Coexisting Zoned Garnets and Clinopyroxenes from Mafic Eclogites of the Maksyutov Complex, South Ural Mountains, Russia

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Abstract. We microprobed the compositions and chemical heterogeneities of garnets and clinopyroxenes, the most important rock-forming minerals of eclogites of the Maksyutov complex. Using the Grt-Cpx maximum-T geothermometer (Powell, 1985) and the Pl-Cpx-Qz minimum-P geobarometer (Perchuk, 1992) allowed us to assess the physico-chemical metamorphic evolution of the complex, and to identify several stages of its progressive and retrograde development. Maximum temperatures and minimum pressures for Grt + Cpx + Pl + Qz equilibrium (T ~ 805-910 °C, P ~ 2.5-3.5 GPa), recorded in the compositions of coexisting phases indicate HP-UHP conditions of formation of the complex, as well as its potential for a stage of stability in the diamond P-T field. Subsequent retrograde and secondary prograde metamorphism occurred under lower grade conditions typical for the blueschist (T ~ 450-700 °C, P ~ 1.2-1.7 GPa) and greenschist (T ~ 380-470 °C, P ~ 0.7-1.3 GPa) facies.

Key words: mafic eclogite, HP-UHP metamorphism, garnet-clinopyroxene geothermometry, Maksyutov complex.

Introduction

The Maksyutov eclogite-glaucophane schist complex is a well-known mid- to late-Paleozoic high-pressure (HP)-ultrahigh-pressure (UHP) subduction terrane in the southern Ural Mountains of Russia. Characteristic UHP phases (coesite pseudomorphs, graphite cuboids after diamond, microdiamond) have been reported in earlier works (Chesnokov and Popov, 1965; Dobretsov and Dobretsova, 1988; Leech and Ernst, 1998, 2000; Bostick et al., 2003). Garnet and clinopyroxene are generally regarded as the most informative, conservative phases in HP-UHP metabasaltic rocks employed to evaluate the temperatures and pressures of the peak metamorphism. Our new study specifically targets zoning and compositions of coexisting garnets and pyroxenes in direct contact, as inclusions, and the re-equilibration of these phases at different subsolidus stages of the evolution of the complex. Microprobe data provide the basis for the thermobarometric calculations of Grt-Cpx equilibrium, which are required to assess the conditions of formation of the Maksyutov complex.

We undertook detailed spatial micro-analysis of large garnet grains along their immediate contacts with clinopyroxene. Mineral inclusions were also investigated. Both sets of data were employed to calculate maximum equilibrium temperatures based on the Grt-Cpx geothermometer of Powell (1985). The Pl-Cpx-Qz barometer of Perchuk (1992) was used to estimate minimum pressures reached attending formation of the Grt + Cpx + Pl + Qz assemblage. However, as plagioclase is lacking in many of the Maksyutov eclogites, actual pressures may have been in excess of those computed. Plagioclase is retained only the low-T (low-P?) metamorphic stages. Therefore, in some cases, only temperature trends based on garnet + clinopyroxene compositions lie within the alleged pressure range. A preliminary pressure interval from 1.0 to 3.5 GPa for Grt-Cpx geothermometry was derived from petrological and UHP mineral data (in accordance with the presence of low-pressure mineral associations or characteristic UHP phases).

Microprobe data and geothermobarometry

Compositions and zoning of coexisting Grt and Cpx were quantified by microprobe analyses of 26 of the most representative rock samples from the Karayanovo-Shubino area, the central part of the Maksyutov complex. Specimens with different degrees of weathering, retrograde changes, and contrasting garnet morphology and structures were studied (Table 1).

Compared with small Grt euhedral in the rock matrix, large porphyroblastic garnet grains are generally more thoroughly obliterated, and exhibit irregular borders and eroded, vague outlines. They are full of inclusions of quartz, epidote, sphene, rutile, rare clinopyroxene and plagioclase. Other garnets are completely replaced. In some cases, a box-like or framework structure of a negative crystal is filled with secondary minerals. They typically show retrograde zonation with computed higher temperatures in the Grt cores, whereas rim compositions correspond to those of small euhedral garnet grains in the matrix. These well-bounded, relatively pure crystals of garnet in the matrix display prograde zonation, recording P-T conditions of a later evolutionary stage of the complex.

