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REFERTILISATION GRADE ESTIMATION OF LITHOSPHERE ROOTS BY THE CHEMICAL COMPOSITION OF GARNETS FROM SIBERIAN KIMBERLITES

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Udachnaya pipe is a unique geological object presenting xenoliths from a continuous section of the continental lithosphere from its roots to the upper crust level. Xenoliths and xenocrysts of deepseated rocks, erupted by kimberlites of this pipe, are fragments of ancient depleted rocks of the lithosphere mantle and testify to the superposed processes that occurred at the time of the kimberlite body formation. Besides, in Udachnaya like nowhere else one can find many not serpentinised xenoliths of deepest lithosphere rocks erupted by kimberlites – high-temperature deformed lherzolites.

These facts allow one to consider Udachnaya pipe as a model for studies of mantle sections in regions of less informative kimberlites.

DEPENDENCES

It is known that a general inverse relationship takes place for a volume fraction of garnet in mantle rocks and its Cr_2O_3 content. In some cases, relationships between volume fractions of minerals in peridotites were also shown. However, these relationships are by no means pronounced and depend on several factors (Pokhilenko, 1990). For Udachnaya pipe, these relationships were found for high-temperature deformed lherzolites (DL) (Sobolev, 1974, this study).

The authors performed an integrated study of the xenoliths in the lherzolites of Udachnaya pipe (Tychkov et al., 2008; Agashev et al., 2010). A sufficient set of suitable data combined with those from other authors (Ionov et al., 2010) allows not only to confirm the presence of mentioned relationships in the DL of Udachnaya pipe together with absence of such dependences in coarse lherzolites, but also to calculate first curves describing these dependences.

Modal composition

In DL of Udachnaya garnet (Gnt) volume fraction shows direct dependence with clinopyroxene (Cpx) (linear, R^2=0,74) and inverse dependence with olivine (Ol) (power, R^2=0.76). Relationships opthopyroxene-garnet and orthopyroxene-olivine are not so certain with R^2 ~ 0.4-0.5. Probably, that is because portion of Opx, calculated as residual phase, decrease first with rising Gnt and Cpx and then tend to rise from 10 vol. % of Gnt.

The use of various mineral thermobarometers shows that DL are the deepest lithosphere mantle rocks transferred to the surface. They are products of secondary enrichment of depleted rocks of the lower lithosphere mantle (dunites and harzburgites for Udachnaya pipe). The enrichment occurs resulting from the influence of melts of asthenosphere origin (containing no Cr and enriched in Fe and Ti) against the background of tectonic processes reflected in the distinctive texture of the rocks (Burgess and Harte, 1998).

Dunites make up 80 % of ultra-depleted rocks of Udachnaya, containing no Cpx or Opx and about 3 vol. % of Gnt (Pokhilenko, 1993). Obviously, garnet and clinopyroxene amount rises with progressing secondary enrichment (refertilisation) of these rocks. Obtained dependences allow to reconstruct general trend of modal composition change in lithosphere rocks during refertilisation (fig.1).

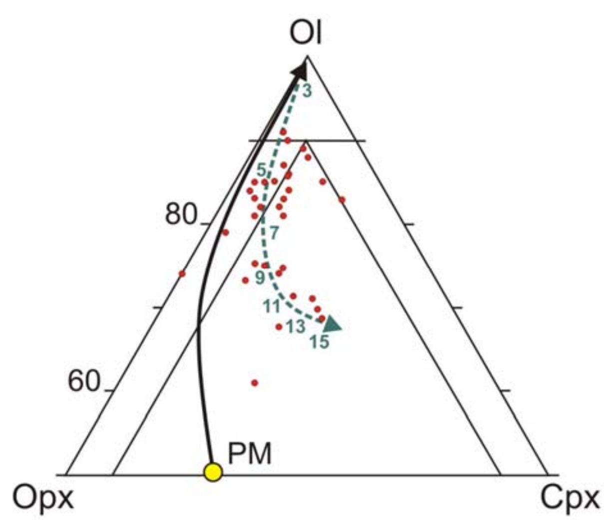

Fig.1. Modal mineral proportions of Udachnaya DL. Bold line – depletion, dashed line – refertilisation. Numbers – portion of Gnt (%). PM – primitive mantle composition after McDonough (1990).

Notice, that refertilisation trend differs appreciably from depletion one with much less Opx portion on the same portion of Cpx.

