ISSN: 2642-9020

Research Article

Journal of Marine Science Research and Oceanography

Zonal Garnet from Eclogite-Blueschist Complexes - Recorder of the History of their Development

Valentin Fedkin*

D.S. Korzhinskii Institute of Experimental Mineralogy, Russian Academy of Sciences, ul. Akademika Osip'yana 4, Russia

***Corresponding Author**
Valentin Fedkin, D.S. Korzhinskii Institute of Experimental Mineralogy, Russian Academy of Sciences, ul. Akademika Osip'yana 4, Russia

Submitted: 2024 Jan 19; **Accepted:** 2024 Feb 07; **Published:** 2024 Feb 14

Citation: Fedkin, V. (2024). Zonal Garnet from Eclogite-Blueschist Complexes - Recorder of the History of their Development. *J Mari Scie Res Ocean, 7*(1), 01-12.

Abstract
Garnet has a unique ability to maintain its composition in the situation of changing conditions of metamorphism and fix the chemical changes in the new grains, outgrowths and replacements associated with the evolution of mineral formation parameters. These properties and capabilities of garnet were studied by the phase correspondence and mineralogical thermobarometry methods using the example of the Maksyutov (Southern Urals) and the Atbashi (South Tien Shan) complexes of crustal mafic eclogites, where they are used as PT indicators of their formation conditions. The issue is considered against the background of solving a specific petrological problem - the origin in eclogite-blueschist complexes (EBSK) of contrasting series of rocks - high-pressure eclogite blocks, boudins and interlayers in the thickness of a weakly metamorphosed gneiss-schist matrix. In the polymetamorphic Maksyutov complex, the garnet demonstrates complex multidirectional, sometimes inversion zoning, which reflects the features of mineral formation at each stage of its development. The corresponding PT trends bear signs of the determining processes of the formation of the complex - tectonic melange and coherent development. In the one-stage Atbashi eclogite-blueschist complex, inversion PT trends in the evolution of metamorphism are noted with a turn in their direction clockwise, indicating a transition from a tectonic melange setting to a coherent stage of the terrane development.

Highlights:
Garnet has the ability to fix and retain in its composition the physicochemical parameters of the metamorphism of eclogite complexes.
The formation of contrasting series of rocks of eclogitic complexes occurs as a result of tectonic mélange and coherent development of the terrane.
The processes of tectonic melange and coherent development of eclogites are independent phases of the general process of metamorphic evolution,

1. Introduction
Garnet is one of the most informative and at the same time conservative minerals of metamorphic rocks, used in equilibrium with other silicates to assess the physicochemical conditions of metamorphism. Due to its ability to change its composition under the influence of physical and chemical conditions of formation and to keep these changes in balance with other minerals for a long time, garnet is widely used as a sensitive mineralogical sensor to assess the thermodynamic parameters of a wide variety of natural systems and processes [1-9]. Its role is especially great in the study of crustal eclogitic complexes, where, in association with pyroxene, it is, in fact, the only reliable tool for determining the parameters of mineral formation and their evolution during the development of the complex.

In this regard, the task was to evaluate the significance and possibilities of garnet and its associations in the study of eclogite-blueschist complexes (EBSK). The study of the chemical heterogeneity of the garnet, its zonation and patterns of change was carried out against the background of solving a specific petrological problem - the origin in the EBS complexes of contrasting series of rocks - high-pressure eclogite inclusions in the strata of weakly metamorphosed metasedimentary or granitoid rocks.

The well-known complexes of mafic eclogites, similar in essence to their origin, but contrastingly different in terms of formation conditions, were chosen as the object of study: the Maksyutov eclogite-blueschist complex in the Southern Urals and the Atbashi complex in the Southern Tien Shan.

The study of the chemical heterogeneity of garnet, the composition and zoning of coexisting minerals was carried out on the basis of the Grt-Cpx-Pl-Qz equilibrium, the main information source of the conditions for the formation of high-pressure and ultra-high-pressure eclogite associations [1]. Garnet in this balance is of key importance, since it is able to accumulate and retain information about the parameters of the formation of mineral associations during the evolution of metamorphism. The associated change in the composition of garnet with other phases of eclogitic paragenesis makes it possible to reconstruct the direction and parameters of metamorphism at different stages of the development of the complex in the entire temperature and baric range of its existence [1]. Mineral abbreviations after Whitney and Evans, 2010

2. Facials System of Crustal Mafic Eclogites

2.1 Research Objective

High-pressure eclogite and eclogite-blueschist complexes, as a rule, form in zones of junction of large geostructural elements of the Earth's crust under conditions of constant tectonic activity and changing metamorphism [6,10]. Due to these circumstances, blocks of basic rocks metamorphosed at high and ultrahigh pressures (HP-UHP) are often included as separate boudins, interlayer's and lenses in metasedimentary or granitic rocks that do not show signs of HP metamorphism. The problem of the formation of contrasting series of rocks in this work is considered as a parallel actual problem in the study of the chemical heterogeneity of garnet and its possibilities for assessing the conditions of metamorphism of crustal mafic eclogites.

Contrasting series of rocks are almost always present in eclogite-blueschist complexes. They reflect the complex history of the development of metamorphic processes, their periodicity and incompleteness. As a rule, these are eclogitic bodies, boudins, interlayers, and lenses included in the metasedimentary or granitoid sequence of host rocks with a low level of metamorphism. Boudins and large eclogitic bodies are traditionally regarded as products of tectonic mélange, while their layers and lenses in an interlayer's host member are considered coherent formations with a lower degree of metamorphism and diaphthoresis. The reasons for the formation and conditions for the joint occurrence of contrasting series of rocks and the conditions for their joint presence have not been fully elucidated and cause active discussions. There are two points of view to explain this phenomenon: the tectonic mélange model - TM- model and the model of coherent formation of layered strata - CU-model [11-13]. The methods of phase correspondence and mineralogical thermobarometry make it possible to assess the significance of these concepts in the formation of these structures and to determine the significance and role of garnet in this process [1].

