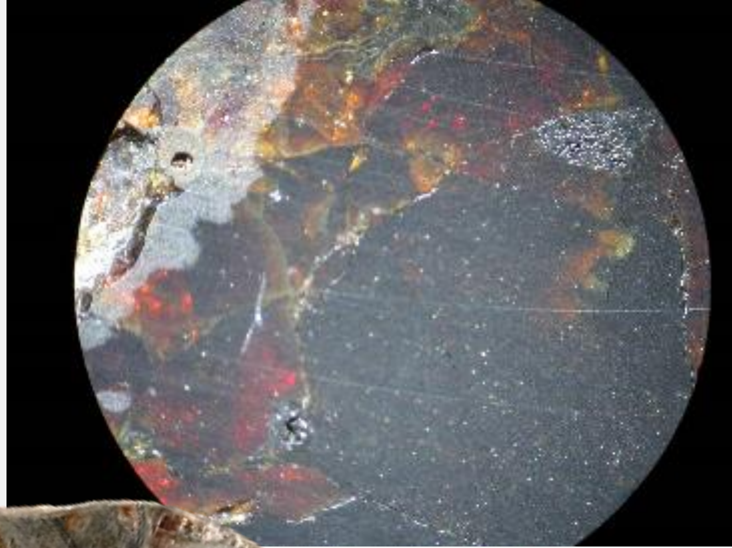
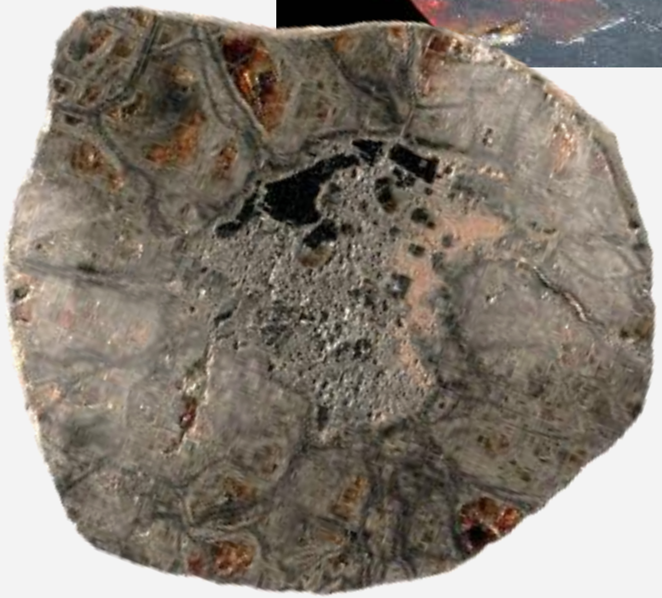
Unusual garnet megacryst with a partly crystallized melt inclusion from Cenozoic alkali basalts of the Shavaryn Tsaram paleovolcano (Mongolia)





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The ultramafic inclusions and megacrysts in the intraplate alkali basalts are one of the most important information sources about the composition of substance of the Earth's mantle and the lower part of lithosphere.

Figure 1. Some variates of ultrabasic inclusions founded in the Shavaryn Tsaram cone (Mongolia), including co-called green and black series.
Green series samples: A- spinel lherzolite in porous basalt, B- spinel websterite and lherzolite contact, C- pyroxenite, D – olivine websterite, E- garnet lherzolite, surrounded by basalt, F- garnet and spinel- bearing websterite.
Black series representatives: J- hornblende pyroxenite, H- pyroxene hornblendite, I- thin section of previous sample (analyzer off/on).

SOME MEGACRYSTS OF THE SHAVARYN TSARAM PALEOVOLCANO

In order to shed light on this problem, alkali basalts of Shavaryn Tsaram paleovolcano (Mongolia), which are extraordinarily enriched with the different types of megacrysts and ultrabasic inclusions, have been studied. Megacrysts are represented by large monocrystals of feldspar, clinopyroxene, olivine, hornblende, spinel, ilmenite, and biotite.

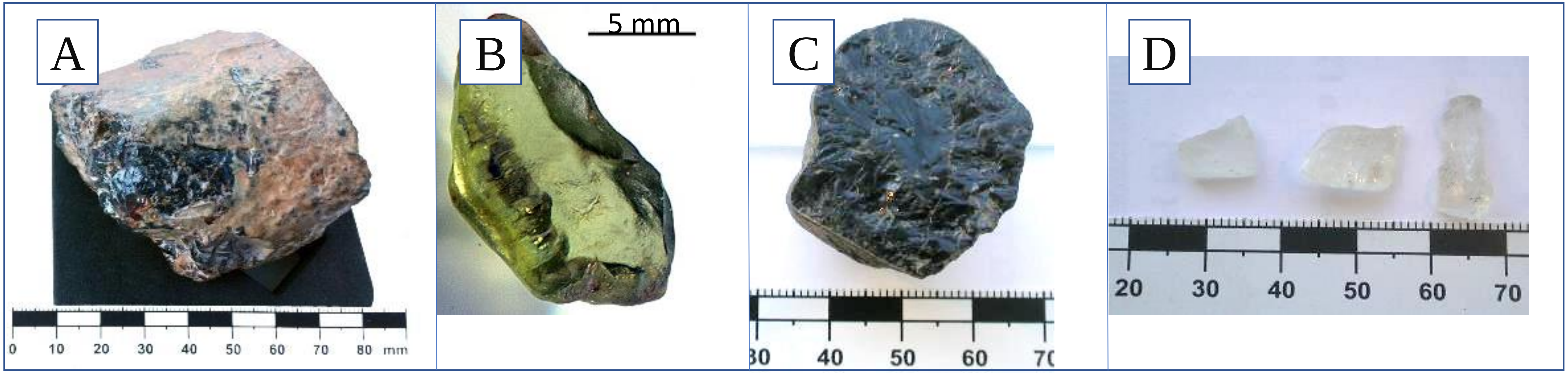


Figure 2. Some minerals of megacryst assemblage from basalts and pyroclastics of the Shavaryn Tsaram:

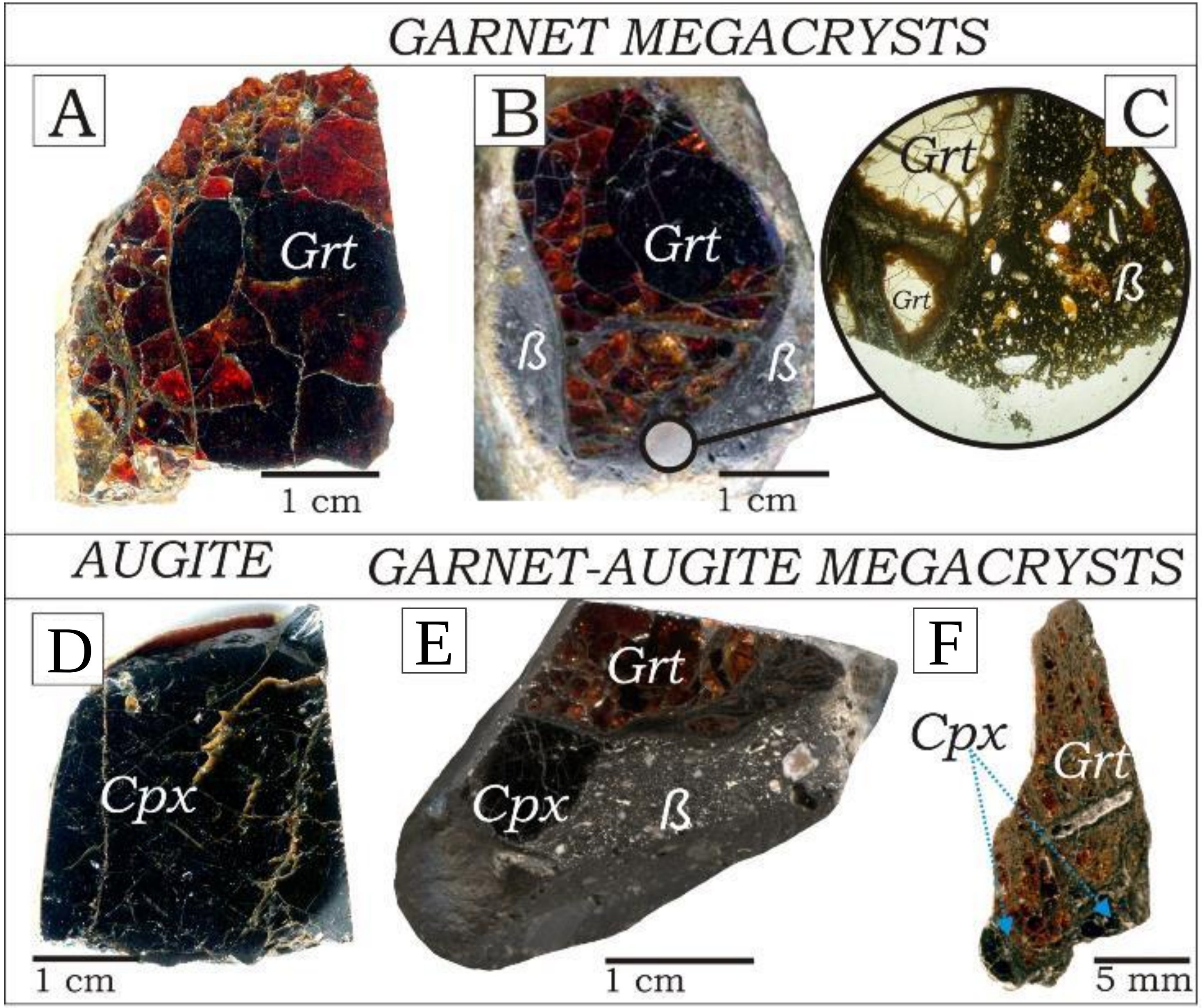
A- gigantic garnet monocrystal in the quenching coat,

B- olivine,

C- cleavage surface of clinopyroxene in the quenching coat,

D- single crystals of sanidine.

