

Diamonds and their mineral inclusions from the A154 South pipe, Diavik Diamond Mine, Northwest territories, Canada

Cara L. Donnelly ^{a,*}, Thomas Stachel ^a, Steven Creighton ^a,
Karlis Muehlenbachs ^a, Sean Whiteford ^b

^a *Earth and Atmospheric Sciences, University of Alberta, Edmonton, AB, Canada T6G 2E3*

^b *Diavik Diamond Mines, Yellowknife, NWT, Canada*

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Abstract

Mineral inclusions recovered from 100 diamonds from the A154 South kimberlite (Diavik Diamond Mines, Central Slave Craton, Canada) indicate largely peridotitic diamond sources (83%), with a minor (12%) eclogitic component. Inclusions of ferropericlasite (4%) and diamond in diamond (1%) represent “undetermined” parageneses.

Compared to inclusions in diamonds from the Kaapvaal Craton, overall higher CaO contents (2.6 to 6.0 wt.%) of harzburgitic garnets and lower Mg-numbers (90.6 to 93.6) of olivines indicate diamond formation in a chemically less depleted environment. Peridotitic diamonds at A154 South formed in an exceptionally Zn-rich environment, with olivine inclusions containing more than twice the value (of ~52 ppm) established for normal mantle olivine. Harzburgitic garnet inclusions generally have sinusoidal rare earth element (REE_N) patterns, enriched in LREE and depleted in HREE. A single analyzed lherzolitic garnet is re-enriched in middle to heavy REE resulting in a “normal” REE_N pattern. Two of the harzburgitic garnets have “transitional” REE_N patterns, broadly similar to that of the lherzolitic garnet. Eclogitic garnet inclusions have normal REE_N patterns similar to eclogitic garnets worldwide but at lower REE concentrations.

Carbon isotopic values ($\delta^{13}\text{C}$) range from −10.5‰ to +0.7‰, with 94% of diamonds falling between −6.3‰ and −4.0‰. Nitrogen concentrations range from below detection (<10 ppm) to 3800 ppm and aggregation states cover the entire spectrum from poorly aggregated (Type IaA) to fully aggregated (Type IaB). Diamonds without evidence of previous plastic deformation (which may have accelerated nitrogen aggregation) typically have <25% of their nitrogen in the fully aggregated B-centres. Assuming diamond formation beneath the Central Slave to have occurred in the Archean [Westerlund, K.J., Shirey, S.B., Richardson, S.H., Gurney, J.J., Harris, J.W., 2003b. Re–Os systematics of diamond inclusion sulfides from the Panda kimberlite, Slave craton. VIIIth International Kimberlite Conference, Victoria, Canada, Extended Abstracts, 5p.], such low aggregation states indicate mantle residence at fairly low temperatures (<1100 °C). Geothermometry based on non-touching inclusion pairs, however, indicates diamond formation at temperatures around 1200 °C. To reconcile inclusion and nitrogen based temperature estimates, cooling by about 100–200 °C shortly after diamond formation is required.

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* Corresponding author. 1-26 Earth Science Building, University of Alberta, Edmonton, Alberta, Canada T6G 2E3. Tel.: +1 519 524 4185; fax: +1 780 492 2030.

E-mail address: carad@ualberta.ca (C.L. Donnelly).

1. Introduction

Mineral inclusions in diamonds provide a means to investigate the deep lithospheric mantle beneath ancient cratons. The majority of inclusion-based studies have been performed on diamonds from the Kalahari and Siberian cratons. The discovery of diamondiferous kimberlites on the Slave Craton in the early 1990s prompted a series of inclusions studies (Chinn et al., 1998; Stachel et al., 2003; Tappert et al., 2005) based on diamonds from the Ekati Mine (Central Slave, Fig. 1) which established derivation from dominantly peridotitic sources with a minor eclogitic component. The Snap Lake kimberlite dyke, in the southern part of the Slave Craton, also yielded a high abundance of peridotitic inclusions (Pokhilenko et al., 2001, 2004). However, studies of pipe DO27 (Davies et al., 1999, 2004a), located in the Tli Kwi Cho kimberlite cluster on the south-eastern side of Lac de Gras, revealed a dominance of eclogitic diamonds (~50%) and a significant number of “ultradeep”, sublithospheric inclusions (~25%). A first comparison of major element data for peridotitic

diamond inclusions from the Slave and Kaapvaal cratons (Stachel et al., 2003) showed the diamondiferous lithospheric mantle beneath the Slave to be chemically less depleted.

The present paper examines 100 inclusion-bearing diamonds from the A154 South pipe at Diavik Diamond Mines, located 295 km northeast of Yellowknife on the eastern end of Lac de Gras (Fig. 1). The Lac de Gras kimberlite field hosts >236 kimberlites (Kjarsgaard and Levinson, 2002) of Cretaceous to Eocene age (86 Ma–47 Ma, Heaman et al., 2004) and is emplaced into an assemblage of Archean and Proterozoic rocks of the Slave Province. The studied A154 South pipe has an emplacement age of 55.5 ± 0.5 Ma (phlogopite Rb–Sr isochron age, Graham et al., 1999).

For our diamond sample we examined the major and trace element composition of mineral inclusions in combination with the carbon isotopic composition ($\delta^{13}\text{C}$) and the nitrogen content and aggregation characteristics of their diamond hosts. Through a combination of high grades and high diamond quality the A154 South kimberlite represents a deposit with a uniquely high ore value (c.f. Kjarsgaard and Levinson, 2002). Our study aims to determine the principal diamond source rocks and the physical conditions of diamond formation and mantle storage for such an exceptional deposit. These results will be compared to previous diamond and inclusion studies from other Slave kimberlites.

2. Analytical methods

One hundred inclusion-bearing diamonds were selected from >10,000 carats of run of mine production in the –11+9 DTC (3.12–2.49 mm square mesh) and +11 DTC to 3gr (3.87–3.13 mm square mesh) sieve classes. The diamond characteristics including morphology, colour, surface features and evidence of plastic deformation were documented and are summarized in Table 1.

To release the mineral inclusions the diamonds were cracked in a steel crusher. Initially, 157 inclusions were recovered from the 100 diamonds, subsequently one inclusion was lost during preparation. The recovered inclusion size ranged from 20 to 375 μm , with an average size of 70 μm . Three Mg-chromite “inclusions” were not completely enclosed within their host diamond, which may have allowed for re-equilibration at depth in the mantle, or by reaction with the kimberlitic magma upon ascent. However, these exposed “inclusions” show no compositional differences to completely encapsulated Mg-chromites and have been included within the data set.

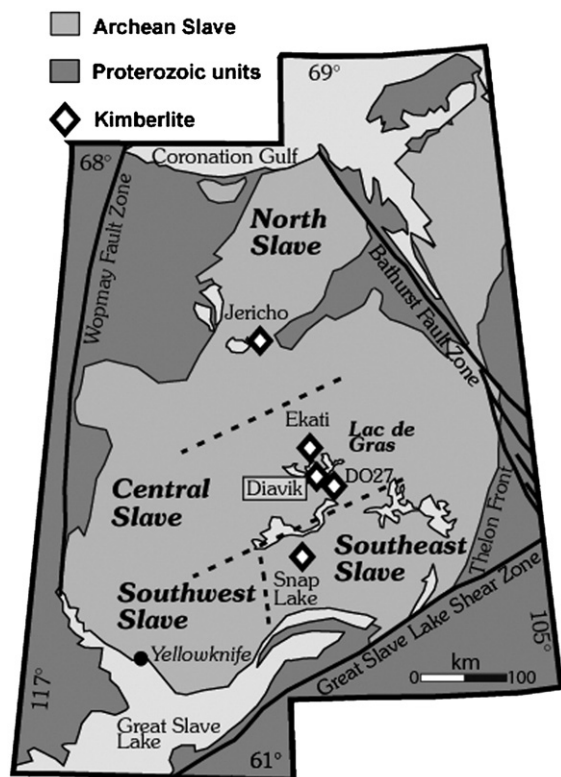


Fig. 1. Map of the Slave Craton modified from Bleeker and Davis (1999). North, central and south subdivisions for the Slave are from Grütter et al. (1999) and the subdivisions of the southern domain are from Carbno and Canil (2002).

