12 IKC
12TH INTERNATIONAL KIMBERLITE CONFERENCE
30 YEARS OF DIAMONDS IN CANADA
8–12 July 2024 • Yellowknife

12th International Kimberlite Conference Extended Abstract No. 12IKC-121, 2024

How old are diamonds beneath Proterozoic cratons? Answers from the State Line Kimberlite District, western Laurentia

Melissa S. Bowerman[a], Suzette Timmerman[a,b], Thomas Stachel[a], Malcom McCallum[c], Ingrid Chinn[d], D. Graham Pearson[a]

[a] *Earth and Atmospheric Sciences, University of Alberta, Canada, bowerman@ualberta.ca, tstachel@ualberta.ca, gdpearso@ualberta.ca*

[b] *Institute of Geological Sciences, University of Bern, Switzerland, suzette.timmerman@unibe.ch*

[c] *Geosciences Department (emeritus), Colorado State University, Fort Collins Colorado, USA, 80523, United States of America, memccallum848@gmail.com*

[d] *De Beers Group, Johannesburg, South Africa, ingrid.chinn@debeersgroup.com*

Introduction

The close association of diamonds and Archean terranes has focused most research and exploration efforts on these regions. Exceptions to this association offer a rare opportunity to look beyond the settings of conventional diamond deposits. One of these rare examples is the diamondiferous State Line Kimberlite District of Colorado, situated in the Paleoproterozoic Yavapai province (1.8–1.9 Ga) of southwestern Laurentia. The age of the lithospheric mantle beneath the Yavapai province and the nature of diamonds in this region has long been debated. Addressing these questions can shed light on the origin of diamonds in Proterozoic cratons and the diamond potential of such terranes.

Character of diamond-bearing lithospheric mantle beneath the George Creek Kimberlites

We examined 316 diamonds and their inclusions from the George Creek kimberlites of the State Line District to better understand their relationship to the mantle substrates they were derived from. Mineral inclusions liberated from 64 diamonds include (in decreasing order of abundance): clinopyroxene, garnet, rutile, sulfide, silica (coesite), phlogopite, ilmenite, feldspar, orthopyroxene and corundum. A total of 46 clinopyroxene and 40 garnet inclusions were analyzed for major and trace element abundance at the University of Alberta. Added to this new data set was the major element chemistry for 30 clinopyroxene and 30 garnet inclusions in diamonds from George Creek from Chinn (1995).

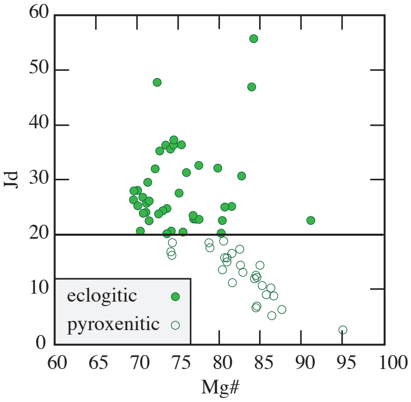

Figure 1: Jadeite content versus Mg# for clinopyroxene inclusions in diamonds from George Creek. Inclusions with jadeite component greater than 20 are classified as eclogitic and less than 20 as pyroxenitic.

All diamonds with inclusions suitable for determining a source paragenesis (N = 78) are classified as eclogitic-pyroxenitic. Based on the major element chemistry of clinopyroxene inclusions (Figure 1), 30 (57%) diamonds contain omphacite (jadeite (Jd) component > 20 mol%) and thus are eclogitic, 20 (38%) contain diopside (Jd < 20 mol%) and are pyroxenitic, and three (6%) diamonds have mixed parageneses, containing both pyroxenitic and eclogitic clinopyroxenes. There is compositional overlap between the two paragenetic suites, with eclogitic clinopyroxenes ranging in Mg# (molar 100Mg/(Mg+Fe)) between 69.6–91.2 and pyroxenitic inclusions have Mg# 74.1–95.1. Clinopyroxene inclusions from George Creek are strongly enriched in K_2O (median = 0.46 wt%) compared to clinopyroxene inclusions from worldwide localities (median = 0.20 wt%; (Stachel et al. 2022)), which may be related to derivation from unusually high pressure or unusually K-rich substrates (Harlow 1997). Garnet inclusions range in Mg# between 40.2–71.0 with a median of 46.7, distinctly below the median of 52.7 reported for garnet diamond inclusions from worldwide localities (Stachel et al. 2022). Garnet diamond inclusions from George Creek have low concentrations of Cr_2O_3 from 0.01–0.95 and CaO of 4.3–15.5 wt%. Based on garnet molar Ca# (100Ca/(Ca+Mg+Fe+Mn)) > 20, most (76%) garnet inclusion-bearing diamonds derive from high-Ca eclogite substrates (Figure 2; Aulbach et al. 2020).

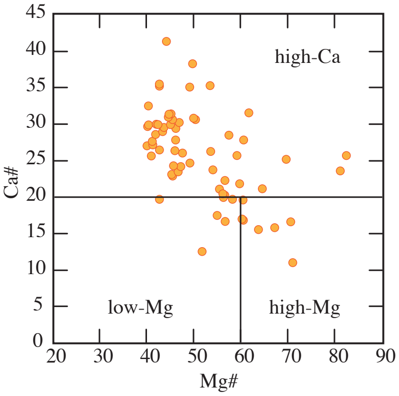

Figure 2: Ca-number versus Mg-number for garnet inclusions in diamonds from George Creek.