Table 1. Summary of Grt-Cpx thermometry for the Maksyutov eclogites

Sample *	Locations	Temperature, C according to Grt-Cpx equilibrium (Powell, 1985)			Pressure (GPa) accoding to:		Tempe-rature trend from core to rim	Trend classification
		Cores and inclusions	Inclusions, middle	Rims and contacts	Petro-logic data**	Pl-Cpx-Qz barometer		
88-16	Shubino	846-914	759	770-858	2,5		retr.914-770	1st retr. 910-730
88-17	Shubino	805-830	849	881-892	3,5		pr.805-892	1st pr. 800-900
154a, prof.	Shubino	448-511		518-620	1,5	1.19-1.26	pr.448-620	3d pr. 460-680
154a, pnt.	Shubino	406-519		511-628	1,5	1.19-1.26	pr.406-628	3d pr. 460-680
158	Shubino	542-563	650-683	599-721	1,5		pr.542-721	2d pr. 500-750
159	Shubino	788-866		731-781	3,5		retr.866-731	1st retr. 910-730
161	Shubino	801-816		892-899	3,5		pr.801-899	1st pr. 800-900
230B-1	Fedoseevka	459-544	433-509	313-385	1,0	1.19-1.04	retr.544-313	4th retr. 544-313
230B-2	Fedoseevka	493-498		545	1,0	1.11-1.16	pr.493-545	3d pr. 460-680
231	Fedoseevka	562-581	587	601-679	1,5	1.20-1.33	pr.562-679	2d pr. 540-700
235	Fedoseevka	470-522	484-541	548-575	1,0	0.74-1.26	pr.470-575	3d pr. 460-680
236-1	Fedoseevka	384-419	372	423-453	1,0	0.96-1.16	pr.384-453	4th pr. 310-515
238-2	Fedoseevka	503	539	628	1,5		pr.503-628	3d pr. 460-680
238-2-2	Fedoseevka	641-666	666-711	729-789	1,5		pr.641-789	2d pr. 500-790
239-1	Fedoseevka	560-624		650	1,5	1.1-1.37	pr.560-650	2d pr. 540-700
239-3	Fedoseevka	541-593	531	450-514	1,5	1.13-1.31	retr.593-450	3 th retr. 680-430
185b-1	Antingan	469-496	498-553	468-657	1,5		pr.469-657	3d pr. 460-680
185v-1	Antingan	427-540	510	527-570	1,5		pr.427-570	3d pr. 410-640
95-18	Karayanovo	741		679	1,5		retr.741-679	2 th retr. 750-610
95-4	Karayanovo	310		515	1,5		pr.310-515	4th pr. 310-515
95-4b	Karayanova	611-637		671-691	1,5		pr.611-691	2d pr. 540-700
95-I-1	Karayanovo	691		605	1,5		retr.691-605	2 th retr. 750-610
95-III	Karayanovo	666		548	1,5		retr.666-548	3 th retr. 680-430
200-I	Karayanovo	622-627		677-680	3,5		pr.622-680	2d pr. 540-700
200-II	Karayanovo	598-637	677	770	3,5		pr.598-770	2d pr. 500-790
200-III	Karayanovo	704-744	691	704-673	3,5		retr.744-673	2 th retr. 750-610
200-IV mt.	Karayanovo	473-516	487	561-627	3,0		pr.473-627	3d pr. 460-680
207-I	Karayanovo	568-699	599-608	625-751	1,5	1.37-1.69	pr.568-751	2d pr. 500-750
207-II	Karayanovo	689		789	1,5		pr.689-789	2d pr. 500-790
207-III	Karayanovo	559	615-639	649-688	1,5		pr.559-688	2d pr. 540-700
216-inner	Karayanovo	694-727	715	613-663	1,5	1.43-1.6	retr.727-613	2 th retr. 750-610
216-outer	Karayanovo	629	631	635-658	1,5	1.44-1.46	pr.629-658	2d pr. 540-700
219	Karayanovo	603-702		690-781	3,5		pr.603-781	2d pr. 500-790
219-2	Karayanovo	683-720	727	765	3,5		pr.683-765	2d pr. 500-790
219-3	Karayanovo	555-708		592-788	3,5		pr.555-788	2d pr. 500-790
219-3-1	Karayanovo	460-556		497-843	3,5		pr.460-843	1st pr. 800-900

Sample *	Locations	Temperature, C according to Grt-Cpx equilibrium (Powell, 1985)			Pressure (GPa) accoding to:		Tempe-rature trend from core to rim	Trend classification
		Cores and inclusions	Inclusions, middle	Rims and contacts	Petro-logic data**	Pl-Cpx-Qz barometer		
267-1	Karayanovo	614-671	753	758-823	3,5		pr.614-823	1st pr. 800-900
267-2	Karayanovo	505-645		654-704	3,5		pr.505-704	2d pr. 500-750
267-2-prof.	Karayanovo	492-559	519-567	601-641	3,5		pr.492-641	3d pr. 460-680
271	Karayanovo	661	681-716	793-907	3,5		pr.661-907	1st pr. 800-900
273	Karayanovo	545-556	586	712-790	3,5		pr.545-790	2d pr. 500-790
288	Ivanovka	464-485		520-670	1,5	1.18-1.42	pr.464-670	3d pr. 460-680
289-3-1	Ivanovka	582-686	528-543	431-461	1,0	(1.04-1.14)	retr.686-431	3d retr. 680-430
289-3sg	Ivanovka	424	535-541	620	1,0		pr.424-620	3d pr.410-640
289-4	Ivanovka	673	541	429	1,0	(1.30-1.08)	retr.673-429	3й retr. 680-430
289-4-1sg	Ivanovka	470-523	484-559	679-709	1,5	(0.67-1.51)	pr.470-679	3d pr. 460-680

Abbreviations: inn. - inner zone of crystal, out. - outer zone of crystal, mt. - matrix, pnt. - microprobe points, pr. - prograde trend, prof. - microprobe profile, retr. - retrograde trend, sg. - small grains.

*) Individual Samples and Locations are separated by bold lines;