Table 1

Summary of the physical and geochemical characteristics of the A154 South diamonds and their mineral inclusions

Sample	Assemble	Suite	Shape	Colour	Deformation	$\delta^{13}\text{C}$	Type	N_{T} (at. ppm)	Aggregation (%B)
ddmi-001	2chr	P	D	Brown	No	-4.5	IaAB	526	15
ddmi-002	fper,s	U	O	Brown	No	0.7	IaAB	125	69
ddmi-003	ol	P	O	Brown	No	-5.5	IaA	49	4
ddmi-004	2chr	P	I	Grey	No	-5.0	IaAB	377	12
ddmi-005	ol	P	D	Colourless	No	-5.3	IaAB	86	65
ddmi-006	chr	P	O	Colourless	No	-5.0	IaAB	344	76
ddmi-008	gnt	P	TM	Brown	No	-5.7	IaA	250	4
ddmi-013	ol	P	O	Brown	Yes	-3.9	IaA	44	0
ddmi-014	ol	P	O	Brown	No	-4.6	IaAB	55	38
ddmi-025	2chr	P	O	Colourless	No	-5.1	IaA	232	0
ddmi-034	2chr,s	P	I	Brown	No	-4.5	IaA	333	3
ddmi-036	chr,3chr*	P	I	Brown	No	-4.5	IaA	247	0
ddmi-037	5s	E	D	Colourless	No	-8.6	IaA	270	9
ddmi-040	2chr	P	O	Brown	No	-4.3	IaAB	142	80
ddmi-043	2chr	P	O	Colourless	No	-4.8	IaAB	179	22
ddmi-044	3chr	P	D	Brown	No	-5.0	IaA	245	0
ddmi-046	chr	P	O	Colourless	No	-4.0	IaAB	385	65
ddmi-047	chr	P	I	Brown	No	-4.6	IaA	435	2
ddmi-048	4cpx	E	D	Colourless	No	-10.5	IaAB	165	81
ddmi-049	ol	P	D	Brown	No	-4.2	IaB	118	97
ddmi-058	chr	P	I	Colourless	No	-5.1	IaA	511	2
ddmi-078	2s	E	D	Colourless	No	-5.2	IaA	560	0
ddmi-093	s	E	D	Colourless	No	-5.1	IaA	724	0
ddmi-098	2chr	P	O	Colourless	No	-4.3	IaA	318	0
ddmi-100	chr,3chr*	P	D	Brown	No	-4.4	IaA	19.5	0
ddmi-101	ol	P	I	Brown	No	-6.0	IaB	410	98
ddmi-103	chr	P	I	Colourless	No	-5.1	IaAB	178	48
ddmi-108	chr	P	I	Colourless	No	-5.3	IaA	432	4
ddmi-110	ol	P	I	Brown	No	-4.8	IaA	481	3
ddmi-111	3ol	P	O	Colourless	No	-6.3	IaA	195	8
ddmi-112	s	P	O	Brown	Yes	-5.4	IaA	366	0
ddmi-114	fper	U	I	Brown	No	-2.9	II	—	—
ddmi-115	s	P	O	Brown	No	-5.5	IaA	48	0
ddmi-119	13chr,2chr*	P	I	Colourless	No	-4.9	IaA	257	0
ddmi-120	chr	P	D	Colourless	No	-4.5	IaA	557	3
ddmi-123	ol	P	D	Brown	Yes	-6.3	IaAB	99	39
ddmi-124	ol	P	OA	Pink	Yes	-5.5	IaA	661	0
ddmi-126	3chr	P	D	Brown	No	-5.0	IaA	193	1
ddmi-127	s	E	D	Colourless	No	-5.3	IaA	711	0
ddmi-129	ol	P	TM	Brown	No	-5.8	IaB	1051	100
ddmi-130	s	P	TM	Colourless	No	-5.4	IaA	1873	0
ddmi-133	2gnt	P	OA	Brown	No	-5.4	IaA	418	0
ddmi-135	3ol	P	OA	Brown	No	-4.4	IaA	549	4
ddmi-139	3ol	P	TM	Pink	No	-6.2	IaA	458	2
ddmi-140	cpx	P	O	Brown	No	-4.6	IaA	21	0
ddmi-141	ol-cpx	P	O	Colourless	No	-5.1	IaA	29	0
ddmi-142	ol	P	O	Brown	No	-4.6	IaA	424	0
ddmi-144	2ol	P	O	Brown	No	-4.5	IaA	149	0
ddmi-145	2chr	P	I	Colourless	No	-5.2	IaA	185	0
ddmi-146	chr	P	I	Brown	No	-4.4	IaA	66	0
ddmi-147	12chr	P	O	Brown	No	-5.2	IaA	182	0
ddmi-148	2ol	P	O	Brown	No	-6.1	IaA	89	6
ddmi-150	2chr,s	P	D	Brown	No	-4.8	IaB	294	98
ddmi-151	2ol	P	TM	Pink	No	-6.3	IaAB	384	19
ddmi-152	4chr	P	D	Brown	No	-5.0	IaA	119	0
ddmi-153	3fper	U	I	Brown	No	-4.2	IaAB	58	57
ddmi-154	gnt,2ol	P	O	Brown	No	-4.8	IaAB	109	58

Table 1 (continued)

Sample	Assemble	Suite	Shape	Colour	Deformation	$\delta^{13}\text{C}$	Type	N_{T} (at. ppm)	Aggregation (%B)
ddmi-155	ol	P	O	Brown	No	−5.3	IaAB	440	19
ddmi-156	s	P	D	Brown	No	−4.9	IaA	105	0
ddmi-159	gnt (alt)	P	DA	Grey	No	−5.1	IaA	1225	0
ddmi-161	ol	P	O	Brown	No	−6.1	IaA	315	6
ddmi-162	ol	P	OA	Colourless	No	−8.6	IaA	41	0
ddmi-165	3ol	P	O	Brown	No	−5.2	IaA	232	0
ddmi-166	10gnt	E	O	Yellow	No	−4.8	IaAB	3833	36
ddmi-167	gnt,2ol	P	O	Brown	Yes	−4.8	IaA	17	0
ddmi-168	ol	P	D	Brown	No	−5.6	IaA	109	10
ddmi-169	2chr	P	O	Brown	No	−5.2	IaA	63	0
ddmi-170	2ol	P	TM	Brown	No	−5.4	IaA	38	7
ddmi-172	2chr	P	I	Colourless	No	−5.0	IaA	78	0
ddmi-173	fper	U	O	Brown	No	−4.8	II	—	—
ddmi-174	ol	P	O	Colourless	No	−4.3	IaA	76	0
ddmi-175	6gnt	P	O	Brown	No	−4.4	IaA	294	0
ddmi-176	chr	P	I	Colourless	No	−5.2	IaA	63	0
ddmi-177	2ol	P	OA	Brown	No	−5.2	II	—	—
ddmi-179	ol,s	P	O	Brown	Yes	−5.6	IaAB	159	11
ddmi-180	2ol	P	I	Brown	No	−6.3	IaAB	126	30
ddmi-182	chr	P	TM	Brown	No	−5.1	II	—	—
ddmi-183	ol,chr	P	O	Brown	No	−5.3	IaB	384	91
ddmi-184	ol	P	I	Colourless	No	−5.4	IaA	414	6
ddmi-186	2cpx	E	O	Colourless	No	−4.9	IaA	822	0
ddmi-187	7chr	P	D	Colourless	No	−4.6	IaA	373	0
ddmi-188	3chr	P	O	Brown	Yes	−5.1	IaA	321	0
ddmi-190	2ol	P	D	Brown	No	−5.6	IaAB	185	11
ddmi-193	coe	E	D	Brown	No	−5.1	II	—	—
ddmi-195	ol	P	D	Brown	No	−6.1	IaAB	61	84
ddmi-196	2s	E	DA	Colourless	No	−5.1	IaA	904	0
ddmi-198	s	E	DA	Colourless	No	−5.3	IaA	629	0
ddmi-199	2gnt,s	P	O	Brown	No	−5.2	IaA	994	4
ddmi-200	dia	U	TM	Colourless	No	−4.6	IaA	863	2
ddmi-202	2s	P	O	Brown	No	−5.0	IaA	502	4
ddmi-203	chr	P	O	Colourless	No	−4.3	IaA	557	7
ddmi-205	2gnt	E	O	Pink	No	−4.8	IaA	860	0
ddmi-206	Ol	P	O	Brown	No	−5.2	IaA	862	7
ddmi-207	2chr	P	I	Colourless	Yes	−5.5	IaA	344	3
ddmi-208	12gnt	E	O	Yellow	No	−5.0	IaAB	1791	34
ddmi-210	2ol	P	O	Brown	No	−5.4	IaAB	134	49
ddmi-213	Ol	P	D	Brown	No	−5.2	IaAB	272	65
ddmi-214	2chr	P	I	Colourless	No	−5.0	IaA	669	8
ddmi-215	3chr	P	I	Colourless	No	−5.0	IaA	2636	0
ddmi-216	2gnt	P	O	Brown	No	−5.7	IaAB	219	37

Abbreviations:

Shape — O: octahedron, D: dodecahedron, I: irregular, TM: triangular macle, A: aggregate.