2.2 Object of Study

The study of contrasting series of rocks, composition and zoning of garnet and other rock-forming minerals was carried out on the example of two eclogite-blueschist complexes that are similar in essence in their origin (geotectonic position, temperature interval, age range, etc.), but quite contrasting in physicochemical conditions of its formation: Maksyutov (Southern Urals) and Atbashi (Southern Tien Shan). Both complexes are part of the system of the intracontinental Ural-Mongolian Hercynian foldbelt, and, in accordance with the concept of paired metamorphic belts; belong to its different branches, external and internal, respectively [14].

Eclogitic mineral associations of these terrains were formed in a wide temperature range − 350–750°C, but they differ in the level of depth of their origin: deeper for the Maksyutov complex, in the area of coesite and diamond stability (at a peak pressure of 3.2 GPa) and less deep, in the area of paragenesis stability Ab-Jd-Qz, (at P in the range = 1.2–1.9 GPa) Atbashi complex. Previously, it was shown that the history of the formation of these complexes also differ in their periodicity, in the number of progressive and regressive stages of metamorphism [9]. In this regard, the problem of studying the chemical heterogeneity of rock-forming silicates (garnet, pyroxene, and other phases) is of wider interest, since their composition and zoning fix the changing conditions of metamorphism at different stages of the development of the complex and may reflect the conditions for the origin and existence of contrasting rock series.

2.3 Maksyutov Complex (General Information)

The Maksyutov complex is located in the zone of the Main Ural Fault on the border of the Riphean strata of the Suvanyak complex in the west and the Kempirsay hypermafic belt in the east. The complex was finally formed in the Late Paleozoic, and isotope dating of various rocks and minerals obtained by different methods give an interval of 390 − 330 Ma for the eclogitic stage of metamorphism [5,6]. The age of the protolith is Riphean; the most ancient dates are 1.1–1.4 billion years. Mineral associations and mineralogical geothermobarometry data show metamorphism parameters P = 0.8–2.4 GPa and T = 400–700°C [7]. What is more, known finds of quartz pseudomorphs after coesite and graphite by diamond testify to the peak parameters of metamorphism at P up to 3.2–3.4 GPa and T up to 700–760°C at an early stage of the formation of the complex [10,15-17]. In the history of the formation of the complex, four stages of conjugated prograde-retrograde metamorphism were recorded with gradually decreasing parameters to T = 310–520°C and P = 0.6–1.2 GPa [9].

2.4 The Position of the Atbashi Complex

The Atbashi eclogite-blueschist complex is confined to the most important tectonic boundary between the middle and southern Tien Shan. The age range of the formation of the complex is 292–427 Ma. There are also older dates: about 570 Ma and even 1100 Ma [6]. Metamorphism parameters (T = 350–650 oC and P=4–12 kb) for various mineral associations indicate several stages of mineral formation: a progressive stage for garnet-clinopyroxene rocks and eclogites, an inversion stage for garnet-glaucophane schists, and a retrograde stage of diaphthoresis for garnet -chlorite and micaceous schists and quartzites [18,19]. However, they all fit into a single evolutionary process of development of the complex with a gradual decrease in its parameters.

The question of the formation of contrasting series of rocks of the Atbashi complex was recently considered in the HP-UHP system of the "Chinese Western Tien Shan" metaophiolite belt, to the southern part of which it belongs. Both concepts of the formation of such series are considered, but both are still controversial [20].

3. Methods and Procedures

3.1 Method of Phase Correspondence and Local Equilibrium

Thermobarometric studies of the parameters of metamorphism of eclogite associations were carried out using traditional methods of cation-exchange thermometry [21]. It is based on the principle of local (mosaic) equilibrium of Korzhinsky, which operates under the conditions of paragenetic compatibility of coexisting minerals, and the assumption that the centers of growing phases, their edges, and mineral inclusions are in a state of thermodynamic equilibrium at different times of their crystallization [22]. In such a situation, the compositions of equilibrium phases fix the temperature conditions of successive stages of metamorphism and make it possible to calculate the physicochemical parameters of their formation at each point of the established paragenesis, to trace the dynamics of their evolution based on grain zoning, and to reproduce the thermal history of these polymetamorphic rocks. Representative samples of eclogitic and host rocks of both complexes were studied in detail using a microprobe for the composition and zoning of the main rock-forming minerals: garnet, clinopyroxene, amphibole, plagioclase, etc.

Samples of varying degrees of weathering were studied, from the central and marginal parts of large boudins, from eclogitic layers, and from the gneiss-schist host complex. The compositions of large porphyroblastic grains of contacting minerals and small newly formed crystals, grains with direct and reverse zoning, as well as various variants of inversion zoning were studied.

3.2 Analytical Methods

The chemical composition of minerals, their heterogeneity and zoning were studied by the method of electron probe X-ray spectral analysis (ESRSA) at the Korzhinskii Institute of Experimental Mineralogy RAS. Microprobe analysis was performed using a Tescan Vega II XMU scanning electron microscope (Tescan, Czech Republic) equipped with an INCA Energy 450 X-ray microanalysis system with an energy- dispersive (INCAx-sight) X-ray spectrometer (Oxford Instruments, UK). Analysis conditions: accelerating voltage 20 kV, absorbed electron current per Co 0.3 nA, analysis time at a point 70–100 s. We used the analytical lines and standards of the IEM RAS, which are used in the ESPSA of minerals [9]. All microprobe analyzes of minerals used in the article were performed and processed by the author in the Laboratory of Physical Research Methods of the IEM RAS.