Garnet composition

A volume fraction of Gnt in DL of Udachnaya strongly depends on Gnt Cr_2O_3 content (Tychkov et al., 2011). Such relation was first shown by the example of garnet lherzolites from the Bohemian massif (Fiala, 1965).

The described dependence of the amount of garnet in the rock on the garnet Cr_2O_3 is an inverse relationship. The presence of the inverse relationship shows that the chromium content in a given rock does not increase proportionally to the increase in the amount of garnet.

In peridotite minerals, chromium is contained in garnet, chromite, and, to a lesser degree, in pyroxenes. Practically no chromite is found in DL (Pokhilenko, 1990) because, resulting from the secondary enrichment process, it transforms into garnet with the decrease of system chromousity (Cr/(Cr + Al)) (Webb and Wood, 1986). Respectively, this garnet then contains the bulk of chromium in the DL.

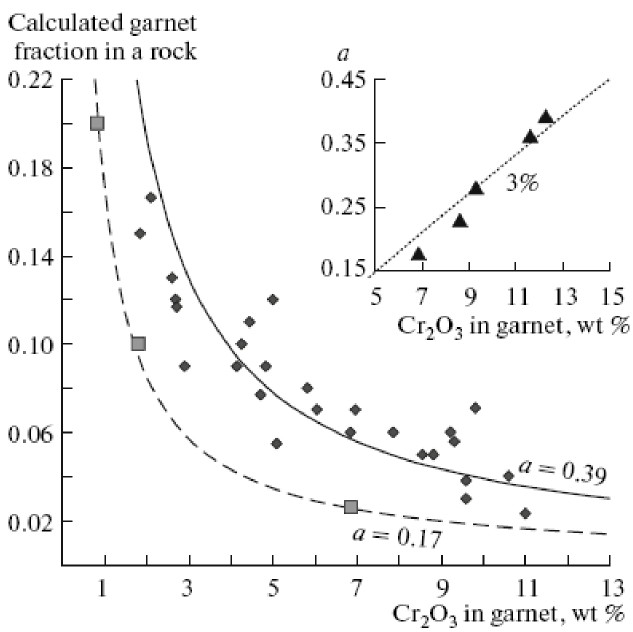

Fig.2. Dependence of the calculated Gnt fraction in a rock on Cr_2O_3 content for metasomatic DL (rhombs denote Udachnaya pipe and squares - the Bohemian massif, after (Fiala, J. 1965)). In the inset: the dependence of the *a* coefficient (Cr content in a rock) on the maximum Cr_2O_3 content in garnets from DL of different sources (triangles) (Fiala, J. 1965; Gregoire 2003; Kopylova et al., 1999; Viljoen, 2010); the dotted line shows the 3% level of Gnt in a rock.

In the case of formation of new Gnt owing to secondary enrichment with no introduction of Cr, the enrichment mechanism should be described by an equiangular hyperbola ($y = a/x$), because the product of the variables in this case is always constant and equal to *a*. Thus, the amount of chromium in the rock is not varied and is always equal to the chromium content in garnet multiplied by its volume fraction in the rock. It is seen in Fig. 2 that the mentioned relationship is described well by the curve $y=a/x$ with $a = 0.39$, where x is a garnet Cr_2O_3, (wt. %), y is the volume fraction of garnet in the rock, and a is the total amount of chromium. This model conforms to the above common mechanism of the formation of high-temperature DL.

According to published data, garnets from the DL of other regions show a similar character of the relationship at different chromium contents in rocks: $a = 0.36$ for Jericho pipe (Kopylova et al., 1999), 0.23 for Bluefontain pipe (Gregoire 2003), and 0.17 for peridotites of the Bohemian massif (Fiala, J. 1965) (Fig. 2). At the same time, if the rocks were initially characterized by a wide range of chromuosity, the relationship might be fuzzy.

REFERTILISATION GRADE

Method

Xenoliths of mantle rocks give insight into the lithosphere composition and structure as well as into the processes of their changing. The data as such may be obtained by means of studies of mantle rock xenocrysts, which are abundant in kimberlites and represent, according to current concepts, the products of decomposition of the lithosphere mantle rocks.