SOME MEGACRYSTS OF THE SHAVARYN TSARAM PALEOVOLCANO



We chose garnet-bearing variates in order to assess P-T conditions of megacrysts formation. Garnet megacrysts occur both as single crystals and as garnet-clinopyroxene intergrowths.

Figure 3. Garnet and clinopyroxene megacrysts from the Shavaryn Tsaram volcano.

A-fractured garnet megacryst,
B- garnet megacryst captured by basalts,
C- thin section of the previous sample,
D- single clinopyroxene megacryst,
E- garnet and clinopyroxene intergrowth trapped by basalts,
F- garnet and clinopyroxene intergrowth.

GEOLOGICAL SETTING

48°02'55.3"N 100°09'43.9"E

The Shavaryn Tsaram volcano is positioned on the peripheral part of the Tariat volcanic field and often associated with the spreading lithosphere of the Baikal rift system [Rasskazov et al., 2010].

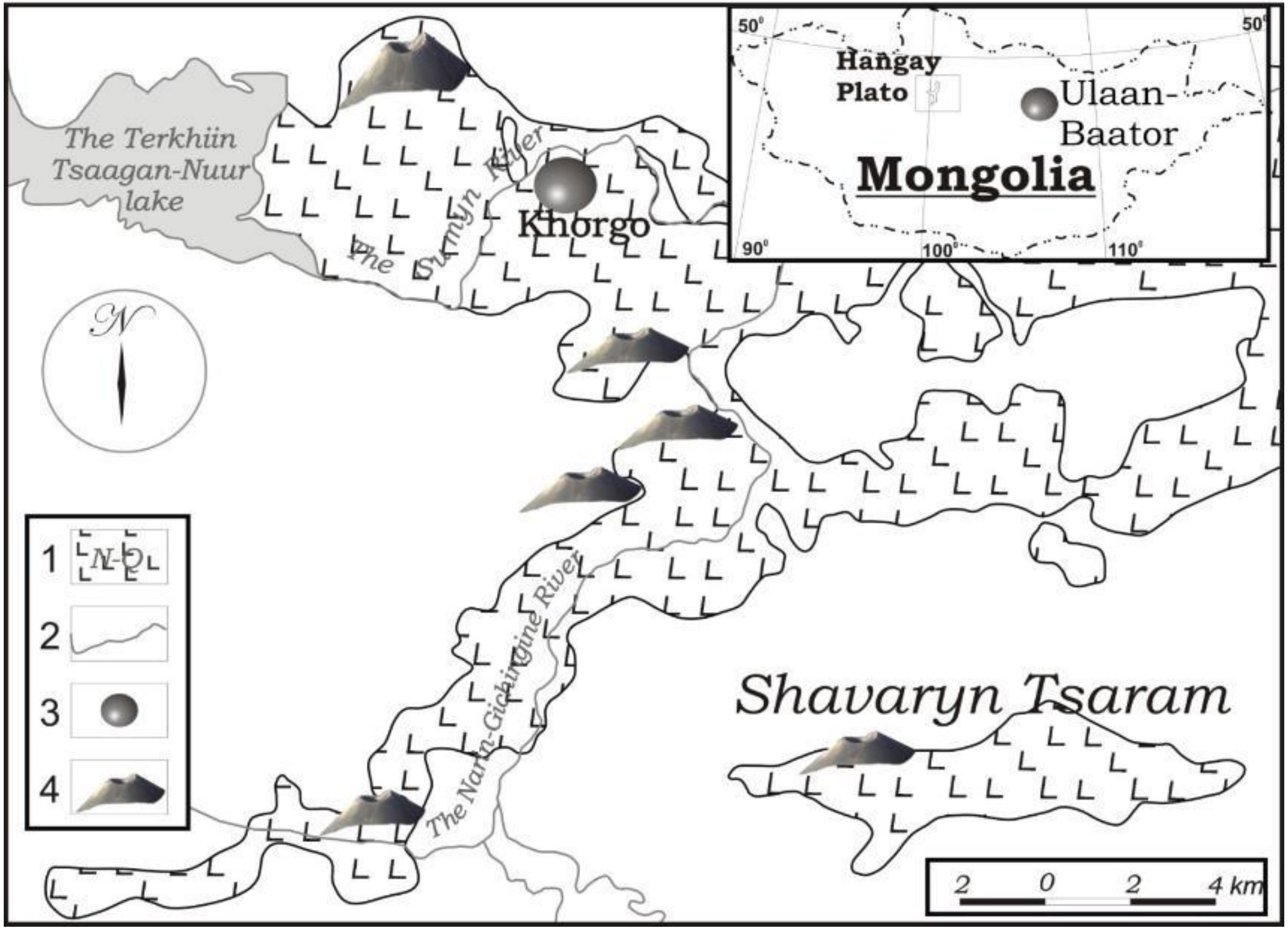
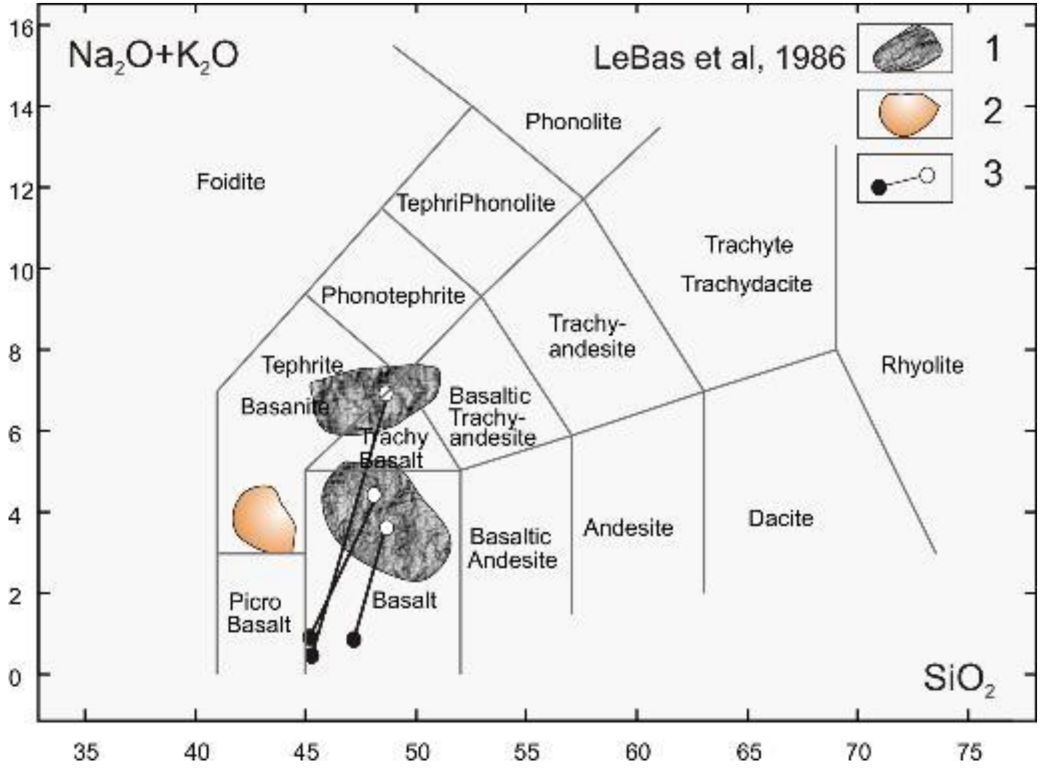


Figure 4. Geological sketch of the Hangay plateau (Tariat, Mongolia):

1- Cenozoic basaltic rocks,
2- watercourses and lakes,
3- localities,
4- cones.
After (Genshaft, Saltykovskii 1990), with modification.

BASLTS and PYROCLASTICS

The nekk of the volcano as well as the adjacent lava flows of the Hangay plateau is composed mostly of a porous (to pumice) basalts [Lesnov et al., 2009]. Basalts, scoria, and pyroclastics are rich in enclosed megacrysts and deep-seated xenoliths [Ionov, 2007; Ionov, 1994; Genschaft, Saltykovsky, 1990; Kepezhinskas, 1979]. The age of the volcano's lava flows, determined by different methods, vary from 1.2 to 0.42 million years [Vysotsky et al., 2011; Krivonosova et al., 2005; Agafonov et al., 1977].



