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Fluid and magma transfer in subcontinental lithospheric mantle of the Siberian Craton and its geochemical evolution

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INTRODUCTION

In the last few decades, abundant evidence has been found for the influence of magma- and fluid transfer on the geochemical evolution of the mantle lithosphere of ancient cratons. The presently dominant hypothesis implies that the primary lithosphere resulted from an intensive melting as an ultra-depleted harzburgite residue left in the process of komatiite melting out [Griffin et al., 1999; Simon et al., 2007]. Thereon the harzburgite restite was enriched with petrogenic and rare incompatible elements during the stage of ancient "cryptic" metasomatism, whose agents may be high-temperature Mg- and Si-rich water fluids [Simon et al., 2007], carbonatite melts [Griffin et al., 1999] and others. Alongside with "cryptic" metasomatism whose traces are revealed in high contents of incompatible trace elements in rocks and minerals of the lithospheric mantle and in characteristic radiogenic isotopic ratios, the modal metasomatic processes are also extensively studied [Solov'eva et al., 1997; Gregoire et al., 2002 and others].

This study involves a consideration of geochemical character of two different groups of modal metasomaties in peridotite-pyroxenite xenoliths (ancient equilibrated metasomatites A and pre-kimberlite reaction metasomatites C [Solov'eva et al., 1997]) and also two main types rocks from the Udachnaya kimberlite pipe (high-temperature deformed and low-temperature coarse-grained garnet peridotites). One metasomatized xenolith of A-types is from the Komsomolskaya pipe (Upper- Myna field). Daldyn-Alakit and Upper-Muna kimberlite fields within the Udachnaya and Komsomol'skaya pipes are situated, are related to Middle Paleozoic (D_3 – C_1) kimberlite cycle. Kimberlite magmatism of this age is the most promising for diamond potential within the Siberian Craton and is believed to have evolved due to upwelling of the Yakutian deep plume [Ernst, Buchan, 1997]).

EQUILIBRATED METASOMATITES A AND REACTIONARY METASOMATITES C

The equilibrated metasomatites of A-type are presented of the suite overprinting minerals – Phlogopite + Diopside ± Ilmenite ± Apatite ± Sulfides ± Graphite. Metasomatized xenoliths are represented by rocks of different lithology: Phl garnet websterites, Phl garnet orthopyroxenite, Phl garnet lherzolite, Phl garnet olivinite, Phl spinel lherzolite, Phl spinel websterites and Phl websterites without spinel and garnet [Solov'eva et al., 1997]. Metasomatic minerals are developed as an even impregnation as well as layers, streaks, veins and veinlet aggregates cementing primary minerals. The most characteristic peculiarity of metasomatites A is a textural and chemical equilibrium of overprinted minerals between themselves and with minerals of primary paragenesis (Fig.1 a,b). The phlogopite forms relatively large, usually weakly curved plates (0.5-2mm, up to 7mm) with rounded and gulf-like boundaries without reaction relationships with primary minerals. In one sample metasomatic aggregates of garnet, graphite, phlogopite and clinopyroxene are observed. These observations confirm a conclusion that metasomatism A occurred in the mantle lithosphere of the central part of the Siberian Craton was temporal closed or simultaneous with general metamorphism of rocks and cratonization of lithosphere [Solov'eva et al., 1997]. The mineralogy of this metasomatic event (clinopyroxene, phlogopite, apatite, ilmenite) suggests that fluids or melts which modified the substance of the mantle lithosphere had a silicate-carbonate nature [Rudnick et al., 1993].

The metasomatites of reactionary type C are also represented by rocks of different lithology (Phl garnet lherzolites, Phl garnet olivine websterites, Phl garnet megacrystalline orthopyroxenites and Phl garnet olivinite).