Suite — P: peridotitic, E: eclogitic, U: uncertain.

Assemblage — gnt: garnet, ol: olivine, chr: Mg-chromite, fper: ferropericlasite, s: sulphide, cpx: clinopyroxene, coe: coesite, dia: diamond.

*: exposed mineral on surface, (alt): altered mineral, *comma*: non-touching inclusion pair, *hyphen*: touching-inclusion pair, *number*: number of inclusions.

The recovered inclusions were embedded in brass rings using Araldite® resin and polished for subsequent electron microprobe microanalysis (EPMA) using a JOEL JXA 8900 Superprobe at the University of Alberta. An accelerating voltage of 20 kV and a beam current of

20 nA (30 nA for spinels) was applied. Natural and synthetic silicate, oxide and metal standards were used. Count times ranged from 20 to 100 s (background time=0.5 to 1 times peak time). Between three and five analytical points were measured on each sample and then

averaged. Resulting detection limits were ≤ 200 ppm with the exception of Cr_2O_3 (643 ppm) for spinel analyses, and Cr (575 ppm) and Zn (257 ppm) for sulphide analyses.

Twelve garnet inclusions (from twelve diamonds) were analyzed using Secondary Ion Mass Spectrometry (SIMS) to determine selected rare earth (REE: La, Ce, Nd, Sm, Eu, Dy, Er and Yb) and other trace elements (Ti, Y, Zr and Sr). Measurements were performed on a Cameca IMS 3f Ion Microprobe at Woods Hole Oceanographic Institute. Instrumental and analytical procedures were the same as described in Shimizu and Hart (1982), Shimizu and Le Roex (1986) and Tappert et al. (2005). Analytical accuracy was verified by analyses of secondary garnet standards. Analytical precision, based on counting statistics, ranges from 10 to 25% (relative) for the REE and 5–15% (relative) for other trace elements.

The Zn content of three Mg-chromite and five olivine inclusions was analyzed at the University of Alberta Radiogenic Isotope Facility using a Perkin Elmer Elan6000 quadrupole ICP-MS. Samples were ablated using a Merchantek UP 213 UV laser system applying the following settings: 30 s ablation time; 30 μm spot size; 10 Hz repetition rate; $\sim 12 \text{ J/cm}^2$ energy density. Due to small sample size only a single spot was analyzed per inclusion. Detection limits were determined to be ~ 5 ppm for Zn in olivine and ~ 16 ppm for Zn in Mg-chromite.

The carbon isotopic composition of the host diamonds was analyzed at the University of Alberta Stable Isotope Facility using a Finnigan Mat 252 Mass Spectrometer. For carbon isotopic analysis 0.5–1.5 mg of inclusion-free diamond fragments were combined with 1–2 g of purified copper oxide and combusted for ~ 12 h at 980°C in evacuated silica glass tubes. The CO_2 gas was extracted under vacuum using nitrogen traps and a mixture of dry ice and ethanol to remove impurities. Results are reported in conventional δ notation as ‰ difference relative to the Pee Dee belemnite standard.

Nitrogen concentration and aggregation characteristics of the host diamonds were determined on transparent, inclusion-free cleavage chips by Fourier transform infrared (FTIR) spectroscopy using a Thermo Nicolet Nexus 470 FT-IR Spectrometer combined with a Continuum infrared microscope. The instrument was purged with a dried mixture of N–O and background measurements were performed approximately every 3 h. Sample spectra (650 to 4000 cm^{-1}) were collected for 200 s. A pure Type II diamond spectrum was subtracted, removing the diamond two phonon absorbance, and simultaneously the sample spectrum was converted to absorption coefficient (i.e. normalized to a sample thickness of 1 cm). Spectra were then

deconvoluted into A, B and D components using software provided by David Fischer (Research Laboratories of the Diamond Trading Company, Maidenhead, UK). The concentrations of nitrogen, in atomic ppm, were calculated from absorption coefficient values at 1282 cm^{-1} for the A-centre and B-centre (Boyd et al., 1994, 1995). Detection limits were typically on the order of 10–20 ppm and largely depend on the quality of the sample. Analytical precision for nitrogen concentrations and aggregation states is generally within 10–20% (relative error, 1σ).

Our results are compared to an analytical reference database for diamonds and inclusions from worldwide sources (see Stachel et al. 1998a and references therein).

3. Major element compositions

3.1. Peridotitic paragenesis

83% of the diamonds from this study are peridotitic (Table 1). Mg-chromite and olivine are, by far, the most commonly occurring peridotitic inclusions, followed by garnet, Fe–Ni sulphides and clinopyroxene.

3.1.1. Garnet

Nine harzburgitic (from six diamonds) and two lherzolitic garnets (from one diamond) were recovered and range in Cr_2O_3 content from 7.0 to 15.7 wt.% and in CaO content from 2.6 to 6.0 wt.% (Fig. 2, Table 2).

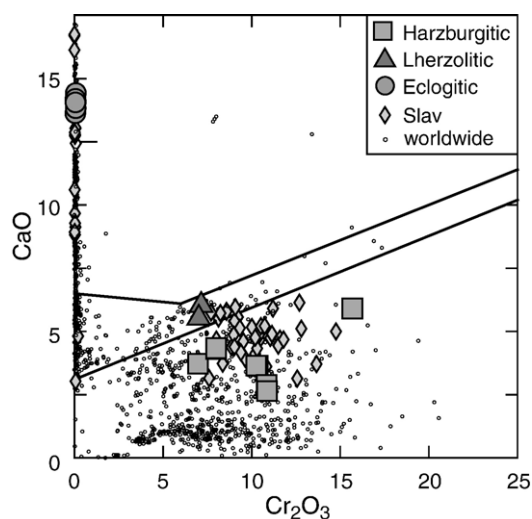


Fig. 2. CaO versus Cr_2O_3 (wt.%) for garnet inclusions in diamonds from A154 South (large symbols), localities on the Slave Craton (Davies et al., 1999, 2004a; Pokhilenko et al., 2001, 2004; Stachel et al., 2003; Tappert et al., 2005) and worldwide sources. The compositional field for lherzolitic garnets is taken from Sobolev et al. (1973).

Table 2

Major element composition (EPMA-analyses, wt.%) of selected inclusions from A154 South diamonds

Mineral	garnet	garnet	olivine	garnet	olivine	garnet	garnet	olivine	chromite	chromite	olivine	clinopyroxene	garnet	garnet
Sample	ddmi– 8a	ddmi– 154a	ddmi– 154c	ddmi– 167a	ddmi– 167b	ddmi–199a	ddmi– 216a	ddmi– 183a	ddmi– 183d	ddmi– 176	ddmi– 141b	ddmi–141a	ddmi–166a	ddmi–205a
Assemblage	gnt	gnt, 2ol	gnt, 2ol	gnt, 2ol	gnt, 2ol	2gnt, sulph	2gnt	ol,chr	ol,chr	chr	ol–cpx	ol–cpx	10gnt	2gnt
Suite	P	P	P	P	P	P (lherz)	P	P	P	P	P	P	E	E
P ₂ O ₅	0.03	0.03	≤0.01	0.02	0.01	≤0.01	≤0.04	≤0.01	–	–	≤0.01	≤0.01	0.06	0.08
SiO ₂	41.33	41.04	41.60	42.07	41.20	41.45	41.32	40.86	0.22	0.10	41.07	54.60	41.17	39.72
TiO ₂	0.12	0.08	≤0.02	≤0.02	≤0.02	0.06	≤0.05	≤0.02	0.29	0.13	≤0.02	0.09	0.36	0.36
Al ₂ O ₃	14.17	11.53	≤0.02	18.47	≤0.02	17.69	17.50	≤0.02	4.84	5.87	≤0.02	1.02	22.77	22.17
Cr ₂ O ₃	10.85	15.68	0.04	6.97	0.04	7.15	7.99	0.05	65.57	64.20	≤0.02	1.14	0.08	0.05
V ₂ O ₃	0.05	0.05	≤0.01	0.04	≤0.01	0.05	0.05	≤0.01	0.25	0.26	≤0.01	0.02	0.02	0.02
FeO	5.85	5.82	7.34	5.50	6.47	6.95	5.94	7.31	16.13	15.44	6.78	2.87	9.75	11.20
MnO	0.23	0.26	0.11	0.21	0.10	0.29	0.25	0.11	0.09	0.11	0.09	0.10	0.21	0.19
NiO	≤0.01	≤0.01	0.31	≤0.01	0.03	≤0.01	≤0.03	0.31	0.08	0.09	0.32	0.06	≤0.01	≤0.01
MgO	22.91	19.88	49.93	22.70	50.50	19.52	21.80	50.93	13.72	13.50	50.45	16.80	11.94	10.79
CaO	2.89	5.91	0.04	3.73	0.04	6.03	4.34	0.03	–	–	0.03	20.80	14.08	13.63
Na ₂ O	≤0.01	0.02	≤0.01	0.02	0.02	0.02	0.02	0.02	–	–	≤0.01	1.29	0.14	0.12
K ₂ O	≤0.01	≤0.01	≤0.01	≤0.01	≤0.01	≤0.01	≤0.02	≤0.01	–	–	≤0.01	0.02	≤0.01	≤0.01
ZnO	–	–	–	–	–	–	–	–	0.09	0.08	–	–	–	–
Oxide total	98.44	100.30	99.45	99.78	98.46	99.24	98.77	99.69	101.27	99.79	98.84	98.83	100.58	98.33