The majority of the megacrysts and ultrabasites - containing rocks are nepheline-leucite basanites and tephrites [Lesnov et al., 2009; Ionov, 2007; Ionov, 1994].

Figure 5. Basalts, ultrabasites and pyroclastics of the Shavaryn Tsaram volcano on TAS diagram.

1- basalts and pyroclastics,
2- ultrabasic rocks of 'black series',
3- co-existing basalts and 'green series' ultrabasic rocks.

RESEARCH METHODS

Mineralogy of basalts was studied in the Analytical Center of FEGI FEB RAS with microprobe JXA-8100 (Jeol, Japan), figure 6. Spot concentrations of the trace elements were determined with secondary ion mass spectrometry in the Yaroslavl Branch of the RAS (Cameca IMS-4F). Whole rock analysis of chemical elements and trace elements in the rocks was accomplished in the Analytical Center of FEGI FEB RAS with ICP-MS Agilent 7500c (Agilent Techn., USA), figure 7. Concentrations of the oxygen isotopes analysis were detected with MAT 253 isotope mass spectrometer (Thermo Scientific, Germany) in the Stable isotope laboratory of the FEGI FEB RAS Analytical Center of the FEGI FEB RAS. The texture and internal structure of the sample was studied with an X-RAY installation "SkyScan 1272" (Bruker microCT).

Figure. 6 Microanalyzer (JXA-8100, Jeol, Japan)

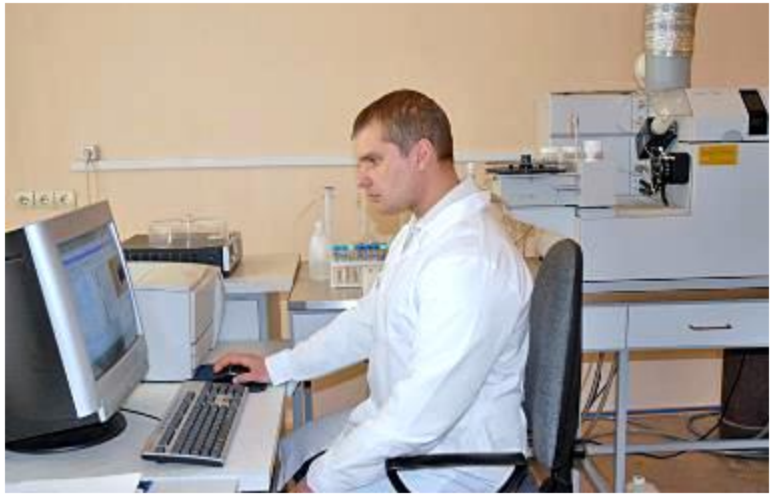


Figure 7. Mass spectrometer (Agilent 7500s spectrometer, USA).

GARNET MEGACRYST WITH MULTIPHASE INCLUSION

Unusual finding of a large (about 5 cm in diameter) garnet megacryst with an aggregate in its core has been made. The aggregate is complex and consists of porous glass and crystallized minerals, such as biotite, orthopyroxene, spinel, clinopyroxene, olivine, and ilmenite. The questions arise - Was it a captured substance of the Earth's interior? Or it was a zone of partial melting inside the garnet megacryst, similar with 'melt pockets' inside ultrabasic inclusions?

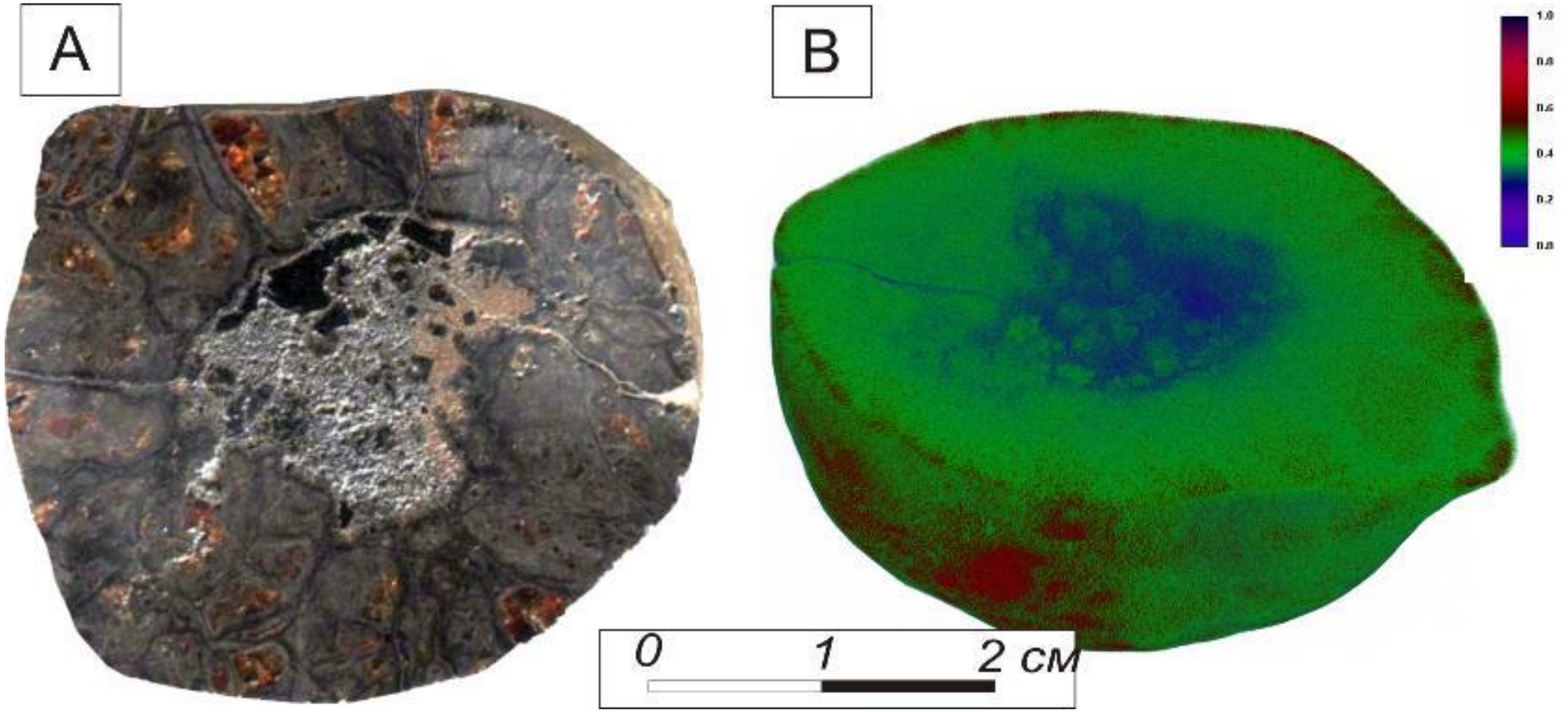


Figure 8.

A- the compound aggregate in the core of the garnet megacryst,

B- 3D X-Ray image of the sample structure. The color scale reflects the density: red color corresponds to the densest, quenching surface areas; the least dense porous glass is blue-colored.

GARNETS OF SHAVARYN TSARAM

The garnet from megacrysts and the garnet from garnet-augite aggregates is similar in composition, containing less pyropic component than the garnet from ultrabasic xenoliths (Fig. 9). It is noteworthy that the chemical composition of garnet megacrysts captured by alkali basalts all over the world is surprisingly constant (Fig. 9).