**) Explanations in text.

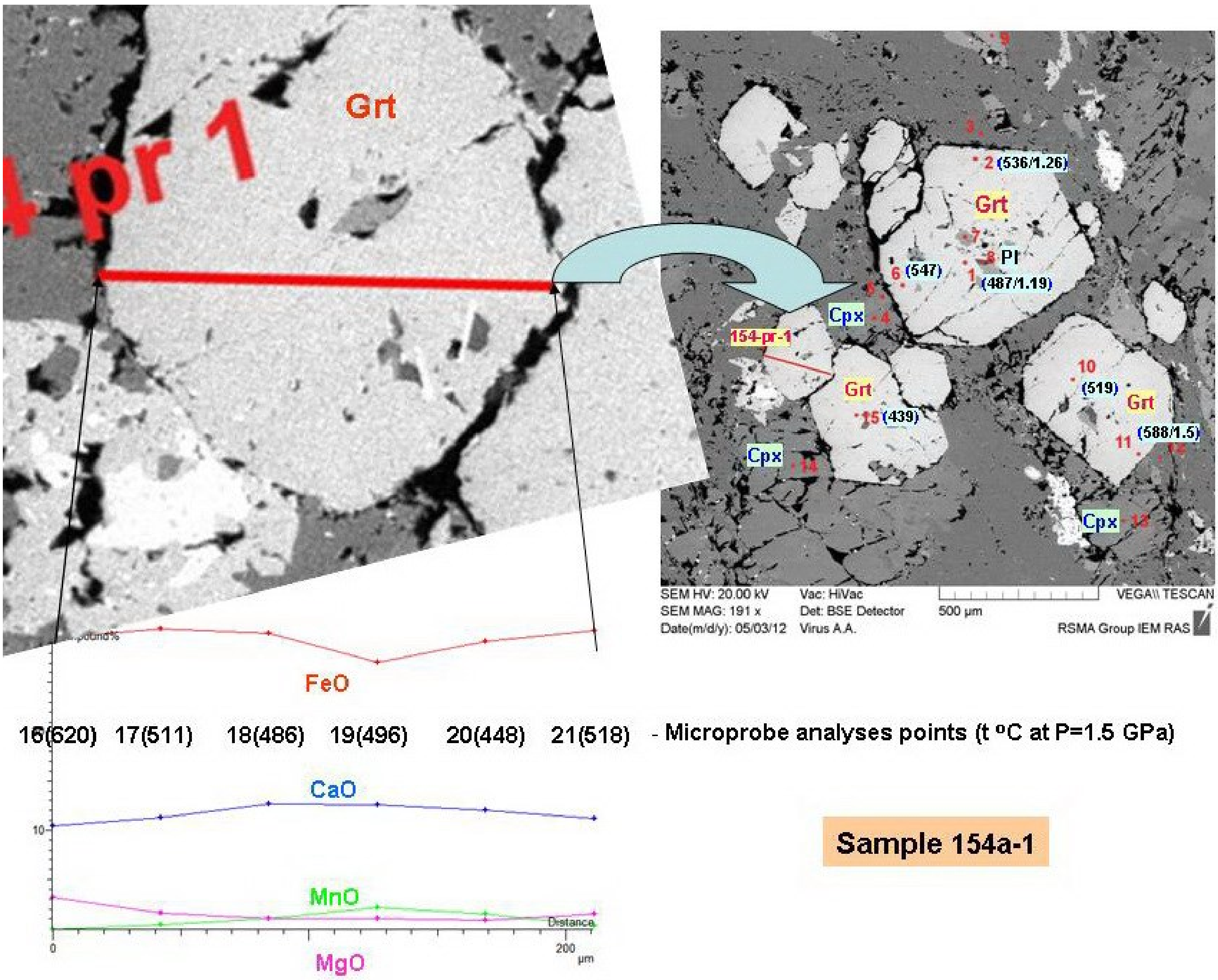

Fig. 1. Euhedral garnet crystals with prograde zoning (Shubino village area). Hereinafter, figures are microprobe analysis points, within brackets - PT parameters of Grt-Cpx-Pl-Qz equilibrium (° C / GPa).

Chemical heterogeneity of large garnet grains in most of the studied samples records both prograde and retrograde temperature trends at different metamorphic stages. In some occurrences, traces of these processes are contained in a single sample or, more interesting, in a single Grt grain. The compositions of Cpx coexisting with garnet in contacts along the rim of grains, in inclusions, or in small pyroxene crystals of the r matrix do not vary significantly. Some eclogites contain plagioclase of nearly pure albite composition (2-3% of anorthite), suggesting relatively low pressures of the late stage-metamorphism.

Table 1 presents data on the temperature conditions (T ranges and trends) of origin of garnet-pyroxene assemblages from the studied samples. The highest T conditions of eclogite formation are present near Shubino village, where mineralogical indications of HP-UHP conditions (coesite pseudomorphs and microdiamond relics) were noted at P ~ 2.5-3.5 GPa (Leech and Ernst, 1998, 2000; Bostick et al., 2003). Large garnet grains from samples 88-17 and 161 preserve progressive zonings and record the maximum P-T parameters of metamorphism of the complex, indicating HP-UHP conditions: T = 805-900 °C and P ~ 2.5-3.5 GPa. Retrograde zoning in garnet grains from samples 88-16 and 159 records a decline in metamorphic temperature after its peak from 914-837 to 770-711 °C.

Another stage of progressive metamorphism from 406 to 628 °C is recorded in the zoned garnet grain in sample 154a, one of the least altered eclogites (Figure 1). Well faceted euhedral garnet crystal cores contain inclusions of plagioclase, the composition of which allows an estimation of the equilibrium pressure of the Grt-Cpx-Pl-Qz assemblage as 1.19-1.26 GPa. These values characterize the second prograde stage, which may be connected with blueschist facies metamorphism in the independent Taschlinsky part of the Maksyutov complex (Valizer et. al, 2015). Some intermediate prograde zoning of garnet occurs in sample 158. Plagioclase is absent from this rock, in line with the calculated P-T origin at 542-721 °C.

The Fedoseevka, Antingan, and Karayanovo areas, north of Shubino village are typified by a gradual decrease in metamorphic conditions for both prograde and retrograde stages. Eclogites of these areas underwent repeated recrystallization during evolution of the complex. Thus, the coexisting mineral compositions record P-T conditions of various stages of metamorphism. Locally, garnet grains with both prograde and retrograde zonings are present within a single rock (samples 230B, 239).

In the Fedoseevka area, garnet zoning patterns are similar to those of the Shubino eclogites. P-T conditions of mineral formation in the region cover a wide range. The presence of albite-rich plagioclase in almost all of the samples (with the exception of sample 238) indicates that these rocks were exposed to retrograde metamorphism at relatively low-P during the latest stages of their evolution. Nevertheless, prograde garnet zoning occurs in the most of eclogites at this location. In relatively little altered (plagioclase-absent) eclogites (sample 238-2), large garnet grains show progressive zonation in the T range 503-628 °C. This trend corresponds exactly to physical conditions of the second stage of prograde metamorphism defined in the Shubino area (Table 1, sample 154a). On the other hand, analyzed small, neoblastic, euhedral garnet crystals in the same sample yield a computed temperature interval of 640-790 °C (sample 238-2-2), which is slightly shifted in comparison to the high-T prograde trend of the Shubino eclogites (samples 88-17, 161). Even lower P-T conditions of prograde metamorphism are recorded in plagioclase-bearing eclogites (specimens 230, 235, 236). In some rocks, retrograde and inverse zoning is marked in garnet formed in the range from 544-593 to 450-313 °C at P = 1.31-1.19 GPa (Table 1). These conditions may reflect intense retrograde processes in the region coupled with incompleteness of garnet recrystallization.