3.3 Garnet-Pyroxene Mineralogical Thermobarometry of Mafic Rocks

In metabasite HPU/HP rocks, garnet and clinopyroxene are considered as the most informative and conservative phases for estimating the temperatures of mineral equilibrium. Thermobarometric calculations of metamorphism parameters of eclogite associations were performed based on microprobe study of the composition and zoning of coexisting phases and mineral inclusions in the Grt + Cpx ± Pl + Qz paragenesis. The temperature of mineral equilibrium was determined using Powell's Grt-Cpx geothermometer [2]. Systematic discrepancies in the readings of different Grt-Cpx thermometers are within the accuracy of their measurements and amount to ± 30–40°C, which is of no fundamental importance for the relative comparison of the crystallization temperatures of zoned garnet between its individual zones and grains in the rock matrix [2,23-26]. To estimate the pressure in equilibrium of garnet with clinopyroxene, plagioclase, and quartz, we used a new version of Perchuk's improved Omp-Ab-Qz geobarometer [4].

3.3.1 Minerals for Estimating the Metamorphism Parameters of Eclogitic Rocks

The garnet during the development of the EBS complex remains a stable phase at all stages of its metamorphism. At the same time, it retains its composition, fixing the PT parameters of the previous stages. Changes in the conditions of mineral formation are reflected in the formation of zoning of growing garnet grains and in the formation of new crystals of a different composition. Because of this property, garnet in eclogites and Grt-Cpx rocks is almost always zoned. Its composition is constantly changing over a fairly wide range, registering multidirectional PT trends of metamorphism in equilibrium with pyroxene.

Clinopyroxene in this regard is a more rigid phase. Its composition varies within rather narrow limits - X_{Jd}=0.22–0.45, and within one grain does not exceed 0.3–0.35 mole fraction of the jadeite component. The composition of clinopyroxene can remain constant when the PT conditions of metamorphism change and practically do not change when changing its direction. In equilibrium with garnet, clinopyroxene acts as a reference phase, clearly reacting to changes in the parameters (temperature) of metamorphism.

Plagioclase used to estimate the pressure in the Grt + Cpx + Pl + Qz paragenesis is close in composition to albite X_{Ab} ~ 0.9–1.0 and is most likely a later mineral of metasomatic origin. In association with garnet and clinopyroxene, plagioclase occurs only in relatively low-pressure rocks of the complex that have undergone retrograde secondary alterations. Plagioclase inclusions in large garnet grains greatly facilitate the task of interpreting the conditions of metamorphism during rock formation. The assessment of the plagioclase composition on the microprobe underestimates the sodium content in the mineral due to its loss during the survey, and the actually measured plagioclase composition does not exceed 3 units of the anorthite component.

This error naturally underestimates the equilibrium pressure in the Grt-Cpx-Pl- Qz association within 0.1–0.2 GPa. For this reason, the compositions of the coexisting phases in Pl- bearing eclogites reflect the parameters (Tmax, Pmin) only of the final, relatively low-temperature stages of the evolution of the complex.

4. Chemical Zoning of Garnet in Crustal Eclogites. Results and Discussions

Eclogite and eclogite-blueschist complexes usually mark convergent suture zones of large structural- tectonic fragments of the Earth's crust and are characterized by a constantly changing regime of metamorphism and tectonic activity. The history of the development of the Maksyutov and Atbashi complexes against this background looks quite contrasting. In addition to the previously established differences in the depth of formation and periodicity of metamorphic events, specific features and conditions for the formation of contrasting series of rocks - high-pressure eclogitic inclusions and host gneiss-schist matrix - were determined for each of them [9,27]. The formation of structures of coherent development and boudinage occurred in different ways: multi-stage sequential development in the Maksyutov terrane and one-stage transformation in the Atbashi complex.

4.1 Maksyutov Eclogite-Blueschist Complex

Metamorphic history has pretty much battered the Ural eclogites. The maximum parameters of metamorphism of the Maksyutov complex are determined by the presence of rocks with the participation of UHP minerals: T=650–780oC and P = 2.7–3.2 GPa [15,25]. Our studies confirmed the top level of the complex formation: prograde stage − 800→900°C and retrograde 910→730°C at P = 3.2→3.5 GPa. Such parameters were preserved in the compositions of coexisting phases in large blocks of titanium eclogites (village Shubino, area Karayanovo), raised to the surface as a result of tectonic mélange - rapid removal and boudinage of eclogite bodies. Subsequent processes of regressive and repeated progressive metamorphism took place at lower parameters, up to 310–460°C at P = 1.1–1.5 GPa [9]. But even with such a decrease in the parameters, garnet in high-pressure inclusions of eclogite rocks, it retains its composition, fixing the conditions of metamorphism in the early stages of the development of the complex. The phenomena of prograde and retrograde metamorphism in the Maksyutov Complex are repeated many times, and their PT trends, constructed from the compositions of the Grt-Cpx paragenesis, form conjugate pairs characterizing the regimes of individual stages (cycles) of Page 8/23 the development of the complex. At least four such cycles have been recorded from microprobe studies of coexisting Grt and Cpx (Table 1). The maximum PT parameters of each cycle are fixed in the compositions of coexisting phases due to the rapid removal of rock to the surface as a result of the pulsating process of tectonic mélange.

Cycle	Prograde trends		Retrograde trends		Age, Ma
1	T=800→900	ºC, P=3,5 GPa	T=910→730	ºC, P=3,5 GPa	533 ± 4,6 [1] 530 − 515 [3]
2	T=500→790	ºC, P=2,5→3,0 GPa	T=740→610	ºC, P=2,5→1,4 GPa	392–485 [2]
3	T=460→680	ºC, P=1,1→1,5 GPa	T=690→430	ºC, P=1,3→1,0 GPa	360–465 [2] 360–380 [3]
4	T=310→515	ºC, P=0,9→1,2 GPa	T=545→310	ºC, P=1,0→0,6 GPa	320–335 [2]

Table 1: Temperature trends and prograde-retrograde cycles of development of the Maksyutov complex (summary) [9]

Generalized conjugate pairs of progressive and regressive PT trends in the development of the Maksyutov eclogite-blueschist complex. Age references are for: [1] Valizer et al., 2013; [6,15].