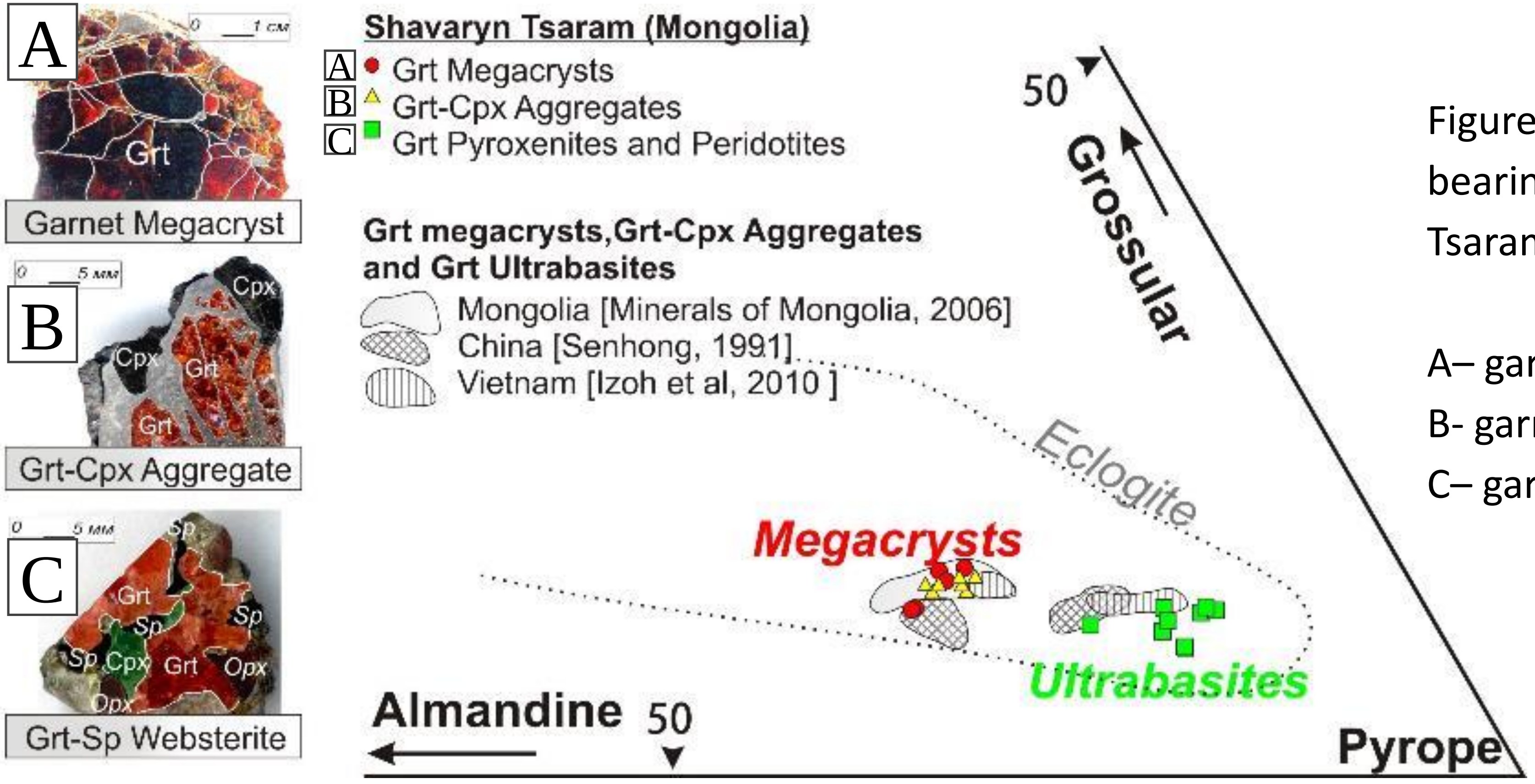


Figure 9. Various types of the garnet-bearing inclusions from the Shavaryn-Tsaram alkali basalts:

A– garnet megacrysts,

B- garnet-clinopyroxene aggregates,

C– garnet-bearing ultrabasic rocks.

GARNETS OF SHAVARYN TSARAM

The primary garnet belongs to the pyralspite group with **$Prp_{56.48}Alm_{29.27}Grs_{13.39}Sps_{0.87}$** (Grt1, Fig. 9, Table1). A garnet symplectite which, in fact, is already a collage of microcrystals of orthopyroxene, spinel, olivine, plagioclase and clinopyroxene, has the same composition (Sympl, Table 1). It can be seen from the figure 10 that the major element concentrations remain unchanged in both red garnet and gray symplectite; so, symplectite, analyzed with a wide beam, is similar the primary garnet in chemical composition (Grt_1, Sympl, Table1).

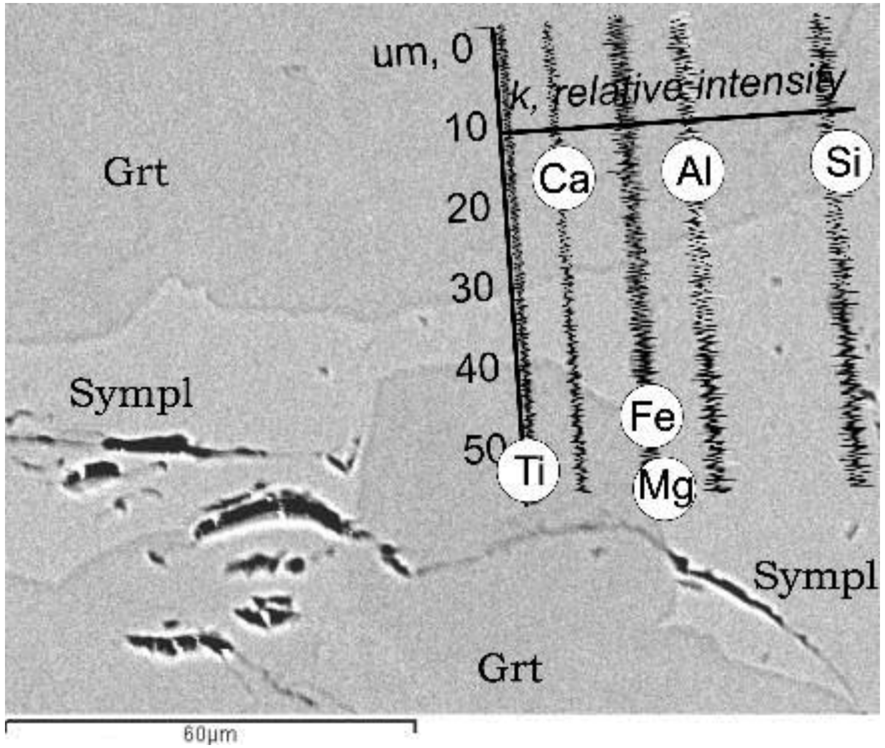


Figure 10. Major components variations (Si, Al, Fe, Mg, Ca, Ti) in the garnet megacryst. Profile across the symplectite-containing zone. BSE image, JXA-8100 (Jeol).

Hereinafter: Alm- almandine, Bt- biotite, Cpx- clinopyroxene, En- enstatite, Fs- ferrosilite, Grs- grossular, Grt- garnet, Hd– hedenbergite, Ilm- ilmenite, Ol- olivine, Opx- orthopyroxene, Pl- plagioclase, Prp- pyrope, Spl- spinel, Sps- spessartine, Wo- wollastonite [Whitney, Evans, 2010]. Cts- tschermacite, Glass- volcanic glass, Mica– mica, Sympl- symplectite, ß- basalts, *f*- ferruginosity ($Fe_{total}/(Fe_{total}+Mg)$), REE- rear earth elements.

GARNET MEGACRYST WITH MULTIPHASE INCLUSION

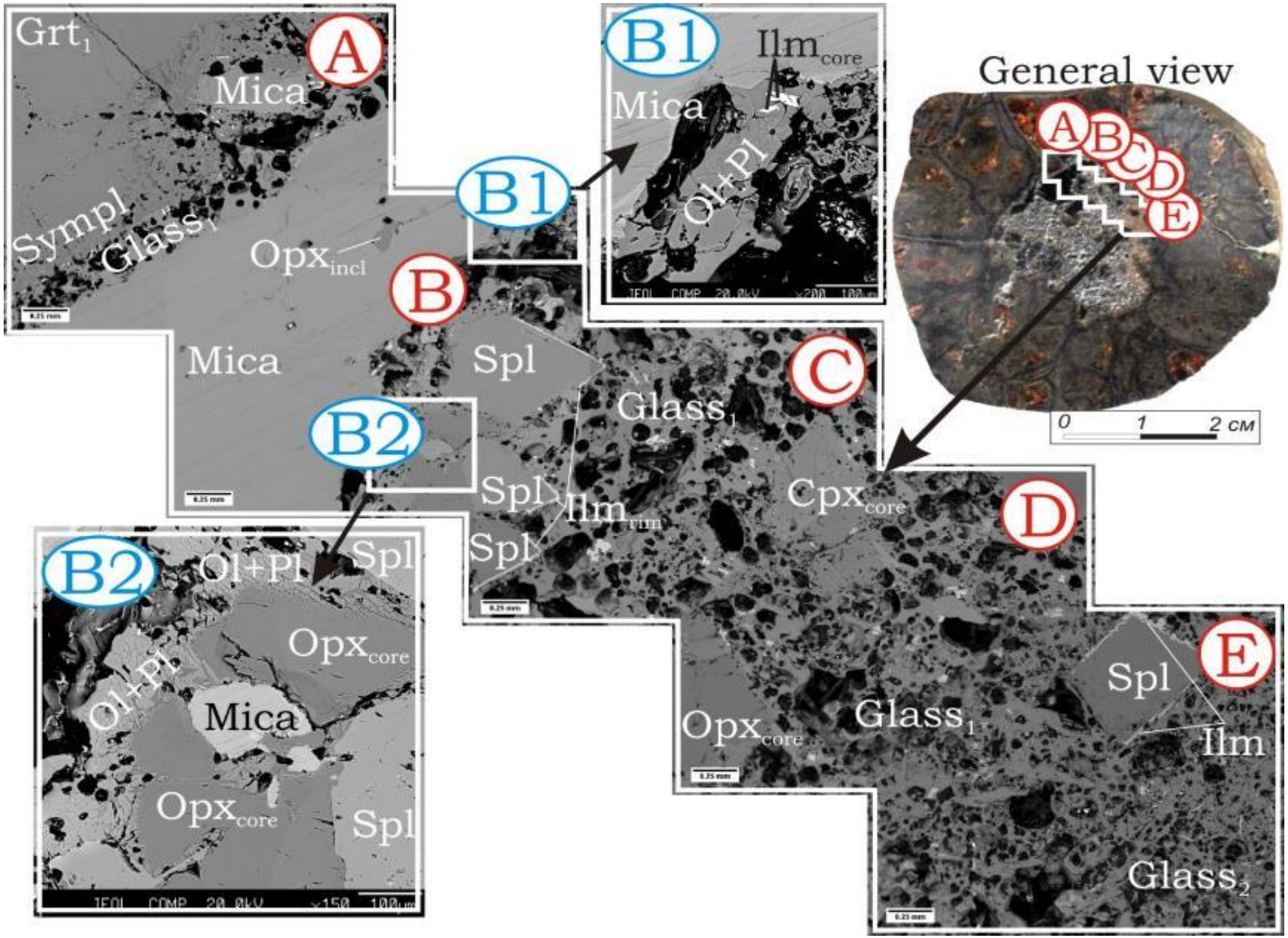


Figure 11. The internal structure of the multiphase inclusion in the garnet megacryst.