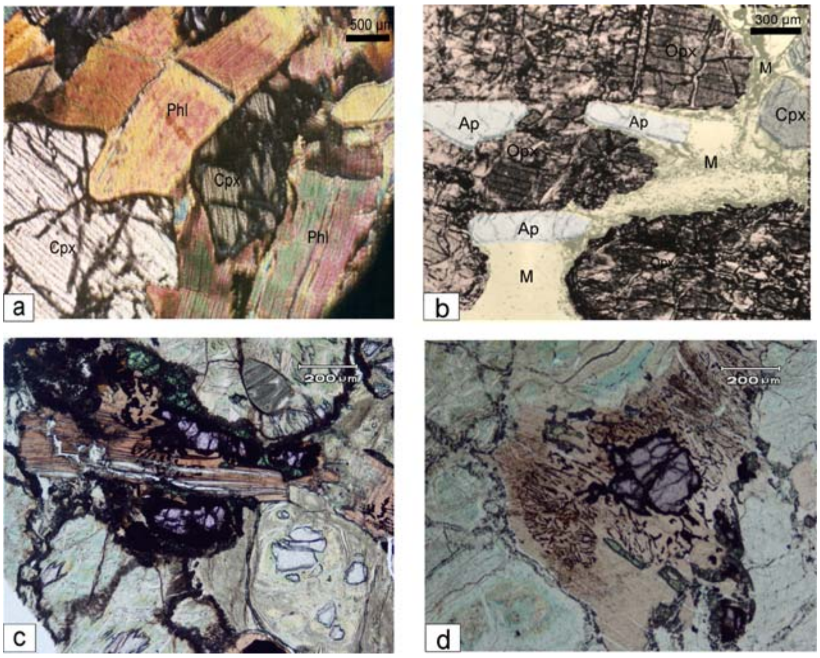

Fig. 1. Photomicrographs of metasomatites A and C. Metasomatites A: (a) Phl + Cpx zone is in megacrystalline orthopyroxenite. (b) Metasomatitic apatite (Ap) and diopside (Cpx) grains in megacrystalline Phl-Grt orthopyroxenite. Late irregular melt pools (M) overprint the general equilibrated texture of rock.

Metasomatites C: (c - d) Garnet relics in black kelyphite are intensively replaced by phlogopite with chromite and Cr-diopside intergrowths. Olivine and orthopyroxene are almost completely replaced with serpentine. (a) with crossed nicols, (b– d) without analyzer.

The metasomatic association consists of the reaction aggregates of Phl + Cr-Di + Chr (chromite) ± Sulf ± Graph intensively replacing garnet (Fig. 1c, d). They develop as windows sized from 0.5 to 3 cm or as a dispersed mineralization at the boundaries of primary minerals. Reaction type of metasomatism and heterogeneity of the composition of primary and metasomatic minerals suggest development of the process during a kimberlite-forming cycle [Solov'eva et al., 1997].

Later metasomatic associations in both groups of metasomatites are thin complex kelyphitic rims on the garnet and orthopyroxene, porous whitish margins on clinopyroxene and rims of Ti-magnetite on spinel. Serpentinization varies in the samples from 1-3 to 50 % by its volume.

Mineral chemistry in equilibrated metasomatites A, is close to one in peridotites and pyroxenites without any traces of metasomatic processes [Solov'eva et al., 1997]. Garnet and clinopyroxene from reaction metasomatites C contain more chromium and less titanium in comparison with these minerals both from metasomatites A and from coarse-grained peridotites of the corresponding lithology.

Clinopyroxene in metasomatites A is an ordinary diopside, and in metasomatites C – a typical Cr-diopside. Phlogopites from equilibrated metasomatites A contain considerably more TiO_2, Cr_2O_3, BaO, F in comparison with this mineral from reaction metasomatites C. In TiO_2, BaO and F contents, phlogopites from metasomatites C are closed to ones from dunite-harzburgite and whole ultramafic paragenesis (H +U) micro-inclusions in the diamonds from Yakutian pipes [Sobolev et al., 2009]. although the latter contain considerably more Cr_2O_3 and Cl.

