Metasomatic processes in the lithospheric mantle beneath the Arkhangelsk province, Russia: evidence from garnet and clinopyroxene of mantle peridotite xenoliths, Grib pipe

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A worldwide studying of geochemical and mineralogical compositions of garnet peridotite xenoliths records a variety of cryptic and modal metasomatic events [Sablukov et al., 2008; Shchukina et al., 2014, 2015 for Arkhangelsk province].

There are as minimum two stage of the modal metasomatic reworking of the lithosphere mantle[for example model by Griffin et al., 1999]:

- Carbonate-silicate usually low-T metasomatism with high rare incompatible elements contents produced crystallization of phlogopite, clinopyroxene and carbonate; probably it is ancient stage of metasomatism long before the formation of kimberlite melts:
- 2. High-T melt metasomatism during the ascent of asthenosphere / plume material and associated with kimberlite melts;

The model by [Russell et al., Nature 2012] supposes the evolution from proto-kimberlite melts like as carbonatite to more silicic composition melts (kimberlite-like) by assimilation of mantle minerals, (especially orthopyroxene).



The subject of this studying is estimate of carbonate and silicate components contribution in metasomatic processes in the lithospheric mantle during the forming of Grib kimberlite

Geological setting of Grib kimberlite



- The Arkhangelsk province is situated in the north part of East European craton.
 Several fields of kimberlites and related magmatism were distinguished within the province;
- The Grib pipe is located in the central part of the Arkhangelsk province (Chernoozerskoe field);
- It is classical kimberlite pipe like as South Africa group 1 kimberlite pipe [Mitchell, 1995];
- The kimberlite age is 374 ± 1.3 Ma (Rb–Sr isotope methods by phlogopite) [Lebedeva et al., 2014].







Mantle peridotite xenoliths and methods



- Geochemical compositions of garnets and clinopyroxenes from 19 mantle peridotite xenoliths (from 0.5 to 10 cm) were studied;
- The peridotite xenoliths have garnetlherzolites composition and contain:
 - ✤ 60-85% olivine;
 - ✤ 5-15% orthopyroxene;
 - ✤ 5-15% clinopyroxene;
 - ✤ 5-15% garnet.
- Methods:
 - Jeol JXA-8200 electron microprobe;
 - SIMS;
 - LA-ICP-MS





Peridotite microscopic textures



 The most of peridotites have heterogranular from medium- to coarsegrained (garnet up to 5–7 mm) microscopic textures;



 One of sample (106-664) has a porphyroclastic, partly blastomylonitic texture that are typical for sheared peridotite





Garnet



- Garnets commonly form zoned porphyroblasts with size from 3 to 10 mm.
 - 1. central zone (Gar1) 98-50% of garnet area;
 - 2. rim zone (Gar2) with uneven, often macules shapes and consist of garnet with metasomatic origin;
 - 3. secondary zone the most later rim zone was formed by aggregate of garnet (*Gar3*), phlogopite, Cr-spinel, carbonate and amphibole, width up to 300 micron.







Cr_2O_3 - CaO garnet classification



The majority of garnets are consistent with the Iherzolite garnet field (G9) [Grutter et al., • 2004] by Cr_2O_3 and CaO concentrations; rarely with harzburgitic (G10) and wehrlitic (G12) garnet fields.



Ti and Zr in garnet – different metasomatic types

• Based on Ti concentrations, garnets were divided into two main groups:

Low-Ti group:

- Low-Ti (< 0.27 wt. %) and low-Zr (< 20 ppm) garnets are comparable with depleted mantle peridotite garnets by [Griffin et al., 1999]; these are the most part of garnet central zones;
- Low-Ti (< 0.15 wt. %) and high-Zr (30-60 ppm) garnets are comparable with secondary kimberlitic (Ca, Cr)-poor garnets [Ziberna et al., 2013] and with low-T "phlogopite" metasomatic garnets by [Griffin et al., 1999]; these garnets were formed after crystallization of Ti-bearing megacryst minerals (ilmenite).

High-Ti group:

1. High-Ti (0.62-0.94 wt. %) and high-Zr (20-60 ppm) garnets are comparable with megacrysts or garnets of "ilmenite" paragenesis [Sablukov et al., 2008] and with garnets of high-T "melt" metasomatic origin by [Griffin et al., 1999]; these garnets were formed before megacrysts crystallization.





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Clinopyroxene



• Clinopyroxene usually form an anhedral phase between olivine and orthopyroxene crystals, sometimes altered the latter. Less common clinopyroxene forms fine-grained crystals up to 1-3 mm in size.



 Sometimes clinopyroxene was altered by a later aggregate of clinopyroxene (Cpx2) and phlogopite.







Clinopyroxene composition



Cpx has a wide range of Cr_2O_3 (0.69-3.93 wt. %), TiO₂ (up to 0.84 wt. %), Al₂O₃ (0.47-5.61 wt. %) contents with Mg# = 0.89-0.95;

By Cr₂O₃ content and Mg# values:

- 1. The most part of clinopyroxenes are comparable with the coarse mantle peridotite clinopyroxenes;
- 2. The less part of clinopyroxenes are comparable with the high-Cr megacryst clinopyroxenes [Kopylova et al., 2009] and form one paragenesis with the high-T "melt" metasomatic garnets.



