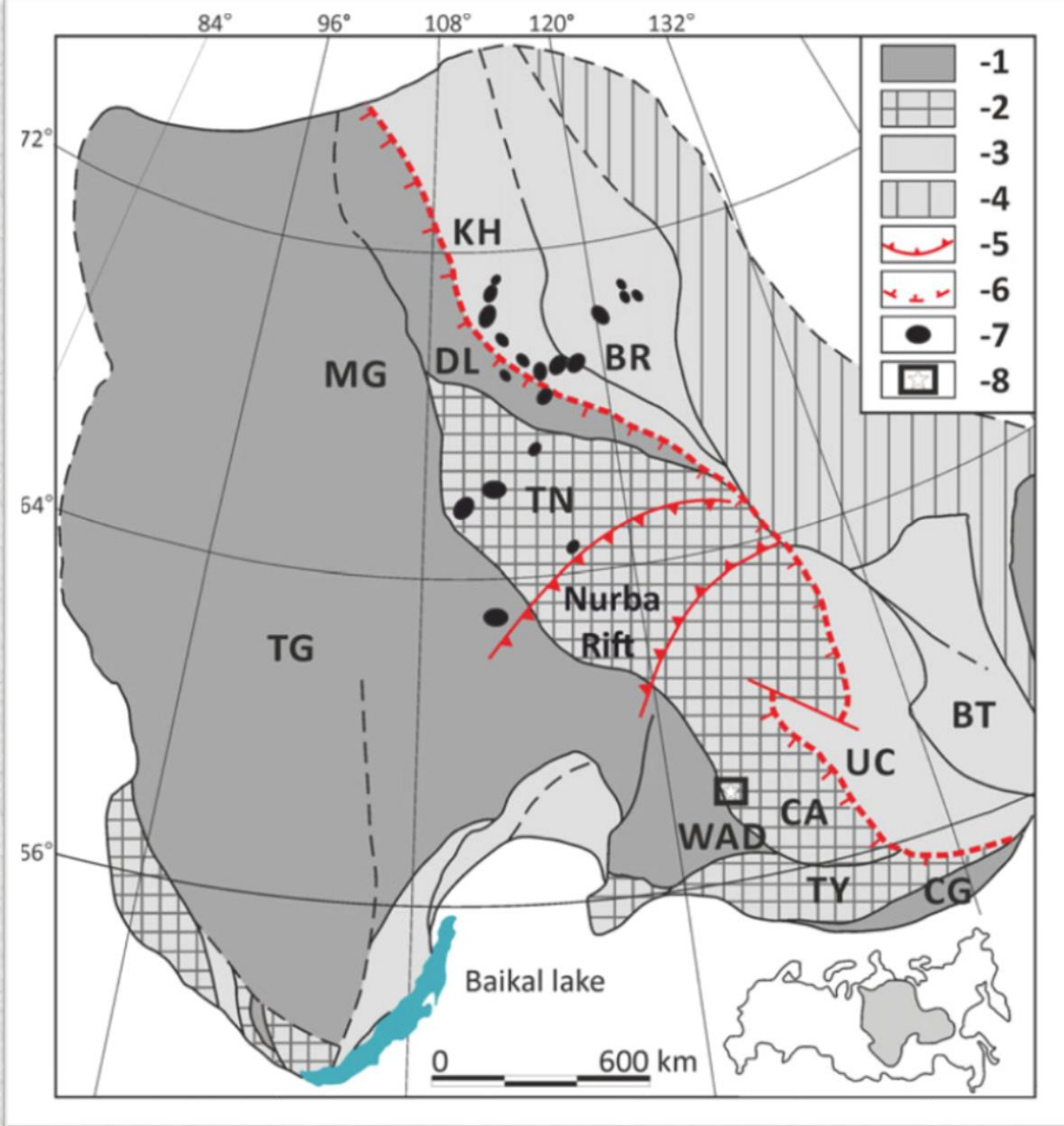


Mineralogy and geochemistry of the inclusion-bearing Cr-pyropes from the Chompolo lamprophyres, Aldan shield, Siberian craton

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Mantle minerals in deep-originated volcanic rocks like kimbelrites, lamproites or lamprophyres represent large ranges in major- and trace-element composition reflecting variety of parent rocks, pressure and temperature of residence rocks and indicate to the mantle metasomatic processes. The most researches are concentrated on objects that are processed industrially. In particular, inside the huge Siberian craton the majority of studies are related to well-known kimberlites like “Udachnaya”, “Mir”, “Inter” etc. As result, the Subcontinental Lithospheric Mantle of central part of North-Asian Craton is good investigated. However, the south part is also representing the fundamental and practical interest related to alkaline magmatism.

In this case, we are talking about the Aldan alkaline province, which includes the fields of alkaline volcanism and some massifs. The rocks of the Aldan alkaline complex have been fairly well studied, but there is a little information about the mantle substrate of this region. Firstly, about mantle garnets with oxide inclusions from Aldanskaya dike were reported in (Kostrovitsky and Garanin, 1992) and mantle inclusions of Chompolo rocks were shortly described by Ashchepkov (Ashchepkov et al., 2001). The Chompolo volcanic rocks are highly interesting geological object for detail investigations (Fig. 1).

Figure 1. Tectonic structure of the North Asian Craton basement (Smelov, Timofeev, 2007) relative to locations of kimberlite fields. [1] Archean terranes; [2] Archean-Paleoproterozoic terranes; [3] Paleoproterozoic terranes; [4] Mesoproterozoic terranes; [5] Mesoproterozoic rift [1.2–1.0 Ga]; [6] Bilyakh-Fedorovskaya subduction zone [2.3–1.9 Ga]; [7] Kimberlite fields; [8] Location of Chompolo field.

Geological background

The Chompolo field of alkaline magmatism are located within Amga tectonic melange zone in the southern part of the Siberian craton (Fig. 2). The Amga tectonic melange zone was formed at 1.9 Ga and separates the West Aldan granite-greenstone terrane and the Central Aldan granulite-orthogneiss superterrane.

Nine magmatic pipe-like (Ogonek, Gornaya, Sputnik, Pereval'naya, Intrusion 104) or dike (Aldanskaya, Kilier-E and etc.) bodies complicated by veins and apophyses are known within Chompolo field now.

Age of Chompolo rocks according to $^{40}\text{Ar}/^{39}\text{Ar}$ dating of K-richterite from Ogonek and Aldanskaya dyke are 137.8 ± 1.2 Ma and 157.0 ± 1.6 Ma respectively.