Different grains from the same xenolith and rims of the same grain of metasomatites A analysis revealed no differences exceeding analytical error in trace element concentrations (SIMS- method). In the Fig. 2a, chondrite-normalized REE patterns of garnet grains from the phlogopite-graphite Grt websterites 3/85 and 4/83 are characterized by near to normal incompatible trace element distribution. Small difference from the normal type is observed in very slight decreasing of Dy, Er and Yb concentrations. The line for garnet from phlogopite garnet olivinite 05/230 significantly differs from the lines for graphite garnet websterites in more high La, Ce, Nd contents and lower contents of elements from Sm to Yb. Garnet REE pattern for the sample 05/230 tends to sinusoidal distribution that is characteristic for garnet from coarse-grained lherzolites from different kimberlite pipes of the world [Griffin et al., 1999; Simon et al., 2007; Solov'eva, 2007]. In the figure, field is also shown for garnet from coarse-grained peridotites with high incompatible element concentration (Solov'eva, 2007). In general, field for clinopyroxene from incompatible element enriched garnet lherzolites without any traces of modal metasomatism, is similar to lines for clinopyroxene from metasomatites A.

In reaction metasomatites C central zones occupy more than 90-95 % of garnet grains, and are homogeneous in trace element contents within one sample.

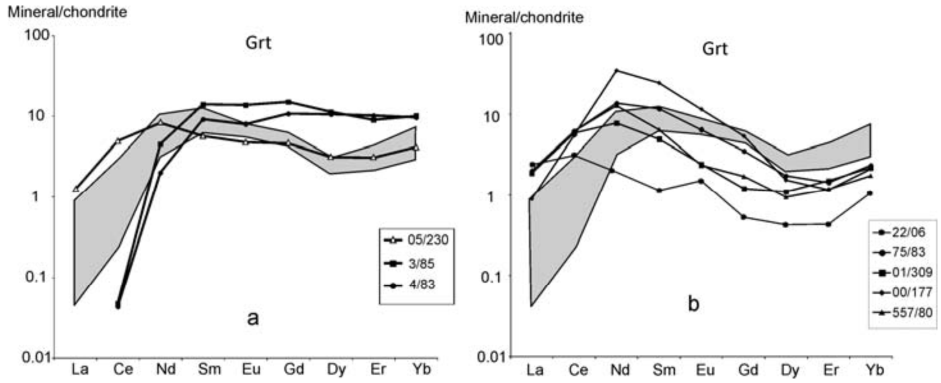

Fig. 2. Chondrite-normalized [McDonough, Sun, 1995] REE patterns for garnet from metasomatites A (a) and C (b). The lines show sample numbers. Field shows patterns for garnet from coarse-grained garnet and spinel-garnet peridotites of enriched type with prevailing orange and yellow olivine from the Udachnaya pipe [Solov'eva, 2007].

Rare element patterns for garnet centers have the characteristic Sr, Zr + Hf and Ti negative anomalies with relatively smooth parts of line for REE [Solov'eva, 2010]. REE patterns are characterized by sinusoidal shape (Fig.2 b) common for garnet from coarse-grained peridotites from the Udachnaya pipe and African kimberlites [Griffin et al., 1999; Simon et al., 2007; Solov'eva, 2007]. The rare element concentrations are slightly higher from Nb to Nd and lower from Gd to Yb for garnet from metasomatites C compared with garnets with maximal trace element concentration from coarse-grained peridotites without any traces of modal metasomatism [Solov'eva et al., 2010]. Rare element patterns for central zones of Cr-diopsides from metasomatites C are similar to lines for clinopyroxenes from metasomatized garnet peridotites from the South Africa kimberlites and differ from clinopyroxenes from deformed peridotites from the Udachnaya pipe [Solov'eva et al., 2010]. Partition coefficients between garnet and clinopyroxene ($D^{grt/cpx}$) for metasomatites A (3/85 and 4/83) are near two lines of grained garnet lherzolites of enriched type and equilibrium lines $D^{grt/cpx}$ calculated from empirical data (Fig. 3). The lines of reactionary metasomatites C show the lack of equilibrium between Grt and Cpx..

