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GREEN GARNETS OF THE "WEHRLITE" MANTLE XENOLITHS FROM KIMBERLITES: THEIR COMPOSITION AND ORIGIN (NEWLANDS DIKE, SOUTH AFRICA; NYURBINSKAYA PIPE, NAKYN FIELD, YAKUTIA)

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INTRODUCTION

Green garnets occasionally occur in concentrates of diamondiferous kimberlite bodies in Yakutia (Udachnaya, Aykhal, Mir, Dalnaya etc.), South Africa (Newlands, Bultfontein, Kampfersdam etc.), Venezuela (Guaniamo sills), and Canada (Mud Lake field).

Clarke and Carswell (1977) have offered four models of formation of such garnets at great depths. 1). The green garnets are part of a "normal", i.e. essentially undepleted, mantle peridotite assemblage at great depths (probably >350 km), and have been brought to the surface as accidental xenocrysts in kimberlitic magma. 2). The green garnets have formed as part of the refractory residuum during a deep-level (probably >350 km) partial melting event. 3). The green garnets are the products of fractional crystallization of magma (not necessarily strictly kimberlitic) produced by the partial melting of mantle peridotite at depths > 250 km. 4). The green garnets have been derived from disaggregated garnet wehrlite xenoliths formed by subsolidus recrystallization of original spinel wehrlite assemblages (abundant olivine + minor chrome diopside and chrome spinel). It is supposed also (Schulze, 1986), that kimberlitic green garnets may have originated through subduction and prograde metamorphism of uvarovite-bearing crustal serpentinites.

All formation models of green garnets have been developed based on the study of individual grains, as xenoliths of rocks with green garnets were found in kimberlites extremely rare (Kharkiv, 1978). Therefore, studies of xenoliths of "peridotites" with green garnet from Newlands dikes (South Africa), as well as mineral intergrowths and individual grains of green garnets from the new district - Nakyn field of Yakutia are of great interest.

GREEN GARNETS FROM THE NEWLANDS DIKE

We found peridotite xenoliths with green garnet and single grain green garnets *in situ* in kimberlites of the Newlands dike.

Appearance and mineralogy

Xenoliths are irregular in form, 4.5*1.9 cm and 1.0*0.5 cm in size, and have similar modal compositions: gar(70)+ol(28)+sp(2) for sample NL-11 (Fig. 1) and gar(50)+ol(30)+sp(20) for sample NL-21 (Fig. 2). Rock texture is medium-crystalline (grains are 2-3 mm in size), while structure is massive.

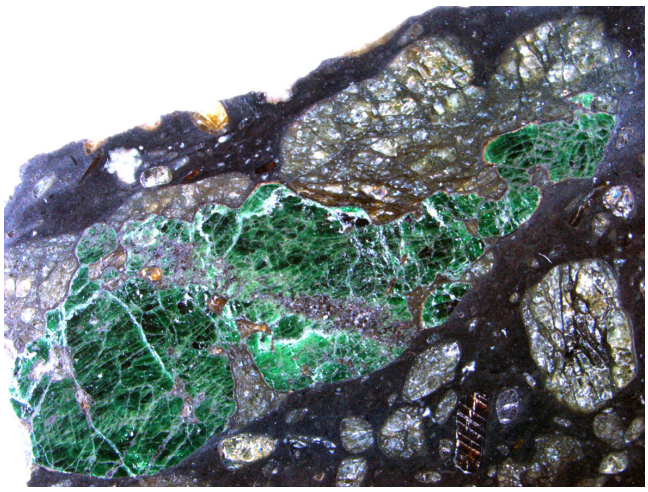

Fig. 1. "Wehrlite" xenoliths, sample NL-11.

Fig. 2. "Wehrlite" xenoliths, sample NL-21.

We also identified a garnet macrocryst of 0.5*0.4 cm in size with a pale green kelyphytic rim (sample NL-31, Fig. 3, top), and a intergrowth of 1.7*1.5 cm in size: a green garnet + weathered olivine + small chrome spinel inclusion (sample NL-41, Fig. 3, bottom).