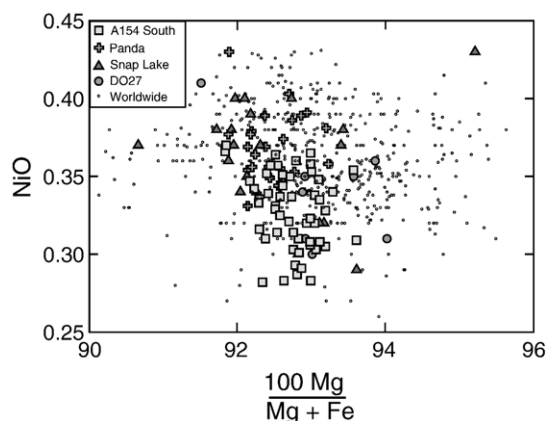


Fig. 3. NiO (wt.%) versus molar Mg-number for A154 South olivine inclusions (squares). Data for DO27 are from Davies et al. (1999, 2004a), for Panda from Stachel et al. (2003) and Tappert et al. (2005), and for Snap Lake from Pokhilenko et al. (2001) and Promprated et al. (2004).

The re-calculated Mg-number (re-calculated to a Ca-free composition to eliminate the effect of Ca on Mg–Fe partitioning between garnet and olivine, see Stachel et al., 2003) of the garnet inclusions ranges from 85.2 to 89.2, with a mean of 87.4. This distribution is similar to that observed for other Slave localities (Stachel et al., 2003, their Fig. 3).

3.1.2. Olivine

Fifty-four olivine inclusions (from 32 diamonds) and one touching olivine–clinopyroxene pair have forsterite contents from 91.8 to 93.6, with the exception of one sample (ddmi-49a with Fo 90.6). CaO ranges from 0.02 to 0.07 wt.% (Table 2). These compositions compare well with the worldwide inclusion database, although

highly depleted compositions ($Mg\# > 94$) are absent at A154 South (Fig. 3).

3.1.3. Clinopyroxene

Two peridotitic clinopyroxene inclusions (one touching with olivine) were recovered from two diamonds. With an Mg-number of 91.2–93.8, a Ca-number ($100Ca/[Ca+Mg+Fe_{total}]$) of 43.3–44.8 and Cr_2O_3 content of 1.1 wt.%, the two clinopyroxene inclusions compare well to the worldwide inclusion database.

3.1.4. Mg-chromite

Fifty-six Mg-chromite inclusions were recovered from 35 diamonds. As many as 15 individual Mg-chromite inclusions were observed in single diamonds. Mg-chromite was observed together with an olivine (Table 2) and a sulphide inclusion (Table 3) in one diamond each.

In their FFM ratio ($100Fe^{2+}/[Mg+Fe^{2+}] = 26.7–35.3$) and Cr-number ($100Cr/[Cr+Al] = 83.2–91.6$) the Mg-chromite inclusions fall into compositional ranges observed elsewhere. The range in FFM ratio is similar to that obtained at Snap Lake (29.4–33.0, Pokhilenko et al., 2001) but is considerably lower than that at Panda (32.8–47.8, Stachel et al., 2003). The Cr-numbers are similar at all three localities, excepting two Snap Lake Mg-chromites with low Cr-numbers of 74.9 and 78.0. In their ferric iron ratio ($100Fe^{3+}/[Fe^{3+}+Fe^{2+}] = \sim 18–30$) A154 South Mg-chromite inclusions fall on the high end of the worldwide database (Fig. 4).

3.1.5. Fe–Ni sulphides

Eight diamonds were found to contain peridotitic Fe–Ni sulphides (Table 3). The designation to the

Table 3
Major element composition (EPMA-analyses, wt.%) of selected sulphide inclusions

Mineral	Fe–Ni sulphide	Fe–Ni sulphide	Fe–Ni sulphide	Fe–Ni sulphide	Fe–sulphide	Fe–sulphide	Fe–sulphide	Fe–sulphide
Sample	ddmi-156	ddmi-179	ddmi-199	ddmi-202	ddmi-002	ddmi-037	ddmi-093	ddmi-127
Assemblage	sulph	ol, sulph	2gnt, sulph	2 sulph	fper, sulph	sulph	sulph	sulph
Paragenesis	Peridotitic	Peridotitic	Peridotitic	Peridotitic	Eclogitic	Eclogitic	Eclogitic	Eclogitic
Si	0.03	0.02	0.02	0.02	0.04	0.05	0.03	0.03
Cr	0.28	0.68	≤0.06	0.22	<0.06	≤0.06	≤0.06	≤0.06
Fe	38.83	39.64	23.89	36.85	45.76	56.47	56.35	56.35
Mn	≤0.02	≤0.02	≤0.02	≤0.02	≤0.02	≤0.02	≤0.02	≤0.02
Ni	22.32	21.19	39.85	22.68	<0.01	1.10	1.56	1.56
Mg	≤0.01	≤0.01	≤0.01	≤0.01	≤0.01	≤0.01	≤0.01	≤0.01
Cu	0.57	0.31	0.20	0.96	0.36	2.33	1.33	1.33
Co	0.51	0.43	0.96	0.50	0.05	0.27	0.34	0.34
Zn	0.07	0.07	0.07	0.04	0.05	0.03	0.05	0.05
S	36.94	36.85	33.75	37.76	52.91	38.54	38.95	38.95
Total	99.54	99.19	98.74	99.03	99.18	98.80	98.60	98.60

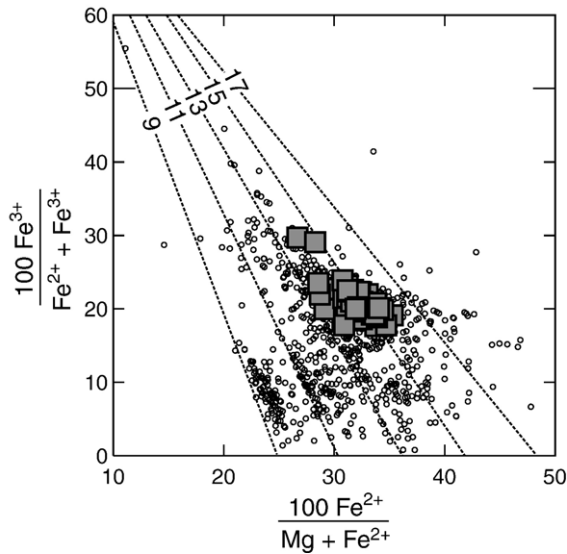


Fig. 4. Ferric iron number versus FFM ratio for Mg-chromite inclusions from A154 South (squares) worldwide sources (open circles). Ferric iron estimates are based on ideal stoichiometry. Dashed lines indicate approximate content of total Fe expressed as FeO (9–17 wt.%).

peridotitic suite is based on high Ni contents of the inclusion (e.g. Yefimova et al., 1983), but for three diamonds a peridotitic paragenesis was further confirmed through co-existing Mg-chromite (ddmi-150), olivine (ddmi-179) and lherzolitic garnet (ddmi-199). Fe contents vary from 23.59 to 47.61 wt.% and Ni contents range from 10 to 56 wt.%, but typically are on the order of ~20 wt.% (c.f. Fig. 5). Cu is present in minor amounts (0.20 to 1.99 wt.%), as is Co (0.37 to 0.96 wt.%) and Cr (≤ 0.06 to 0.68 wt.%).

3.2. Eclogitic paragenesis

Eclogitic inclusions were found in 12 diamonds which contained sulphides (six diamonds), garnet (three), clinopyroxene (two) and “coesite” (one diamond).

3.2.1. Garnet

Seven eclogitic garnet inclusions were recovered from three diamonds. In two diamonds (ddmi-166 and ddmi-208) in excess 10 garnet inclusions were observed. No significant compositional variations were found to exist for multiple garnets from the same diamond.