The magmatic bodies of Chompolo field are characterized by close placement (Fig. 2A) and have some evidence of local structural control. With a large probability they have common deep mantle source and therefore sampled the same mantle section. To increasing the representativeness of data we are considering together the mantle mineral association from the Aldanskaya dyke and Ogonek pipe.

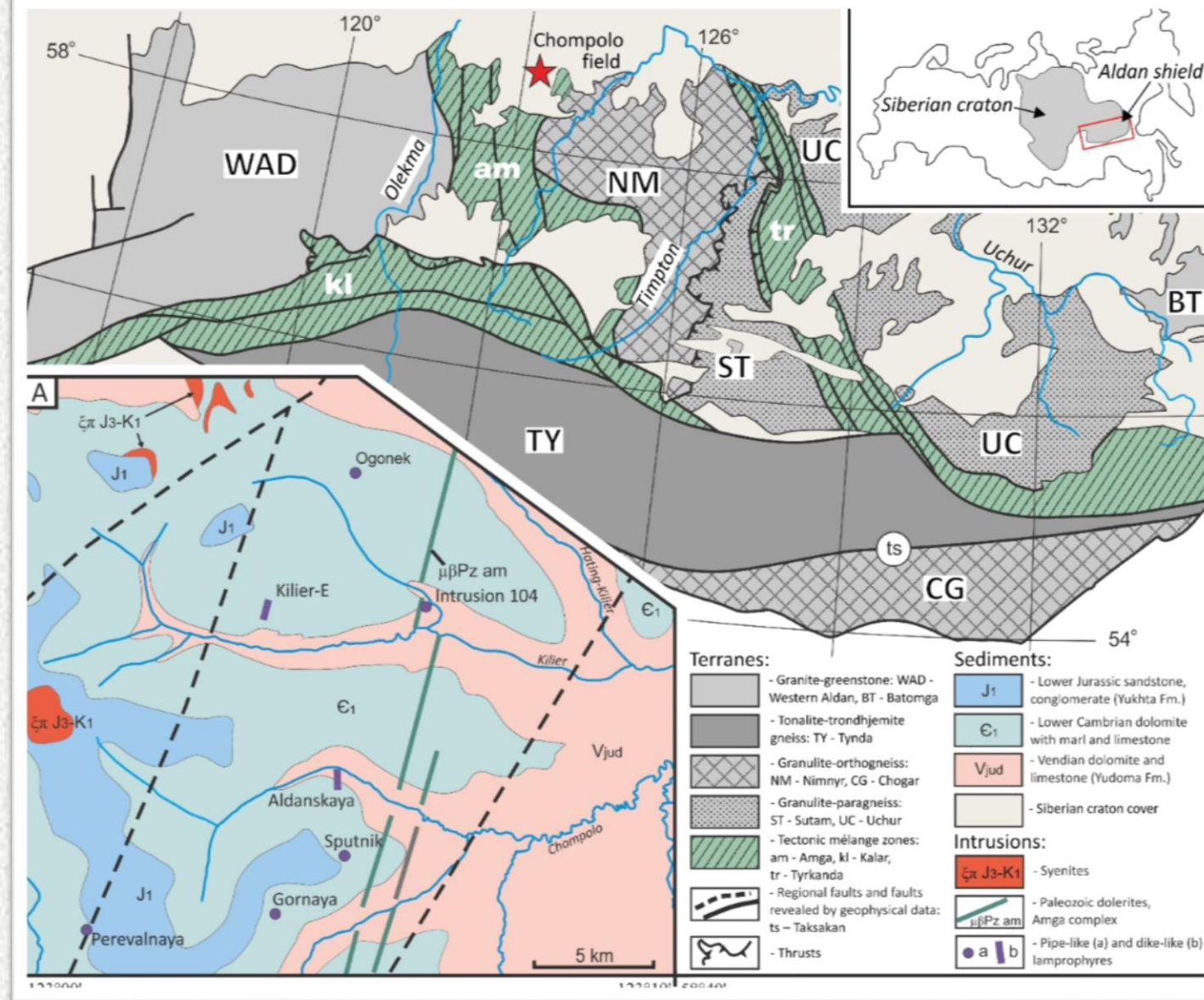


Figure. 2 Tectonic structure of the Aldan-Stanovoy shield (modified after Smelov et al., 2007) and local geology of the Chompolo field (inset A).



Heavy mineral concentrate from the upper level of Aldanskaya and Ogonek lamprophyres are the main material for this investigation. The heavy fraction was extracted by gravity differentiation using special equipment. We picked up the mineral fractions of garnets, diopsides and chromium spinels sized in 0.5-3 mm in diameter. Olivine in the weathered Chompolo rocks has been found only as pseudomorphs of serpentine in the Aldanskaya dike samples taken from 5 m depth below the surface.

Samples preparation includes the mounting of mineral grains in epoxy resin and further cutting up to half of grain size and the final polishing. These garnet crystals were polished to bring the shallowest inclusions to the surface. Minerals within the exposed inclusions in pyropes were identified by Raman spectroscopy and an electron probe microanalysis (EMPA) but unexposed mineral inclusions were identified by Raman spectroscopy only.

Figure. 3. Field works, Aldanskaya dyke, Chompolo field.