Fig. 3. Top – garnet macrocryst with keliphytic rims, sample NL-31; bottom – intergrowth: garnet + olivine + chrome spinel, sample NL-41.

Garnet composition in the studied samples (Table-1) is quite constant and is characterized by the high Cr_2O_3 content (10.94-11.99%) at the reduced contents of TiO_2 (0.24-0.52%) and FeOt (3.73-5.33%). The CaO content (19.52-24.94%) is the most variable and is inversely related to MgO (10.20-6.66%).

The chrome spinel composition is also constant and is characterized by the high Cr_2O_3 (53.45-55.36%) content and the low TiO_2 (0.47-0.57%) content.

Olivine is high-Mg (Fo_{95}), but is characterized by the elevated CaO content (0.09% and higher than that of olivine from deep-seated peridotites) that is likely related to a total high calcium content in the system.

Table-1. Chemical (wt. %) and oxygen isotope composition of green garnets grains from Newlands dike.

Sample	NL-11			NL-21		NL-31		NL-41	NL-51
Minerale	Grt	Sp	Ol	Grt	Sp	Grt	Kel	Grt	Ol
SiO_2	38.47	-	40.85	38.48	-	38.85	35.33	38.85	-
TiO_2	0.52	0.47	0.00	0.48	0.57	0.24	0.42	0.45	-
Al_2O_3	12.37	14.59	0.02	12.57	13.24	13.94	12.09	12.98	-
Cr_2O_3	11.99	55.36	0.03	11.76	53.45	10.94	6.27	11.88	-
FeO	3.73	14.75	5.81	5.15	18.98	4.90	7.71	5.33	-
MnO	0.22	0.23	0.08	0.25	0.30	0.29	0.12	0.47	-
MgO	6.66	14.15	51.78	8.02	13.10	10.20	22.45	9.49	-
CaO	24.94	-	0.09	22.79	-	19.52	2.38	19.61	-
Na_2O	0.03	-	0.05	0.00	-	0.00	0.03	0.00	-
K_2O	-	-	-	-	-	-	6.31	-	-
NiO	-	-	0.48	-	-	-	-	-	-
Total	98.93	99.55	99.19	99.50	99.64	98.88	93.11	99.06	-
Uvar, %	36.71	-	-	35.92		33.23		33.23	-
$d^{18}O$, ‰	4.20	-	4.91	4.25	-	-	-	4.05	5.11

GREEN GARNETS FROM THE NYURBINSKAYA PIPE

In kimberlites and placers of the Nyurbinskaya pipe (Nakyn field, Yakutia) there are 4 green garnet grains of 0.5-2.0 mm in size, including one intergrowth gar + sp.

All garnet grains from placer deposit are completely non-rounded, with an irregular shape with jagged edges, replaced by light brown cracks microlaminal aggregate of secondary minerals (Fig. 4). These grains of garnet (3 grains, including one intergrowth gar+sp) are probably microfragments of mantle xenoliths.

The garnet composition is ordinary and quite constant (Table-2). However, most garnets are characterized by the higher TiO_2 (1.46, 1.65, 1.75%) contents not noted before for similar garnets. Only in one garnet from intergrowth

with chrome spinel, the TiO_2 content is “normal” low (0.35%) and analogous to garnets from the Newlands dike. Composition of chrome spinel from this intergrowth is also characterized by the reduced TiO_2 (0.35%) content and low Cr_2O_3 (36.71%) content.

Fig. 4. Green garnet grains from Nyurbinskaya placer deposit. Right - intergrowth “garnet + chrome spinel” size 2 mm.

Table-2. Chemical composition of green garnet grains from Nyurbinskaya pipe (wt. %).