Compositionally (Table 2) the eclogitic garnets fall on the high side of the worldwide distribution with respect to their Mg-numbers (63.2 to 69.5) and CaO contents (13.7 to 14.6 wt.%) but have typical concentrations of Cr₂O₃ (0.05 to 0.08 wt.%), Na₂O (0.12 to 0.16 wt.%) and TiO₂ 0.30 to 0.36 wt.%.

3.2.2. Clinopyroxene

Four eclogitic clinopyroxene inclusions (from two diamonds) are compositionally homogenous within individual host with Mg-numbers of 83 and 90 for samples ddmi-48 and ddmi-186, respectively. The Mg-number obtained from ddmi-186 is unusually high for eclogitic clinopyroxenes. However, high Al₂O₃ (17.6 wt.%) and NaO (5.8 wt.%) clearly document a non-peridotitic source. Eclogitic clinopyroxene inclusions with similarly high Mg-numbers and high Al were previously only observed in diamonds from the Argyle and Ellendale lamproites (Kimberly area, Western Australia, Jaques et al., 1989).

3.2.3. SiO₂

A SiO₂ inclusion was found as a single phase inclusion in diamond ddmi-193. No visible fractures or alteration were associated with the inclusion, as such the SiO₂ inclusion was likely included as coesite. Analysis of the inclusion revealed no notable elemental impurities.

3.2.4. Fe sulphides

Eight eclogitic sulphide inclusions (from six diamonds) were found to be Fe-monosulphides (Table 3). The Fe contents range from approximately 54 to 60 wt.%, with minor amounts of Ni (0.35 to 1.6 wt.%) and Co (0.17 to 0.37 wt.%) and variable concentrations of Cu (0.49 to 5.0 wt.%).

3.3. Uncertain parageneses

3.3.1. Diamond

A colourless octahedral inclusions of diamond, without notable surface features, were found within a colourless triangular macle (spinel twin). The host diamond had a $\delta^{13}\text{C}$ value of -4.6‰ , while the

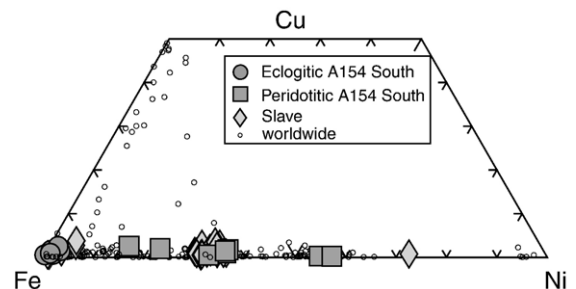


Fig. 5. Cu–Fe–Ni quadrilateral (atomic proportions) for sulphide inclusions from A154 South, other occurrences from the Slave Craton and worldwide sources. Data from the Slave Craton are from Davies et al. (1999) and Tappert et al. (2005).

included diamond was isotopically lighter at -6.1% . The host diamond was a Type IaA diamond with nitrogen concentrations of 863 ppm. The included diamond was also a Type IaA diamond, but had lower nitrogen concentrations of 334 ppm. Inclusions of diamond in diamond have previously been reported from other localities on the Slave Craton by Davies et al. (2004a). Diamond can occur as an inclusion in both the peridotitic or eclogitic suites.

3.3.2. Ferropericlasite

Six ferropericlasite inclusions without other coexisting phases were recovered from three diamonds. A fourth ferropericlasite bearing diamond (ddmi-2) contained pyrite as an additional mineral phase (Table 3), which was classified as an ‘eclogitic’ sulphide based on very low Ni and Cr contents. Normal NiO and Cr_2O_3 concentrations (1.09 and 0.60 wt.% respectively) in the co-existing ferropericlasite suggest either that the two inclusions were not in equilibrium or that Ni and Cr strongly partition into ferropericlasite, rendering the eclogitic designation of the coexisting sulphide spurious.

The ferropericlasite inclusions are characterized by high Mg-numbers (81.3 to 87.0) and NiO contents (0.98 to 1.12 wt.%) typical for ferropericlasite inclusions from localities other than Juina-São Luiz (Harte et al., 1999). One ferropericlasite inclusion from A154 South has exceptionally high NiO (2.03 wt.%), similar to two inclusions from Panda (Tappert et al., 2005). Notable impurities include Cr_2O_3 (0.36 to 0.60 wt.%), Na_2O (0.13 wt.% to 0.34 wt.%) and MnO (0.15 wt.% to 0.22 wt.%), which are normal

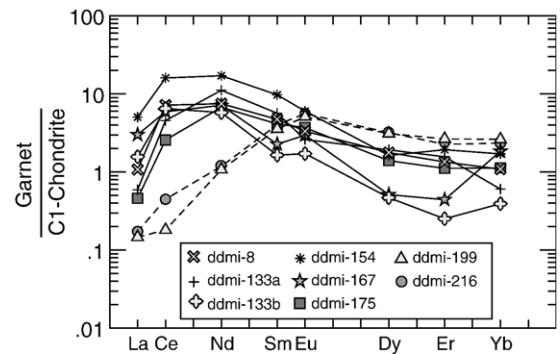


Fig. 6. Rare earth element concentrations of peridotitic garnet inclusions from A154 South normalized to C1-chondrite after McDonough and Sun (1995). Sample ddm-199 is of lherzolitic paragenesis. An average composition is shown for the two harzburgitic garnets from diamond ddm-216. “Sinusoidal” REE_N patterns are shown as solid lines, nearly “normal” REE_N patterns as dashed lines.

ranges for ferropericlasite inclusions from worldwide sources.

4. Trace element compositions

Nine peridotitic garnets and three eclogitic garnets have been analyzed for selected rare earth elements (REE), Ti, Zr, Y and Sr (Table 4). The rare earth element concentrations are normalized (REE_N) to the C1-chondrite composition of McDonough and Sun (1995). Eight of the analyzed peridotitic garnets belong to the harzburgitic and one to the lherzolitic paragenesis.

Six of the harzburgitic garnets are characterized by sinusoidal REE_N patterns with a crest in the light REE (Ce–Nd) and a trough in the middle REE (Fig. 6).

Table 4
Trace element harzburgitic paragenesis

Sample	ddmi-8a	ddmi-133a	ddmi-133b	ddmi-154a	ddmi-166a	ddmi-167a	ddmi-175b	ddmi-199a	ddmi-205b	ddmi-208c	ddmi-216a	ddmi-216c
Assemblage	gnt	2gnt	2gnt	gnt, 2ol	10gnt	gnt, 2ol	6gnt	2gnt, sulph	2gnt	12gnt	2gnt	2gnt
Suite	P	P	P	P	E	P	P	P (lherz)	E	E	P	P
Ti (ppm)	988	858	1059	680	2034	210	153	437	1568	2159	311	175
Sr (ppm)	4.18	6.26	4.39	10.79	6.15	3.77	2.79	0.86	2.63	5.60	1.87	0.76
Y (ppm)	2.25	1.98	2.23	2.04	12.78	1.14	3.34	1.36	11.32	11.45	6.70	5.40
Zr (ppm)	29.02	15.77	26.76	49.88	27.05	4.59	39.43	8.52	8.41	25.52	65.54	62.15
La (ppm)	0.26	0.32	0.14	1.19	0.12	0.71	0.11	0.03	0.10	0.15	0.04	0.04
Ce (ppm)	4.40	3.98	2.79	9.81	0.91	3.62	1.58	0.11	0.83	1.12	0.24	0.27
Nd (ppm)	3.43	2.64	5.10	7.82	1.74	3.27	3.08	0.49	1.61	1.72	0.67	0.41
Sm (ppm)	0.70	0.24	0.84	1.44	1.10	0.34	0.61	0.53	1.05	0.77	0.44	0.66
Eu (ppm)	0.19	0.10	0.15	0.34	0.50	0.17	0.21	0.29	0.31	0.50	0.32	0.31
Dy (ppm)	0.44	0.12	0.47	0.40	1.68	0.13	0.34	0.79	1.15	1.38	0.98	0.74
Er (ppm)	0.22	0.04	0.25	0.31	1.19	0.07	0.18	0.42	0.99	1.05	0.43	0.39
Yb (ppm)	0.18	0.06	0.10	0.27	1.22	0.30	0.18	0.42	0.85	0.81	0.35	0.38

Such patterns are typical for harzburgitic garnets worldwide (e.g. [Stachel et al., 2004](#)). Two harzburgitic garnets (diamond ddmi-216) and one lherzolitic garnet (ddmi-199) have low LREE contents and almost flat MREE_N–HREE_N peaking at Eu (Fig. 6), similar to the “normal” REE_N patterns of [Hoal et al. \(1994\)](#). These three garnets also have the lowest Sr contents (<2 ppm, Fig. 7). For the harzburgitic paragenesis the two garnets with near normal patterns also fall closest to the lherzolitic field in a Ca–Cr plot (Fig. 2).