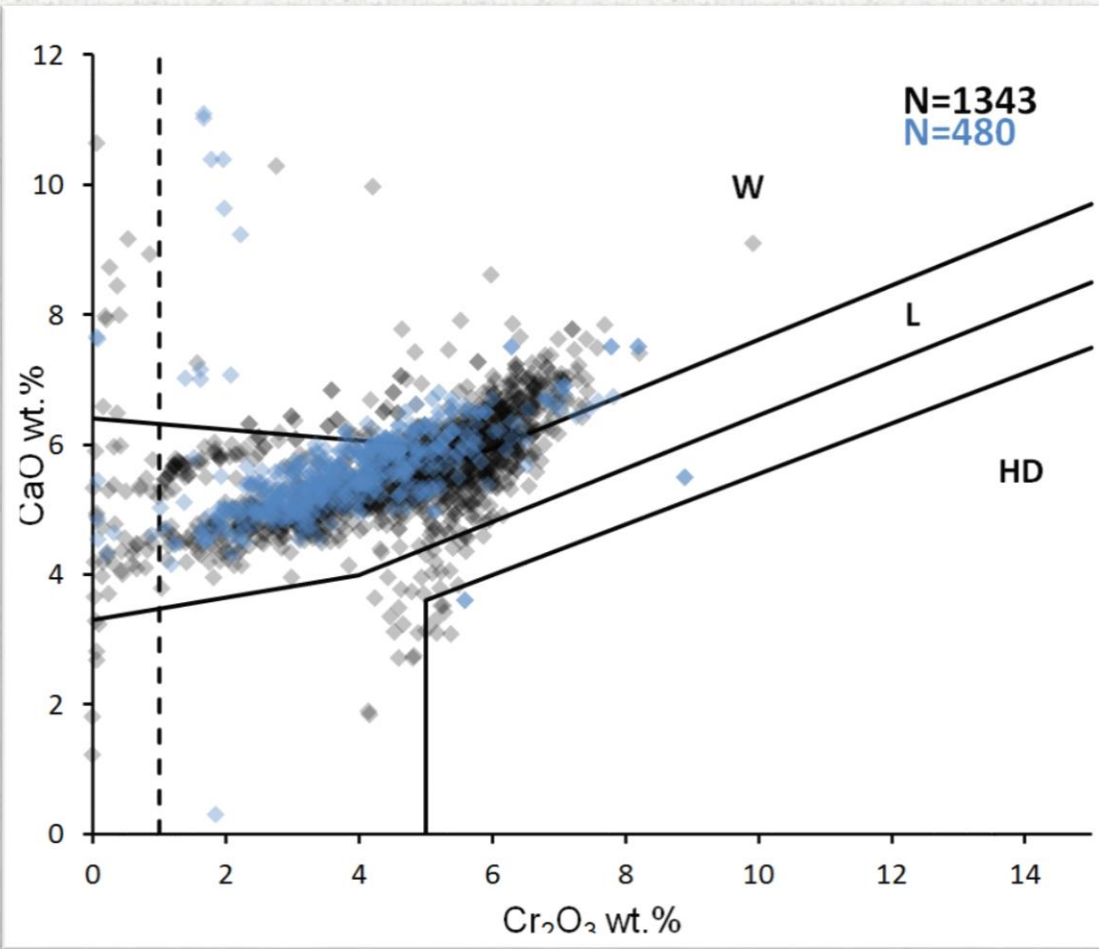


Fig. 4. The composition of studied pyrope garnets (black rhombs) from Aldanskaya dike and Ogonek pipe in CaO–Cr₂O₃ discriminant diagram (Sobolev et al., 1973), blue rhombs reflects the typical distribution of peridotite pyropes from the nondiamondiferous mesozoic kimberlites of northern Yakutia.

On the CaO–Cr₂O₃ diagram the association of peridotitic garnets from the Chompolo alkaline rocks is depicted (Fig. 4). Total amount of 1343 analyses showed on the diagram includes the data not only for the Aldanskaya and Ogonek lamprophyres but also for the Sputnik, Gornaya pipes and Kilier-E dike. All garnets are chromium pyropes with Cr₂O₃ contents from 0.5 to 9.92 wt. % and the Mg# in the range 61.8–86.4. But the majority of pyropes (73 %) are characterized by more narrow limits (76.5–81) of the Mg# variation. The CaO contents varies between 1.85 and 10.29 wt.% and TiO₂ does not exceed 0.47 wt.%. The pyropes are enriched in MnO with values usually more than 0.4 up to 1.29 wt. %.

The pyropes can be characterized by the paragenetic types according to CaO–Cr₂O₃ discrimination diagram. The association is enriched with lherzolitic garnets and also includes small percentages of dunite-harzburgite garnets but lacks megacrystalline as well as subcalcic high-Cr varieties. The abnormal character of composition of these pyropes is expressed in a distinct trend of partitioning of their compositions on the Cr₂O₃–CaO discrimination diagram. The discrepancy stems from a different ratio of Cr₂O₃ and CaO contents, owing to which the high-Cr part of the trend falls on the field of garnets of wehrlite paragenesis. Wehrlite pyropes also occur but very rare.

Garnets and inclusions

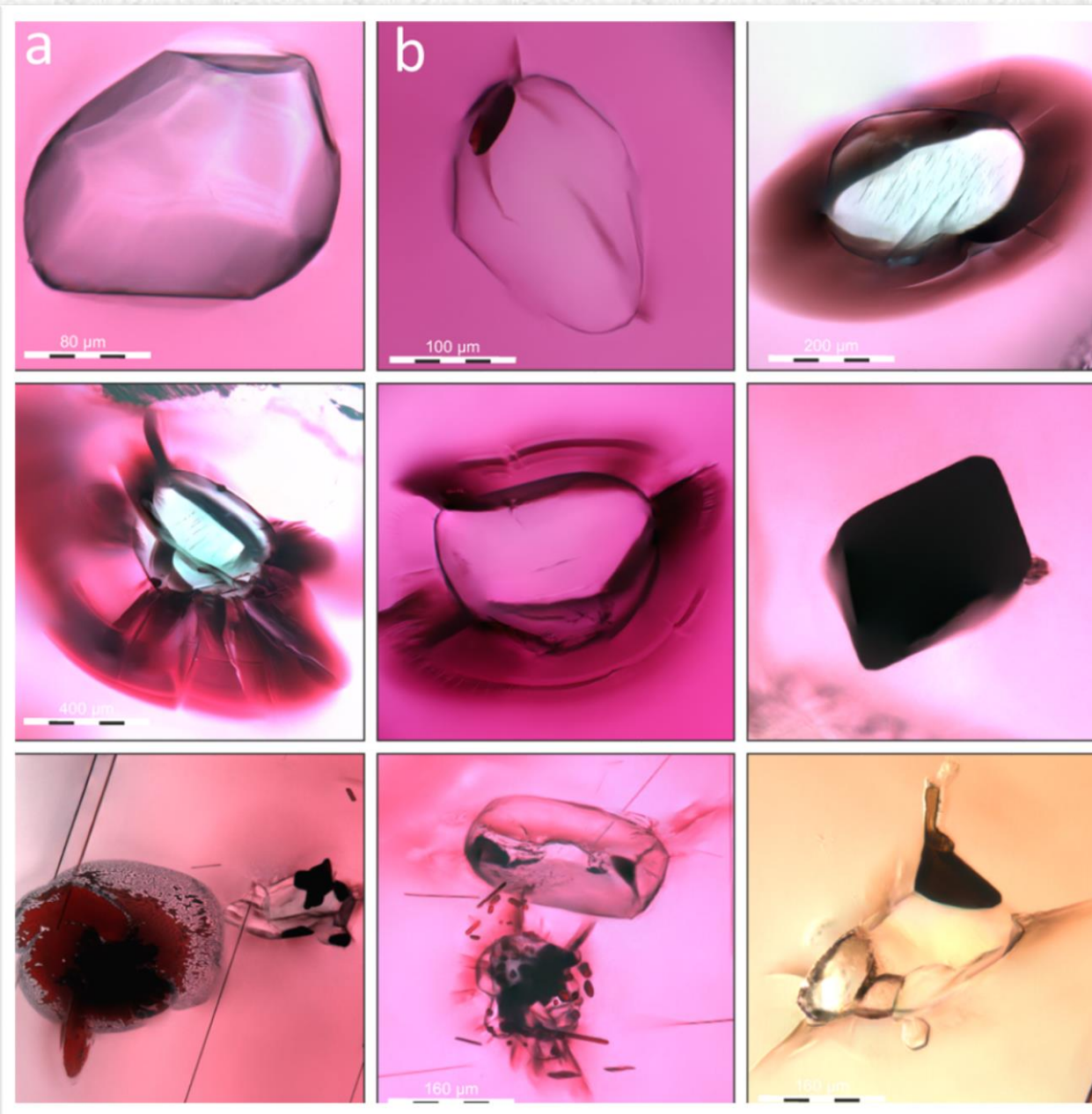
Pyropes vary in colour from orange to saturated purple without any visual nonhomogeneity and characterized by irregular or rounded shape.

