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Diamonds from Fort à la Corne – post-Archean formation in exceptionally cool and fertile lherzolitic substrates

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Situated between the extensive Hearne and Superior cratons, the smaller Sask Craton is underpinned by a lithospheric mantle root that likely originated during a Wilson cycle culminating in the 1.9-1.8 Ga Trans Hudson orogeny (Czas et al. 2020). Despite this post-Archean origin, the lithospheric mantle of the Sask Craton became richly endowed with diamonds at ~1.2 Ga (Milne et al. 2024) during an event contemporaneous with the early assembly of Rodinia (Elzevirian orogeny), the onset of the Midcontinent Rift, and the Mackenzie large igneous province. Diamond sampling occurred during Early Cretaceous magmatism in the Fort à la Corne (FalC) kimberlite field. Here we present the results of the first detailed study of diamonds and their mineral inclusions from FalC, representing three different stratigraphic units (Early Jolie Fou, Pense and Cantuar) of the Star kimberlite complex.

Diamond Samples

Among the 154 inclusion-bearing diamonds studied here, 140 diamonds are ~2 mm in diameter (DTC sieve class -7 +5) and only 14 are >3.5 mm (DTC +11). The diamonds are dominated by octahedral to dodecahedral shapes with varying degrees of resorption. The majority of diamonds have a flattened morphology, whereby octahedra or rounded dodecahedra are distorted in an elongate direction. This “elongation” is also observed in the shape of the inclusions. The diamonds are predominantly colorless with minor proportions of yellow, brown and grey colours.

The studied FalC diamonds are mostly low in nitrogen (13% are Type II and an additional 61% have N <50 at.ppm) and predominantly pure Type IaA (63% of nitrogen-bearing diamonds have B-centres below the limit of detection, i.e. ≤ 2 %B). The carbon isotope composition ($\delta^{13}C$) of the diamonds has a sharp, prominent mode at ~-16 ‰ and a second minor mode in the mantle range at ~-5 ‰ (Milne et al. 2024).

Mineral Inclusions

The diamonds from the Star kimberlite have a very distinct inclusion population. The recovered suite of silicate and oxide inclusions is dominated by Cr-diopside, Cr-pyrope garnet, olivine, orthopyroxene and eclogitic low-Cr garnet (in descending order of abundance), with single occurrences of kyanite, magnesio-wüstite, aluminous orthopyroxene (likely former bridgmanite) and ruby inclusions. Silicate/oxide-included diamonds are principally of lherzolitic paragenesis (95%), with a minor eclogitic suite (4%) and a single presumed lower mantle diamond (wüstite-bridgmanite assemblage). With the caveat that syngenetic inclusions were recovered from only 8 diamonds >3.5 mm (DTC +11), the proportion of eclogitic diamonds increases strongly with stone size.

Of the 39 diamonds containing sulphides, 22 also include lherzolitic silicates, while 17 contain lone sulphides. The Ni content of the sulphides co-existing with lherzolitic silicates (2.0-9.0 wt%) is indistinguishable from eclogitic sulphides worldwide, but they all have Cr contents ≥0.02 wt%. Applying the Cr criterion to the lone sulphide inclusions indicates that 13 are lherzolitic and four are eclogitic. Confirmed lherzolitic sulphides have been reported from only one other location (Victor; Stachel et al., 2018) and inferred from another (Ellendale; Smit et al., 2010). The abundance of lherzolitic sulphide inclusions found at Star is exceptional, making it the first reported significant population of confirmed lherzolitic sulphide inclusions worldwide.

Notably, the lherzolitic inclusion assemblage exhibits unusually low Mg-numbers for garnet, olivine and orthopyroxene inclusions and very low NiO in olivine, clinopyroxene and orthopyroxene. For example the FalC lherzolitic olivine inclusions have Mg-number 88.9 ±1.0 [mean ±1 SD] versus 91.9 ±1.0 worldwide and NiO contents of 0.14 ±0.06 wt% versus 0.37 ±0.04 wt% worldwide. On its own, the low Mg-number may suggest a fertile, primitive mantle-like diamond substrate, however when combined with the extremely low Ni contents, melt-rock reaction involving a fractionated, Ni-poor melt is implicated instead.

Geothermobarometric constraints

The Mg-number of lherzolitic Cr-diopside inclusions is within the normal range (91.9 ±0.5 FalC versus 91.9 ±4.1 worldwide), suggesting equilibration with low Mg-number olivine, orthopyroxene and garnet occurred at unusually low temperatures. Consistent with this observation, pressure-temperature estimates derived from Cr-diopside inclusions ($PT_{NT2000\text{-}N2020}$) indicate a well-constrained, exceptionally cool cratonic model geotherm (~36-37 mW/m² surface heat flow; Fig. 1), indistinguishable from the xenocryst-based Cretaceous paleo-geotherm for the area. FalC clinopyroxene inclusions derive from 150-190 km depth with a mode and median at ~165 km. This suggests a diamond-forming event focused in the deep lithosphere but well above the local lithosphere-asthenosphere boundary (~220 km; see Fig. 1). The observation that clinopyroxene inclusions with and without orthopyroxene exsolutions fall on identical geotherms (Fig. 1) suggests a protogenetic origin from previously cooled lithospheric mantle.