Body	Placers				Kimberlites
Sample	36/420-7		24/340-6	12/300-3	26/510-439
Minerale	Grt	Sp	Grt	Grt	Grt
SiO_2	38.80	-	38.66	38.02	37.15
TiO_2	0.35	0.35	1.46	1.65	1.75
Al_2O_3	14.68	29.90	12.58	11.33	9.96
Cr_2O_3	9.63	36.71	11.25	12.67	13.72
FeO	7.05	18.91	6.18	5.85	5.63
MnO	0.46	0.47	0.49	0.47	0.41
MgO	10.17	13.15	10.07	9.20	7.68
CaO	18.06	-	18.67	20.16	22.87
Na_2O	0.04	-	0.03	0.03	0.05
Total	99.24	99.49	99.39	99.38	99.22
Uvar, %	29.34	-	33.64	38.37	42.50

TRACE ELEMENTS

Trace-element analyses of garnet were made with LA-ICP-MS at the Centre for Isotope Research, VSEGEI, St.-Petersburg, Russia. Methods and operating conditions have been described by Norman et al., 1996.

Green garnets from Newlands dikes are characterized with a similar "sine wave" type of REE distribution with slight depletion in medium REE and significant enrichment in light REE (Fig. 5 top). Only for the sample NL-41 one can also note enrichment in the medium REE (from Gd to Nd).

Garnets from Nyurbinskaya pipe have the similar "sine wave" type of REE distribution that is observed only for low-Ti garnets from the Cr-spinel intergrowth (sample 36/420-7). At the same time, high-Ti garnet can have a "raised" type of REE distribution with enrichment in medium and light REE.

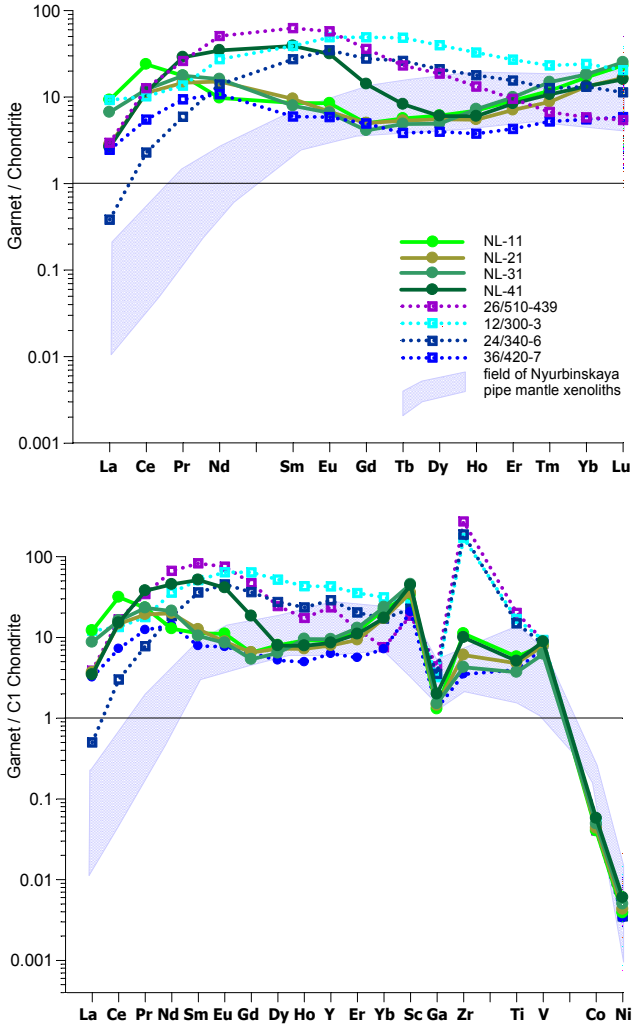

Fig. 5. REE (top) and trace element (bottom) patterns of green garnets in the Newlands dike and Nyurbinskaya pipe and placer deposits (normalized after McDonough and Sun, 1995)

The diagram of general distribution of trace elements shows (Fig. 5 bottom), that all green garnets are characterized by an increased content of light REE and Sc. High-Ti garnets are characterized by an increased content of light and middle REE, as well as titanium, and a particularly sharply increased content of Zr (!).

