CRYSTALLINE INCLUSIONS AND C-ISOTOPE RATIOS IN DIAMONDS FROM THE SNAP LAKE/KING LAKE KIMBERLITE DYKE SYSTEM: EVIDENCE OF ULTRADEEP AND ENRICHED LITHOSPHERIC-MANTLE

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INTRODUCTION

The Snap Lake/King Lake (SL/KL) kimberlite dyke system of the southern Slave Craton, Canada was discovered in 1997 by Canadian junior exploration company, Winspear Resources Ltd. An abnormal thickness of lithosphere beneath the SL/KL area is indicated by: (1) an abnormally wide range of Cr_2O_3 content and character of the REE distribution in pyropes, (2) a very high proportion of high-Cr chromites, and (3) some other specific geochemical and isotope characteristics of the SL/KL kimberlite system (Pokhilenko *et al*., 1998, 2000, 2001, 2003; Agashev *et al*., 2001; McLean *et al.,* 2001). Preliminary results from study of the SL/KL diamonds, and their crystalline inclusions, reveals increased ^{13}C isotopic compositions in the SL/KL diamonds, as well as providing additional evidence to suggest that a relatively enriched and abnormally thick lithosphere lies beneath the Southern Slave Craton (Pokhilenko *et al*., 2001; Reutsky *et al*., 2002). This paper contains the results of a more detailed study of the crystalline inclusions and C-isotope compositions of a representative collection of the SL/KL diamonds.

METHODS

Major-element data on crystalline inclusions have been obtained with a Cameca CAMEBAX-Micro Electron microprobe, using a wide range of natural minerals and synthetic glasses for standards, at the Analytical Center of the United Institute of Geology, Geophysics and Mineralogy, Siberian Branch of Russian Academy of Sciences. All the C-isotope analyses were carried out at the same Analytical Center, using a Finnigan-MAT Delta mass spectrometer with a typical precision of 0.2‰. Methods and techniques for the preparation and carbon isotope analysis is described in detail by Reutsky *et al.* (1999). Isotopic composition is given in delta notation (parts per thousand) as the deviation from the VPDB standard.

MINERAL INCLUSIONS IN SL/KL DIAMONDS

Mineral inclusions from 115 diamond crystals (-4 +2mm size) obtained from the SL/KL kimberlites have been studied. Approximately 75% of the diamonds are colorless octahedrons, while the rest are crystals of transitional shape (octahedron – dodecahedron) and spinel twins. Crystals of pale smoky brown and greenish tint were rare in the study group. Inclusions of U-type minerals predominate, occurring in 94.7% of the diamonds. The most common inclusions (number of diamonds are listed in brackets) are olivine (90; up to 5 separate inclusions in some diamonds) and enstatite (22). Sulphide, Cr-pyrope, chromite and Cr-diopside inclusions are less abundant (15, 10, 5 and 1, diamond respectively). Different U-type mineral inclusions coexisting in one diamond are: olivine + sulfide (9 diamonds), olivine + enstatite (8), pyrope + olivine (4), chromite + sulfide (2), pyrope + olivine + enstatite (2), chromite + olivine + enstatite (1), olivine + chromite (1), pyrope + sulfide (1) and enstatite + Cr-diopside (1).

E-type mineral inclusions are represented by clinopyroxene (5 diamonds), garnet (2) and sulfide (1) with the following associations noted in single diamonds: garnet + clinopyroxene + sulfide (1) and garnet + clinopyroxene (1).

OLIVINE INCLUSIONS

Olivine inclusions observed in 90 diamonds are characterized by a relatively narrow range of composition: about 80% of them have Mg# [100Mg/(Mg+Fe)] ranging from 91.8 to 93.0. A single inclusion has Mg# less than 91 (SL_5-44 = 90.7), and olivine inclusions in two diamonds have Mg# higher than 93 (SL_3-20 = 93.6; SL_5-14 = 94.8). The NiO content varies from 0.29 to 0.40 wt.%, with over 80% between 0.33 to 0.37 wt.%. The Cr_2O_3 ranges from 0.01 to 0.07 wt.%, and CaO from 0.01 to 0.05 wt.% (Table 1).