The successive change and alternation of prograde and retrograde stages is reflected in the composition of the garnet, which demonstrates complex multidirectional, sometimes inversion zoning.

Figure 1 shows garnet from the central part of the eclogitic boudina of the Karayanovo site, which contains the entire history of its crystallization: the initial prograde stage at 568–751°C, retrograde replacement of the central part of the grain for secondary minerals (Gln + Mu + Chl + Qz) and the formation of a high-temperature garnet rim at maximum parameters (689–789 oC). Fractured and slightly rounded garnet grain from eclogite of the second prograde level of metamorphism (Table 1) shows in its composition the maximum the PT trend for this location: T=568→751oC (Figure. 1a).

Its central part contains an inclusion of acid plagioclase (Pl0.95-Pl0.85), which makes it possible to estimate the value of the equilibrium pressure of 1.4–1.7 GPa. The presence of inclusions of plagioclase and clinopyroxene in the center of the garnet grain indicates a confident thermodynamic equilibrium between the phases, the composition of which reflects the initial moment of their crystallization at T = 568°C. The progressive growth of garnet occurred with a temperature difference of more than 180°C, and this grain could only be preserved as a result of tectonic mélange. During the retrograde pause, the original garnet grain was dissolved and partially replaced by secondary minerals (Gln + Mu + Chl + Qz) (Figure. 1b).

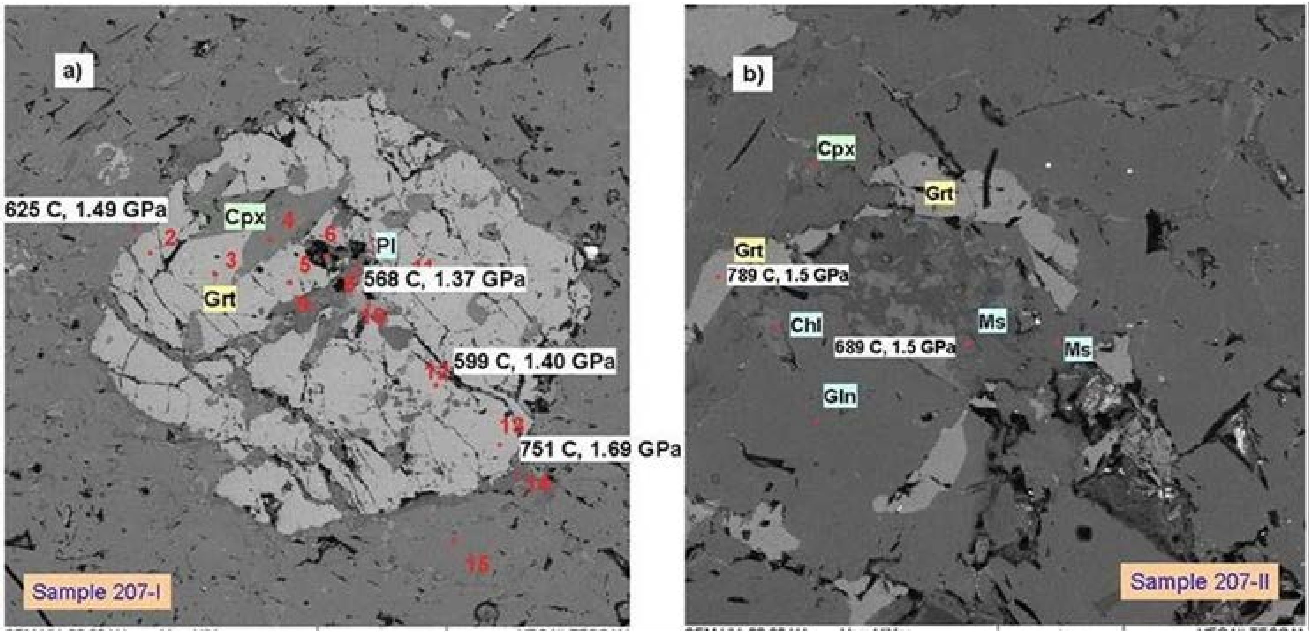

Figure 1: Two-stage prograde crystallization of garnet from eclogite boudina

At the same time, the outlines of an idiomorphic, well-faceted center are preserved, which are overgrown with a high-temperature rim of a newly formed garnet with maximum parameters of its composition XPrp=0.56 and an advanced prograde trend up to T = 789 ^{o}C. The preservation of low-temperature phases in the center of a garnet grain and a significant difference in its crystallization temperatures indicates a fairly rapid advancement of the rock to the surface in the process of tectonic mélange and boudinization. The absence of regressive changes in the composition of the garnet indicates that the rock was not affected by diaphthoresis and was preserved in the wake of one (albeit discontinuous) prograde cycle of the development of the complex.

The four-stage development of the Maksyutov Complex makes it possible to trace the transition of high- pressure rocks from the state of autonomous and isolated boudins, bodies, and inclusions into the host complex at the stage of its coherent development. Figure 2a shows complex inversion zoning of garnet in sample 216-1 from an eclogite lens (Karayanovo site). The central part of the coarse grain retains traces of a regressive change in composition from Prp15Alm57Sps2Grs26 to Prp14Alm61Sps2Grs23, fixing the PT conditions of the second stage of metamorphism (Table 1).