The three eclogitic garnets analyzed have REE_N patterns that are similar to other eclogitic garnets worldwide in their overall shape, but the MREE and HREE concentrations are considerably lower (Fig. 8). Average eclogitic garnet inclusions have La at about 1 times and HREE at about 30 times chondritic abundance ([Stachel et al., 2004](#)). Eclogitic garnet inclusions from A154 South, however, have La at about 0.5 times and HREE at 5–8 times chondritic abundance (Fig. 8). The other analyzed high field strength elements Ti, Y and Zr also show lower concentrations than observed worldwide (see Fig. 7). For example, Ti contents range from 1570 to 2170 ppm, which is less than half the worldwide average of 4330 ppm. Sr contents are comparable to those observed worldwide and range from 3 to 6 ppm.

5. Geothermometry

Two non-touching garnet–olivine pairs (ddmi-154 and ddmi-167, see Table 2) allow estimating the temperature conditions of diamond formation (Fe–Mg exchange thermometer of [O'Neill and Wood, 1979](#); [O'Neill, 1980](#)). Temperatures of 1220 and 1230 °C were calculated at an assumed pressure of 50 kbar. Additionally, one olivine–Mg–chromite inclusion pair (Table 2) yielded a temperature of 1170 °C at the same assumed pressure (Fe–Mg exchange thermometer of [O'Neill and](#)

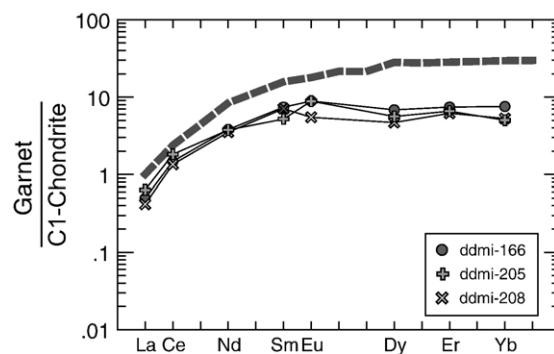


Fig. 8. Rare earth element concentrations of eclogitic garnet inclusions from A154 South and the average composition of eclogitic inclusions from worldwide sources (thick dashed line) normalized to C1-chondrite after [McDonough and Sun \(1995\)](#).

[Wall, 1987](#)). Overall, the inclusion pairs reflect temperatures of about 1200 °C, which is slightly higher than the average garnet–olivine temperatures of 1180 °C from DO27 ([Davies et al., 2004a](#)) and Ekati (average for pipes Misery, Sable, and Jay, [Chinn et al., 1998](#)), 1140 °C from Panda ([Stachel et al., 2003](#)), and 1130 °C from Snap Lake (calculated using data of [Pokhilenko et al., 2001](#)).

Two peridotitic clinopyroxene inclusions (ddmi-140 and 141) yielded temperatures of 1190 °C and 990 °C applying the thermometer of [Nimis and Taylor \(2000\)](#) for an assumed pressure of 50 kbar. Combination with the single-clinopyroxene barometer of [Nimis and Taylor \(2000\)](#) resulted in pressure–temperature conditions of 52 kbar/1190 °C (ddmi-140) and 71 kbar/1030 °C (ddmi-141) equivalent to 42 and 33 mW/m² model geotherms ([Pollack and Chapman, 1977](#)), respectively. The latter value is inconsistent with conditions of diamond formation (e.g. [Phillips et al., 2004](#)) and suggests that the touching pair of clinopyroxene and olivine in ddmi-141 re-equilibrated after diamond formation to changing physical conditions and hence represents a garnet- and orthopyroxene-free (wehrlitic) paragenesis to which this geothermobarometer must not be applied.

Fifty-six Mg–chromite inclusions (Zn-in-spinel thermometer of [Ryan et al., 1996](#)) produced an uncommonly low temperature range of 790 to 1020 °C (average: 940 °C). For diamond ddmi-183, Zn-in-spinel (920 °C) and olivine–spinel (1170 °C) temperatures deviate by 250 °C, well beyond the errors of both thermometers. Accuracy of our Zn in spinel analyses with EPMA was verified with LA-ICP-MS and agreement of the two methods is within 50 ppm. To test if the anomalously low temperatures relate to unusually high Zn contents in co-existing olivine – the Zn-in-spinel thermometer of [Ryan et al. \(1996\)](#) assumes a constant Zn content in coexisting olivine of ~52 ppm – we also analyzed five

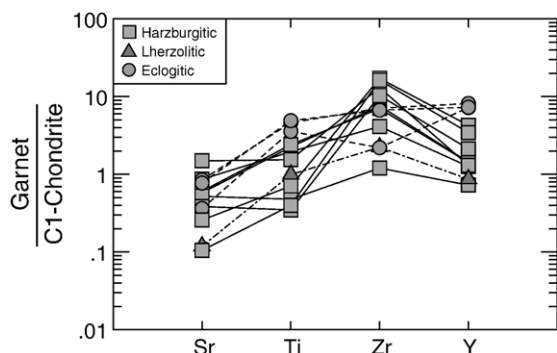


Fig. 7. Sr, Ti, Zr and Y concentrations for garnet inclusions from A154 South normalized to C1-chondrite ([McDonough and Sun, 1995](#)).

olivine inclusions with LA-ICP-MS. Four olivines yielded Zn contents of 109 to 126 ppm, the olivine co-existing with Mg-chromite in ddmi-183 contains 410 ppm. Very low apparent Zn-in-spinel temperatures hence are an artifact of unusually high Zn in olivine inclusions at A154 South.

6. Physical and chemical characteristics of the host diamonds

6.1. Morphology and colour

Four population surveys, with sample sizes of 520 to 1020 diamonds, were conducted on run of mine production in the $-11+9$ and $+11$ to 3gr sieve-classes. Diamonds were characterized based on colour, morphology, presence/absence of coating and inclusion content using the methodology outlined in Robinson (1979). While the Diavik mine is well known for producing high quality colourless, octahedral diamonds, within the smaller diamond sizes studied here the population is actually dominated by resorbed dodecahedral morphologies (30% diamonds with $>50\%$ resorbed faces). Octahedral stones comprise 14% of the diamond population and only about 1/3 of these are essentially unresorbed, sharp-edged octahedra. In the studied size range the Diavik production also contains a high percentage ($\sim 12\%$) of diamonds with cubic morphologies, compared to $<1\%$ for the production of southern African mines (Harris, 1992). The cubic stones are dominantly re-entrant cubes, but some flat-faced and rounded cubes were observed. Triangular macles and aggregates of three or more stones were also present.

A different morphological distribution was observed within the inclusion-bearing diamond population where octahedra (41%) dominated, followed by rounded dodecahedra (22%), irregular crystals/fragments (21%), twins (8%) and aggregates (8%). Cubic stones are not represented since they very rarely contain mineral inclusions. Overall, inclusion-bearing diamonds comprised $<2\%$ of the surveyed production. With increasing diamond size (1, 3 and 5 carat stones), the proportion of octahedral diamonds strongly increases at the expense of cubes and rounded dodecahedra.

The dominant body colour of the surveyed run of mine production is colourless (63%), followed by brown (23%). Yellow, pink and grey diamonds were observed, but are rare. Conversely, the subpopulation of inclusion-bearing diamonds is dominated by brown diamonds (58%), followed by colourless (34%), pink (4%), yellow (2%) and grey (2%).

For both run-off-mine production and inclusion-bearing diamonds fibrous coats, ranging from thin, nearly transparent layers to grey to grey-black opaque covers over clear octahedral diamonds, occur throughout all size ranges. The fibrous overgrowths may show extensive etching in form of trigons.

