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Diamonds from Knee Lake, Manitoba: A Neoarchean aged unconventional diamond deposit on the northwestern Superior Craton

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Introduction

The Knee Lake region of Manitoba hosts an unconventional diamond deposit within Neoarchean (2730 Ma) ultramafic volcaniclastic rocks of the Oxford Lake-Knee Lake greenstone belt, on the northwestern margin of the Superior Craton. Diamond deposits of similar age are rare, e.g. Tree River (Changleng et al. this volume, Timmerman et al. 2022) and Wawa (Lefebvre et al. 2005; Stachel et al. 2006) in Canada, and have not yet been found to be economic because, despite very promising microdiamond counts, they lack macro-stones. Here we present the results of a study of a large population of Knee Lake diamonds with the aim of understanding their genetic environment, examining the possible differences to other lithospheric diamond deposits, and constraining the processes that lead to diamond stability in the Archean mantle.

Methods and results

A 2020 drilling campaign at southern Knee Lake resulted in 2822 m of core and an unusually high number of microdiamonds. From 208.8 kg of core, 3472 microdiamonds >0.075 mm were recovered, including only 8 diamonds >0.5 mm in two dimensions. The average yield was 17 diamonds per kg of rock. In this study, a subsample of 3257 diamonds in the size range >0.075 to <0.850 mm (98.3% <0.300 mm) was classified for dimensions, colour, shape, surface features and the presence of internal imperfections. After photoluminescence spectroscopy, 830 diamonds were studied by Fourier Transform Infrared (FTIR) for nitrogen aggregation. Inclusions were identified *in situ* by Raman spectroscopy and Single Crystal X-ray Diffraction (SC-XRD). Three inclusions were analyzed by Electron Probe Microanalyzer (EPMA) and one also by Laser Ablation Mass Spectrometry (LA-ICP-MS) for major and trace element compositions, with the aim of reconstructing the P-T conditions of diamond growth. Inclusions discovered include garnet, olivine and omphacite. Finally, 356 diamonds were analysed by Secondary Ion Mass Spectrometry (SIMS) for carbon and nitrogen isotope compositions and nitrogen content. Carbon isotopes ($\delta^{13}C$) range from -16.4 to +1.3 ‰ and nitrogen isotopes ($\delta^{15}N$) show a ~80 ‰ variation across the suite, from -46.8 to +31.8‰, the most extreme values ever found in terrestrial diamonds.

Discussion

Along with emplacement age, nature of the host rocks and high diamond counts, unusual features of the Knee Lake diamonds are their small dimensions and restricted size range, their prevalent cuboid shape, with decreasing proportions of cubo-octahedral and octahedral shapes, dendritic and fibrous growth forms indicative of rapid growth, low nitrogen aggregation (with single N-center bearing stones), their green to red fluorescence, and their extreme nitrogen isotope compositions. Some of these features are more often observed in ultrahigh pressure (UHP) metamorphic diamonds from crustal terranes, as also noted by De Stefano et al. (2006) when describing the Wawa diamonds. A lithospheric nature of the Knee Lake diamonds is, however, uncontrovertibly demonstrated by their mineral inclusions, which reveal a dominant peridotitic paragenesis with a minor eclogitic contribution. The P-T estimate for diamond formation from coexisting olivine and harzburgitic garnet inclusions is in agreement with the most common conditions recorded by lithospheric diamonds (Stachel and Luth 2015) and plot in a region of P-T space congruent to a relatively cool modern-day reference model geotherm of 38 mW/m^2 (Hasterok and Chapman 2011). The size frequency distribution (SFD) of the Knee Lake and Wawa diamonds is very different to the "ultra fine" SFD of UHP metamorphic diamonds such as those from Kokchetav (Fig. 1). The unusual nature of the SFDs for lithospheric diamonds erupted from the mantle during the Archean (Knee Lake and Wawa), with respect to those erupted in much younger volcaniclastic deposits (like Fort a la Corne) is reflected in the unusually high number and restricted size range of the diamonds, with a near absence of macro-stones. This type of SFD is indicative of higher-than-normal nucleation rates during diamond formation, potentially a result of greater levels of undercooling during the growth process.