OXYGEN ISOTOPES OF THE MINERALS

We have determined an oxygen isotopic composition in garnets and olivines of xenoliths of Newlands dikes.

Isotopic composition of oxygen in green garnets ($\delta^{18}O$ = 4.05-4.25 $^{o}/_{oo}$) differs drastically from the mantle values and may testify to action of metasomatic processes on the formation of these rocks (Table-1).

Olivine from the sample NL-11 is also characterized by a "light" oxygen composition ($\delta^{18}O$ = 4.91 $^{o}/_{oo}$), while the olivine from normal garnet peridotite of Newlands dikes has the oxygen isotopic composition ($\delta^{18}O$ = 5.11 $^{o}/_{oo}$) that corresponds to the mantle values ($\delta^{18}O$ = 5.5+/-0.4 $^{o}/_{oo}$) (Mattey et al., 1994)

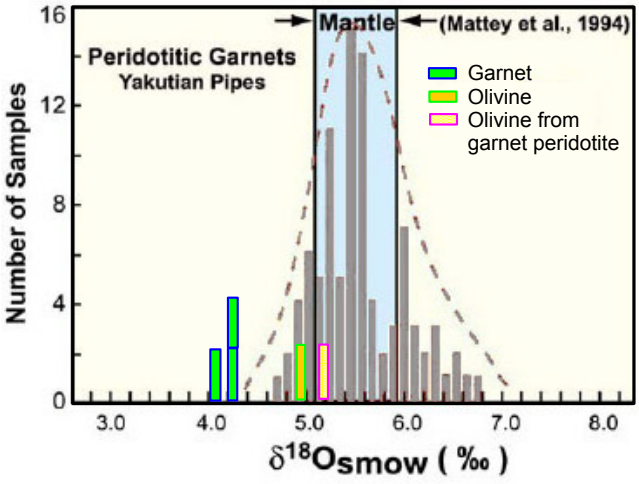

Fig. 6. Oxygen isotope values for green garnets grains from Newlands dike (diagram after Taylor et al., 2003).

RB-SR AND SM-ND ISOTOPES OF THE ROCKS

We have determined Rb-Sr and Sm-Nd isotopic composition of the largest and practically unaltered sample "wehrlites" (sample NL-11) of Newlands dikes (Table-3).

Judging by the relatively "young" model age of the sample relative to the depleted mantle (1.78 billion years), the age of formation of the "wehrlites" is also relatively "young" – probable mezoproterozoic.

Table-3. Sr-Nd-iIsotopic composition of "wehrlite" xenoliths from Newlands dike

Sample	NL-11
Rb, ppm	20.56
Sr, ppm	112.5
$^{87}Rb/^{86}Sr$	0.5282
$^{87}Sr/^{86}Sr$	0.711689+/-6
Sm, ppm	1.797
Nd, ppm	9.408
$^{147}Sm/^{144}Nd$	0.1155
$^{143}Nd/^{144}Nd$	0.511999+/-9
$T_{(Nd)}DM$, BA	1.784

TP PARAMETERS

TP-parameters of formation of green garnets were performed for the composition of garnet: the temperature was determined by thermometer Canil, 1999 (C99T), and the pressure of the barometer Grutter, Latti & Menzies, 2006 (GLM06P).

As can be seen from Table-4, green garnets of Newlands dikes and Nyurbinskaya pipe are characterized by very close TP-paramenters of formation: 1019-1106°C at 24.5-27.4 kbar and 990-1028°C at 25.3-28.1 kbar, respectively. (Mean values are much closer: 1058 и 1010°C , 25.9 и 27.1 kbar). The obtained values of TP-parameters are generally confirmed by using independent methods of mineral paragenesis. The temperature of paragenesis formation ol + gar (O'Neill & Wood, 1979 – NW79T) of the sample NL-11 is about 1085°C, which is comparable to 1019°C. At the same time, for paragenesis ol + sp of the same sample NL-11 the pressure is practically the same - 23.4 kbar (Finnerty & Boyd, 1978 – FB78P), but the temperature (Ballhaus, Berry & Green, 1991 – BBG91T) is far below - 805°C.