The Antingan area lies between Fedoseevka and Karayanovo. Relatively little altered eclogites of the area do not contain plagioclase or clear signs of retrogression. The garnet grains from the Antingan eclogites are slightly rounded. Garnet-clinopyroxene equilibrium yields a prograde trend from 427-496 to 555-657°C at a pressure of 1.5 GPa - average for the northern part of the Maksyutov complex (Fig. 2, Table 1). Small Grt grains in equilibrium with Cpx record only a small T range of formation.

The chemistry of coexisting minerals and Grt-Cpx thermometry of the eclogites of the Karayanovo plot were extensively studied by electron microprobe analysis. Eclogites of this area underwent the most thorough reprocessing during evolution of the complex. As recorded in some cases, even in the single sample, garnet grains display both prograde and retrograde zoning. The clinopyroxene composition changes slightly along a microprobe profile: Jd = 0.320-0.381 to 0.347-0.371 (Figure 3).

Among eclogites studied in the Karayanovo area, five samples, collected 2 km to the south of Karayanovo village along the Sakmara River (specimens 200, 219, 267, 271 and 273) are of greatest interest. At this location, jadeite-bearing eclogites associated with UHP ultramafic rocks of the lower part of the complex were described previously (Valizer et. al, 2011, 2013, 2015a). The initial P-T conditions of generation of these rocks are estimated as T > 700 °C and P > 4.4 GPa. These rocks underwent a regressive transformation at T = 633-740 °C and P = 3.1-3.4 GPa. In this connection, the temperatures for the samples listed above were calculated at P = 3.0-3.5 GPa, (assuming conditions of diamond stability) or at P = 2.0-2.5 GPa in heterogeneous zones of the host rock, where there is evidence of uneven back-reaction (Table 1).

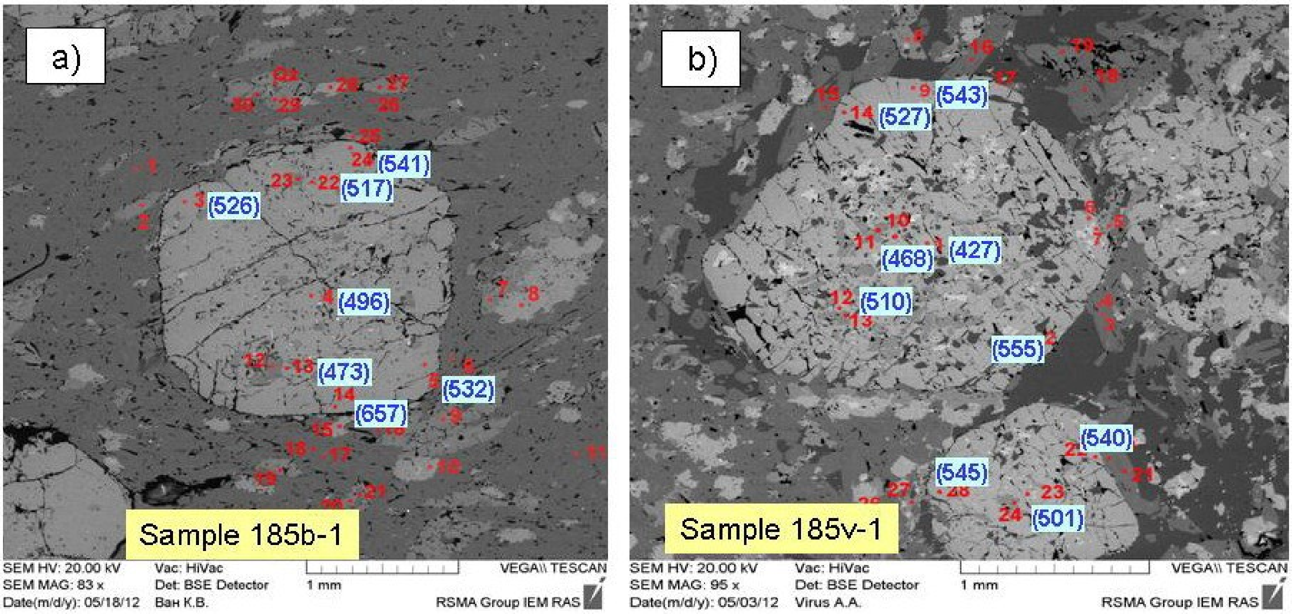

Fig. 2. (a) Prograde zoning of garnet from the Antingan area eclogites. (b)Small garnet grains are rounded in shape as a result of dissolution during lower temperature recrystallization.