Some grains contain different types of silicate, sulfide, oxide or polymineral inclusions. Often red garnets and less often purple garnets are characterized by structurally oriented elongated inclusions sometime looks like solid solution decay. A few grains have footprints on the surface from other minerals.

Single mineral inclusions in garnets are represented by olivines, enstatites, diopsides Cr-spinels and rutiles. Polymineral inclusions are characterised more wide list of minerals, including volatile-bearing minerals like phlogopite, amphibole and apatite (Table 1).

Single-mineral inclusions	Polymineral inclusions
Forsterite, Diopside, Enstatite,	Forsterite, Diopside, Enstatite, Phlogopite,
Cr-spinel, Rutile	Amphiboles (K,Na), Apatite, Graphite., Talc,
	Carbonates, Barite, Sulfides, Rutile, Cr-spinel,
	Minerals of Crichtonite group, Mg- illmenite

Figure. 5. Microphotographies of the mineral inclusions within pyrope xenocrysts from the Aldanskaya and Ogonek lamprophyre: a , b - forsterite; c, d – diopside; e- enstatite; f- Cr-spinel; g - sulfide inclusion; h, l – polymineral inclusions.



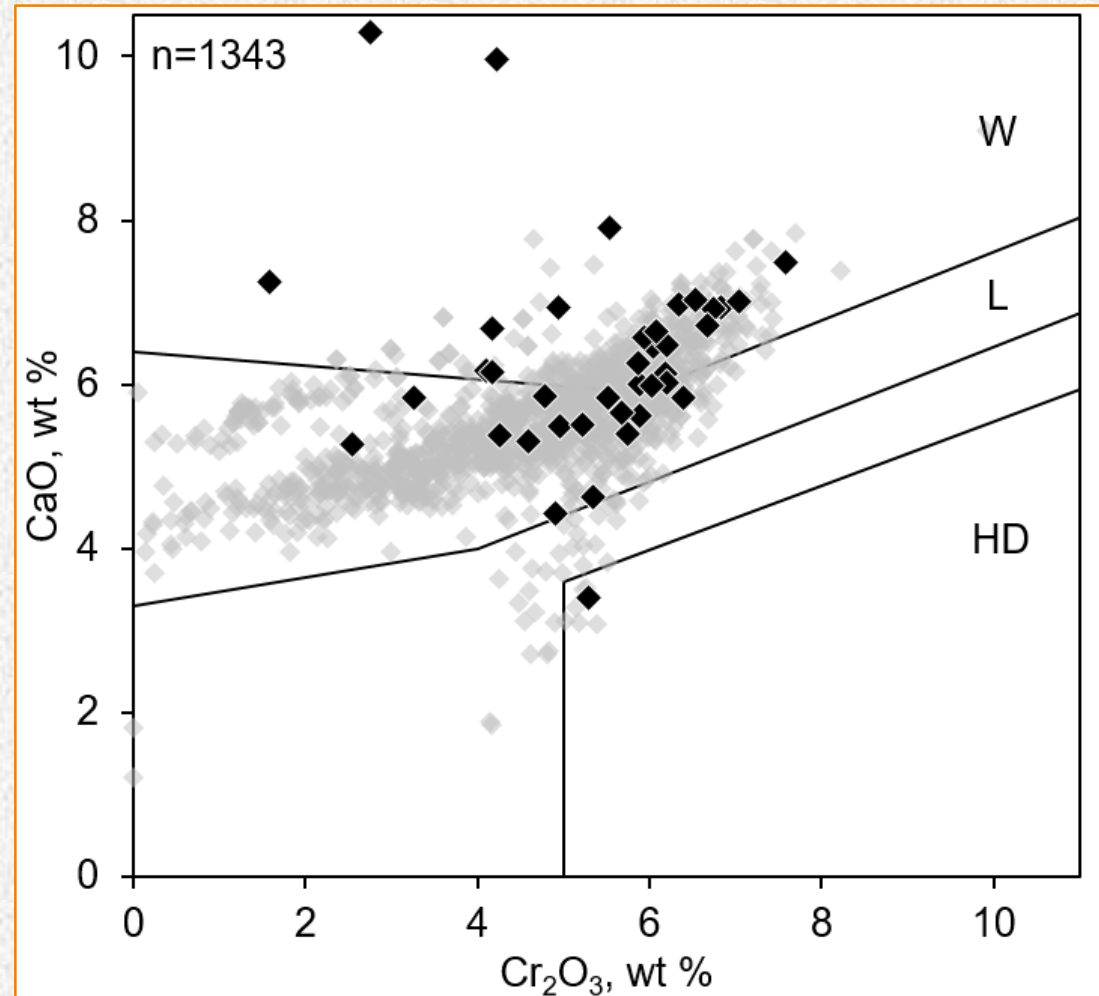


Figure 6. The composition of studied pyrope garnets with Cr-spinel inclusions (black rhombs) from Aldanskaya dike and Ogonek pipe in CaO–Cr₂O₃ discriminant diagram (Sobolev et al., 1973).