It is separated from the outer zone by a rim of low-temperature minerals Chl + Gln + Mu + Pl + Qz + Ilm, which may have shielded the crystal core from the impact of the changed conditions of the next stage of the development of the complex. As a result, a new composition of garnet with opposite progressive zoning from Prp19Alm58Sps1Grs20 to Prp26Alm60Sps2Grs12 was formed in the outer newly formed shell, which reflects the conditions of the third prograde stage of metamorphism (T = 430–680°C).

Thus, garnet, which originated in eclogitic rock under high-pressure conditions, after its rise and possible boudination, remains in the rock in a stable state and, at a new stage of coherent development, retains its original composition with the parameters of previous events, despite a sharp (opposite) change of direction evolution of metamorphism between the second and third stages.

At the coherent stage of the development of the complex, in the process of a regressive decrease in the parameters of mineral formation in the enclosing stratum of Grt-Cpx-Gln gneisses and schist's, eclogite- like rocks with plagioclase (Grt + Cpx + Pl + Qz) are often formed in the form of interlayers and lenses involved in joint processes of folding and diaphthoresis. In these rocks, garnet also remains a stable phase, sensitively reacting to changes in the parameters of mineral formation. Simultaneously, new prograde garnet grains of the next cycle in the interval can crystallize in the rock matrix. In sample 154a-1 (Figure. 2b), the inclusion of plagioclase in the center of a well-faceted garnet grain allows us to estimate the PT parameters of the initial stage of the third cycle: T = 440–490°C at P = 1.2–1.3 GPa. The combination of high inertness of garnet to changes in its initial composition and high activity of crystallization of new grains and outgrowths under changed conditions of metamorphism makes it possible to reproduce the entire history of the development of the complex.

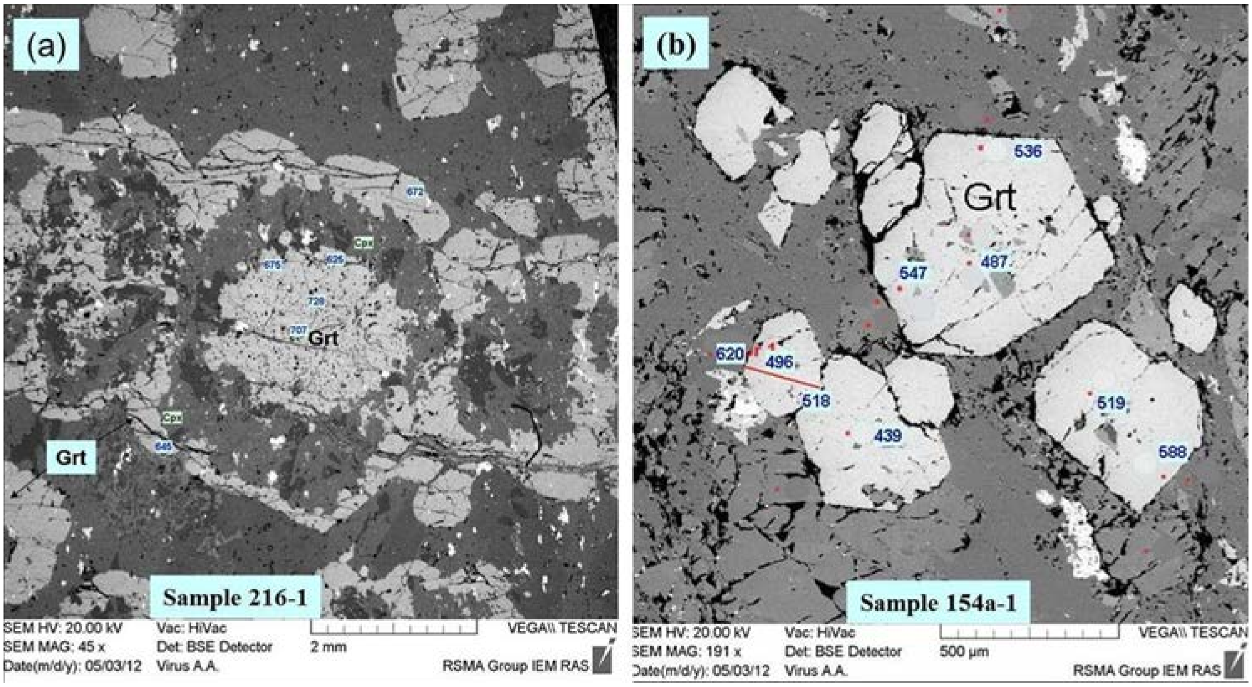

Figure 2: Contrasting zoning of garnet in eclogites of the Maksyutov Complex on stages of coherent development:
(a) inversion zoning of garnet (Sample 216-1, Karayanovo site): regressive (695 °C/1.6 GPa → 615 °C/1.4 GPa) in the center of the grain and slightly progressive (630 °C/1.44 GPa → 660 °C/1.46 GPa) - in the marginal part; (b) Newly formed garnet of the third prograde stage of metamorphism, Shubino village [9].

