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Diamond ages from Victor (Superior Craton): Intra-mantle cycling of volatiles (C, N, S) during supercontinent reorganisation

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A B S T R A C T

The central Superior Craton hosts both the diamondiferous 1.1 Ga Kyle Lake and Jurassic Attawapiskat kimberlites. A major thermal event related to the Midcontinent Rift at ca. 1.1 Ga induced an elevated geothermal gradient that largely destroyed an older generation of diamonds, raising the question of when, and how, the diamond inventory beneath Attawapiskat was formed. We determined Re–Os isotope systematics of sulphides included in diamonds from Victor by isotope dilution negative thermal ionisation mass spectrometry in order to obtain insights into the age and nature of the diamond source in the context of regional tectonothermal evolution. Regression of the peridotitic inclusion data ($n = 14$ of 16) yields a 718 ± 49 Ma age, with an initial $^{187}Os/^{188}Os$ ratio of 0.1177 ± 0.0016, i.e. depleted at the time of formation (γ_{Os} −3.7 ± 1.3). Consequently, Re depletion model ages calculated for these samples are systematically overestimated. Given that reported $^{187}Os/^{188}Os$ in olivine from Attawapiskat xenoliths varies strongly (0.1012–0.1821), the low and nearly identical initial Os of sulphide inclusions combined with their high $^{187}Re/^{188}Os$ (median 0.34) suggest metasomatic formation from a mixed source. This was likely facilitated by percolation of amounts of melt sufficient to homogenise Os, (re)crystallise sulphide and (co)precipitate diamond; that is, the sulphide inclusions and their diamond host are synchronous if not syngenetic.

The ∼720 Ma age corresponds to rifting beyond the northern craton margin during Rodinia break-up. This suggests mobilisation of volatiles (C, N, S) and Os due to attendant mantle stretching and metasomatism by initially oxidising and S-undersaturated melts, which ultimately produced lherzolitic diamonds with high N contents compared to older Kyle Lake diamonds. Thus, some rift-influenced settings are prospective with respect to diamond formation. They are also important sites of hidden, intra-lithospheric volatile redistribution that can be revealed by diamond studies. Later emplacement of the Attawapiskat kimberlites, linking the carbon cycle to the surface, was associated with renewed disturbance during passage of the Great Meteor Hotspot. Lherzolitic diamond formation from oxidising small-volume melts may be the expression of an early and deep stage of the lithospheric conditioning required for the successful eruption of kimberlites, which complements the late and shallow emplacement of volatile-rich metasomes after upward displacement of a redox freezing front.

1. Introduction

The Superior Craton represents a large tract of Archaean lithosphere, the centre of which is covered by younger sediments (Hoffman, 1989) that obscure the crust and lithospheric mantle record. A growing number of diamondiferous kimberlites have been discovered in the Superior Craton over the last two decades, which carried xenoliths and xenocrysts (including diamond) to the surface that can help reveal the hidden processes affecting the mantle keel through time (Kong et al., 1999; Scully et al., 2004; Smit et al., 2014a, 2014b). Diamonds are manifestations of the passage of volatile-rich fluids and small-volume melts, from which they form during wall rock-buffered redox reactions or due to carbon saturation in response to isobaric cooling, ascent along a

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cratonic geotherm or diminishing fluid volumes (Luth and Stachel, 2014; Stachel and Luth, 2015). Diamonds therefore are indirect archives of the compositions and sources of the ephemeral fluids and melts from which they grew. Inclusions in diamond are particularly useful to identify the nature of diamond source rocks and their formation conditions (Stachel and Luth, 2015).

The diamondiferous Victor kimberlite occurs within the Jurassic Attawapiskat kimberlite cluster, located ∼100 km SW of James Bay (Fig. 1). There, the diamond inclusion suite formed in an apparently moderately depleted lherzolitic mantle, and the mine produces diamonds of exceptional value, which is contrary to the current paradigm of diamond formation in predominantly harzburgitic source rocks (Stachel et al., 2018). Based on a comparison of N aggregation and carbon isotope systematics of diamonds from both kimberlite age groups, it was hypothesised that the Attawapiskat kimberlites sampled a young generation of diamonds formed after dissipation of the heat associated with the Midcontinent Rift (Smit et al., 2014a). This is interesting because the majority of dated diamond suites are significantly older (Gurney et al., 2010). However, age dating is required to confirm the timing and nature of the inferred young diamond-formation event beneath the central Superior Craton.

Sulphides are known to be the main hosts of highly siderophile elements, among them Re (including the radionuclide ^{187}Re) and Os (including the radiogenic isotope ^{187}Os), and therefore lend themselves to the determination of single-sulphide Re–Os isotope systematics (Shirey and Walker, 1998; Pearson et al., 1998; Harvey et al., 2016). We studied a suite of peridotitic sulphide inclusions in diamonds from two Victor kimberlite units, part of the Attawapiskat kimberlite field, for major elements by Scanning Electron Microscope (SEM), and their Re–Os isotope systematics by Isotope Dilution Negative Thermal Ionisation Mass Spectrometry (ID-NTIMS), in order to obtain constraints on the nature of their source rocks and formation ages. This not only allows us to establish a link to regional tectonothermal evolution with repeated lamprophyre-kimberlite emplacement events, but also to explore broader implications for the role of supercontinent reorganisation in lithospheric diamond formation as part of the deep carbon cycle.