6.2. Carbon isotopes

The carbon isotopic composition ($\delta^{13}\text{C}$) of the 100 diamonds studied (Table 1 and Fig. 9) ranges from -10.5‰ to $+0.7\text{‰}$, with an average value of -5.1‰ . The observed mode in class -5.5 to -5.0‰ is similar to that observed for eclogitic and peridotitic diamonds

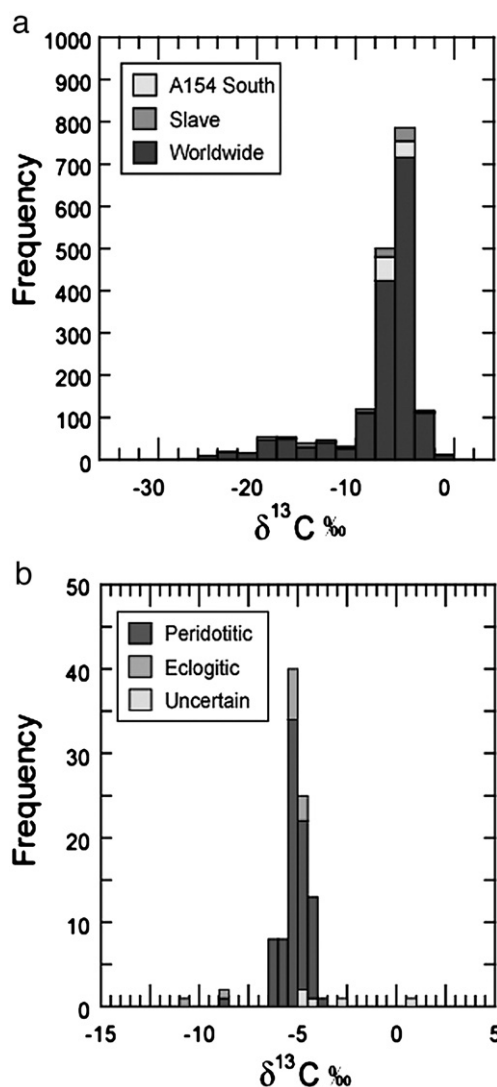


Fig. 9. Histograms showing the carbon isotopic composition of diamonds from (a) worldwide sources and (b) A154 South.

worldwide. When a few outliers are removed, a narrow distribution with 94% of the diamonds falling between -6.3‰ and -4.0‰ becomes apparent. The two highest values are from ferropericlasite-bearing diamonds, while the two lowest values represent diamonds with eclogitic inclusions (Fig. 9).

6.3. Nitrogen contents and aggregation levels

Nitrogen concentrations of the 100 inclusion bearing diamonds typically range from below detection (≤ 10 ppm) to ~ 1200 atomic ppm (Table 1 and Fig. 10). Higher contents were observed in two Type IaA ($>90\%$ of nitrogen in the poorly aggregated A-centre) diamonds with ~ 1800 ppm nitrogen and two yellow, octahedral Type IaAB (between 10 and 90% of nitrogen in the fully aggregated B-centre) diamonds with abundant eclogitic garnet inclusions, containing 1800 and 3800 ppm. Poorly aggregated Type IaA diamonds predominate (65%), intermediate Type IaAB diamonds comprise 25% of the population, and Type IaB diamonds, with $>90\%$ of nitrogen in the fully aggregated B-centre, represent 5%. The remaining 5% are Type II (nitrogen-free) diamonds. Excluding all diamonds showing evidence of plastic deformation (brown body colour or presence of deformation lines), all but seven of the remaining ninety-two diamonds have less than 25% of the nitrogen aggregated to B-centres.

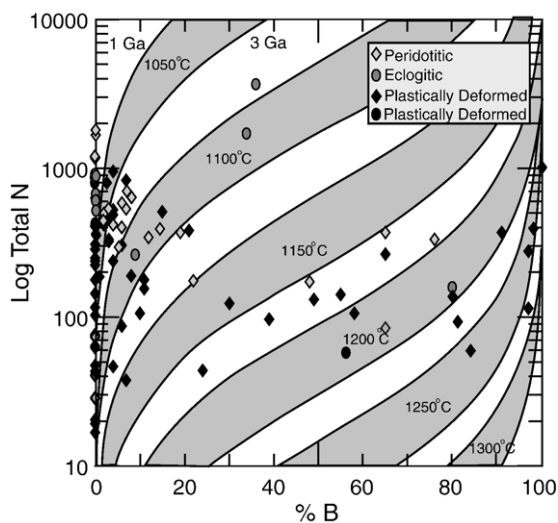


Fig. 10. Total nitrogen concentration (atomic ppm) versus nitrogen aggregation state (expressed as relative percentage of the fully aggregated nitrogen B-centre). Isotherms for time averaged residence temperatures (mantle residence times of 1 and 3 Ga) are from Taylor et al. (1990).

7. Discussion

7.1. The diamond source region at A154 South

A154 South diamonds mainly ($\sim 83\%$) reflect peridotitic mantle source regions. Predominantly peridotitic diamond populations were also observed for the nearby Ekati Mine (Chinn et al., 1998; Stachel et al., 2003; Tappert et al., 2005) and at Snap Lake dyke (Pokhilenko et al., 2004). Pipe DO27 appears to be an exception in the Central Slave Craton as eclogitic diamonds dominate (Davies et al., 1999, 2004a).

Elevated CaO in harzburgitic garnets and lower Mg-numbers of olivine relative to inclusions in diamonds from the Kaapvaal Craton (Stachel et al., 2003) indicate that diamond formation beneath A154 South occurred in a moderately depleted peridotitic environment. The REE data from garnet inclusions in diamonds from A154 South, Panda (Tappert et al., 2005) and Snap Lake (Promprated et al., 2004) indicate that this less depleted nature may, in part, reflect secondary metasomatic influences. In particular, sinusoidal REE_N patterns of harzburgitic garnets provide strong evidence for metasomatic modification of originally strongly depleted trace element signatures (e.g. Shimizu and Richardson, 1987) in the diamond source regions beneath the Slave Craton.

On a detailed level, a more complex history is recorded by some of the A154 South garnets. The one analyzed lherzolitic garnet has a 'normal' REE_N pattern, characterized by fairly flat MREE_N–HREE_N. Two harzburgitic garnet inclusions from diamond ddmi-216 also have low almost flat MREE_N–HREE_N (and low Sr) more typical found among lherzolitic garnets. Stachel et al. (2004) attribute the transition from sinusoidal towards normal REE_N patterns in peridotitic garnets to a transition from fluid dominated to melt dominated metasomatism (Fig. 11). Stachel et al. (2004) note that harzburgitic garnets that have undergone "lherzolitic style" melt metasomatism (i.e., showing evidence of MREE and HREE enrichment) also appear to have refertilized major element compositions, as seen e.g. by low molar Cr-numbers [$100\text{Cr}/(\text{Cr} + \text{Al}) < 30$]. This observation holds true for the two harzburgitic garnets from diamond ddmi-216 with near normal REE_N patterns which have Cr-numbers of less than 25.

The eclogitic garnets from A154 South are anomalous in having REE concentrations and Ti, Y and Zr contents that are considerably lower than usually observed for eclogitic garnets worldwide. Based on xenolith studies, Beard et al. (1996) suggested that eclogitic garnets with high CaO and low REE, like the

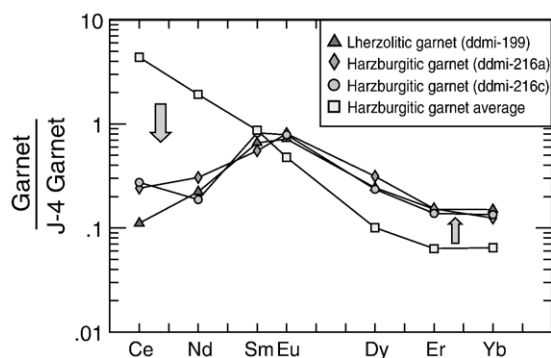


Fig. 11. Illustration of the metasomatic re-enrichment event affecting harzburgitic garnets ddmi-216a, ddmi-216c and lherzolitic garnet ddmi-199. The rare earth element concentrations are normalized to a garnet from a primitive mantle bulk rock composition (J-4 garnet peridotite xenoliths from Jagersfontein; analysis of Jagoutz and Spettel in Stachel et al., 1998b). Compared to harzburgitic garnets with sinusoidal REE_N, these garnets experienced enrichment in MREE–HREE, suggestive of melt metasomatism. The associated decrease in LREE is usually attributed to equilibration with clinopyroxene, and hence is difficult to reconcile with the harzburgitic nature of the two garnets in ddmi-216.

inclusions from A154 South, may be related to crustal protolith (gabbroic reservoirs in oceanic lithosphere) having experienced plagioclase and/or clinopyroxene accumulation.