Points of Grt metasomatites A in general are lying near the Udachnaya pipe geotherm using different geothermometers and termobarometers. For metasomatites C, the T values calculated with geothermometer [Brey, Köhler, 1990] are 200 – 300º C higher then common Udachnaya geoterme. It may suggest a considerable temperature increase due to influence of hot deep fluids [Solov'eva et al., 2010].

HIGH-TEMPERATURE DEFORMED AND LOW-TEMPERATURE COARSE-GRAINED GARNET PERIDOTITES FROM THE UDACHNAYA PIPE

Distribution of incompatible elements for garnet from high-temperature deformed garnet lherzolites of coarse-porphyroclastic type and garnet megacrysts agree with normal magmatic trend [Solov'eva et al., 2008]. Maxima of high field strength elements (Nb, Zr+Hf and Ti) compared with REE are characteristic for garnet from the rocks and megacrysts. Garnets from deformed peridotites of fine-porphyroclastic type show sinusoidal REE lines and the HFSE negative anomalies compared with REE in rare element patterns. The latter rocks are thought to be lower lithosphere slices trapped by plume melts [Solov'eva et al., 2008]. The zonal distribution of main and rare elements is common for minerals from such litospheric «xenoliths» in asthenosphere (Fig. 4a, b).

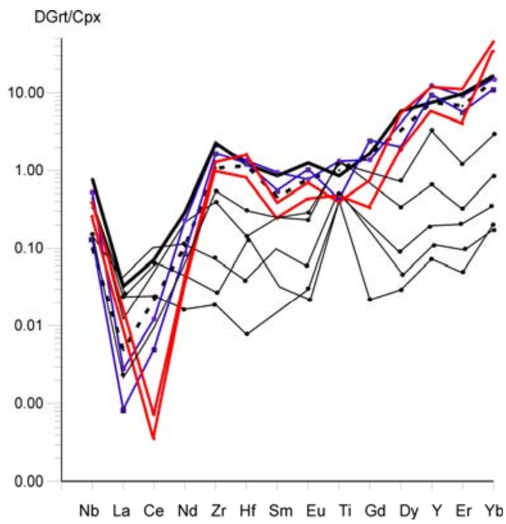

Fig. 3. Partition coefficients between garnet and clinopyroxene ($D^{grt/cpx}$) for metasomatites A (3/85 and 4/83), calculated as the ratios of rare element concentration in garnet and clinopyroxene. $D^{grt/cpx}$ for two coarse-grained garnet lherzolites of enriched type with orange and yellow olivine from the Udachnaya pipe are showed as the blue lines. Metasomatites C are thin black lines. The thick black lines are $D^{grt/cpx}$, calculated using published $D^{grt/melt}$ and $D^{cpx/melt}$ value for basaltic melt: solid line - $D^{grt/melt}$ and $D^{cpx/melt}$ [Burgess, Harte, 2004; Xie et al., 1995]; dashed - $D^{grt/melt}$ and $D^{cpx/melt}$ [Johnson, 1998, Xie et al., 1995].