This can specify nonequilibrium character of the ol+sp+gar paragenesis in the sample NL-11.

Points of garnet at the TP-diagram (Fig. 7) form compact areas at moderate depths of the upper mantle (80-90 km) and correspond to very hot geotherm (Nyurbinskaya pipe and Newlands dike: 52 and 55 mW/m^2).

Table-4. TP-parameters of formation of green garnets

Para-genesis	T,°C			P, kbar	
	Grt	GrtOl	OlSp	Grt	Ol
Metods	C99T	NW79T	BBG91T	GLT06P	FB78P
Sample					
NL-11	1019	1084	805	24.5	23.4
NL-21	1037			25.3	
NL-31	1070			26.2	
NL-41	1106			27.4	
26/510-439	1024			27.7	
12/300-3	1028			28.1	
24/340-6	1000			27.2	
36/420-7	990			25.3	

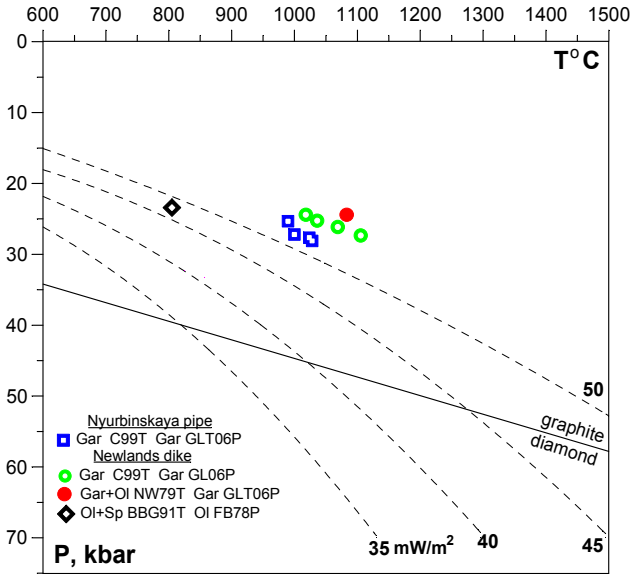

Fig. 7. TP-diagram of formation of green garnets from Newlands dike and Nyurbinskaya pipe and placer deposits.

CONCLUSIONS

Xenoliths of rocks with green garnets are characterized by a very unstable modal composition: from essentially garnet rocks to olivine rocks with single garnet inclusions and to chromite rocks with a streaky texture (Kharkiv, 1978). There is practically no clinopyroxene.

Garnet grains in some samples (Fig. 1) are characterized by irregular contours, but clear boundaries straightened, as if it grew up in free space. One can note fine-grained phlogopite-bearing vein-like buildups, as well as small inclusions of olivine and chrome spinel in garnet.

With the generally close content of macroelements, the Ti content in garnets of different samples may vary 7 time reaching very high values (up to 1.75% of TiO_2).

A sharp increase of content of light REE, Sc and especially Zr, is typical.

Isotopic composition of oxygen in green garnets ($\delta^{18}O$ = 4.05-4.25 $^{o}/_{oo}$) and olivine ($\delta^{18}O$ = 4.91 $^{o}/_{oo}$) differs drastically from the mantle values.

We have determined a relatively "young", probably mezoproterozoic age of rock formation ($T_{Nd}DM$ = 1.78 billion years).

The rocks are characterized by nonequilibrium paragenesis ol+sp+gar and formation at moderate depths (80-90 km) under conditions of high heat flow (52-55 mW/m^2).

By these features, these rocks with green garnets are not "wehrlites" and likely represent metasomatic rocks such as uvarovite-chromite veins or schlierens at the moderate depths of upper mantle – it is similar to uvarovite-chromite veins of the metasomatic or a hydrothermal origin in the crustal serpentinites.

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