Inclusion assemblages within pyrope xenocrysts from the Aldanskaya and Ogonek lamprophyres are characterized by the wide list of minerals found as inclusions. Partially the assemblages within pyropes was previously described in association with graphite (Nikolenko et al., 2017), oxides (Rezvukhin et al 2016) and carbonates (Sharygin et al., 2017).

Studied mineral inclusions can be divided in several groups by their structure, morphology and mineral association within the host pyrope.

We can highlight the group of single-mineral or pair-mineral inclusions that includes a lot of the chromium spinels and in fewer amounts the diopsides, enstatites and olivines.

Cr-spinel inclusions, type - I

Majority of the studied chromium-spinels within pyropes represented by the mentioned above single-mineral inclusions (CrSp I) that have clear octahedral morphology but some of them can be described by more complex morphology that looks as shapeless or rounded. Single Cr-spinel inclusions are commonly large and ranges in size from 100 to 500 μm (Fig. 7).

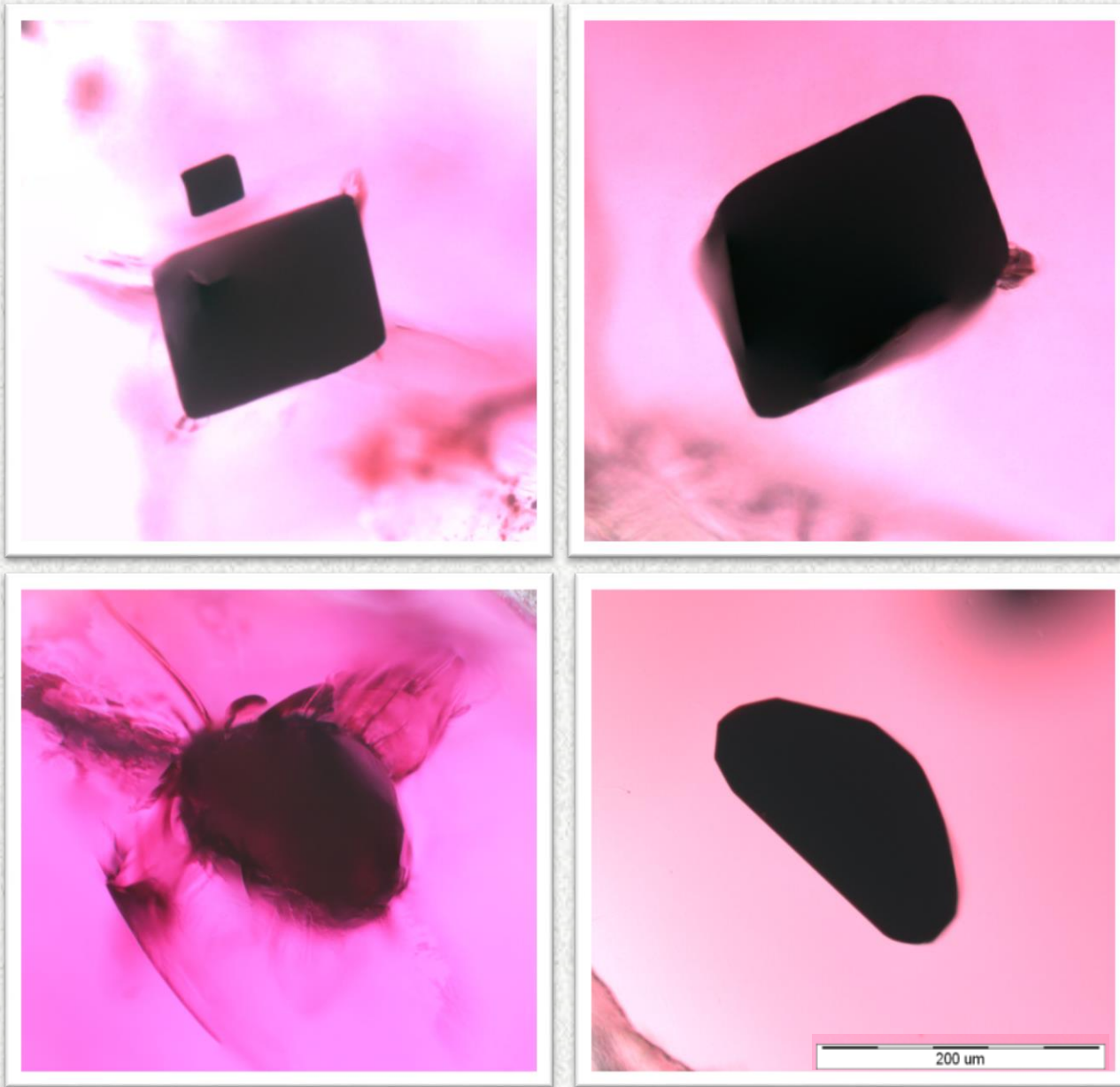
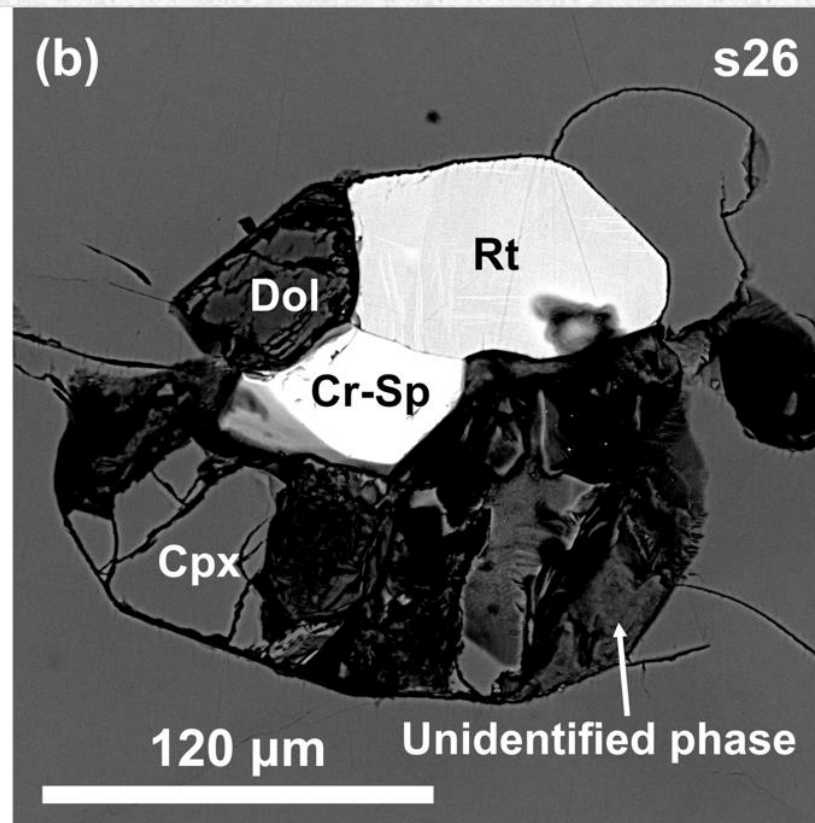
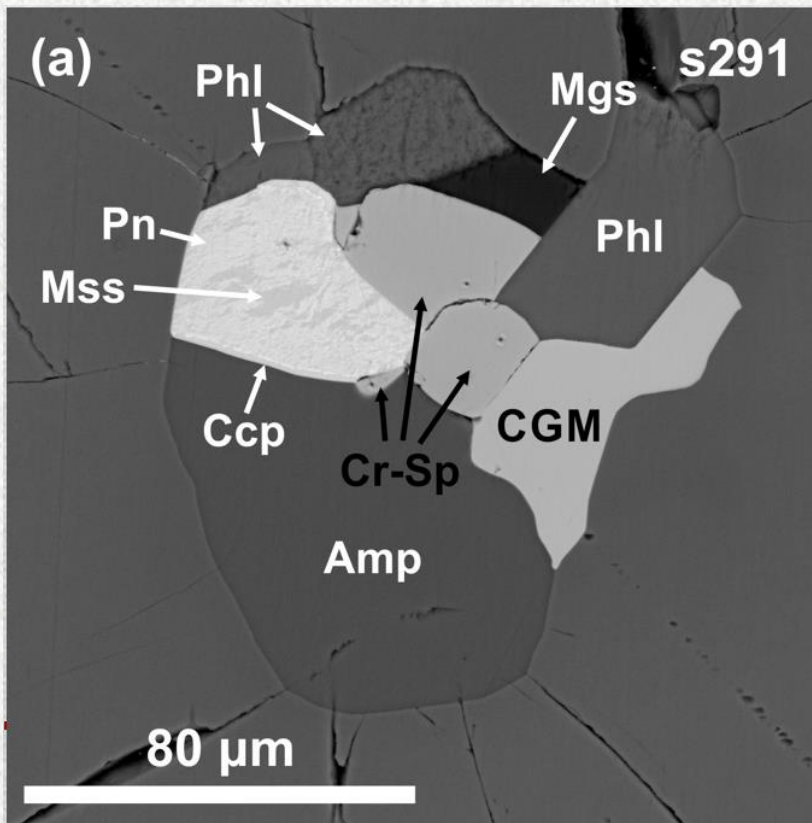