Table 1: Representative analyses of olivine, enstatite and chromite inclusions in SL/KL diamonds

Sample	SL_3-20	SL_3-31	SL_3-8	SL_5-44
Mineral		Olivine		
SiO_2	41.00	41.70	41.40	41.00
TiO_2	nd	nd	nd	nd
Al_2O_3	nd	nd	nd	nd
Cr_2O_3	0.02	0.07	0.02	0.07
FeO	6.34	7.51	7.64	9.09
MnO	0.10	0.11	0.10	0.13
MgO	52.10	50.20	50.20	49.50
CaO	0.01	0.03	0.02	0.01
NiO	0.29	0.34	0.35	0.37
Na_2O	nd	nd	nd	nd
Total	99.9	100.0	99.7	100.2
Mg#	93.6	92.3	92.2	90.7

SL_5-96	SL_3-12	SL_5-100	SL_5-64a	SL_5-64b	SL_5-14
Enstatite			Chromite		
57.3	58.4	58.0	0.26	0.24	0.09
<0.01	<0.01	<0.01	0.09	0.11	0.11
0.68	0.41	0.35	12.5	4.79	7.37
0.49	0.33	0.26	55.6	64.4	63.3
3.98	4.69	6.29	15.5	15.3	13.6
0.08	0.12	0.15	0.12	0.19	0.17
36.4	36.1	33.4	14.3	13.8	14.4
0.16	0.35	0.42	nd	nd	nd
0.11	0.10	0.07	0.13	0.13	0.11
0.02	0.06	0.03	nd	nd	nd
99.2	100.5	99.0	98.5	99.0	99.2
94.2	93.2	90.4	62.2	61.6	65.4

ENSTATITE INCLUSIONS

Twenty enstatite inclusions have been analyzed and most have a narrow range of composition. For 16 inclusions the FeO content varies from 4.40 to 4.80 wt.%, with the other 4 falling outside this range (3.97, 3.98, 4.34 and 6.29 wt.% respectively, Table 1). Al_2O_3 content for 18 inclusions varies from 0.4 to 0.6 wt.% (Fig. 1). An enstatite from an enstatite-Cr-diopside intergrowth (SL_5-100, Table 1) has the minimum Al_2O_3 (0.35 wt.%) and Cr_2O_3 (0.26 wt.%) contents, and maximum CaO (0.42 wt.%) values. The maximum Al_2O_3 content (0.68 wt.%), from sample SL_5-96 (Table 1), also has maximum Cr_2O_3 (0.49 wt.%) and minimum CaO (0.16 wt.%) values. The majority of enstatite inclusions have Cr_2O_3 and CaO contents between 0.30 and 0.40 wt.%, and Na_2O values between 0.02 and 0.06 wt.%.

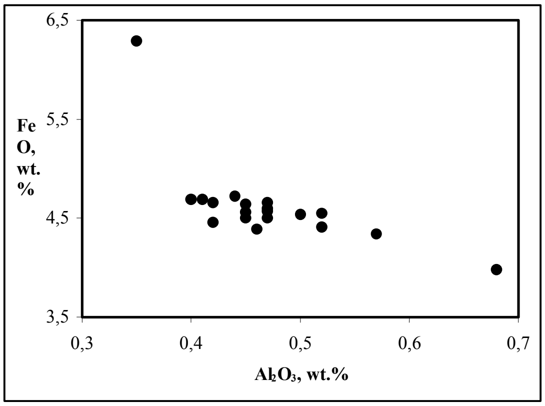

Figure 1. Plot of FeO vs Al_2O_3 for enstatite inclusions in the Snap Lake diamonds.