A zone, in the upper-left corner, demonstrates the fresh garnet, which is gradually replacing by a symplectite (Sympl, Table1, Fig. 11A).

B zone illustrates presence of the large idiomorphic crystals of a very rare type of mica – highly titanium and magnesium biotite (Table 1).

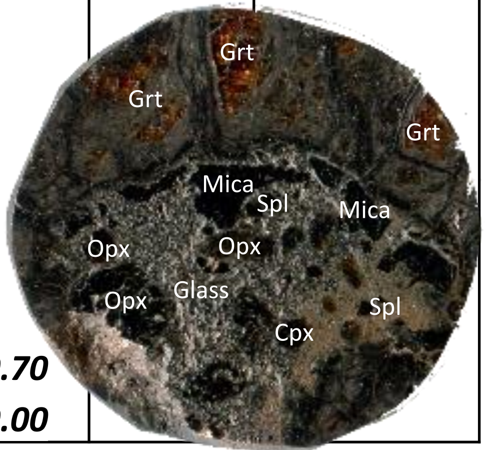
Orthopyroxene (hypersthene, f =0.19) forms large crystals with indistinct boundaries, and in some cases, it gradually turns into volcanic glass (Fig. 11 C, D). Wormlike olivine grains could be observed on the outer border of some orthopyroxene crystals (Fig.11, inserts B1 and B2). The gaps between olivine grains are filled with plagioclase.

Clinopyroxenes also have indistinct grain outlines, with transitions to glass. They belong to augite (f =0.25) and are characterized by high Al content and impurity of Na and Ti (Cpx_{core}, Table 1).

Spinel of multiphase inclusion is represented by idiomorphic octahedral crystals, high in aluminum, with equal amounts of iron and magnesium (Spl, Table 1). Spinel crystals are chemically homogeneous, but near to the border with glass, they are turned into a rim of ilmenite (Ilm_{rim}, Table 1). Small (20-30um) grains of ilmenite (similar in composition to those which associated with spinel) were found among the crystallized phases of the multiphase inclusion (Ilm_{core}, Table 1).

Table1. Chemical composition of the garnet megacryst, Grt symplectite, crystallization products of the multiphase inclusion, along with associated glass, tephrite, and biotite megacrysts

	Crt_1	Sympl	Cpx_1	$Mica_1$	$Mica_{core}$	Opx_{core}	Cpx_{core}	Spl_{core}	Ilm_{core}	Ol	Ilm_{rim}	Glass	Pyroclastics
	Primary	Symplectite	Primary	Megacryst	Minerals of the multiple-phase inclusion inside the garnet megacryst							Glass	Tephrite
On Fig. 7	A	A	Out of the area	Out of the area	A, B,B1,2	B2, C,D	C	B, B2, E	B1	B2	B, B2, E	B2,C,D,E	Out of the area
SiO_2	40.92	41.01	49.27	35.15	36.82	51.89	49.39	0.00	0.00	38.86	0.00	47.67	47.54
TiO_2	0.48	0.73	1.84	11.32	11.04	0.58	1.70	0.52	51.31	0.00	51.40	4.90	2.40
Al_2O_3	23.10	22.89	9.08	14.89	15.87	6.51	8.41	63.07	0.58	0.00	0.66	18.33	15.62
FeO	14.40	13.87	9.30	12.51	11.95	11.15	8.33	19.61	37.82	20.57	37.31	10.07	11.53
MnO	0.42	0.38	0.00	0.05	0.00	0.25	0.00	0.30	0.46	0.35	0.00	0.00	0.15
MgO	15.59	15.02	11.64	12.07	12.69	26.78	14.22	16.44	9.00	38.68	8.75	3.62	6.04
CaO	5.14	4.93	16.59	0.83	0.00	1.71	16.20	0.00	0.00	0.25	0.00	8.61	6.61
Na_2O	0.00	0.00	2.29	0.48	0.00	0.00	1.38	0.00	0.00	0.00	0.00	1.44	5.53
K_2O	0.00	0.00	0.00	9.06	9.63	0.00	0.00	0.00	0.00	0.00	0.00	4.62	3.21
Total	**100.05**	**98.83**	**100.01**	**99.94**	**98.00**	**98.87**	**99.63**	**99.94**	**99.17**	**98.71**	**98.12**	**99.26**	**98.63**
Prp	*56.48*	*56.55*											
Alm	*29.27*	*29.30*											
Sps	*0.87*	*0.81*											
Grs	*13.39*	*13.34*											
En			*40.44*			*77.48*	*46.57*						
Fs			*18.13*			*18.59*	*15.30*						
Wo			*41.43*			*3.57*	*38.13*						
f	***0.34***	***0.34***	***0.28***	***0.41***	***0.35***	***0.19***	***0.25***	***0.40***	***0.70***	***0.23***	***0.70***		
Ca	***0.13***	***0.13***	***0.43***	***0.03***	***0.00***	***0.04***	***0.38***	***0.00***	***0.00***	***0.00***	***0.00***		



GEOCHEMICAL EVIDENCE

The distribution of REE in some minerals and phases of the sample, as well as distributions of the typical associated rocks: lherzolite, basalt, and pyroclastics were studied point-by-point, using ion probe.

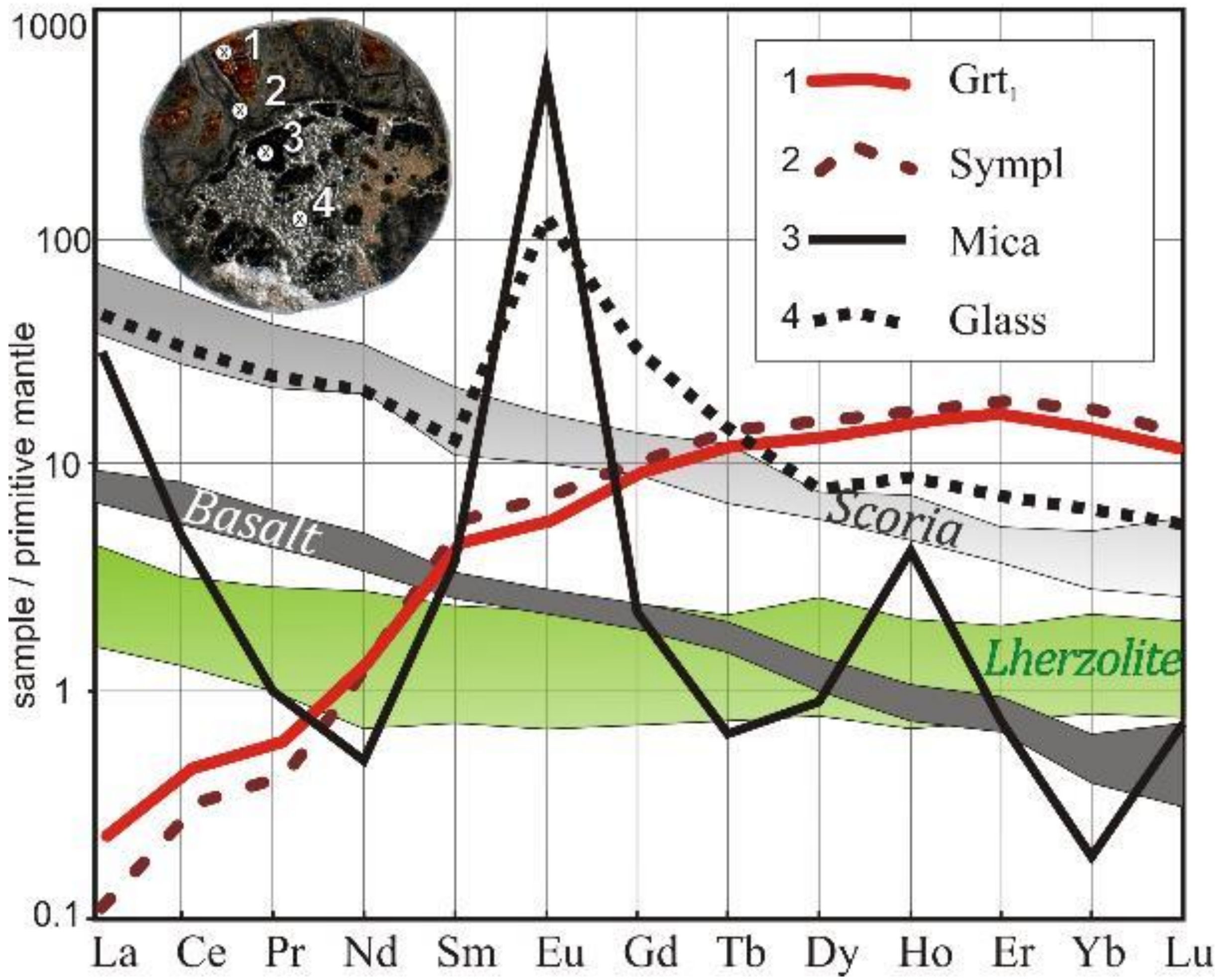


Figure 12. REE in some minerals and aggregates of the multiphase inclusion and associated rocks of the Shavaryn Tsaram:
1- garnet, 2- symplectite, 3- biotite, 4- glass;
light grey field – scoria and pyroclastics, dark grey field –basalts, green field – salic inclusions (lherzolite).

