11th International Kimberlite Conference Extended Abstract No. 11IKC-4543, 2017

The origin of Type II diamonds: Insights from contrasting mineral inclusions in Cullinan Type I and Type II stones

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We investigated the differences in mineralogical characteristics and mineral inclusions in Type I and Type II diamonds from the Cullinan mine. Diamonds for the study were selected from the run-of-the-mine production from Clivage, Breakage, Gem Quality and Melee classes, with 0.01-0.07 ct diamonds comprising 87% of the 341 samples. Of the studied stones, 75 are Type II diamonds with N contents below 20 ppm, as identified by FTIR analysis. Most stones are represented by single crystals or fragments, the proportion of macles and aggregates is less than 14%. Approximately 70% of all stones and 59% of Type II diamonds have dodecahedral habit, hence the majority of diamonds fall into resorption categories 1 and 2. Octahedrons comprise 15% (Type I) to 32% (Type II) of the collection. There are no correlations between the diamond type and the morphology. Color was evaluated visually by a binocular microscope. All diamonds are white, and only 46 diamonds display brown color of different shades, ten of them are Type II. Other colors were not recognized. Very weak blue UV fluorescence is detected in 6 samples out of 75 Type II diamonds (8%), whereas 138 out of 266 Type I stones (40%) show weak blue - turquoise fluorescence.

Raman and EPMA measurements defined a variety of primary mineral inclusions, i.e. garnet, majorite, clinopyroxene, orthopyroxene, olivine, $CaSiO_3$ phases, coesite, spinel and kyanite. All inclusions (n=332 from 202 diamonds) can be subdivided into four parageneses, lithospheric peridotitic (1) and eclogitic (2), mixed (3) (peridotitic-eclogitic) and sublithospheric mafic (4) (Table 1). There is also a small group of diamonds with an undetermined paragenesis in both types of diamond represented by Fe and Fe-Ni sulphides. One Type I diamond contains a unique super-deep inclusion, the unreverted $CaSiO_3$ phase with the perovskite lattice structure, found in nature for the first time.

Table 1. Parageneses and mineral association from the studied Cullinan mine diamonds.

Parageneses	Mineral association	Type-I (n diamonds)	Type-II (n diamonds)
Sublithospheric mafic	Mj	5	5
	Mj + Omp	2	1
	Mj + Co + Ky	-	1
	Mj + Prp-Alm	1	-
	$CaSiO_3$ (Wo and Prv)	2	2
Total:		**10** (6%)	**9** (22%)
Lithospheric eclogitic	Grt + Cpx	14	-
	Grt + (Co)	32 (1)	-
	Cpx + (Co)	70	7 (2)
	Co + (Ky)	10	6 (1)
	En + Co	-	1
Total:		**126** (79%)	**14** (33%)

Lithospheric peridotitic	Grt + Fo + (En)	2	2 (1)
	Cr-Aug + (En)	-	3 (1)
	Fo	17	13
	En	4	-
	Spl	-	1
Total:		**23** (14%)	**19** (45%)
Lithospheric mixed	Fo + Co	**1** (1%)	**-**
Total:		**160**	**42**

The overwhelming majority of peridotitic inclusions are of lherzolitic paragenesis, as evidenced by the chemical composition of garnets, the average Mg# of olivines (92.2 - very close to the average for lherzolitic olivine diamond inclusions worldwide of 92.0) and the low Al_2O_3 contents in enstatites (below 1.0 wt.%). The eclogitic inclusions are very diverse, with ranges of garnet composition Prp 28.3-72.8, Alm 19.3-43.2, Grs 1.6-46.1 and ranges of omphacite composition Jd 12.5-59.2, Aeg 0-9.0, Wo+En+Fs 40.8-79.6. These observations suggest that the studied minerals represent both A and B types of eclogite, and only one Type I diamond contains grossular and diopside inclusions similar to the grospydite association (type C eclogite). Rare associations such as Mj + Co + Ky and Mj + Prp-Alm that combine inclusions incompatible by the depth of origin, highlight that some diamonds could grow sequentially in different PT-ranges.