Figure. 7. Microphotographies of Cr-spinel inclusions (CrSp-I type) within pyrope xenocrysts from the Aldanskaya and Ogonek lamprophyres.



Cr-spinel inclusions, type - II

Another inclusions type represents Cr-spinels as part of complex polymineral association (see Fig. 8). In such inclusions occur joint associations of silicates, carbonates, sulfides, graphite, volatile-bearing minerals and series of Ti-oxides including second type of Cr-spinels (CrSp II). Size of Cr-spinels II in this samples usually 10-50 μm and rare reach up to 100 μm.

Figure. 8. Microphotographies of the mineral inclusions within pyrope xenocrysts from the Aldanskaya and Ogonek lamprophyre: a , b - forsterite; c, d – diopside; e- enstatite; f- Cr-spinel; g - sulfide inclusion; h, I – polymineral inclusions.

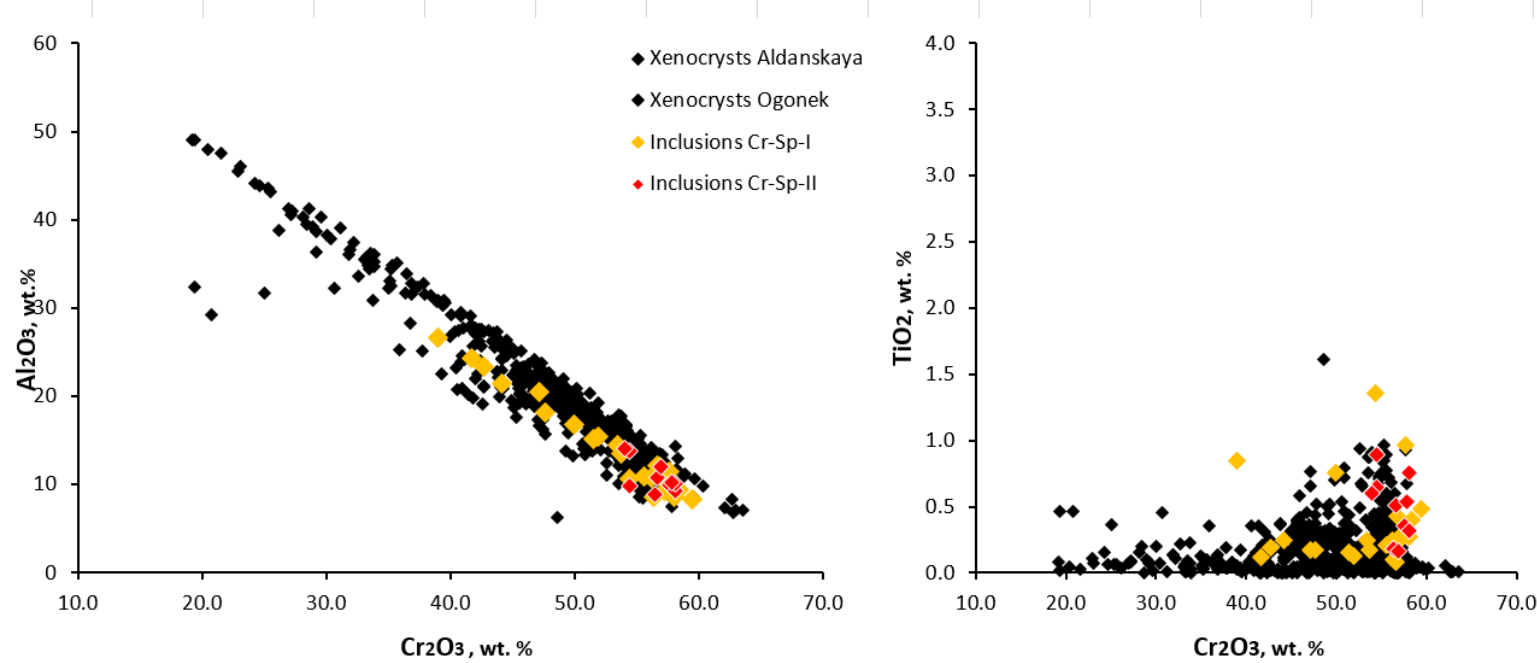


Figure. 9. Relations between Al_2O_3 , Cr_2O_3 and TiO_2 in the Chompolo Cr-Spinels