Table 2. The trace element composition of the garnet megacryst, garnet symplectite, biotite and glass from the multiphase inclusion as well as associated basalts, pyroclastics and garnet-bearing xenoliths

	 Grt_1	 Sympl	 Grt_{lherz}	 Mica	 Glass	 Basalt	 Tephrite	 Grt Lherz
Ti	5026	4217	1345	86929	296884	н/а	н/а	н/а
V	236	207	153	810	1790	105	97	83
Ni	592	484	201	9584	39423	39	91	1794
Zr	77	75	34	13	328	265	250	24
Hf	5.04	4.39	1.75	2.6	8.47	6.18	5.25	0.58
Ta	1.56	1.2	0.6	3.01	5.05	2.55	2.22	0.17
Nb	0.5	0.39	0.28	14.21	117	39	35	2.06
Rb	2.09	1.46	5.196	488	553	26	39	1.74
Ba	0.49	0.59	0.19	7975	2193	551	830	53
Sr	0.87	0.58	0.45	388	696	854	906	54
Y	77	67	36	2.1	30	15.83	25	4.88
Cs	0	0.01	0.01	0.94	0.42	0.22	0.98	0
La	0.04	0.15	0.02	22	30	27.53	49.4	2.92
Ce	0.56	0.81	0.32	6.77	58	50.7	90.65	5.17
Pr	0.11	0.17	0.03	0.24	6.22	6.77	10.82	0.69
Nd	1.78	1.89	0.48	0.69	29	29.54	42.82	3.66
Sm	2.39	2.08	0.66	2.11	5.82	5.28	8.68	0.99
Eu	1.22	0.99	0.4	96	21	2.33	2.62	0.35
Gd	6.01	5.62	2.19	1.34	18	5.91	7.92	0.93
Tb	1.49	1.33	0.59	0.07	1.57	0.74	1.27	0.17
Dy	11.16	9.92	4.92	0.7	5.71	4.53	5.24	1.13
Ho	2.61	2.5	1.26	0.68	1.44	0.82	1.15	0.24
Er	8.82	8.08	4.82	0.4	3.51	1.91	2.46	0.53
Yb	8.38	7.32	5.016	0.1	3.12	1.29	2.4	0.41
Lu	0.96	0.9	0.53	0.05	0.38	0.2	0.41	0.08
Σ REE	46	42	21	131	184	138	226	17
Method	Ion probe	Ion probe	Ion probe	Ion probe	Ion probe	ICP-MS	ICP-MS	ICP-MS

- Grt_{1}- garnet megacryst, Sympl- symplectite, Grt_{lherz}- garnet of the garnet-bearing xenoliths in basalts, Mica- biotite, Glass- glass, Basalt- basalt, Tephrite- pyroclastics и Grt Lherz - garnet-bearing xenoliths in basalts.
- The minerals and the glass has been studied using precise secondary ion spectrometry method on Cameca IMS–4F in the Yaroslavl division of the Institute of Physics and Technology, Russian Academy of Sciences.
- The whole rock trace element composition has been determined on Agilent 7500c spectrometer (Agilent Techn., USA) in the Analytical center of the Far East Geological Institute, Russian Academy of Sciences

ISOTOPIC EVIDENCE

The oxygen isotope analysis of the primary garnet and biotite, which crystallized inside the melt inclusion, showed that the values of $\delta^{18}O_{VSMOW}$ in them are equal and accounted for 5.30 ±0.1 µm. This value corresponds to the typical 'mantle' amount $\delta^{18}O_{VSMOW}$= +5.37 ±0.36 µm in peridotite garnet, [Mattey et al., 1994].

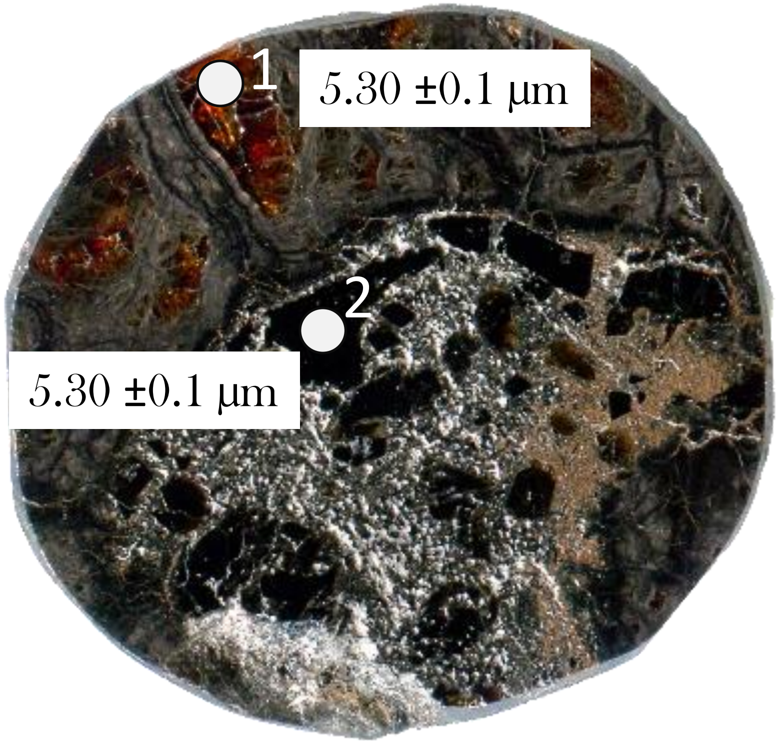


Figure 13. Isotopic composition $\delta^{18}O_{VSMOW}$ of the garnet megacryst which contains the multiphase inclusion: 1- garnet, 2- biotite.

PHYSICAL AND CHEMICAL MODELING

In order to evaluate stages of garnet megacryst evolution, WinTWQ 2.32 thermodynamic modeling [Berman, 2007] was used, due to relatively low (for deep-seated inclusion) pressure and high temperatures of assemblage closure [Berman, 2007]. The program calculated the minals and drew the equilibrium curves. The intersection of these curves was taken as the calculated equilibrium parameters.

The chemical composition of minerals was an input data. For determination assemblages which are in equilibrium (quasi-equilibrium) and which could be used for further calculations, careful petrographic analysis and calculation of crystal formulas were carried out.