Clinopyroxene inclusions have typical humped REE_N patterns peaking at Gd_N, whereas garnet inclusions show exceptional depletion of LREE (0.06–0.1 × chondritic abundance for La) with enriched and flat $HREE_N$ (Figure 3). These observations are indicative of MORB-like protoliths that became depleted in LREE as a consequence of prograde metamorphism and associated melt extraction during subduction. Additional geochemical characteristics, such as high Sr concentrations of 104–827 ppm in some clinopyroxene inclusions, indicate subsequent re-enrichment by metasomatic agents.

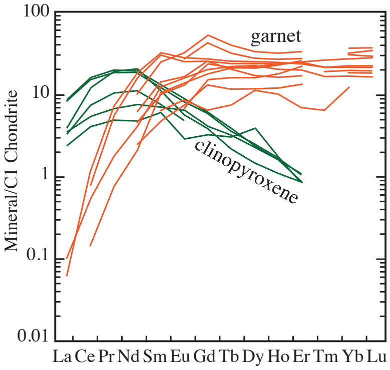

Figure 3: C1 chondrite (McDonough and Sun 1995) normalized REE abundances in clinopyroxene (green) and garnet (orange) diamond inclusions from George Creek.

Temperatures derived by using the reliable Fe-Mg exchange thermometer (Krogh 1988) for garnet and clinopyroxene cover a restricted range of 1130–1260 ºC except for a single outlier at 1062 ºC. This temperature range overlaps with the average equilibration temperature of 1170 ± 110 ºC calculated for eclogitic inclusion pairs world-wide (Stachel and Luth 2015). Projecting these temperatures onto the average cratonic geotherm of 40mW/m^2 ((Hasterok and Chapman 2011); Figure 4) yields a depth range for these inclusions of 155–175 km, showing that kimberlite magmas sampled an approximately 20 km layer of diamondiferous lithospheric mantle during ascent. Touching inclusions provide a temperature range of 830–970 ºC, which is a drop of 240-380 ºC below the average temperature (1210 ºC) derived from non-touching inclusions. Similarly, diamond localities in South Africa (Kimberley "Pool" mines and Jagersfontein) have calculated temperatures for touching eclogitic inclusions 100–180 ºC below non-touching inclusions and this has been used as evidence of a post-diamond formation cooling event (Phillips et al. 2004; Tappert et al. 2005).

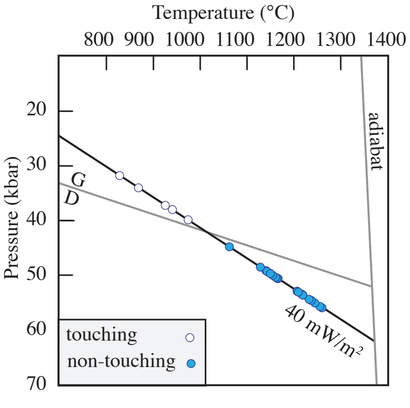

Figure 4: Estimates of temperature derived by using the Krogh (1988) thermometer and projected onto an average cratonic geotherm of 40 mW/m^2 (Hasterok and Chapman, 2011).

Timing of diamond formation and origin of diamond forming fluids

Using radiometric dating of the clinopyroxene and garnet inclusions, we show that diamond formation occurred in the Mesoproterozoic, well after Paleoproterozoic craton stabilization. Our suite of inclusions is characterized by a wide span in Sm/Nd ratios (Figure 3) that, with Nd isotopic measurements yield a Sm-Nd isochron age of circa 1.3 Ga, with three inclusions from a single diamond defining an identical isochron age. This age of diamond growth closely follows a major phase of tectonomagmatic activity across southern Laurentia, including the 1.50–1.38 Ga Picuris Orogeny (Daniel et al. 2013) and widespread granitic magmatism at 1.4 Ga (Frost and Frost

2023). Most of the inclusions have distinctly unradiogenic Nd isotopic compositions (εNd_i -4.3 to -13.2), a clear signal of a contribution from an ancient and likely Archean, enriched component to the mantle protolith where these diamonds formed.

Conclusions

Our results confirm cratonic lithosphere of the Paleoproterozoic Yavapai province had the thickness and temperature profile necessary to form diamonds during the Mesoproterozoic. This episode of diamond formation was likely in response to tectonothermal modification of the Laurentian lithosphere, causing a temporary elevation of temperature in the lithospheric mantle that dropped after diamond formation. The trace element and isotopic compositions of inclusions in George Creek diamonds document contributions from multiple sources, including a recycled Archean component and a younger eclogitic diamond substrate derived through subduction of oceanic crust. Our findings reveal the nature of post-Archean diamond formation within the portions of cratons outside of the Archean nuclei. Such regions also typically have deep lithospheric mantle roots (Pearson et al. 2021) and our results emphasize the value of investigating these areas as settings for diamond formation.

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