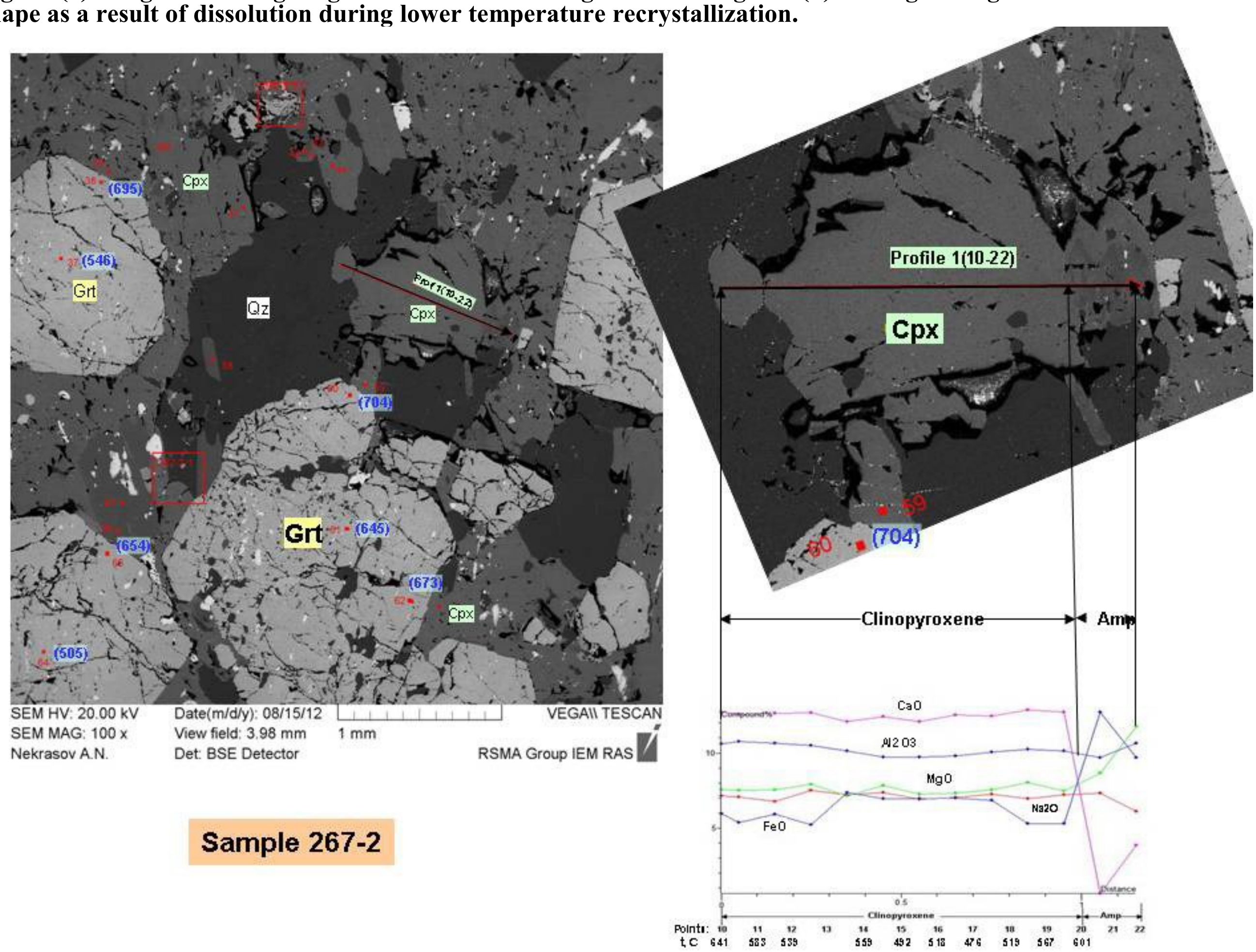

Fig. 3. Prograde garnet crystals in equilibrium with homogeneous clinopyroxene (Karayanovo area).

Zoned Grt grains in all five samples in equilibrium with Cpx yield a prograde trend showing a wide T range from 460-683 °C, recorded in garnet cores to 680-907 °C at their rims. Maximum conditions of metamorphism up to 850-907 °C at P = 3.5 GPa were reported for samples 219, 267, 271. These same rocks contain other grains or small sectors with a lower gradient of garnet composition and corresponding temperature trends. Similar values are repeated in samples 200 and 273, where they reach values of 770-790 °C.