These relationships are most clearly seen in the eclogitic layers within the enclosing gneissic matrix (Figure. 3). In the eclogite layer in the Grt-Cpx-Gln-Mu-Qz matrix, the garnet has multi-directional zoning. In the central parts of large destroyed grains (Figure. 3, area 200-1), the progressive zoning of the initial stage of crystallization (622→680 ^{o}C) was preserved. Their oppressed rounded shape indicates the processes of dissolution and recrystallization of garnet with a continuing increase in temperature. Inside the eclogite layer, on a progressive wave of mineral formation, well-faceted euhedral crystals with PT parameters of the second level of metamorphism are formed (Figure. 3, area 200-II). This part of the eclogite interlayer was preserved as a result of tectonic mélange even before the inclusion of the layer in the total mass of the host rock unit. Their joint development under the influence of the regressive stage of metamorphism gradually manifests itself in the contact zone with the matrix. As we move towards the contact with the host rock (Grt + Cpx + Gln + Ms + Qz), the zoning of the garnet reverses, Grt-Cpx pairs record a general trend of decreasing temperatures: 770→677→619 ^{o}C (Figure. 3, area II). At the boundary with the matrix, the regressive zoning of the garnet gradually increases: 744→673, 691→547°C (Figure. 3, areas III, IV), fixing the influence of the host complex. In the gneissic-schist matrix, newly formed small euhedral garnet crystals, as a rule, have weak variable zoning. They contain almost no inclusions and register an interval of relatively low temperatures: 487–564°C (Figure. 3, area IV). The presence of progressive and regressive zoning in one sample, as well as grains with different levels of temperature gradient, indicate the cyclical nature of the process of formation of these rocks under quasi-equilibrium conditions. Thus, during the coherent development of the complex, high-pressure eclogite inclusions and the gneissic-schist host member ended up in a single section of the terrane. Characteristically, clinopyroxene in the eclogite layer and in the matrix retains a stable composition within XJd=0.34–0.41, and only the garnet zoning XPrp=0.11–0.21 fixes the temperature spread (> 280 ^{o}C) during the formation of this rock.

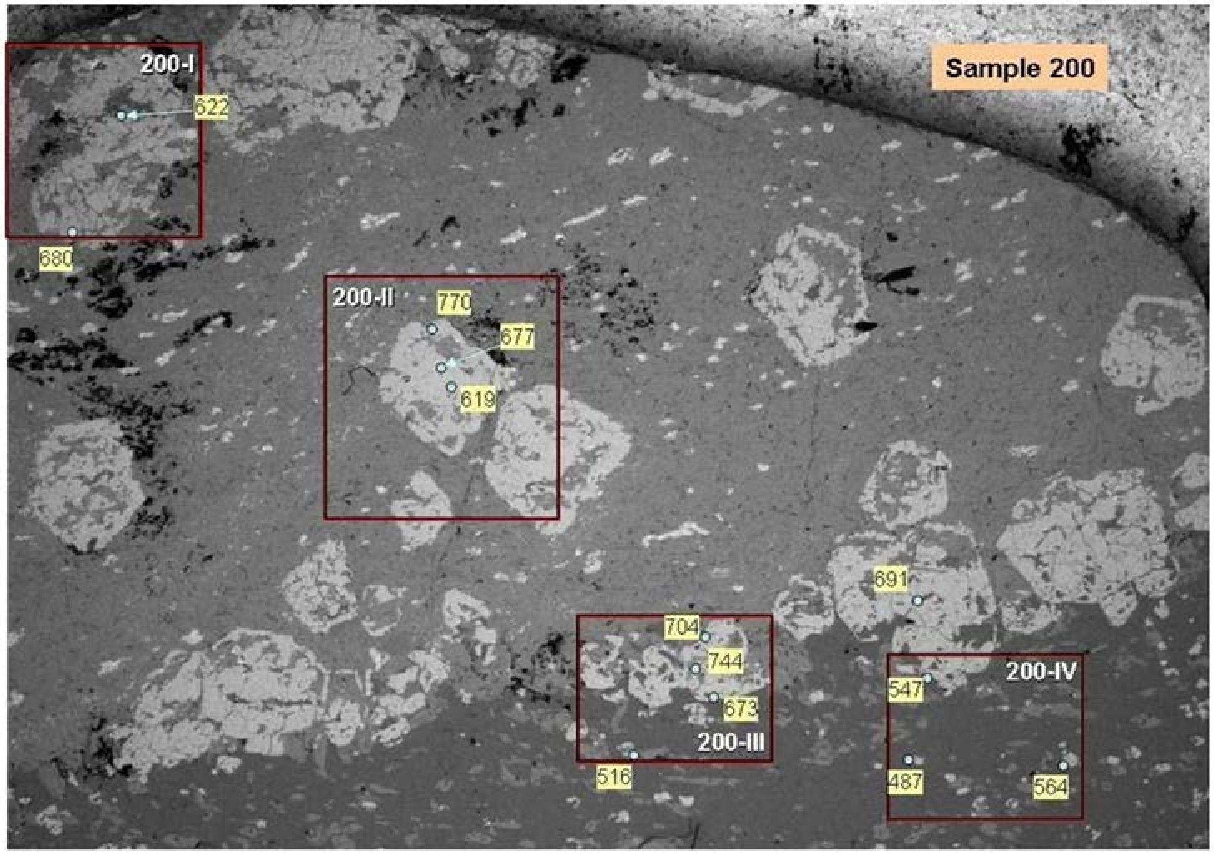

Figure 3: The large grains of garnet from the eclogite interlayers retain progressive zonality (620→770 ºC). On the boundary with the matrix (Grt + Cpx + Gln + Mu + Qz), garnet shows inverse zonality with parameters 690→550 ºC. Small idiomorphic garnet crystals in the matrix of rock show a weak progressive zonality at an even lower temperature of 490→560 ºC. Rectangles mark individual areas of microprobe studies

4.2 Atbashi Eclogite-Blueschist Complex

The Atbashi eclogite-blueschist complex differs in contrast from the Maksyutov EBSK in terms of the level of metamorphism and one-act history of its development [3,6,10]. The question of the origin of the contrasting series of rocks of the Atbashi complex has recently been discussed in the system of the high-pressure metaophiolite belt "Chinese Western Tien Shan" [13]. Both concepts of the formation of such series have been discussed, but both are still controversial. The fact is that the varied composition of the host rocks of the complex - pelitic, pelitic-feldspar, mafic, quartz-carbonate rocks, quartzites and quartzite schist's, does not have clear evidence of high pressure (HP) conditions. The maximum formation pressure of matrix rocks does not exceed 5–7 kb, while eclogitic and eclogite-like (Grt-Cpx, Grt-Cpx-Gln) mineral associations indicate higher parameters: P up to 14–15 kb (in some samples up to 17–19 kb) in the range T=350–650 ºC [28]. In addition, prominent eclogite inclusions, both separate blocks and as part of layered rock units, are involved in the process of coherent development and cannot be considered as a product of tectonic mélange [20].