5 peridotite groups – Group II

Group II contains:

High-Ti garnets with "normal" CI-normalized REE patterns are similar to megacrysts but enriched in all REE contents; these garnets have high-T "melt" metasomatic origin by [Griffin et al., 1999] like as Group I garnets;





5 peridotite groups – Group III

• Group III contains:

Garnets with low concentration of TiO₂, Cr₂O₃, CaO and "normal" CI-normalized REE patterns that are similar to megacrysts except for depleted in LREE; these garnets have depleted peridotite origin by [Griffin et al., 1999];

Clinopyroxenes with medium degree of REE fractionation.





5 peridotite groups – Groups IV-V



Groups IV-V contain:

- Garnets with low concentration of TiO₂ and mildly (Group IV) to humped (Group V) "sinusoidal" CI-normalized REE patterns with a maximum at Nd-Sm and a minimum at Dy-Ho; these garnets are comparable with G9 and G10 garnets accordingly and have depleted peridotite origin by [Griffin et al., 1999];
- Clinopyroxenes (Group IV) have the highest degrees of REE profiles with flat pattern for LREE and depleted in Ti.





La Ce Pr Nd Pm Sm Eu Gd Tb Dy Ho Er Tm Yb Lu



Garnet-clinopyroxene equilibrium



- Calculating a garnet-clinopyroxene equilibrium coefficients ($^{Gar/Cpx}D = X_i^{Gar}/X_i^{Cpx}$, where X_i concentration of element *i*) for I, III and IV peridotite groups suggests that:
 - Group I peridotites have the Gar/CpxD values, which are consistent with experimental dataset for near-solidus carbonatitic liquid at pressures of 6.6 and 8.6 GPa and temperatures 1265 °C (base of lithospheric mantle condition) [Dasgupta et al., 2009];
- Groups III-IV peridotites have the Gar/CpxD values, which are consistent with dataset for deep lithospheric mantle situations [Burgess and Harte, 2004] at low-temperature 900°C and nature garnet peridotites [lonov et al., 2004].





Estimates of metasomatic melts composition



- The REE profiles of calculated melts in equilibrium with Group I garnets and clinopyroxenes are very similar with composition of autoliths from Grib kimberlite and theoretical 1.5 % partial melt carbonated depleted mantle [Grassi, 2010] using partition coefficient for near-solidus carbonatitic liquid at T = 1265 °C [Dasgupta et al., 2009];
- The REE profiles of calculated melts in equilibrium with Group II garnets are similar to Grib kimberlite using partition coefficient for deep lithospheric mantle situations at T = 1300 °C [Dasgupta et al., 2009; Johnson et al., 1999];



This suggests evolutionary increasing in silicate components for melts in equilibrium with Group I garnet to Garnet II.

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Estimates of metasomatic melts composition



- The calculated melts in equilibrium with Group III-IV-V garnets and clinopyroxenes don't show similar with composition of Grib kimberlite that suggest their more differentiated metasomatic origin;
- The calculating was performed using partition coefficient for deep lithospheric mantle situations [Burgess and Harte, 2004].





Evolution of metasomatic agent for Group III-V



- To explain evolution of REE composition form sinusoidal" to "normal" patterns we used the model of melt injection and percolation through a refractory mantle column [Nimis et al., 2009; Ziberna et al., 2013]:
- In this model, the melt progressively changes its composition owing to chromatographic ion exchange, fractional crystallization and assimilation of peridotitic minerals, under decreasing melt/rock ratios



Plate model numerical simulation

At a distance from the region of kimberlitic melt generated the peridotite garnet has C1-normalized "sinusoidal" REE patterns;

In the proximity to the region of kimberlitic melt generated garnet has C1-normalized REE patterns close to megacrysts.





Evolution of metasomatic agent for Group III-V



- In the mantle peridotite xenoliths suit we have a nature example of this model:
- A zoned garnet crystal, which has progressive change of composition from relict zone with "sinusoidal"- harzburgitic REE profiles to megacryst-like REE profiles for the latest zone.



Ziberna et al., 2013: Plate model numerical simulation



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Evolution of metasomatic agent for Group III-V



• The calculated AFC-model with very intensive assimilation of depleted mantle material (orthopyroxene) and fraction crystallization (clinopyroxene and garnet) suggests the possible for this evolution of kimberlite melts composition:



The calculating was performed using partition coefficient for deep lithospheric mantle situations [Burgess and Harte, 2004; Johnson et al., 1998]. The composition of orthopyroxene was performed using composition of DM by [Salters et al., 2004].



Conclusions



The studying of the geochemical composition of Gar and Cpx form the mantle peridotite xenoliths suggests evolution of the metasomatic agent from early protokimberlitic melts with high carbonate contents to later more silicate kimberlitic melts:

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1. Early (protokimberlitic) high-T melts:

enriched in LREE and Fe-Ti (HFSE);

- high carbonate/silicate ratio within the evolutionary increasing silicate components to megacryst equilibrium melt composition;
- were existed before the crystallization of the megacryst assemblage (garnet, clinopyroxene, olivine, spinel, ilmenite);
- probably were formed by melting of carbonated peridotite mantle source.



2. Later (kimberlitic) low-T melts

- depleted in Fe-Ti and low carbonate/silicate ratio;
- were existed after the crystallization of the megacryst assemblage (garnet, clinopyroxene, olivine, spinel, ilmenite);
- could be metasomatic agent for peridotite xenoliths of III, IV, V groups where the different C1-normalized REE patterns ("sinusoidal" and "normal") may be explained by the model of melt injection and percolation through a refractory mantle column.