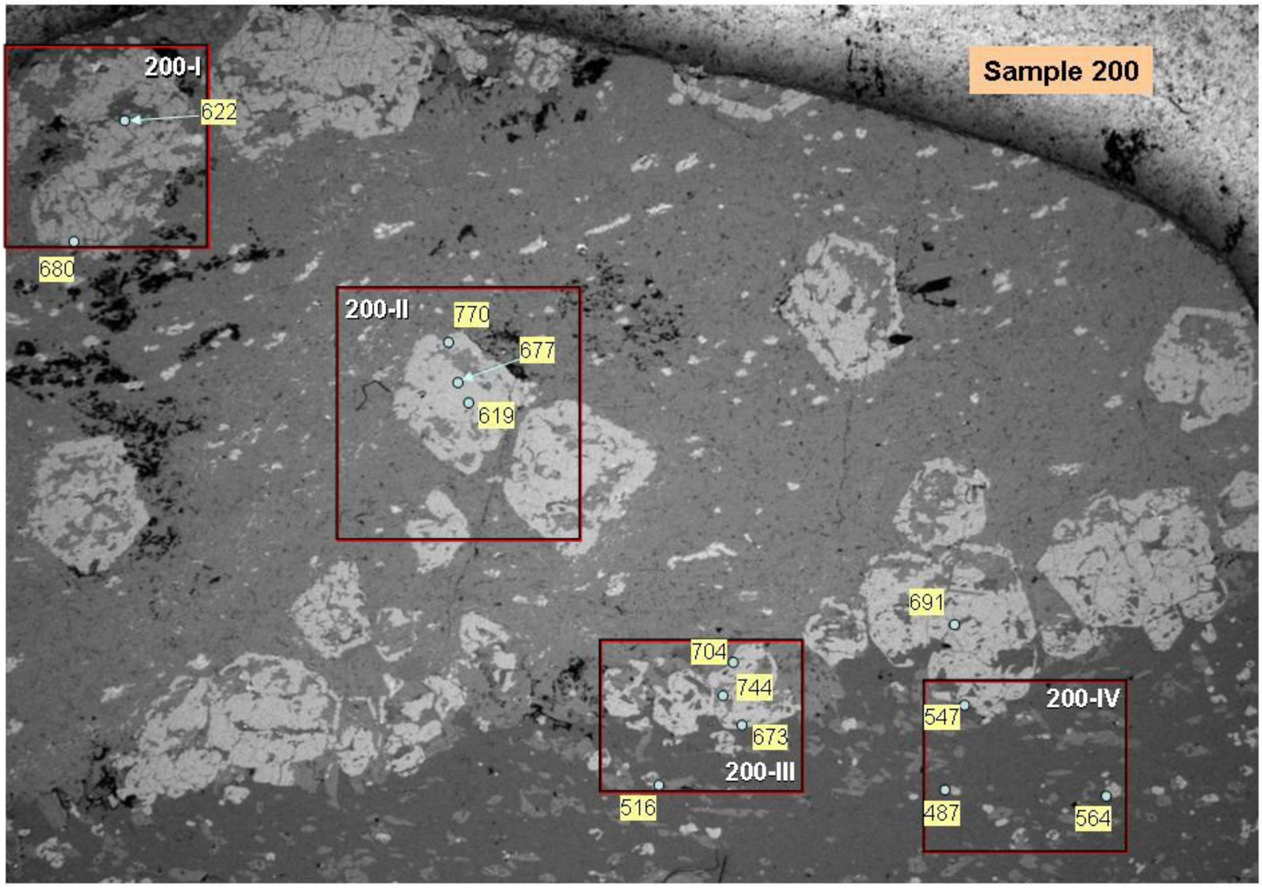

Fig. 4. Banded Grt-Cpx eclogite and Grt-Gln rock with different zoning of garnet.

The temperature trends in such layered eclogites differ depending on bulk chemistry and structure of the rock, its permeability, and extent of reprocessing by retrograde metamorphism. The garnet and clinopyroxene compositions were analyzed in 4 different sectors of sample 200 (Fig. 4). A progressive zoning from Alm-Grs –rich ($Prp_{8.6}Alm_{63.6}Sps_{2.1}Grs_{25.1}$) in the core to Prp-Alm-rich ($Prp_{21.4}Alm_{64.6}Sps_{2.4}Grs_{11.6}$) on the grain margins is clearly present in the euhedral grains (sectors 200-I and 200-II). Clinopyroxene composition changes modestly, from 25.9-40.8 mol% Jd, defining the sample prograde path from 598-637 °C to 677-770 °C (Table 1).

Garnet grains are rounded at the border with the fine-grained Grt-Gln matrix. The garnet has weak retrograde zoning yielding a T range of 744-673 °C (sector 200-III). Garnet grains are much smaller and more scattered in the matrix (sector 200-IV). Pyroxene in the matrix is FeO-poor ($Fe2/Mg=0.214$) and more heterogeneous ($Fe^{2+}/Mg=0.076-0.579$), than the Cpx inclusions in garnet ($Fe2/Mg=0.477-0.479$). The Jd content in clinopyroxene remains almost unchanged in both matrix and eclogite layers, 0.34-0.39 mol%, and the Grt-Cpx equilibrium yields a small temperature range of 473-627 °C (Table 1).

In a number of cases, the prograde metamorphism is followed by a retrograde stage, the P-T path of which is recorded by garnet reverse zoning. The latter phenomena are best represented in sample 216 and in several samples of series 95.Sample 216 shows a clear combination of regressive and progressive zoning in a single garnet grain. Central parts of the box-like garnet grains are rounded, heavily corroded, and contain small inclusions of quartz, clinopyroxene, rutile ± rare amphibole. Retrograde zoning of garnet is recorded in its core, whereas weak prograde zoning characterizes the edge of the neoblastic rim. The outer zone exhibits a well-marked outline of the external grain margin and contains minor inclusions of quartz, actinolite, and clinopyroxene. The Cpx composition in both zones is rather homogeneous (0.44-0.50 % Jd). In contrast, the composition of garnet varies from Grs-Alm in the middle of largely resorbed grains ($Prp_{15.1}Alm_{56.9}Sps_{1.7}Grs_{26.3}$) to Prp-Alm ($Prp_{26.6}Alm_{59.9}Sps_{2.0}Grs_{11.5}$) in its outer zone. However, Grt-Cpx equilibrium computations yield similar physical conditions of garnet recrystallization with the change of retrograde temperature trend in the range of 727-613 °C in the inner zone, and a weak progressive zoning of 629-658 °C in the outer zone (Figure 5). The presence of small grains of albite-rich plagioclase (XNa=0.97-1.00) allows evaluation of pressure for this rock formation employing the Cpx-Pl geobarometer (Perchuk, 1992). P-T values are similar for both zones, 1.43-1.60 GPa. We note that albite-rich plagioclase is scarce in Maksyutov eclogites. It is probably secondary and marks the latest stage of metamorphism (attending exhumation-decompression?). The combination of prograde and retrograde zoning of garnet in a single eclogite sample is rather common in the Maksyutov complex (samples 230, 239, 289). Based on these data, we suppose that changes in the metamorphic events occurred in a rather narrow temperature range, or they present stages of a P-T continuum. This indicates that the physicochemical conditions of metamorphism at different stages inherited the settings of the previous stages and are transitional. However, in the absence of the geochronological data on the frequency or duration of the various metamorphic episodes, such allegations are hypothetical.

Most other investigated samples from the Karayanovo area (Table 1) are similar to those described above. Garnet at a number of individual spots from sample 207 unambiguously records a prograde stage of metamorphism with a temperature range of 559-789 °C. Inclusions of Cpx and Pl in the large garnet grain cores allow tracking both the T change and the total P of crystallization. Rounded shapes of garnet from sample 207-I (Fig. 6) emphasize its formation at the incipient state of prograde metamorphism at T=568-751 °C and P=1.4-1.7 GPa. Another garnet core, as a negative euhedral crystal (sample 207-II), was fully replaced by the assemblage Gln + Ms + Chl + Qz + Rt mixture. Nevertheless, the analyzed Grt-Cpx pair allowed detection of a relatively high temperature (789 °C) .The outer Grt shell growing over the formerly euhedral crystal has a normal composition of $Prp_{15.5}Alm_{61.8}Sps_{2.0}Grs_{20.7}$ but its equilibrium with nearby Cpx records the maximum metamorphism parameters for this area: T=789 C at P ~1.5 GPa. Recalculation of the garnet edge compositions and neighboring pyroxene at P = 3.5 GPa (assumed initial crystallization conditions of the Grt in the diamond P-T stability field) shows an even higher temperature (848 °C), making its physical conditions of formation close to those of the Shubino samples (samples 88-17, 161).