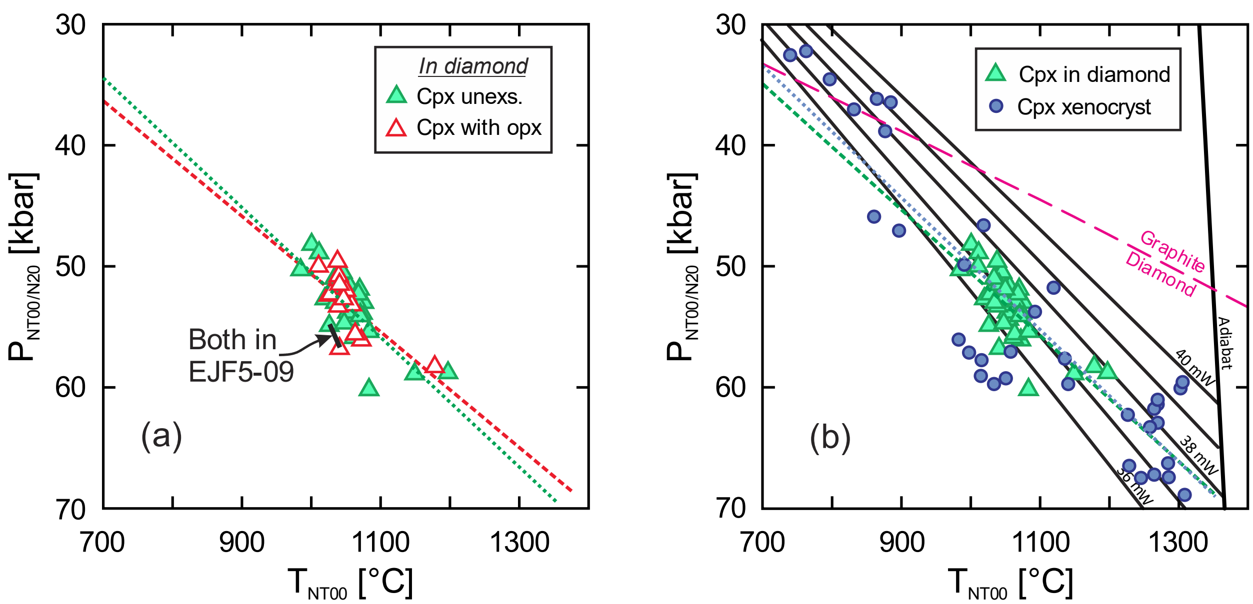

Figure 1: Geothermobarometric estimates for FalC clinopyroxene inclusions in diamond and xenocrysts. Left side (**a**) shows pressure-temperature estimates using the revised single-clinopyroxene thermobarometer of Nimis et al. (2020) for unexsolved (unexs.) lherzolitic clinopyroxene inclusions (green triangles) and lherzolitic clinopyroxene inclusions with orthopyroxene exsolutions (open red triangles). The two data sets overlap and yield indistinguishable geotherms (shown as green and red linear regression lines). Also note the perfect agreement (within 1.9 kbar and 15 °C) between

exsolved and unexsolved clinopyroxene from diamond EJF5-09 (connected by a black line). Right side (**b**) shows pressure-temperature estimates for all clinopyroxenes included in diamond (with and without exsolutions) and occurring as xenocrysts in FalC kimberlites (Czas et al. 2020). Indistinguishable geotherms are derived via linear regression of the inclusion (green dashed line) and xenocryst (blue dashed line) data and compared to the reference steady-state cratonic model geotherms of Hasterok and Chapman (2011) relevant for modern Earth. Graphite-diamond transition is from Day (2012). Mantle adiabat from Hasterok and Chapman (2011).

Discussion and Conclusions

With their low Mg-numbers and the presence of clinopyroxene inclusions with exsolved orthopyroxene, the lherzolitic inclusion suite from FalC resembles the transitional websteritic-lherzolitic inclusions suite in diamonds from the Voorspoed kimberlite on the Kaapvaal craton (Viljoen et al. 2018). The formation of the Voorspoed diamond suite was linked to percolation of mafic/ultramafic melts related to the 2.7 Ga Ventersdorp large igneous province, consistent with high temperatures of formation of reconstructed inclusion compositions, high nitrogen aggregation states and degradation of platelets in diamonds (Viljoen et al. 2018). In contrast to the FalC lherzolitic suite, the Voorspoed transitional pyroxene inclusions show normal to elevated Ni and elevated Mn contents. Refertilization of the FalC diamond substrates thus relates to a distinct process, likely involving a fractionated (low Ni) melt, that in contrast to Voorspoed did not progress to the near elimination of olivine. In addition, diamond formation beneath FalC occurred after a thermal anomaly that likely was associated with this melt-metasomatic re-enrichment event had decayed (causing opx exsolution), as inclusion thermobarometry indicates a cold conductive geotherm, indistinguishable from the paleogeotherm at the time of kimberlite eruption (Early Cretaceous).

The diamond forming event at ~1.2 Ga (Milne et al. 2024) may be associated with: the onset of magmatism associated with the Midcontinetal Rift; far field effects of the Grenville orogeny; the MacKenzie Large Igneous Province; or an unrelated event, without detectable thermal impact on the Sask Craton lithospheric mantle. The strong ^{13}C depletion of FalC diamonds (Milne et al. 2024) implies that this diamond-forming event involved fluids carrying carbon derived from subducted oceanic crust, possibly remobilized from within the lithospheric mantle due to subtle thermal perturbation.

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