Eclogites among the rocks of the complex are of subordinate importance. On the one hand, they have clearly separated independent outlines, form separate blocks and forms in the form of boudins, layers and lenses. On the other hand, they are involved in folded structures of later origin. The degree of metamorphism decreases from the central parts of eclogite inclusions to the contacts of the host complex. The petrographic relationships of rock-forming minerals demonstrate the constant reaction relationships of HP minerals with newly formed low-temperature associations with the participation of Gln, Chl, Ep, Zo, Tc, etc. The thin sections show how depressed the eclogitic parageneses feel in the host greenschist complex [29,30].

4.2.1 Stage of Tectonic Mélange in the Development of the Atbashi Complex

Mass determinations of the formation parameters of Grt-Cpx associations from contrasting series of rocks of the Atbashi complex demonstrate a single-act evolutionary history of its formation. In the central parts of large eclogite boudins and separate isolated bodies, the progressive zoning of garnet (XPrp=0.11–0.53) and the omphacitic composition of pyroxene (XJd=0.4–0.6) fix prograde PT metamorphism trends with low (~ 10 deg /km) geothermal gradient and parameters up to T = 650–700°C and P = 14–15 kb, sometimes up to 18–19 kb (Figure. 4a). These conditions arose at an early stage of the formation of the complex and were preserved in the bodies of eclogites as a result of tectonic mélange.

They are not associated with the subsequent formation of host rocks, which, in contact with eclogites, record lower parameters - up to P = 0.8-4.0 kb and T-300-550°C. The initial (?) rocks contacting them – Grt-Am gneisses and schist's have preserved traces of prograde metamorphism of boudins, and continue the eclogite PT trend at low temperatures down to T-300-550°C at P = 8–10 kb (Figure. 4a) .

4.2.2 Transitional Stage of Development of the Atbashi Complex

As we move away from the central part of the boudina, the Grt-Cpx associations still retain a prograde tendency at a fairly high pressure: from 385C/11.0 kb to 600C/13.5 kb, but some decrease in parameters to the area of lower values is already noticeable. In the low-pressure Grt-Chl matrix associations, negative slopes of P-T trends are already manifested (Figure. 4b).

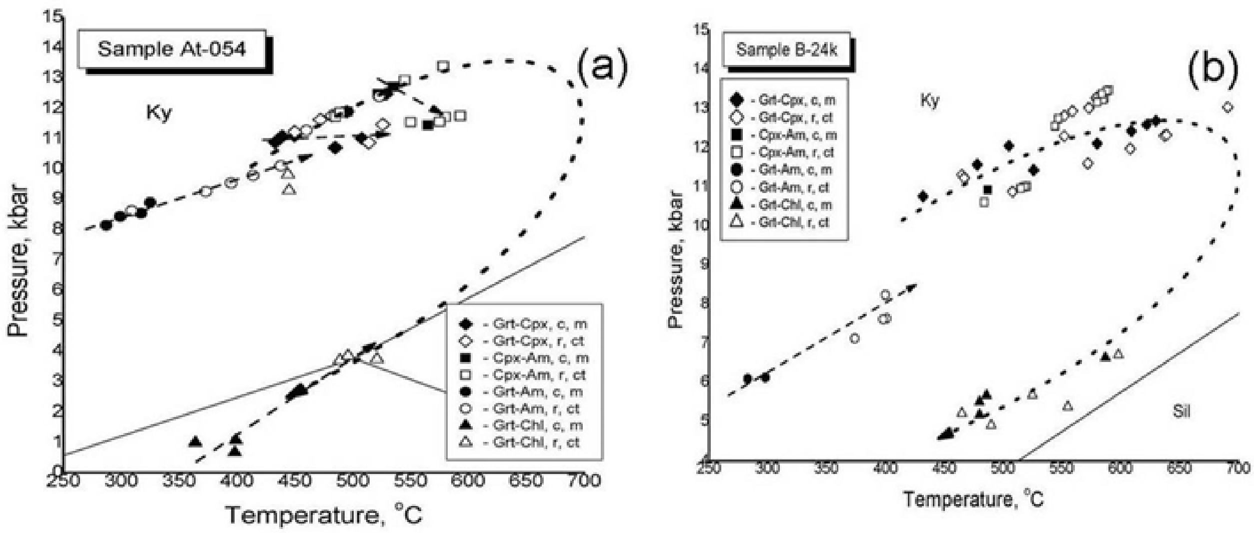

Figure 4: PT conditions for the formation of high-pressure (HP) rocks of the eclogite-blueschist complex of the Atbashi, preserved as a result/process of tectonic mélange: (a) progressive PT trend in eclogite from the central part of the boudina; (b) conjugate prograde Grt-Cpx and Grt-Am PT trends at the contact of eclogite with Grt-Am gneiss in the host Grt-Chl schists

Further - more, when moving to the host quartzite-schist strata, a change in the direction of the PT trend of metamorphism is signed to be "clockwise", which means the transition to the coherent stage of development of the complex. This trend extends to a wider composition of the host rocks, in which rather high parameters of the Grt-Cpx balance and the progressive direction of its trend remain. In the marginal parts of the eclogite bodies and in the rocks surrounding them, there is a tendency for the PT trends to reverse clockwise ("clockwise"). The progressive zoning of the rock-forming phases (Grt, Cpx, etc.) reverses, marking the beginning of the retrograde stage of metamorphism. The maximum parameters of metamorphism at this stage do not exceed P = 1.8-5.0 kb and T = 450–600°C (Figure. 5a).