Cr-spinel inclusions within pyropes were also has been studied in detail and revealed some differences in the chemical composition between two groups.

The CrSp I group are characterized by negative correlation between Cr^{3+} and Al^{3+} and have wide interval of Cr# from 49.5 to 82.5, unlike most of CrSp II with substantially more narrow limits of Cr# in the range 72.0-84.5. The ratio $\text{Fe}/(\text{Fe}+\text{Mg})$ (Fe#) for CrSp I group varies more broadly (42.0-64.6) than for CrSp II group (50.0-65.5).

The chromium spinels of CrSp I group contain less amount of ZnO admixture relatively the xenocrystic spinel and CrSp II populations and demonstrate the values range of 0.103-0.221 wt. % with average value about 0.156 wt.%. ZnO contents in the CrSp II group significantly higher and ranges in the limits of 0.139-0.335 with mean value 0.242 wt.%. Contents of TiO_2 in the CrSp I population ranges widely from 0.09 to 1.32 wt.% but the large proportion of values are localized inside narrow interval from 0.09 to 0.34 wt.%. Also, very close interval of TiO_2 contents from 0.14 to 1.36 wt.% is belong to the CrSp II population. NiO admixture in chromium spinel populations varies in the ranges 0.061-0.223 wt.% for the CrSp I and from 0.055 to 0.215 for the CrSp II groups.

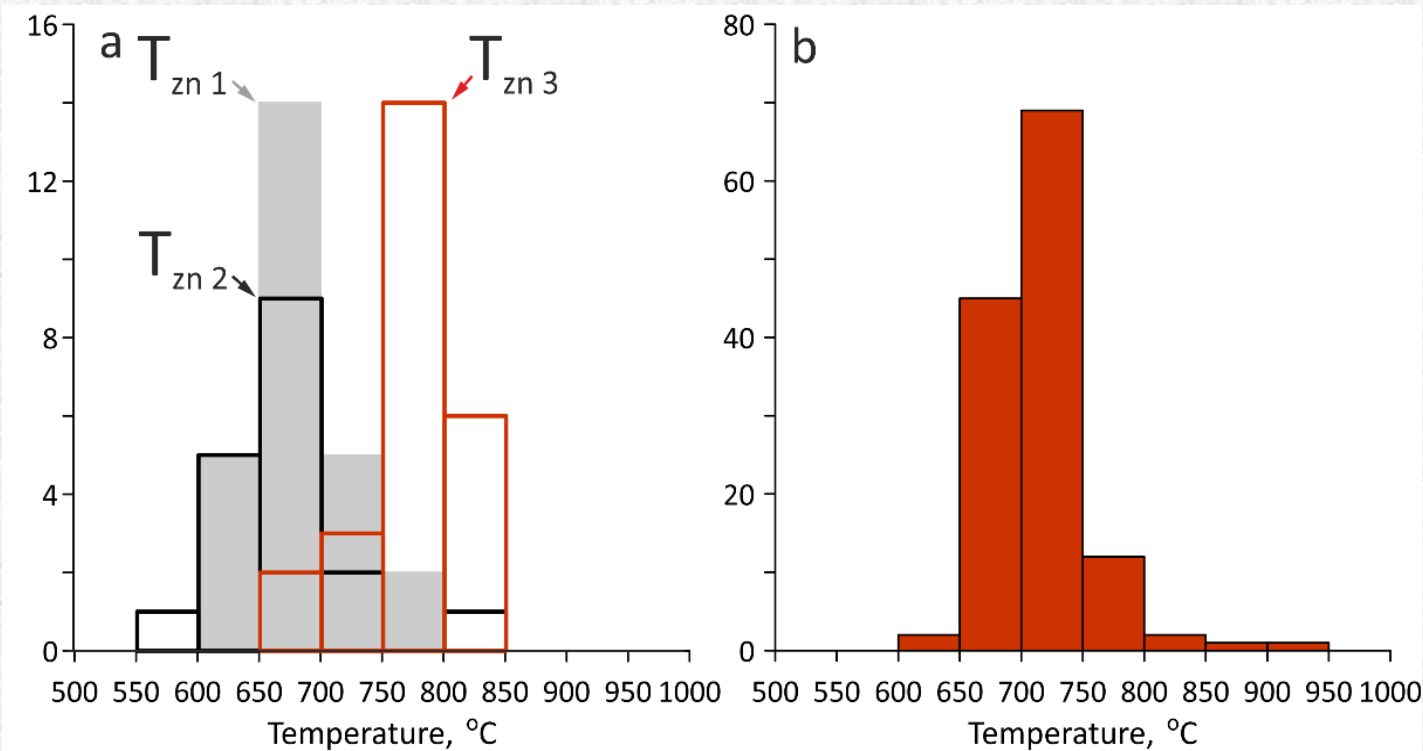


Figure. 10. Temperature distribution histograms: (a) Zn-in-chromite thermometer for chromium spinel xenocrysts (TZn1); CrSp-I type inclusions within pyropes (TZn3); CrSp-II type inclusions within pyropes (TZn2); (b) Ni-in-pyrope thermometer for pyrope xenocrysts with mineral inclusions of the Aldanskaya dike.