Xenolith and xenocryst studies (Griffin et al., 1999b; Pearson et al., 1999; MacKenzie and Canil, 1999; Doyle et al., 2003; Grüter and Moore, 2003; Menzies et al., 2004) from the Lac de Gras area also indicate a moderately depleted composition of the deep (diamond stable) subcratonic lithosphere dominated by lherzolitic mineralogies. These studies also indicate that the moderately depleted deep layer is overlain by a strongly depleted shallow layer, resulting in a stratified mantle lithosphere for the Central Slave. The shallow layer indicates a lower geothermal gradient (equivalent to 35–37 mW/m² surface heat flow) than the deeper layer (~40 mW/m²). Based on non-touching inclusion pairs, A154 South diamonds formed at temperatures of approximately 1200 °C, implying slightly hotter conditions than obtained elsewhere on the Slave. This result is nevertheless consistent with diamond formation along 40–42 mW/m² model geotherms similar to other diamond deposits worldwide (Stachel et al., 2003, and references therein) and also coincides with the syn-ruptive paleogeotherm for the deeper lithospheric layer at Lac de Gras.

Previously, Zn in spinel thermometry (Ryan et al., 1996) has been successfully applied to concentrate from the Diavik mine including A154 South (Griffin et al., 1999b) and to inclusions in diamonds from the nearby

Panda kimberlite (Stachel et al., 2003). The anomalously high Zn contents in olivine inclusions from A154 South are more than double the estimated normal Zn content for mantle olivine of ~52 ppm (Ryan et al., 1996). This precludes the application of this thermometer to our sample suite, and indicates that Zn enrichment was limited both temporally (to the time on diamond formation) and spatially (so far to A154 South).

The aggregation of nitrogen in diamond is a function of nitrogen content, mantle residence time and residence temperature. Plastic deformation has been suggested to accelerate the aggregation of nitrogen in diamond (Evans, 1992). However, nitrogen based estimates of mantle residence temperatures are relatively insensitive to the choice of particular mantle residence time (Taylor et al., 1990). Hence an accelerating effect of plastic deformation would need to be rather strong to significantly shift calculated residence temperatures to higher values. When diamonds showing evidence of plastic deformation are excluded from our data set the proportion of diamonds with higher aggregation levels (Type IaAB or Type IaB) is significantly reduced. This may indicate that plastic deformation indeed enhanced nitrogen aggregation but it could also merely reflect increasing strain towards the base of the lithosphere, where diamonds reside at higher temperatures.

A high proportion of diamonds with poorly aggregated nitrogen is not unique to A154 South but appears to be a common feature in the Central Slave, being recognized at Ekati (Westerlund et al., 2001, 2003a; Stachel et al., 2003) and DO27 (Davies et al., 1999, 2004a). Low nitrogen aggregation levels, as observed for the majority of diamonds from A154 South, may indicate either a mantle residence <1 Ga or long term mantle storage at temperatures <1100 °C (Fig. 10). Peridotitic sulphide inclusions in diamonds from Panda yielded an isochron age of 3.41±0.28 Ga (Westerlund et al., 2003b). Combining old inclusion ages and low nitrogen aggregation states would argue for mantle storage at lower temperatures, i.e. a fairly shallow depth.

A possible sub-population is indicated by the only yellow (indicating a presence of nitrogen in the N3 centre) diamonds in this study (ddmi-166 and ddmi-208, also containing numerous eclogitic garnet inclusions) which have elevated nitrogen contents of 1800 and 3800 ppm and similar aggregation levels of 34 and 36% B, respectively. In view of the high nitrogen contents the elevated nitrogen aggregation state in these two diamonds is, however, still consistent with mantle storage at fairly low temperatures (≤1100 °C, Fig. 10).

Temperatures of diamond formation based on non-touching inclusion pairs (~1200 °C) are inconsistent

with the low mantle residence temperatures obtained for the majority of diamonds from nitrogen aggregation levels. However, the low nitrogen based temperatures are in agreement with temperature estimates based on touching inclusion pairs from Panda (Stachel et al., 2003). To explain the observed nitrogen aggregation distribution, Stachel et al. (2003) proposed that diamond formation was followed by rapid cooling of the diamond source region by about 100–150 °C. They propose that elevated temperatures (equivalent to a 40–42 mW/m² model geotherm) during diamond formation represent only a short-lived event, possibly related to magmatic intrusions and that a stable 35–37 mW/m² geotherm was already established during the Archean (Tappert et al., 2005). Independent evidence for diamond formation followed by cooling by about 150 °C is provided through a detailed comparison of geothermobarometric results for touching and non-touching pairs of garnet and orthopyroxene inclusions from De Beers Pool, South Africa (Phillips et al., 2004). Such a model is in agreement with the data from A154 South which requires cooling of the diamond source region on the order of 100–200 °C to reconcile inclusion and nitrogen based temperature estimates.

In their carbon isotopic composition the bulk of A154 South diamonds (94%) fall within a narrow range (−6.3‰ to −4.0‰) around the mantle value (around −5.0‰), irrespective of their paragenesis. For diamond deposits worldwide such a narrow distribution is atypical (with few exceptions such as diamonds from the Birim deposits in Ghana, Stachel and Harris, 1997) but it appears to be a commonality in the Slave Craton with Panda (Westerlund et al., 2001, 2003a) and Snap Lake (Pokhilenko et al., 2004) each having a limited range in $\delta^{13}\text{C}$ values. In a study of diamonds from the Ekati pipes Misery, Jay and Sable, Chinn et al. (1998) found a similarly narrow distribution for peridotitic diamonds, with eclogitic diamonds from these locations covering a wide range towards isotopically lighter compositions (down to −27.4‰). At DO27 a large range in $\delta^{13}\text{C}$ values was observed (−35.8‰ to +0.2‰) reflecting a dominance of eclogitic diamonds (Davies et al., 2004a,b). The narrow distribution seen at A154 South may be suggestive of diamond formation, irrespective of paragenesis, from a fluid/melt carrying carbon with a mantle isotopic signature.

7.2. Ferropericlasite-bearing diamonds: an uncertain paragenesis

Diamonds of sublithospheric origin appear to be less common in the Slave than initially thought: Tappert

et al. (2005) reported that only 5% of diamonds from Panda contained mineral inclusion pairs of definitive lower mantle origin. All of the diamonds containing inclusions of ferropericlasite in this study and the bulk of the ferropericlasite-bearing diamonds from DO27 (Davies et al., 1999, 2004a) lack the necessary inclusion pairs to unequivocally confirm a lower mantle origin. Inclusions of ferropericlasite alone are not conclusive evidence for a lower mantle origin (Stachel et al., 1998a, 2000; Brey et al., 2004). Ferropericlasite can occur as an inclusion in diamond in the upper mantle if Si activity and $f\text{O}_2$ are sufficiently low, conditions that would be met in a reduced dunitic source (Stachel et al., 1998a). Hence, besides the lower mantle, ferropericlasite-bearing diamonds at Lac de Gras could also be sourced in lithospheric dunites. Such dunites may well have existed during diamond formation in the Archean, and several studies (see Griffin et al., 1999a; Pearson et al., 1999; O'Reilly et al., 2001), indicate that they may still locally persist.

It has been noted by Hutchinson et al. (1999) that diamonds from the lower mantle typically have irregular or highly resorbed, dodecahedral morphologies and classify either as Type II, or, in rare cases where some nitrogen is present, as Type IaB (with >94%B). This observation holds true for Panda, where all lower mantle diamonds were Type II diamonds with irregular morphologies. While Davies et al. (2004a,b) reported that >80% of the ferropericlasite-bearing diamonds from DO27 were Type II diamonds, moderately resorbed, octahedral morphologies were observed. Ferropericlasite-bearing diamonds from A154 South showed both resorbed octahedral and irregular morphologies. Two were Type II diamonds, the other two had low nitrogen concentrations (<110 ppm) can classify as Type IaAB (59 and 82%B). The observed octahedral morphologies and nitrogen aggregation states that are inconsistent with residence at the high temperatures of the lower mantle are in support of a lithospheric origin for some ferropericlasite-bearing diamonds.

8. Conclusions

1. Inclusion-bearing diamonds only represent a sub-population of the production of A154 South, with cubes being notably absent.
2. The bulk of the inclusion-bearing diamonds come from moderately depleted harzburgitic sources (based on garnet inclusions the ratio of lherzolitic: harzburgitic diamonds is 1:5).
3. Diamonds with eclogitic inclusions are relatively rare (12%). Ferropericlasite inclusions (4% of diamonds)

may indicate a minor sublithospheric diamond population or relate to highly depleted dunitic sources.

4. Peridotitic garnet inclusions document metasomatic re-enrichment that was largely restricted to the most incompatible elements (LREE). Evidence for MREE–HREE enrichment commonly associated with more intense high-T (melt) metasomatism is restricted to two diamonds (one with lherzolitic, one with harzburgitic garnet inclusions).
5. Mg-chromite is the most abundant mineral inclusion. High Zn-contents of Mg-chromite and olivine inclusions preclude application of Zn in spinel thermometry and suggest that diamond precipitation was associated with enrichment in Zn.

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