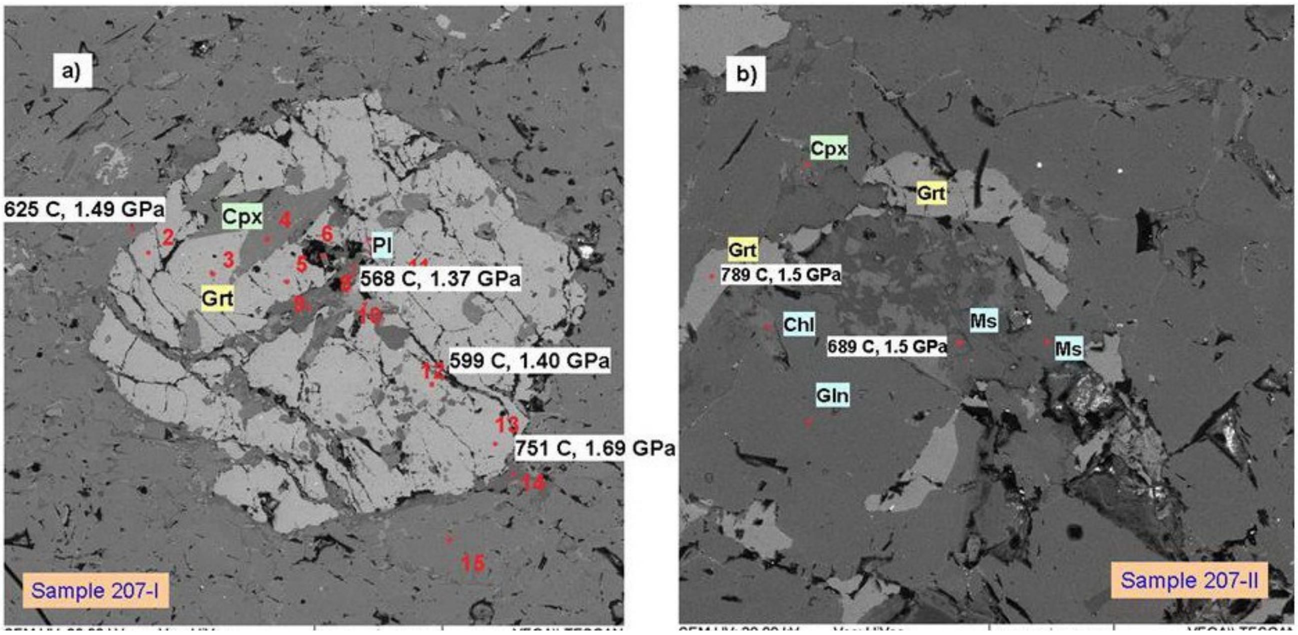

Fig. 6. (a) Zoned garnet grain with Cpx and Pl inclusions in its core. (b) Remnants of high-temperature garnet with its core replaced by secondary minerals.

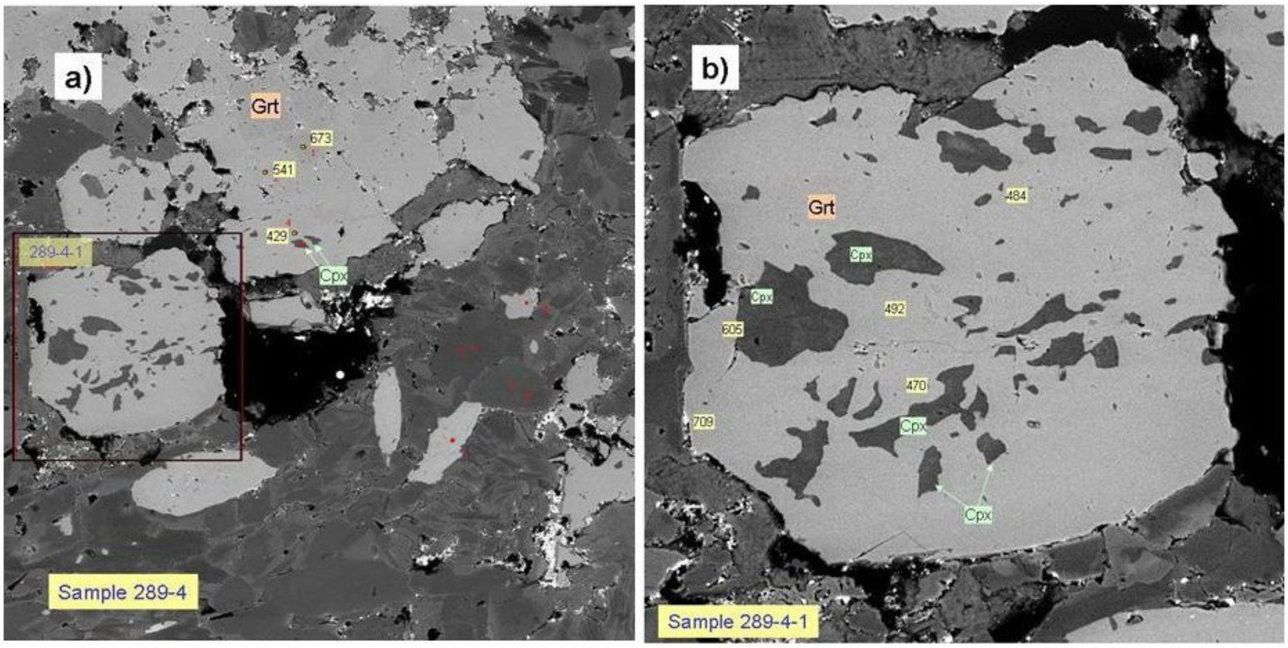

Fig. 7. Progressive (b) and regressive (a) metamorphism temperatures paths recorded by garnet compositions, from sample 289-4 (Ivanovka area).