We evaluated the temperature ($T_{\text{Zn-in-CrSp}}$) by use the Zn-in-spinel thermometer (Ryan et al., 1996) for the xenogenic Cr-spinel macrocrysts for the single-mineral inclusions of Cr-spinel within pyropes (CrSp I) and for the Cr-spinel from composite inclusions (CrSp II) separately. In general, we obtained the temperature range from 550 to 850 degree C for all samples. However, the distribution of values is not equal for all groups of Cr-Spinel. We can see on the histograms (Fig. 10) that the temperature distribution is the same for the xenocrystic spinel group and for the CrSp II group with maximum on 650-700 degree C. The CrSp I group shows another temperature distribution with maximum frequency on 750-800 degree C.

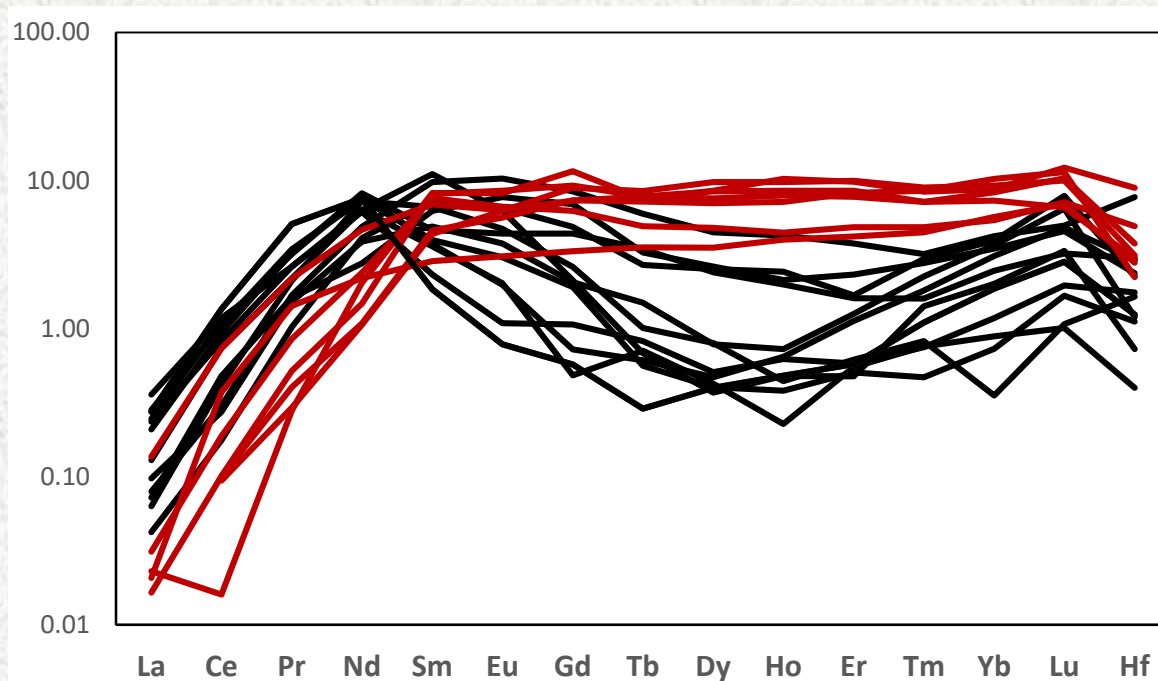
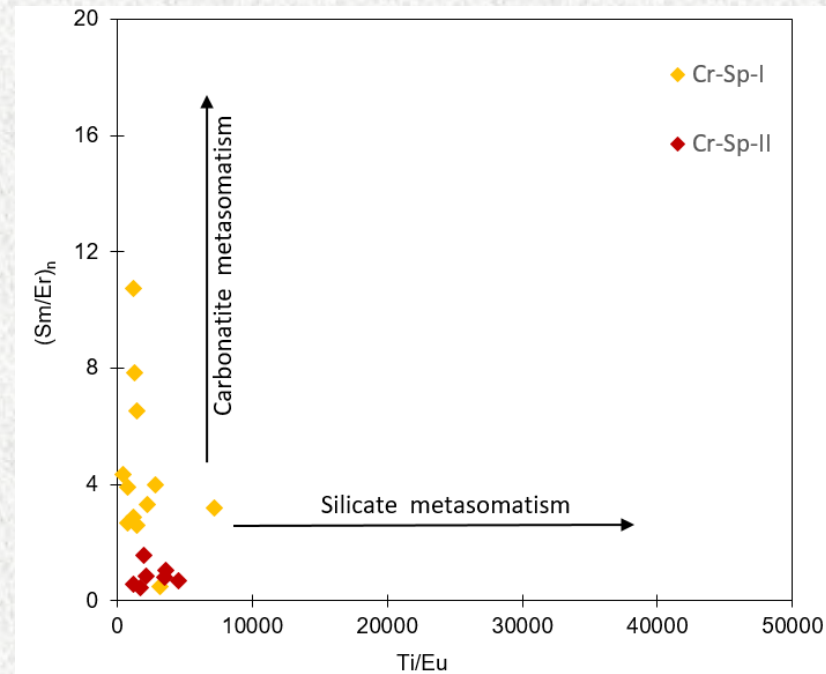


Figure. 11.

The distribution of the rare earth elements (REE) for most of pyropes containing CrSp-I inclusions (black lines) in chondrite-normalized REE-diagram has a sinusoidal pattern and is characterized by the chondrite normalized ratio $Sm_N/Er_N > 1$ at low Ti/Eu values (Fig. 11), which is a sign of carbonatite metasomatism (Shchukina et al., 2017). Pyropes containing complex polyphase inclusions with CrSp-II carry signs of silicate (melt) metasomatism, expressed in elevated contents of Y (up to 20.5 ppm) and Zr (9.5–44.6 ppm) and an increased Ti impurity. Pyropes with CrSp-II inclusions have typical for lherzolites distribution of REE with Sm_N/Er_N ratio in the range of 0.5-1.



- The chemistry of the studied garnets, namely their high Cr₂O₃ contents and Mg#, clearly points to their mantle origin (Sobolev et al., 1973).
- The pyropes contain complex association of inclusions which is represented by volatile-bearing minerals (mica, amphibole, and apatite) together with carbonates and titanium-rich oxides such as ilmenite, rutile, and minerals of crichtonite group in mantle rocks.
- The morphology, composition and spatial distribution of the inclusions are evidence of their syngenetic origin with host garnets and their feasible metasomatic origin.
- The geochemical features, the composition of inclusions and the results of thermometry of the two described pyrope populations with Cr-spinel inclusions indicate different metasomatic processes associated with their formation in the lithospheric mantle of the Central Aldan superterrane of the Siberian craton.

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