This suggests that the fluid was reducing and Cl-poor, conditions under which highly siderophile elements behave conservatively (Righter et al., 2008).

Garnet inclusions in diamonds from the central Slave craton consistently plot with garnets in the HREE-rich diamondiferous eclogites. Therefore, it appears that fluid flow not only catalysed eclogitisation of subducting oceanic crust, but also was a prerequisite for the majority of eclogitic diamond formation beneath the central Slave craton. Thus, we suggest that precipitation of eclogitic diamond was triggered during redox reactions of a reducing, serpentinite-derived fluid with the oxidising, seafloor-altered oceanic crust.

Diamond Formation in the Mantle "Wedge"

A distinct group of sulphide inclusions in diamond from Diavik is inferred to be derived from the cratonic mantle "wedge". They yield a Re-Os isochron age of 1.70±0.26 Ga, which agrees within error with the age of accretion at the craton margin and with eclogitic diamond formation, and an unradiogenic $\gamma_{Os(i)}$ that is typical of Archaean depleted lithospheric mantle (Aulbach et al., in prep.). The sulphide inclusions have typically peridotitic mantle-like Ni contents (e.g. Pearson et al., 1998) that are markedly distinct from those of eclogitic sulphide inclusions, but their average Os content (~4 ppm) is lower and $^{187}Re/^{188}Os$ higher (1.5) than that of other peridotitic sulphide inclusions in diamonds (250 ppm and 0.08, respectively) (Fig. 1). By contrast, an older suite of inclusions in peridotitic diamonds from Ekati (3.3 Ga), which were also linked to subduction, have radiogenic initial Os isotope composition and high Os contents typical for the peridotitic suite (Westerlund et al., 2006).

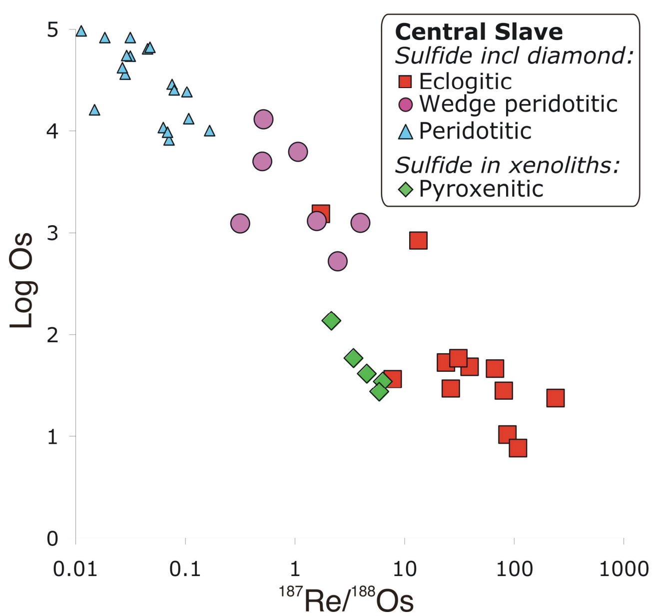

Fig. 1 $^{187}Re/^{188}Os$ vs Os content (ppb) for different sulphide suites from the central Slave craton. Note that even though there is some overlap between wedge peridotitic and eclogitic sulphide inclusions in this plot, the latter have markedly lower Ni contents than those inferred to be derived from the mantle wedge and thus, these two suites are well separated in a plot of Ni content vs log Os.

We suggest the low-Os peridotitic diamonds from Diavik formed through interaction of initially reducing, serpentinite-derived Os-poor fluids with residual cratonic mantle, which is on average more oxidising than oceanic mantle (Foley, 2011). The serpentinite-dervied fluids may have remained reducing during flow along conduits in the oceanic crust because they were armoured by a reaction assemblage. Upon interaction with the cratonic mantle "wedge", the fluids may have become oxidising enough to begin scavenging Os from the "wedge" peridotites, while still supporting diamond precipitation and facilitating isotopic rehomogenisation of this mantle portion. Serpentinite-derived fluids could also have transported substantial amounts of N (Halama et al., 2011), which could explain higher average N contents in inferred "wedge" diamonds compared to other peridotitic diamonds (see Table 1).

Subduction-Related Pyroxenite Formation

One mode of pyroxenite formation is related to the reaction of silicic slab-derived melts with peridotite in the overlying mantle wedge (e.g. Rapp et al., 1999). Sulphide grains in a single low-temperature pyroxenite xenolith from the central Slave craton lie on a 1.85 Ga isochron with an initial $^{187}Os/^{188}Os$ that agrees with that derived from eclogitic inclusions in diamond within error. This suggests that the pyroxenite inherited its radiogenic initial Os - and perhaps also S - from a slab-derived melt related to Palaeoproterozoic subduction beneath the western Slave craton (Aulbach et al., 2009b).

Diamond growth has been shown to be feasible in hydrous silicate melts similar to those expected in subduction zones (Fagan and Luth, 2011). Nevertheless, contrary to eclogites, pyroxenites and websterites represent a small fraction of the diamondiferous eclogite suite in the central Slave craton (Aulbach et al., 2011) and of inclusion-bearing diamonds in general (Stachel and Harris, 2008). This suggests that the conditions during pyroxenite formation in subduction zones are not conducive to diamond formation. This may be due to melts derived from the oxidising eclogitised oceanic crust being even more oxidising and not saturating in carbon. Alternatively, pyroxenite formation via slab melt addition may generally occur at too shallow depths, outside the diamond stability field. By contrast, abundant diamondiferous high-Mg eclogites from the northern Slave craton have major-element compositions similar to pyroxenite xenoliths from the central Slave craton, but contain diamonds with extremely light carbon and low N contents; their formation was suggested to be related to an oxidised fluid containing recycled organic matter (Smart et al., 2011), demonstrating the multiplicity of fluids and redox reactions involved in diamond formation in the slab and mantle wedge.

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