CHROMITE INCLUSIONS

Six chromite inclusions were identified in 5 diamonds: Chromite was found in association with sulphides (2 diamonds), with olivine (1) and as an intergrowth with olivine and enstatite (1). One diamond, (SL_5-64a,b, Table 1), had only 2 chromite inclusions with significantly different compositions: Cr_2O_3 – 55.60 and 64.40 wt.%; Al_2O_3 – 12.50 and 4.79 wt.%; and MgO – 14.30 and 13.80 wt.% respectively. In two of the diamonds, the chromites have unusual, relatively low Cr_2O_3 (55.60 and 59.10 wt.%) contents. All the inclusions have low TiO_2 content (0.05-0.11 wt.%).

GARNET INCLUSIONS

Ten Cr-pyrope, and two E-type garnet inclusions were analyzed (Table 2). For the Cr-pyropes, Cr_2O_3 values vary from 7.71 to 12.8 wt.%, CaO from 3.7 to 5.75 wt.%, TiO_2 from <0.01 to 0.19 wt.%, and Mg# from 82.9 to 86.7. Two Cr-rich, high-Mg, subcalcic pyrope inclusions of harzburgite paragenesis (SL_3-31 and SL_3-30, Table 2), have significant excess of Si, indicating the presence of a majorite component (11.6 and 16.8 mol.%). Both E-type garnet inclusions also contain this majorite component (5.0 and 6.1 mol.%, Table 2), and have a Na_2O content of 0.33 and 0.38 wt.%.

CLINOPYROXENE INCLUSIONS

Clinopyroxene (cpx) inclusions were found in 6 diamond crystals, 5 of which contained E-type cpx. All of these are omphacitic (jadeite component of 29.4 to 36.2 mol.%; Mg# - 66.5 to 75.8), with elevated TiO_2

values of up to 0.49 wt.%. Of special interest is the significant amount of K_2O in the cpx: two discrete inclusions in a single diamond (SL_5-52) contain 1.27 and 1.37 wt.% K_2O. A single inclusion of U-type cpx has an unusual composition: K_2O content (0.71 wt.%) is significantly higher than the Na_2O (0.42 wt.%) content, making this inclusion unique among previously studied U-type cpx inclusions in diamonds.

Table 2: Representative analyses of U-, E-type garnet and cpx inclusions in SL/KL diamonds

Sample	SL_3-12	SL-133	SL_5-5	SL_3-31	SL_3-30
Mineral		U-type garnets			
SiO_2	41.3	41.2	42.0	42.2	42.3
TiO_2	0.13	0.05	0.06	0.19	0.06
Al_2O_3	15.2	16.7	17.2	12.3	9.46
Cr_2O_3	10.2	7.71	8.37	11.8	12.8
FeO	6.50	7.38	6.06	6.52	7.64
MnO	0.32	0.33	0.28	0.32	0.33
MgO	21.1	20.0	22.2	21.1	21.2
CaO	4.76	5.7	3.73	4.68	5.11
Na_2O	0.03	0.02	<0.01	0.03	0.01
K_2O	-	-	-	-	-
Total	99.5	99.1	99.9	99.1	99.0
Mg#	85.2	82.9	86.7	85.2	83.2
Mj,mol.%	0.9	2.2	2.3	11.6	16.8

SL_5-6	SL_5-86	SL_5-100	SL_5-86	SL_5-6	SL_5-52a
E-type garnets		U-t.cpx	E-type cpx		
42.1	40.1	55.4	55.0	55.9	55.1
0.44	1.44	<0.01	0.49	0.45	0.48
21.7	19.9	0.82	7.42	8.52	0.82
0.07	0.02	1.36	0.02	0.09	0.04
15.5	20.2	2.53	8.18	6.73	5.64
0.34	0.36	0.12	0.10	0.12	0.06
16.6	7.19	16.7	9.10	11.8	9.27
3.03	10.6	21.2	15.0	9.20	14.1
0.33	0.38	0.42	4.16	5.16	4.53
-	-	0.71	0.03	0.23	1.37
100.1	100.2	99.3	99.5	98.2	99.3
65.5	38.8	92.2	66.5	75.8	74.6
5.0	6.1				

C-ISOTOPE COMPOSITION

The C-isotope composition has been determined for 34 diamonds with U-type inclusions (olivine, enstatite), 1 diamond with E-type inclusions (garnet + cpx), and 4 diamonds without inclusions. The U-type diamonds show a range from $\delta^{13}C$ -3.2 to -9.0‰, with an average of -4.02‰. The E-type diamond has a $\delta^{13}C$ of -13.4‰.