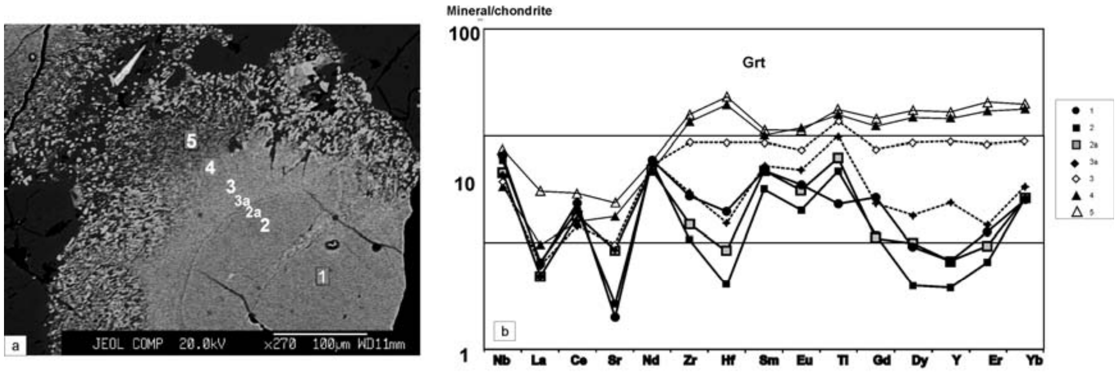

Fig. 4. The zonal distribution of rare elements (b) in garnet grain (a) from deformed fine-porphyroclasic Grt lherzolite. See the text.

In central zone of garnet at 50-70 μm from kelifite the distribution of incompatible rare elements is typical for garnet from coarse-grained garnet lherzolites, representing lithosperic mantle.The sharp minimum for Zr, Hf and sinusoidal distribution for REE are observed in lines 1, 2, 2a. In point 3, locating at 20-30 μm from kelifite rime, the rare elements distribution approximates to normal, exceptionally on the right margin of the grain and in kelifite (points 4, 5). Obtained data agree with the model of percolative fractional melt crystallization [Burgess, Harte, 2004; Harte et al., 1993]. The calculation of diffusion time according to [Van Orman, 2001] showed, that diffusion time for Sm and Nd in garnet at 1200°C and 700°C are ~200 y. and 90 Ma, respectively. The last value may correspond with time of whole kimberlite-forming cycle, as a first approximation.

Geochemical modification of matter and disequilibrium of chemical processes are observed also in coarse-grained lherzolites without traces of modal metasomatism. Very broad range of incompatible rare elements contents is shown in garnet and clinopyroxene from coarse-grained garnet and spinel-garnet peridotites from Udachnaya pipe [Solov'eva, 2007]. This fact is interpreted by author as the result of the different degree of rare elements extraction due to passing of redox asthenosperic fluids in early stage of kimberlite cycle. The conclusion is confirmed by $logfO_2$-data for xenolithes with widely differing rare elements contents in garnets from garnet- and spinel-garnet peridotites (Fig. 5). Samples with maximum rare elements contents (49/06 and 545/80) show the highest $logfO_2$. The $logfO_2$ of these xenolithes and xenolithes with the lowest rare elements contents (2/84 и 544/80) differ in 10^5 and $10^{2.5}$, respectively. Xenoliths with intermediate line on spidergram for garnet demonstrate the intermediate value of $logfO_2$.

MODEL OF THE PLUME-LITHOSPHERE INTERACTION

Model of the plume-lithosphere interaction and diamond formation in subcontinental lithosphere of the Siberian Craton during the Middle Paleozoic kimberlitic cycle is offered (Fig. **6**).