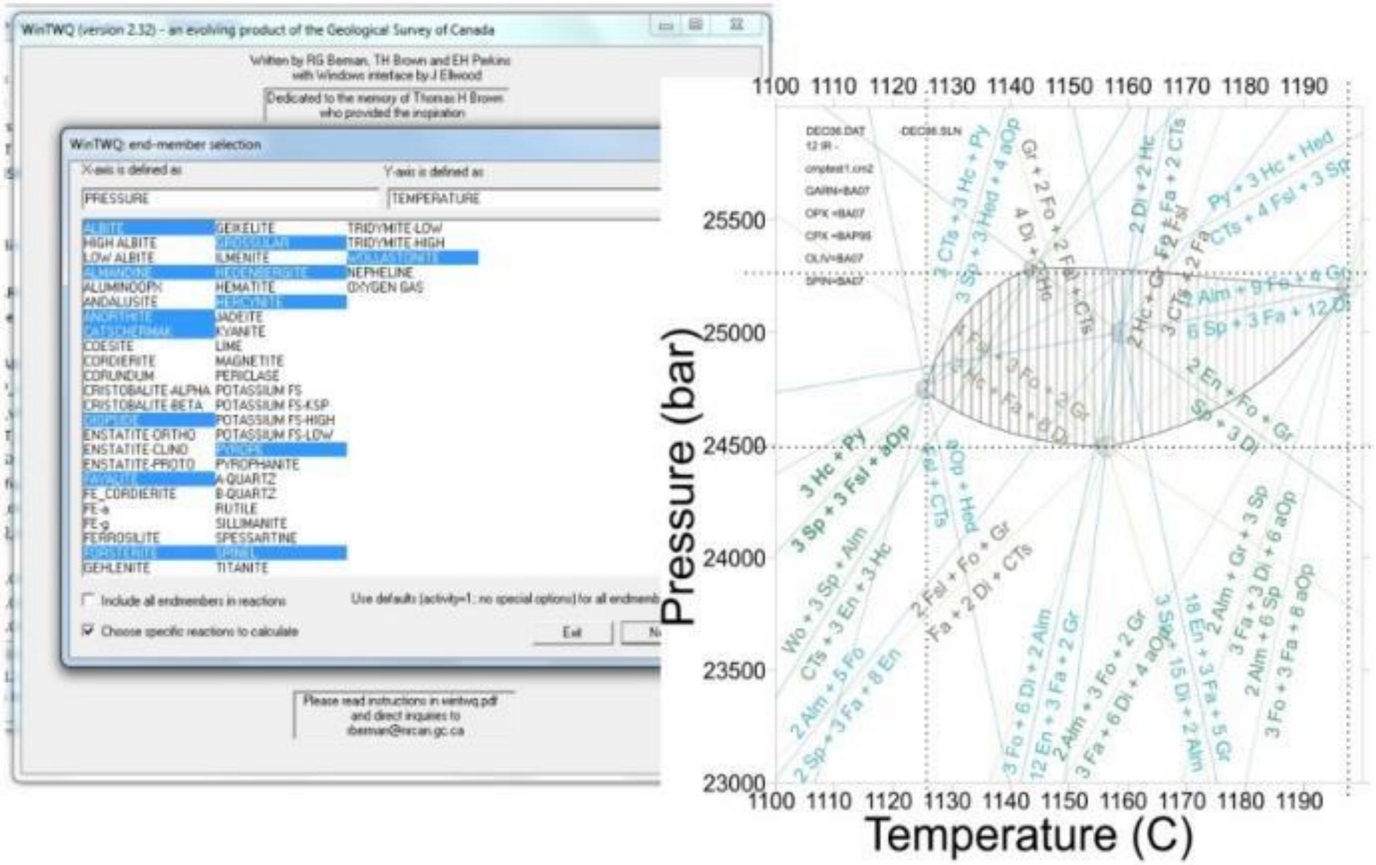


Figure 14. WinTWQ 2.32 interface and example of data obtained (garnet-bearing ultrabasic inclusion in Shavaryn Tsaram basalts with multiple equilibrium).

PHYSICAL AND CHEMICAL MODELING

1. "Initial association" modeling.

Since a tiny augite was found on the external side (under the quenching surface) of the garnet megacryst, the object under study is a complex garnet-clinopyroxene intergrowth (Table 1, Cpx_1). That is why it was possible to obtain the data about the conditions when an equilibrium between the garnet, clinopyroxene and the basalt was established. Temperatures ranged from 1125 to 1150^{0}C at a pressure of 0.75-0.8 GPa. Similarly, temperatures and pressures were calculated for other samples of Shavaryn Tsaram (T 1100 - 1200^{0}C, and P 0.8 - 1.1 Gpa).

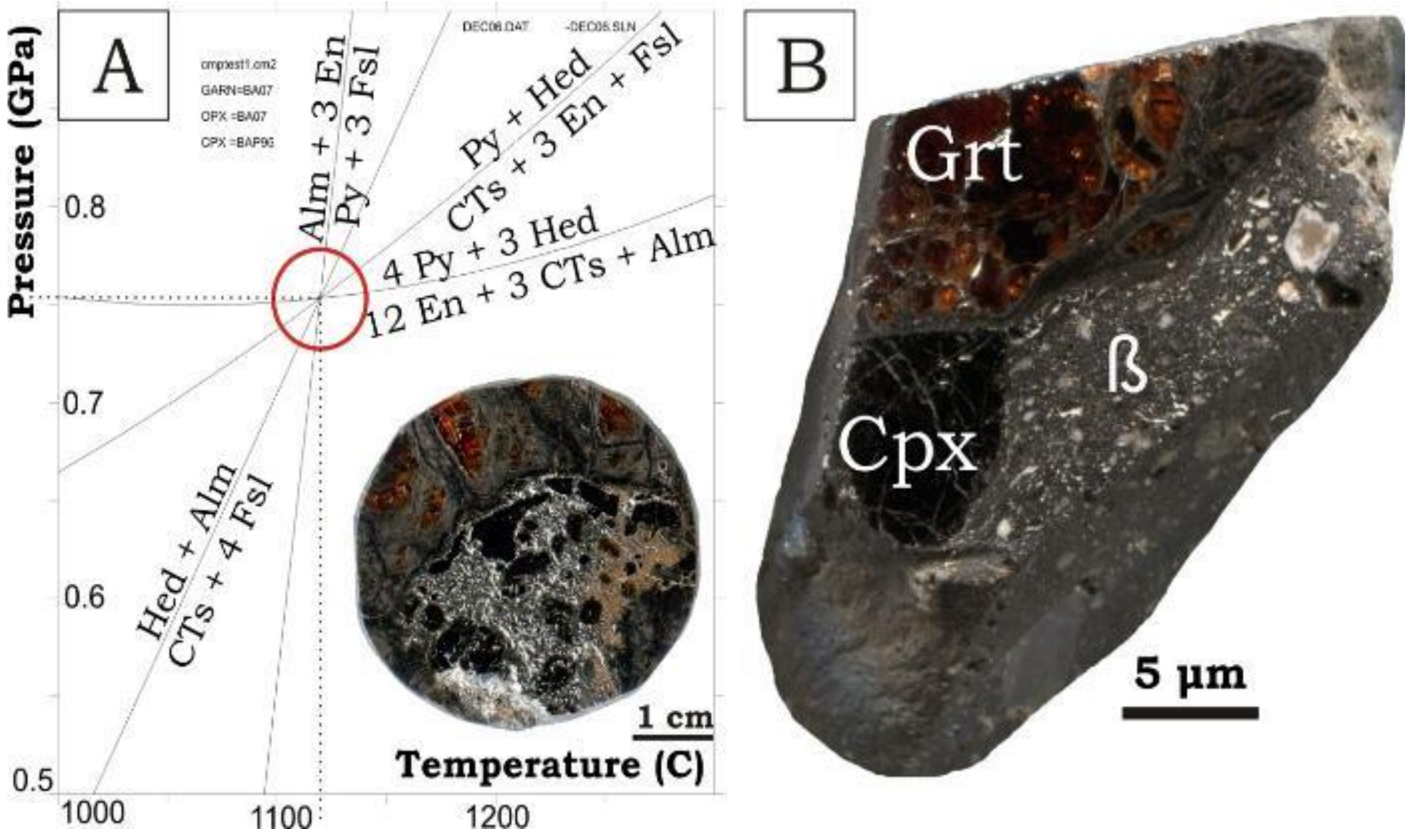


Figure 15.

A- The equilibrium curves for the garnet megacryst with the multiphase inclusion.

B- Grt-Cpx aggregate captured by alkali basalt.

PHYSICAL AND CHEMICAL MODELING

2. Modeling of minerals crystallized in the core of the melt pocket.

Several areas were selected for modeling. For example, the lowest values (T 980^0C and P 0.6 GPa) were obtained for the orthopyroxene-spinel-olivine paragenesis (Fig. 16 A). Overall, for minerals which crystallized in melt pocket, model temperature varied within $980\text{-}1100^0$C, and model pressure was 0.6-1 GPa.