When presented on a frequency histogram there is a strong peak at $\delta^{13}C$ -3.5‰, which is significantly heavier compared to U-type diamonds from Siberia and South Africa (near -4.5‰). The studied diamonds can be divided into two groups based on their C-isotope composition, and Mg# (Fig. 2) and Ni/Fe ratio of their olivine inclusions. Most have a narrow variation of $\delta^{13}C$ from -3.2 to -4.8‰ (average -3.72‰) and olivine inclusions with Mg# less than 92.3 and relatively high Fe/Ni ratios. A small group is characterized by a much wider variation of $\delta^{13}C$ from -3.8 to -9.0‰; (average -5.97‰), higher Mg# (up to 93.6) and relatively low Fe/Ni ratios of their olivine inclusions.

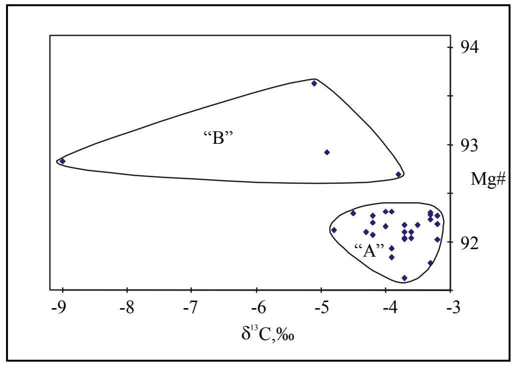

Figure 2. Variations of Mg# in olivine inclusions vs. $\delta^{13}C$ of diamond.

DISCUSSION

Previous petrological and mineralogical studies of mantle samples from the Slave Craton have produced a number of reliable results, suggesting a significant increase in lithosphere thickness towards the south of the craton: a) data obtained from mineralogical and petrological studies of SL/KL kimberlites and mineral inclusions in their diamonds, indicate that the lithosphere thickness beneath the SL/KL area was as much as 300 km at the time (Cambrian) of kimberlite emplacement (Pokhilenko *et al*., 1998, 2000, 2001); b) upper mantle xenolith studies have shown that the lithosphere thickness was 160-190 km in the northern part of the Slave Craton (Kopylova et al., 1999), ~ 200 km for the central Slave (Pearson et al., 1999), and a minimum 230 km in the southern (Kennady Lake area) Slave Craton (Kopylova *et al*., 2001); c) evaluation of pyrope compositions from the Slave Craton kimberlites demonstrated a progressive increase of maximum Cr_2O_3 content in pyropes from the north to south of the craton (Grutter et al., 1999).

The small proportion of E-type mineral inclusions in the SL/KL diamonds is good evidence that depleted peridotites predominate in the SL/KL area lithospheric mantle, at depths corresponding to the diamond stability field. The presence of high-Cr high-Mg subcalcic pyrope inclusions in SL/KL diamonds is definitely related to the diamondiferous depleted ultramafic rocks of the lithospheric mantle. From experiments modeling natural ultramafic systems, pressures of at least 110 kbar (corresponding to depths of over 300 km) are required to achieve ~ 16-17 mol.% dissolution of a majorite component into magnesian garnets (Irifune, 1987, Fig. 3). Other indications that some SL/KL diamonds were formed under very high pressures are: a) cpx inclusions with high K_2O admixture in both E-type (up to 1.37 wt.%) and U-type (0.71 wt.%) parageneses; b) both E-type garnet inclusions contained significant Na_2O admixture, and one of them (SL_5-6) has Na content (0.046 for 12 atoms of O) significantly higher than Ti (0.024 for 12 atoms of O). Furthermore, an absence of P (<0.001 for 12 atoms of O) suggests that the reaction $R^{2+}Al \leftrightarrow NaSi$ may occur, accompanied by partitioning of Si into octahedrally coordinated sites (Sobolev, Lavrent'ev, 1971).