Since there are several types of mineral parageneses in Cullinan diamonds, we used different ways to evaluate PT-parameters of mineral associations. The temperatures were evaluated using an Al-in-Ol thermometer (Bussweiler et al., 2017) (17 samples), an Opx-Cpx thermometer (Taylor, 1998) with a Opx-Grt barometer (Nickel, Green, 1985) (1 sample) and a single crystal Cpx thermometer (Nimis, Taylor, 2000) (1 sample) for peridotitic inclusions and a Grt-Cpx thermometer (Nakamura, 2009) for eclogitic inclusions (14 samples). Approximately two thirds of the lithospheric inclusions can be projected onto the local geotherm approximated by a 40 mW/m^2 geotherm (Hasterok and Chapman, 2011) and show PT-parameters consistent with the lithospheric conductive thermal regime; 1090-1400°C and 45-63 kb. One third of the diamonds yield very high Al-in-Ol and Cpx-Gar temperatures, above the upper error limit of potential temperatures for non-plume convecting upper mantle adiabats (1327±40°C, Katsura et al., 2010); these super-adiabatic temperatures are common for peridotite xenoliths in kimberlites. These diamonds are interpreted to have formed in a mantle region with potential temperatures from ~ 1327 to 1440°C, labeled as a dark field on Fig. 1. The high potential temperatures suggested by this Cullinan inclusion cluster suggest that we are seeing a unique snap-shot of diamond formation at plume-like temperatures, at 1200 Ma, the time of the Cullinan kimberlite emplacement. For the lithospheric diamonds, the PT-conditions of origin for inclusions of eclogitic and peridotitic parageneses are identical. To calculate the pressure of majorite origin, the new improved majorite geobarometer was chosen (Wijbrans et al., 2016). The majorite barometry yields pressures of 93-138 kb (17 samples) when projected onto 1327 and 1440°C adiabats . The sublithospheric mafic diamonds are thus sourced from the transition zone, based on the stability of Ca-Si perovskite (below 500 km) and 300-460 km based on the inferred depth of majorite origin. The pressure estimates for sublithospheric Type II diamonds are identical to those of Type I diamonds (Fig. 1).

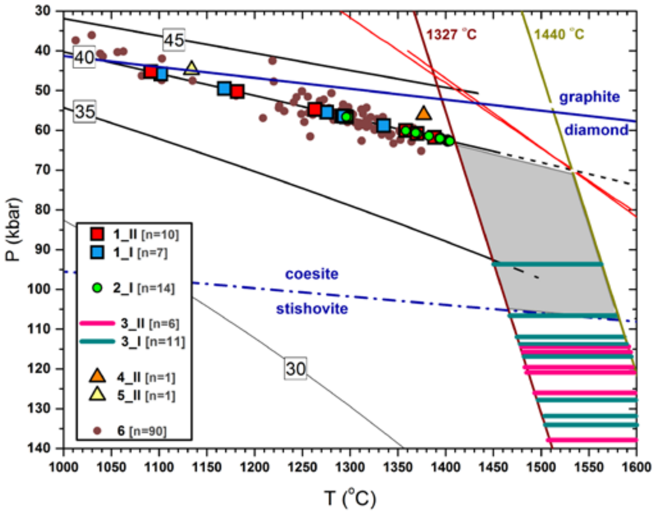

Fig. 1. Pressure-temperature estimates for studied Cullinan diamond inclusions using the following thermometers and barometers: 1 – Al-in-Ol thermometer (Bussweiler et al., 2017); 2 - Grt-Cpx thermometer (Nakamura, 2009); 3 - Mj geobarometer (Wijbrans et al., 2016); 4 - Single-Cpx geothermobarometer (Nimis, Taylor, 2000); 5 - Opx-Grt barometer (Nickel, Green, 1985) and Opx-Cpx thermometer (Taylor, 1998); 6 – Peridotitic xenoliths from Premier pipe (Viljoen et al., 2009). The legend contains sample numbers with "_II" and "_I" labelling type-II and type-I diamonds, respectively. Red univariant P-T lines calculated from Nakamura, 2009) and Al-in-Ol thermometer (Bussweiler et al., 2017) are for inclusions with the highest PT-parameters. An intersection of the lines with the local geotherm defines the 1440°C potential temperature. Dark field is a probable area of origin for eclogitic diamonds with high Cpx-Gar temperatures and peridotitic diamonds with high Al-in-Ol temperatures. The field is limited by the ambient 1327°C adiabat, the 1440°C adiabat, the 40 mW/m^2 geotherm (Hasterok and Chapman, 2011) and the coesite-stishovite phase boundary, since only coesite inclusions are common in the studied diamonds.

We conclude that the peridotitic paragenesis predominates in Type II diamonds, whereas 79% of the Type I stones are sourced from eclogites. The result confirms a well-known fact that E-type diamonds contain more nitrogen than P-type diamonds. This may reflect natural N heterogeneity of the parent diamondiferous rocks, but may also be controlled by the external diamond-forming fluid. Another contrast in the parageneses of Type I and Type II diamonds relates to the higher incidence of sublithospheric inclusions in the Type II stones, 22% against 6% in Type I diamonds. Type II diamonds are more commonly derived from the transition zone, where low N contents in Cullinan sublithospheric diamonds may be linked to the presence of Fe or FeC (Smith and Kopylova, 2014). We conclude that Type II diamonds are diverse in paragenesis and consequently in origin, as originally emphasised by Moore (2009).

The study was funded by the Dr. Eduard Gübelin Association through the 2015 Dr. Eduard Gübelin research scholarship to N. Korolev.

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