2. Geological background and prior work

2.1. Tectonomagmatic evolution of the Superior Craton

The Superior Province (Fig. 1) is the largest known Archaean craton on Earth and forms the nucleus of the Canadian Shield (Percival et al., 2012). The Superior Craton is an amalgamation of east-west trending cratonic nuclei and granite-greenstone belts that assembled largely in the Neoarchaean; including the ca. 3.0 Ga North Caribou Superterrane at the core, the 2.9–2.7 Ga Oxford-Stull domain to the north, and the ca. 3 Ga Uchi domain to the south (Percival et al., 2012). Southward craton growth involved accretion of island arcs and sedimentary prims to the older proto-continent, which were amalgamated between 2.72 and 2.68 Ga, followed by a late-tectonic granite bloom (Percival et al., 2012) and assembly of a Neoarchaean supercraton (Kenorland/Superia; Bleeker, 2003, and references therein). The late Neoarchaean evolution of the Superior Craton was accompanied by episodic emplacement of small-volume melts, such as the intrusion of calc-alkaline to shoshonitic lamprophyre dikes at Wawa in the southern Superior Province at 2.67 Ga (Wyman et al., 2006).

During the Proterozoic, the Superior Craton was the nucleus of multiple supercontinent cycles and subject to associated geodynamic processes without being broken up, such as formation of large igneous provinces (LIP) and widespread alkaline magmatism. The oldest and arguable most widespread Palaeoproterozoic LIP in

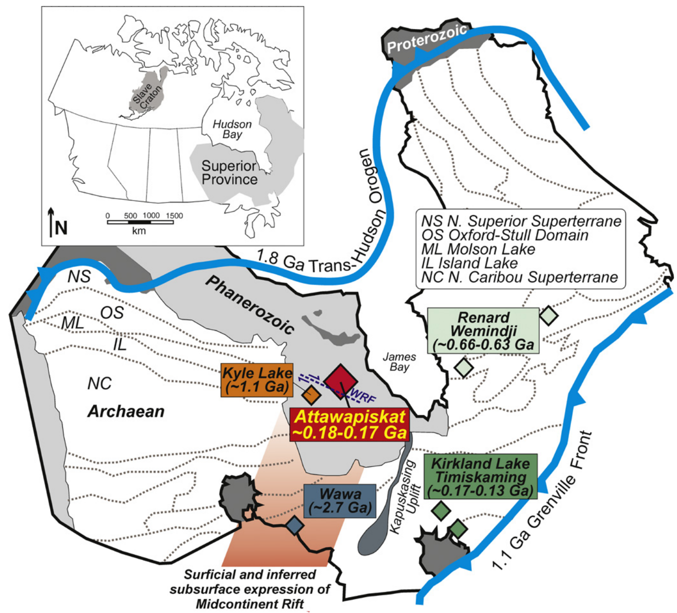

Fig. 1. Map of the Superior Province and adjacent areas after Hoffman (1989), Eaton and Darbyshire (2010) and Percival et al. (2012), with kimberlite localities and other elements after Scully et al. (2004), Heaman et al. (2004), Hunt et al. (2012) and Smit et al. (2014a). Inset shows outline of the Superior Province and the Slave craton and some provincial boundaries. Note the Winisk River Fault (WRF) separating older Kyle Lake from younger Attawapiskat kimberlites.

the Superior Province is the 2.52–2.46 Ga Matachewan igneous events, which includes several widely dispersed dyke swarms (Heaman, 1997; Maurice and Francis, 2010) and can be linked to an initial stage of Kenorland breakup. Palaeoproterozoic rifting of Kenorland occurred between 2.2 and 2.1 Ga (Halls and Heaman, 2000), and was followed by collapse and development of several 1.9–1.8 Ga accretionary orogens (Trans Hudson, Ungava, New Quebec, Penokean; Hoffman, 1989) along the Superior Craton margin, creating the supercontinent Laurentia at 1.8 Ga.

Several younger Proterozoic LIPs occur within or proximal to the Superior Craton including (1) 2.2 to 2.1 Ga and 1.90 to 1.87 Ga mafic to ultramafic magmatism due to passive upwelling along the entire thinned northern margin of the Superior Craton (Heaman et al., 2009), (2) the 1.11 to 1.09 Ga Keweenawan LIP in the Lake Superior region (Heaman et al., 2007), which is associated with the failed Midcontinent Rift and coeval kimberlites (Kyle Lake and Bachelor Lake; Heaman et al., 2004), and (3) the 723–713 Ma Franklin LIP (Heaman et al., 1992; Denyszyn et al., 2009), which extends >1300 km from the Yukon/Alaska border to Ellesmere Island, and may be related to initial Rodinia supercontinent rifting and linked either to mantle plume impingement (Heaman et al., 1992) or to lithospheric extension prompted by coeval prolonged subduction around the Rodinian periphery (Cawood et al., 2016). Further Neoproterozoic rifting of Rodinia, birth of the 615 Ma Iapetus Ocean (Kamo et al., 1989), and development of the 620–550 Ma St. Lawrence rift (Kumarapeli and Saull, 1966) represent a final period of extension.

2.2. Kimberlite and related magmatism in the Superior Craton

The James Bay area of the Superior Craton hosts a number of kimberlites and related rocks (UML: ultramafic lamprophyres, melilitites) that vary in age from Mesoproterozoic to Jurassic (Heaman and Kjarsgaard, 2000; Heaman et al., 2004; Januszczak et al., 2013; Tappe et al., 2017). Southwest of James Bay are the ∼1.1 Ga Kyle Lake kimberlites, 236 Ma Hecla Twp UML, Jurassic diamondiferous Attawapiskat kimberlites (180–174 Ma; includ-