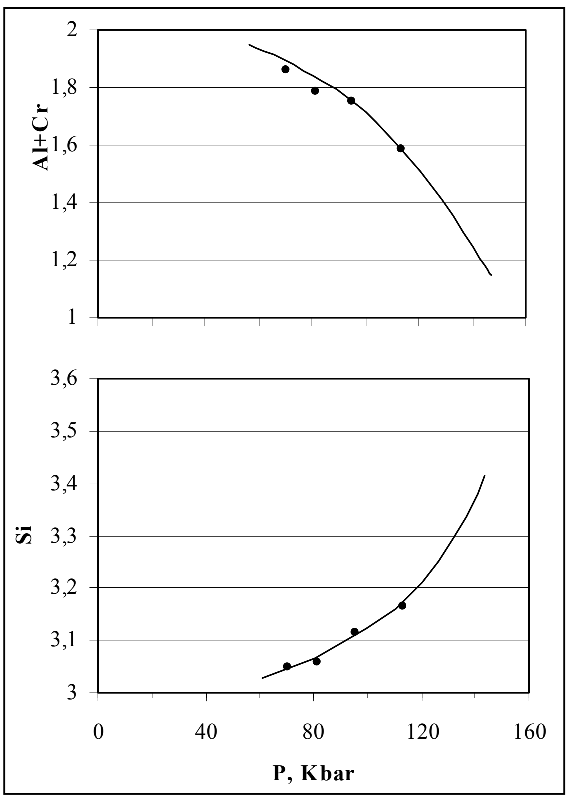

Figure 3. Distribution of Al+Cr and Si (for 12 atoms of O) in garnet inclusions of SLK diamonds in relation with pressure parameters. Calibration curves from Irifune, 1987

The relatively low degree of both depletion and differentiation of ultramafic rocks comprising lithospheric mantle beneath SL/KL area is indicated by: a) relatively low Mg# for olivine, enstatite and pyrope inclusions: b) a significantly higher average CaO content for Cr-pyrope inclusions (4.6 wt.%) compared to CaO contents of Cr-pyrope inclusions in Siberian and South African diamonds; c) very uniform compositions of olivine and enstatite (Fig. 1, 4); and d) a comparative abundance of enstatite inclusions.

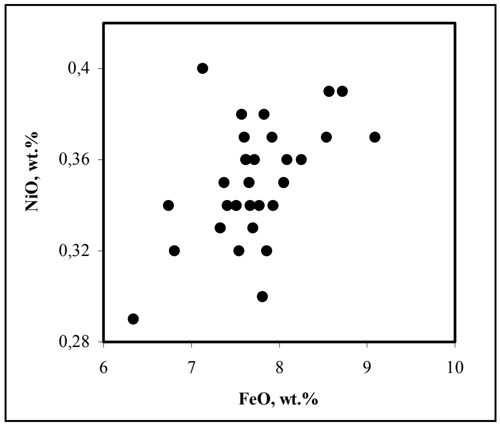

Figure 4. Plot of NiO vs FeO olivine inclusions in the Snap Lake diamonds

The C-isotope variations of the studied diamonds can be related to a number of reasons, including: a) peculiarities of asthenosphere degasation (Galimov, 1991) coupled with the abnormal thickness of the lithosphere; b) the abnormal thickness and relatively enriched character of the lithospheric mantle; and c) the involvement of subducted crustal C in the processes of diamond formation.

The formation of subcalcic Cr-pyrope inclusions with up to 17 mol.% of majorite component is firm evidence of the existence of diamondiferous depleted peridotites of lithospheric mantle at depth ~300 km beneath the SK/KL area. This feature can be the most important among the main reasons for the much heavier C isotope composition of the SL/KL diamond population.

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