Pyropes belonging to secondary enriched DL may be distinguished from other pyropes by their composition (Sobolev, 1969; Tychkov et al., 2008; Schulze, 2003). With a sufficiently large sampling of pyropes as such from a definite region, using the above scheme, one may calculate the average amount of new formed garnet in the parental DL, i.e., the degree of secondary enrichment of the lithosphere roots. To obtain reliable data on the volume ratio of the rocks of different enrichment degrees, one must apply a correction compensating for the large fraction of garnets supplied into kimberlite from more enriched rocks.

The unknown *a* coefficient of the curve $y = a/x$ may be estimated by the maximum level of the Cr_2O_3 content in garnets from the DL. Kimberlites of the treated pipes contain xenocrysts of the garnets of dunite–harzburgite paragenesis. If nonmodified rocks are also present in the lithosphere base along with secondary-enriched rocks, those of minimum enrichment degree should be present (captured) as well. In these rocks, chromite is absent and the all of the chromium is contained in garnet, but its amount is still minimum and the chromousity is maximum in the entire series.

Figure 2 (see inset) shows the observed direct dependence of the *a* coefficient (Cr content in a rock) on the maximum Cr_2O_3 content in the garnets from DL of different regions. The relationship is close to the 3% level of garnet content in the rock, i.e., to the minimum observable content of garnet in DL. The same and smaller amounts of garnet are characteristic for the ultra-depleted rocks (dunites and harzburgites (Pokhilenko, 1993)) forming DL in the course of their enrichment.

The authors examined 865 pyrope grains from the kimberlite concentrate of Udachnaya pipe, and 34.5% of them, in view of their composition, originated from DL. The average Cr_2O_3 content in these grains is equal to 4.6 wt. % (1.9 standard deviation). The *a* coefficient calculated by the maximum Cr_2O_3 of the DL garnets from Udachnaya pipe (12.3 wt. %) is equal to 0.37. (The *a* value is equal to 0.39 for the curve plotted by xenoliths of Udachnaya pipe.) The Gnt fraction in these rocks, being calculated by the DL garnets from Udachnaya pipe, amounts to 0.82 (0.29 standard deviation); i.e., it is practically the same as the value calculated by 26 xenoliths of this pipe (0.81 with a standard deviation of 0.37).

Estimation

Using the procedure proposed, the degree of secondary enrichment was estimated for the roots of the lithosphere affected by different Siberian kimberlite pipes. In total, the data on the composition of 4139 garnets from 13 pipes were used for calculations.

The results are presented as the histogram in Fig. 3 and in the Table.

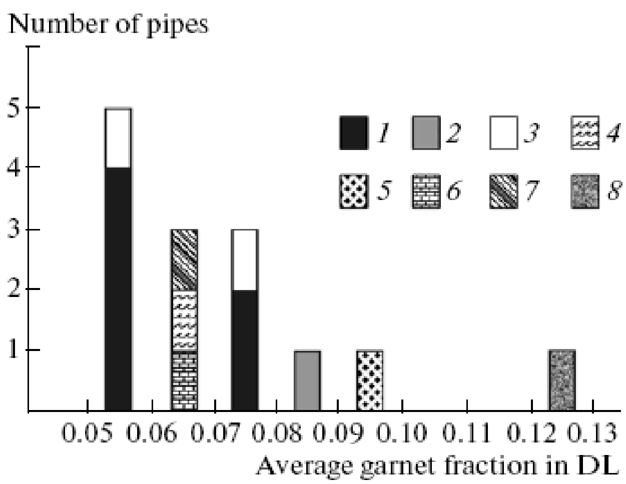

Fig. 3. Average garnet fraction in DL of the lithosphere being affected by the pipes of different kimberlite fields: *1*—Mirnyi, *2*—Daldyn; *3*—Nakyn; *4*—Kuoik; *5*—Taigikun–Nemba (*a* = 0.37, see text), *6*—Upper Muna, *7*–Toluop; and *8*—peridotites of the Bohemian massif (Fiala, 1965).

On average, the garnet fraction in DL of the considered areas of the Siberian platform is mainly within 0.05–0.09. Different pipes of the same kimberlite field show a wide spread of values (from 0.05 to 0.08 for the pipes of the Mirnyi and Nakyn fields).

A direct relationship is observed between the calculated fraction of garnet in DL and the amount of DL garnets in the kimberlite concentrates of the pipes (Fig. 4). The existence of this relationship shows that the use of the proposed procedure really gives an estimate of the degree of secondary enrichment of the lithosphere roots. The value for the Khorkich pipe falls out of the general relationship (Fig. 4). The underestimation of the amount of garnet in DL of this pipe might be caused by undervaluing the amount of chromium in the rock (*a* = 0.26 in this case), because no pyropes showing the minimum degree of secondary enrichment were retained.