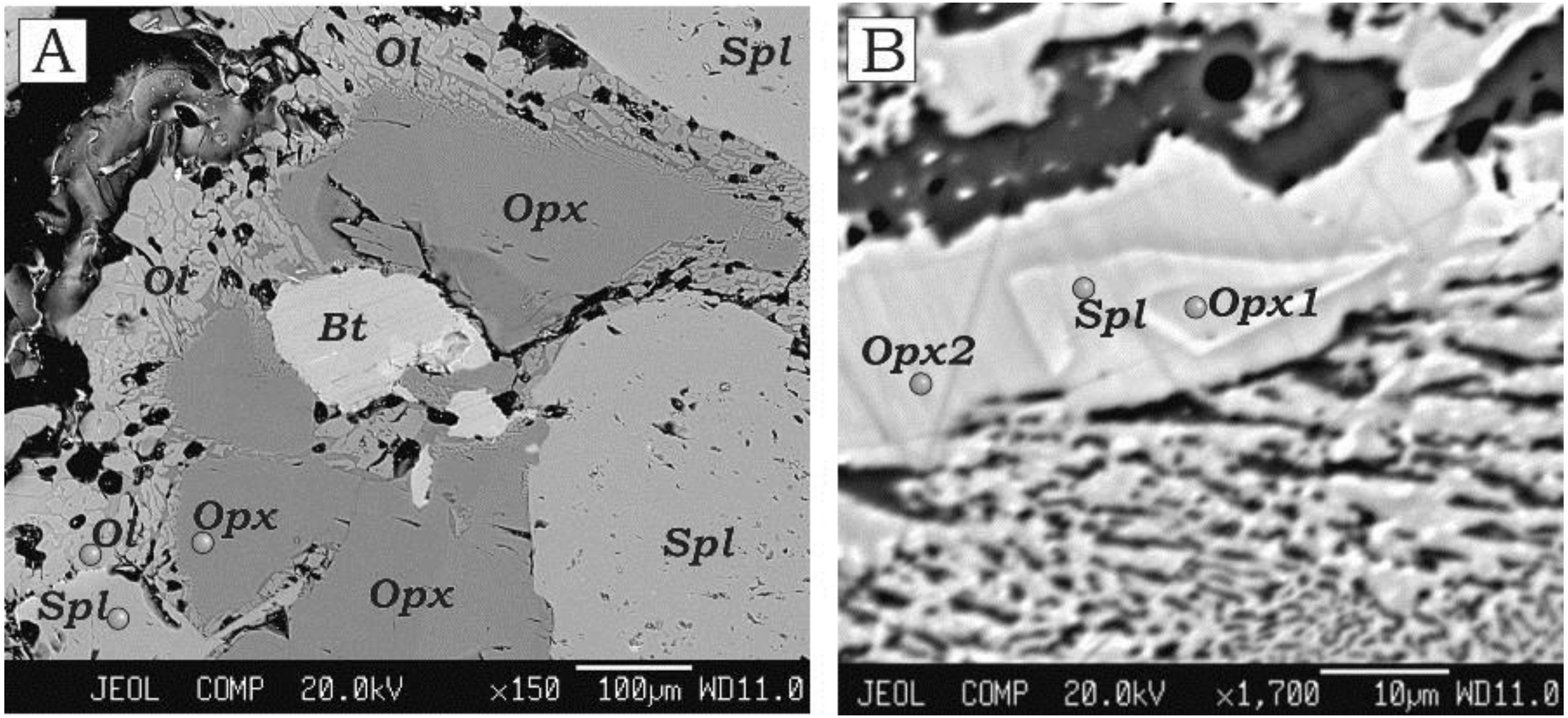
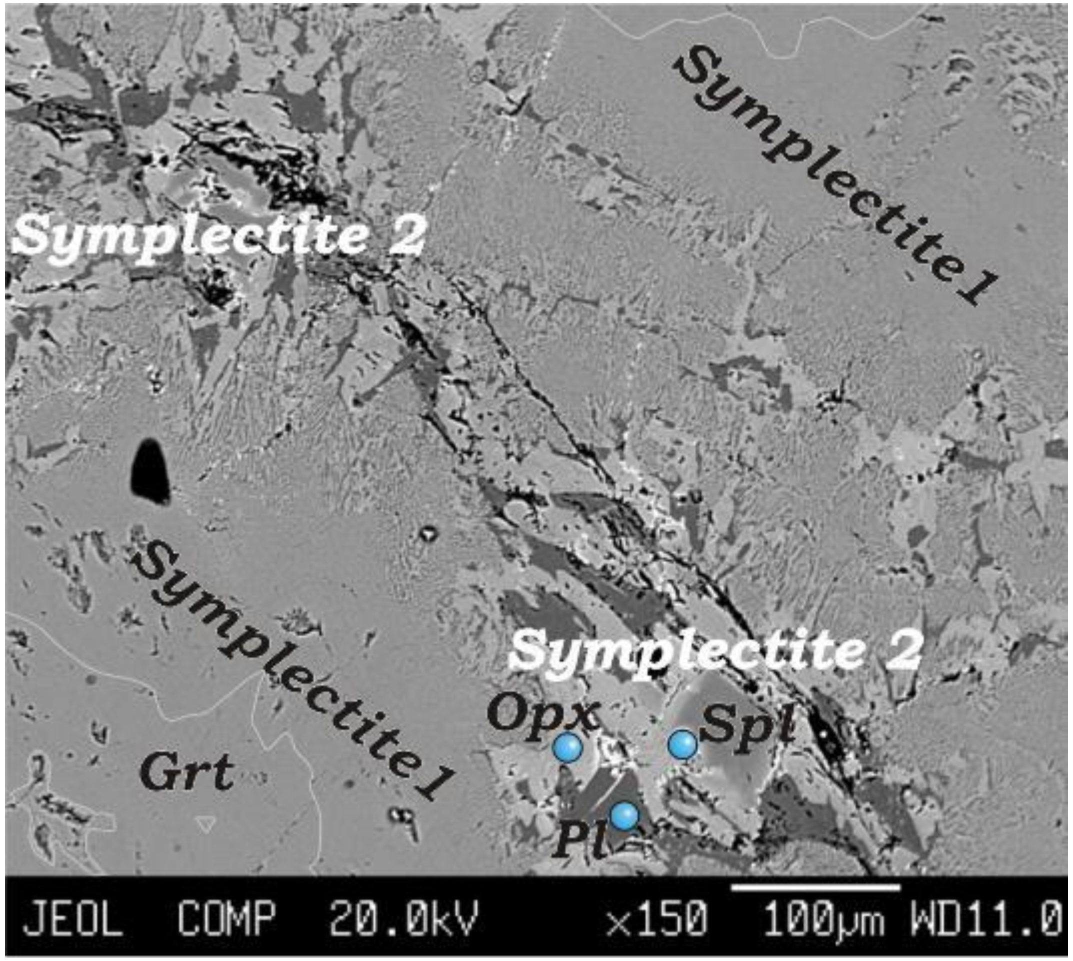


Figure 16. A- The minerals crystallized in the core of the inclusion, B- containing a double inclusion orthopyroxene.

PHYSICAL AND CHEMICAL MODELING

3. The minerals of symplectite assemblage modeling.

On their way to the earth's surface, megacrysts went through several metastable states. Since these are isomorphic series (for instance, almandine-pyrope-grossular-spessartine, wollastonite-enstatite-ferrosilite), a chemical components redistribution takes place.



Firstly, a primary garnet megacryst turn into a coarse grain mass; further, the newly formed minerals could reach a visible size. A large part of the sample with multiphase inclusion was transformed this way. The symplectite assemblage is represented by orthopyroxene, spinel, and plagioclase (Grt→Ops+Sp+Pl). Calculations showed that the formation of the minerals of this assemblage inside studied garnets of the Shavaryn-Tsaram paleovolcano occurred in a wide range of temperatures (850 to 930^{0}C) and pressures from (0.55 to 0.70 GPa).

Figure 17. A- The minerals crystallized in the core of the inclusion, B- containing a double inclusion orthopyroxene.

DISCUSSION OF THE RESULTS OBTAINED

Generally, there are **two opposite opinions** in respect of the megacrysts genesis. The **first hypothesis** suggests that megacrysts are xenoliths of giant-grained eclogite-like (syenite-like rocks); they initially located in the upper mantle (or in low horizons of the earth's crust) and were captured by basaltic melt [Righter, Carmichael, 1993; Barns, Roeder, 2001; Shulze, 1987]. **The second hypothesis**, the theory of mantle metasomatism, consider megacrysts as products of basalt-related fluidized melts (or fluids) which crystallized at high pressure in middle part of the Earth's crust [Irving and Frey, 1986; Harte et al., 1986; Sharkov et al., 2017 and others].

However, the data we obtained **does not fit entirely** into any of the existing hypotheses.

On the one hand, the undoubted disequilibrium between the megacrysts and host basalts, presence of garnet-pyroxene intergrowths, symplectitic alteration of garnet, as well as a significant difference in the chemical and microelement composition, support the first hypothesis. Moreover, the concentrations of oxygen isotopes in garnet megacryst was the same as in garnet peridotites [Mattey et al., 1994], which may indicate the affinity of megacrysts and garnet-containing xenoliths.

On the other hand, influence of the fluid phase during the megacrysts crystallization is evident. There was, obviously, supply of the water-bearing phase which is reflected in the formation of water–containing glass and mica. In addition, the large size of the crystals, their homogeneity, transparency, along with the absence of micro-inclusions in the "primary megacrysts" and in unchanged sections of transformed garnet megacrysts can indicate their growth from a homogeneous solution, with full immersion of the growing crystal [Zhabin, Grigoriev, 1975]. Another probable evidence in favor of this hypothesis is unusually low temperature and pressure of the garnet formation, since in the "classical, eclogitic' case, the equilibrium TP will be much higher.

CONCLUSIONS

1. The studied megacryst with the melt pocket could not be formed in basalts 'in situ' but was captured at conditions of P=0.75-0.8 GPa; T=1125-1150^{0}C, which probably corresponds to the lower horizons of the Earth's crust. At the same time, megacrysts of Shavaryn Tsaram widely co-exist with ultrabasic xenoliths, including garnet-containing ones. Nevertheless, measured oxygen isotope concentrations in the garnets of these associations are the same, indicating a common, probably, mantle source.

2. The multiphase inclusion in the garnet megacryst under consideration served as a trap for the Earth's deep substance. The formation of a multiphase inclusion/melt pocket was not only due to the garnet melting, as due to the bringing material. Fractional crystallization inside the garnet megacryst (at P=0.6-1 Gpa; T=980-1100^{0}C) led to the growth of idiomorphic crystals of biotite and spinel. Ortho-and clinopyroxene, and, with high probability, ilmenite crystallized from a melt with the composition close to the amorphous phase (glass) of melt pocket.

3. The symplectite assemblage in the garnet megacryst formed a result of decompression, according to the Grt→Ops+Sp+Pl scheme, at P=0.55-0.7 Gpa, T= 850-930^{0}C. This reaction was due to the garnet own substance.

4. The parental melts, from which the Shavaryn Tsaram megacrysts crystallized, was saturated with water and fluids. This factor determines low melt viscosity and the explosive way of paleovolcano discharge.