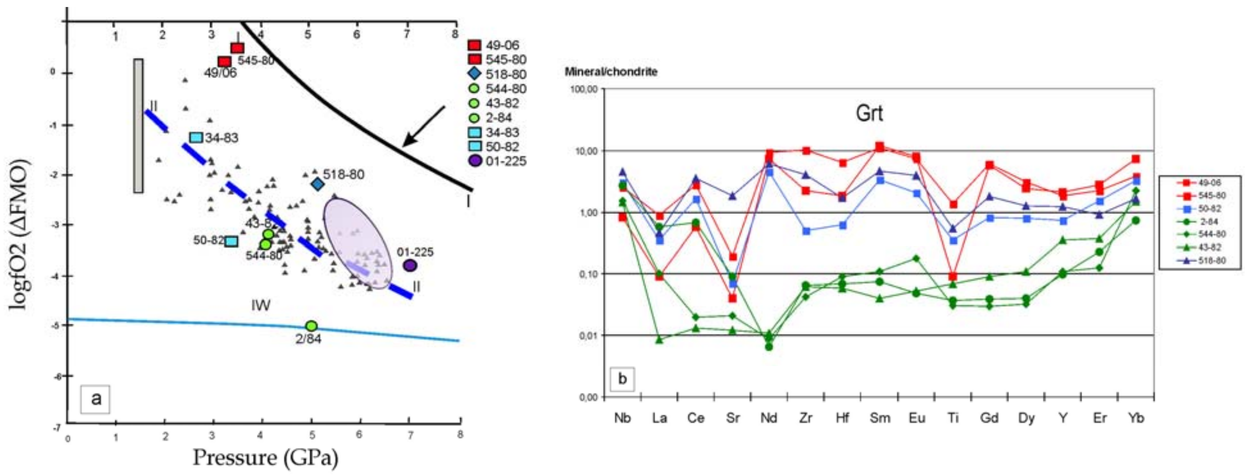

Fig. 5. (a). $logfO_2$ – P(GPa) [Frost, McCammon, 2008]
Line I-I – equation showing the dependence measured fO_2 from P [Frost, McCammon, 2008]; Line II-II – trend of log fO_2 in xenoliths from world kimberlites – small triangles [Frost, McCammon, 2008]; IW – buffer Fe-FeO [Lazarov et al., 2009]; field – deformed peridotites [Lazarov et al., 2009]; vertical column – abyssal peridotites [Frost, McCammon, 2008]. The samples from Udachnaya pipe: coarse-grained peridotites (49-06, 545-80, 544-80, 43-82, 2-84, 34-83, 50-82); metasomatized orthopyroxenite of C-type – 518-80; deformed coarse-porphyroclastic Grt lherzolite – 01-225 (our data, method Gudmundsson and Wood, 1995).
(b). The distribution of rare elements in Grt from coarse-grained peridotites (pipe Udachnaya) – our date.

This model considers the triggering influence of the Yakutian plume and development of local sources of mafic melts similar to intraplate basalts in the asthenosphere and lower part of lithosphere plate [Ernst, Buchan, 1977; Solov'eva et al., 2008]. Percolation of melts through the rock matrix with simultaneous crystallization of Cr-poor megacrysts, geochemical evolution of melts and magmatic substitution of the asthenosphere matter. Geochemical modification of the mantle lithosphere above zone of melts by redox fluids. The formation of reaction metasomatites C and crystallization of graphite and diamond under adequate T-P parameters at geochemical barriers.

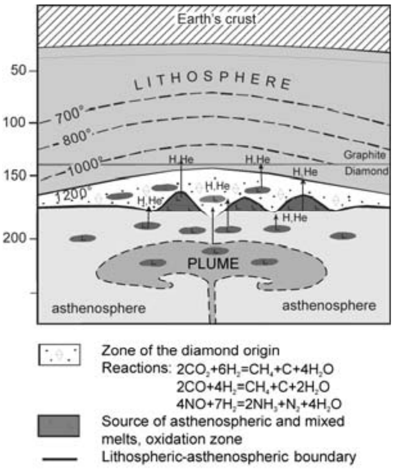

Fig. 6. Model of the Middle Paleozoic thermo-chemical plume influence on the asthenosphere and the mantle lithosphere of the Siberian Craton. The model proposes the development of the mafic melts (L) in the asthenosphere and in the lower part of the lithospheric plate, and the rising hydrogen (helium) flow from the melts. Reactions between hydrogen and gases buried in the mantle lithosphere are shown at the bottom of the figure. It leads to evolve a reduced zone where graphite and diamond form if P-T parameters are adequate.

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