Location Ivanovka provides strong evidence for the retrograde stage of metamorphism. Large grains of garnet have fuzzy boundaries, are filled with inclusions of secondary low-T minerals, and commonly record a retrograde path in the temperature interval from 686 to 429 °C (Table 1). Grt compositions range from $Prp_{13.2}Alm_{51.5}Sps_{3.0}Grs_{32.3}$ in the core to rim values of $Prp_{3.0}Alm_{58.7}Sps_{1.4}Grs_{36.8}$. The larger the garnet grain, the higher is the temperature of the Grt-Cpx equilibrium in the grain core. The garnet compositions are almost identical in the rims and in small euhedral matrix grains. However, small grains record a progressive zoning in almost the same temperature range from 424-523 °C in the cores, to 620-709 °C in the rims. Such new-formed garnets adjacent to larger, retrograded grains are evident in the different parts of sample 289 (Figure 7). In another sample from this area (sample 288), garnet retains a clear progressive zoning like that in sample 289, and yields a path of temperature increase from 464-485 to 520-670 °C. Compositions of pyroxene grains (Jd 36-38%) and plagioclase (0.64% An) are typical of those from Karayanovo and Ivanovka eclogites. Pressures calculated by the Pl-Cpx-Qz geobarometer do not exceed 1.18-1.42 GPa and likely record conditions of the last stages of metamorphism in the northern part of Maksyutov complex.

Conclusions

New microprobe analytical data on the composition and zoning of the most important rock-forming minerals provide strictures on the formation and evolution of physical-chemical conditions of metamorphism of the mafic eclogites of the Maksyutov complex. Temperature trends attending crystallization of garnet in equilibrium with clinopyroxene provide information on the P-T conditions of individual prograde and retrograde metamorphic stages. Temperature ranges of these trends, in some cases overlap and are not invariably reproduced in the different samples and in different parts of the complex. Nevertheless, on the basis of our new data, we are justified in proposing a complex, multi-step history of the complex. At least four paired prograde and retrograde stages stand out in the P-T evolution of the eclogitic complex.

(1) The highest level of prograde metamorphism for eclogites of the Maksyutov complex reached 800-900 °C at P = 3.5 GPa (UHP samples 88-17, 161, 271), with other samples reflecting a maximum temperature involved the range 910-730 °C at P = 3.5 GPa, in the same localities near the village Shubino (samples 159, 88-16). The T range of both forward and reverse trends in several samples from the area practically coincide, and are supported by the thermobarometric data from the Karayanovo area.

(2) The second stage of progressive mineral formation is exemplified in the Karayanovo area in the wide T range 500-790 °C at the same P of 3.5 GPa (samples 200, 219, 273). Similar conditions of 633-740 °C at P = 3.1-3.4 GPa were obtained earlier in the same Karayanovo area from ultramafic rocks and from UHP eclogite (Valizer et al, 2013, 2015a.). The P-T trend of the second stage metamorphism for Pl-bearing retrograded rocks was calculated using the Grt-Cpx geothermometer and the Cpx-Pl-Qz geobarometer: T = 560-769 °C and P = 1.1- 1.7

GPa (samples 231, 239, 207). This retrograde stage, recorded in rocks from this area, involved the range 750-610 °C, and apparently proceeded also at a lower pressure (samples 95-18, 95-I-1, 216). However, the calculated values P ~ 1.4-1.6 GPa may be underestimates due to the probable incorrect use in the calculation of the p-T stability and composition of secondary (?) plagioclase.

(3) The third conjugate pair of prograde (T = 410-680 °C at P = 1.2-1.5 GPa) and retrograde (T = 680-430 °C at P = 1.0-1.3 GPa) metamorphic is widely manifested in the Fedoseevka and Antingan localities, and is recorded in various parts of some other rocks (samples 154a, 235, 238, 239, 185, 95-III, 200, 267? 288, 289). Eclogites of this stage tend to exhibit strong back-reaction and typically contain plagioclase. However, zoned garnet grains commonly preserve their initial compositions as well as structural evidence of the previous higher temperature prograde transformations.

(4) The fourth stage of prograde (T = 310-515 °C at P = 0.9-1.1 GPa) and retrograde (T = 545-310 °C at P = 0.6-1.0 GPa) low-grade trends are recorded in a few samples from the Fedoseevka and Karayanovo areas (samples 230, 236, 95-4). They describe P-T conditions of the final, greenschist facies stages of metamorphic evolution of the rocks of the complex.

The compositions of coexisting Grt and Cpx allow computation of the temperature intervals and P-T trends of the studied eclogites. Many samples show multiple stages of what are evidently incompletely re-equilibrated paragenetic assemblages. The several stages complement each other, creating an overall picture of the multistage evolution of the Maksyutov complex. On the other hand, the presence in a single sample of several sections with different levels of physical conditions and with opposite P-T trends, indicate incompleteness of the re-equilibration process in the studied eclogitic rocks—suggesting cyclic and intermittent recrystallization.

Acknowledgments

The authors thank the Fulbright Program (Scientific Scholar Grant 2011 and Small Grant 2015) for financial support of this research and funds to support V.V. Fedkin's stay and work at Stanford University and San Francisco State University during six months in 2011. The authors also thank the GeoAnalytical Lab., Washington State University for the excellent analyzes of the Maksyutov rocks, made with the support of Stanford University.

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