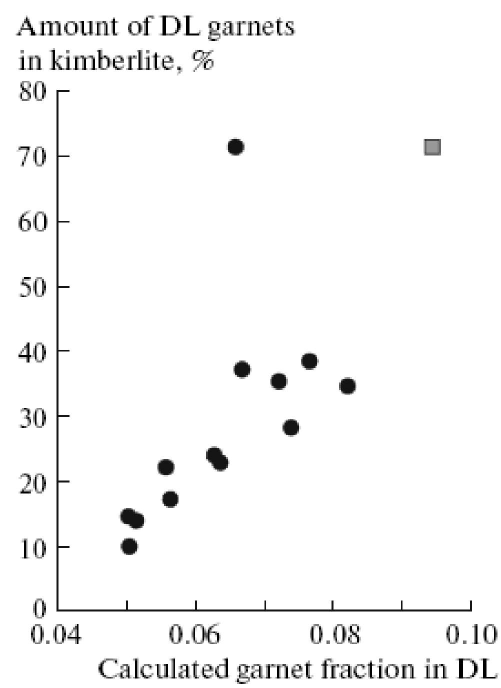

Fig. 4. Dependence of the calculated garnet fraction in the lithosphere DL on the amount of garnets (xenocrysts) belonging to DL, in the kimberlite concentrate of the pipes. The square denotes the value for Khorkich pipe at *a* = 0.37.

The concentrate of this pipe contains the largest amount of DL garnets (71.4%), and the garnets characteristic for dunites and harzburgites are completely absent (Tychkov et al., 2008). Thus, the kimberlites of this pipe captured no relics of the nonmodified depleted lithosphere because the process of refertilisation had gone much farther here than that in DL of other pipes considered. Taking the maximum Cr_2O_3 of DL garnets for Khorkich pipe to be equal to that for Udachnaya pipe (12.3% wt %), the *a* coefficient should be equal to 0.37 and the garnet fraction in DL should amount to 0.94; i.e., the value for Khorkich pipe would take its place within the general sequence (Fig. 4).

CONCLUSION

The performed studies showed that the values of secondary enrichment of the rocks in lower parts of the lithosphere in different regions of the Siberian plat form are little different and amount on average to 6 – 7 vol. % of Gnt in the DL. To compare, the data on the peridotites of the Bohemian massif might be presented, in which the average amount of garnet is equal to 12.8% (Fiala, J. 1965). Quite a high degree of enrichment for the Siberian platform is shown by Khorkich pipe (10.7%).

This might be caused by the fact that Khorkich pipe was introduced in the Triassic at the southwest edge of the Tungus syneclise during the development of the rocks of the trappean formation. The root parts of the lithosphere of this region might be pronouncedly modified by that time by the processes promoting the introduction of Siberian trapps of Permian–Triassic age, similarly to the processes occurring in the north eastern part of the Siberian platform (Tychkov et al., 2008, Pokhilenko et al., 1999).

Calculated average garnet content in the deformed lherzolites from Siberian kimberlite pipes

Pipe	1	2	3	4	5
Mir	1	487	5.1	1.2	9.9
Severnaya	1	209	5.1	1.6	13.9
Sputnik	1	340	5.0	1.9	14.4
Taezhnaya	1	305	5.7	1.5	17.0
XXIII s’ezd KPSS	1	689	7.4	2.7	28.2
Internatsional’naya	1	196	7.2	3.0	35.2
Botuobinskaya	2	205	7.7	2.2	38.3
Nurbinskaya	2	173	5.6	1.6	22.0
Udachnaya	3	865	8.2	2.9	34.5
Zimnyaya	4	170	6.7	2.3	37.1
Ivushka	5	193	6.4	2.7	22.8
Dianga	6	147	6.3	2.1	23.8
Khorkich	7	160	6.6	0.9	71.4
total		4139	6.6	2.0	28.3

Columns: 1 – kimberlite field (Mirnyi (*1*), Nakyn (*2*), Daldyn (*3*),Upper Muna (*4*), Toluop (*5*); Kuoik (*6*), and Taigikun–Nemba (*7*)), 2- Number of analyses, 3 - Average content, 4 - % Standard deviation of the content, 5 - Garnet fraction in DL, vol. %.

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