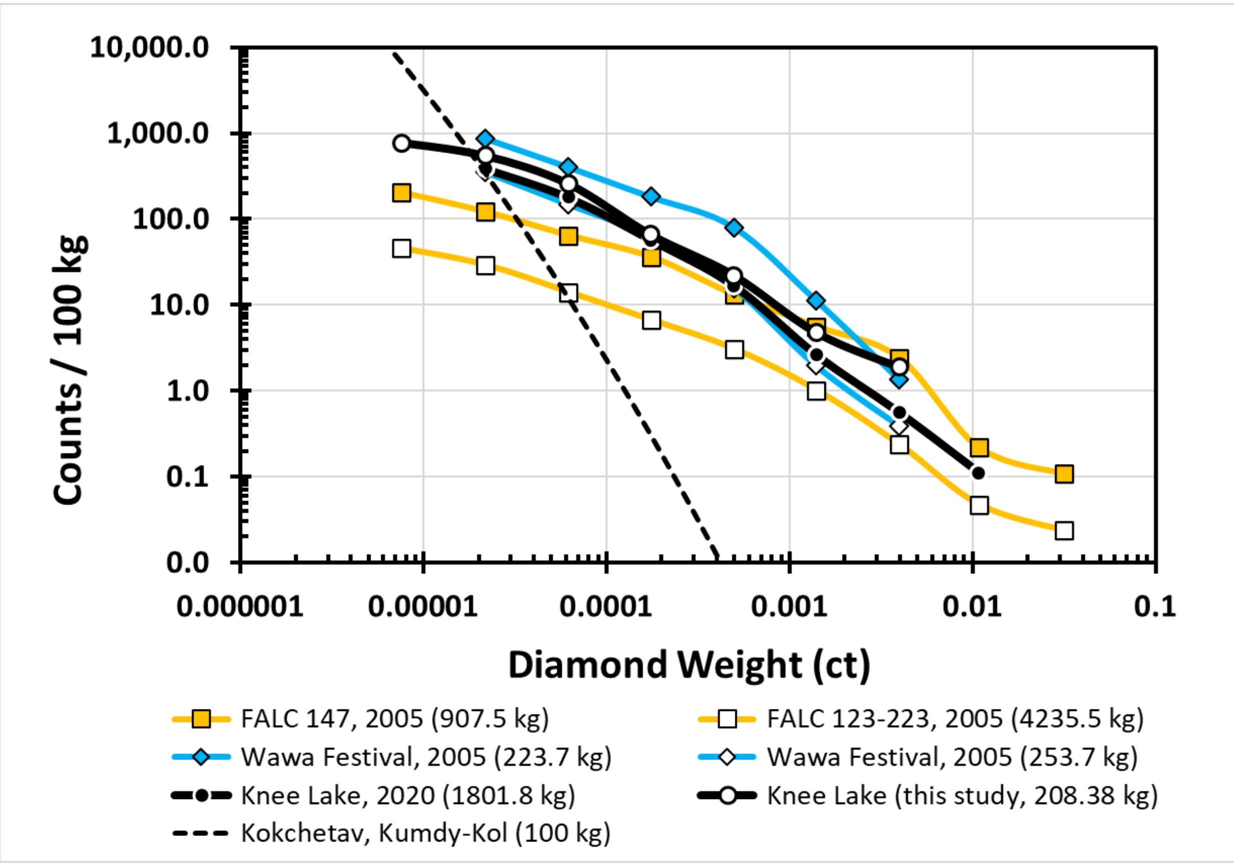

Figure 1: Microdiamond count rates (number of diamonds per kilogram mass) versus diamond size for volcaniclastic kimberlite from Fort a la Corne (FALC) localities, Archean-age volcaniclastic settings at Wawa and Knee Lake (from company releases), and the ultrahigh pressure metamorphic diamond deposit at Kumdy-Kol, Kokchetav (Pechnikov and Kaminsky 2011).

There is a relationship between diamond shape and nitrogen aggregation that points to a single, rapid growth event for most of the diamonds. Nitrogen in cuboid crystals is less aggregated than in octahedral crystals. This can be explained by the different activation energy for nitrogen aggregation from C- to A-centers for the two growth forms (Taylor et al. 1996). Nitrogen aggregation shows that after formation, the Knee Lake diamonds resided for a short time (~0.5 Ma) in a cool lithospheric mantle environment. The unperturbed temperature of the diamond host substrate may have been as low as ~960 °C as calculated from both nitrogen aggregation variability and thermal decay assuming a single diamond growth event from an ascending asthenospheric fluid/melt.

The cool thermal conditions in the lithospheric mantle hosting the Knee Lake diamonds, together with evidence for recycled crustal lithologies derived from the discovery of an omphacite inclusion in one diamond and the crustal-like carbon isotope compositions of some diamonds, suggest accretion of cool subducted lithospheric layers to form the keel of the nascent Superior Craton. The cool P-T conditions recorded by the Knee Lake and other diamonds extracted from Earth's mantle in the Archean (e.g., Tree River, NWT) are in stark contrast with evidence for possible high mantle potential temperatures derived, e.g., from komatiite lavas. Lithosphere formed so early in Earth's history will be in a transient state of geothermal adjustment, with any single P-T condition recorded by inclusions in diamond likely reflecting a period of thermal disequilibrium in the nascent subcontinental lithosphere (Michaut et al. 2009). The extreme N isotope variability of the Knee Lake diamond suite is difficult to explain through distinct isotope compositions of possible N sources. The observation that the most negative $\delta^{15}N$ values are associated with cuboid crystals, whereas the most positive values occur in octahedral crystals, instead suggests the possibility of kinetic isotopic effects during diamond growth. However, our current modeling of chemical and thermal diffusion cannot explain the observed variability and successful models may need to incorporate different crystal-fluid interfaces (octahedral-fluid vs. cuboid-fluid) and driving forces during diamond growth.

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