4.2.3 Coherent Stage of Development of the Atbashi Complex

The coherent stage of development of the complex is characterized by a noticeable decrease in pressure to 5–6 kb at T = 550–600°C and a significant reversal of the PT trends of mineral associations clockwise (Figure. 5a). Simultaneously, in the Grt-Gln-Chl shale strata at the regressive stage, the prograde P-T trends change to retrograde ones, the disappearance of eclogites and Grt-Cpx gneisses from the section, and the formation of differently directed zonality of minerals.

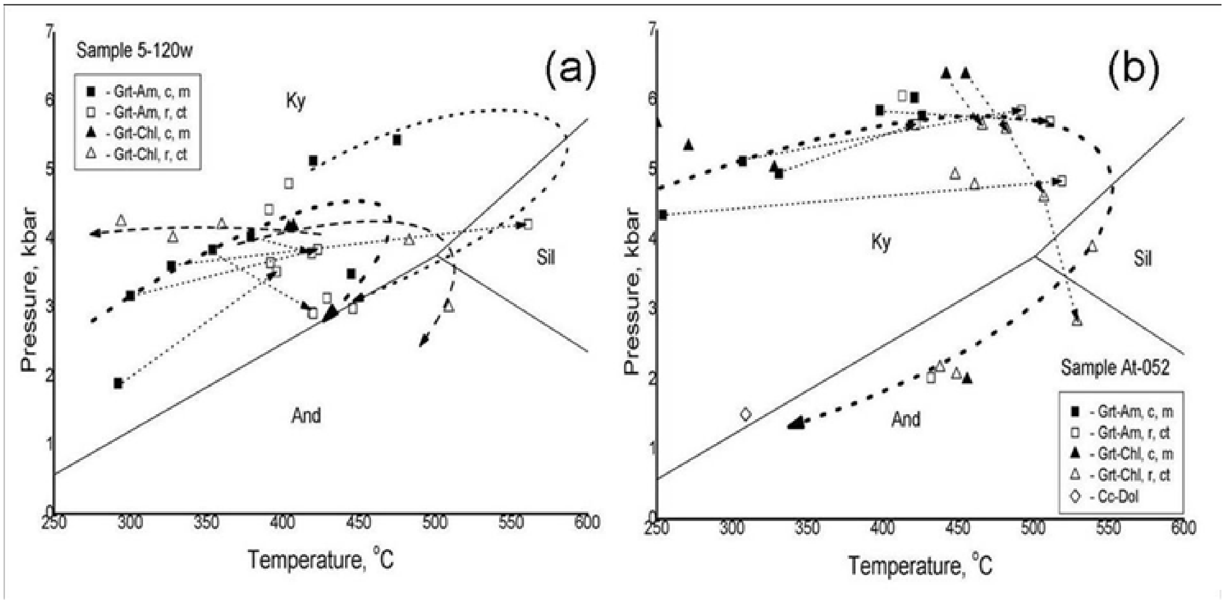

Figure 5: Coherent developmental stage of the Atbashi eclogite-blueschist complex: (a) clockwise change of direction of P-T metamorphism trends in the Grt-Am and Grt-Chl paragenesis; (b) the final stage of the coherent formation of the Atbashi complex under the conditins of retrograde low-pressure metamorphism according to the data on the compositions of coexisting phases in the Grt-Am and Grt-Chl mineral vapors

The progressive zoning of the rock-forming phases (Grt, Cpx, etc.) reverses, marking the beginning of the retrograde stage of metamorphism. The maximum parameters of metamorphism at this stage do not exceed P = 1.8-5.0 kb and T = 450–600°C.

In the Grt-Cpx and Grt-Cpx-Gln crystalline schist's of the host complex, second-generation pyroxene is formed with a minimum proportion of the jadeite component (XJd=0.03–0.08). Its composition in equilibrium with garnet (XPrp=0.05–0.21) shows parameters that are fundamentally different from the HP conditions for the formation of eclogite boudins. At the later stages of the development of the complex, eclogite inclusions, interlayers, and boudins formed under HP conditions as a result of tectonic mélange are included in the enclosing glaucophane-schist complex and, in the process of its coherent development, form a single final terrane complex. The series of PT trends of these rocks is mainly retrograde in nature from P = 4.0-3.5 kb and T = 550 − 500°C, to P = 2.0-1.2 kb and T = 450 − 300°C, which characterizes the final stage of the coherent development of the complex.

5. Discussion

A comparative study of two eclogite-blueschist complexes (the Maksyutov complex and the Atbashi complex) quite contrasting in terms of the level and periodicity of metamorphism showed, within the framework of the tasks set, comparable results, both in terms of the properties of garnet and in the formation of contrasting series of rocks in EBSC.

5.1 Information Properties of Minerals in the Eclogitic Paragenesis Grt + Cpx + Pl + Qz

Garnet, originated in eclogite rock under high-pressure conditions, after its rise and possible boudination, remains a stable phase in the process of further development of the complex. It goes through all the stages of terrane development: UHP stage of eclogite formation at the stability parameters of diamond and coesite (in boudins and large eclogite bodies), HP conditions of stability of Pl-bearing eclogite-like rocks in the interlayers and lenses of the host complex, in the gneiss-shale strata of rocks of medium and low stages of metamorphism. The mobility of its composition and the ability to save traces of previous stages of development make garnet an indispensable sensor (indicator) of the evolution of the physicochemical conditions of the terrane formation.

Clinopyroxene, compared to garnet, is a more stable phase to changes in its composition. With a change in the conditions of metamorphism and the direction of its evolution, the composition of pyroxene can remain relatively constant both in magnesian content when estimating the temperature in equilibrium with garnet, and in terms of the jadeite component when estimating pressure in equilibrium with plagioclase. In the eclogitic paragenesis, clinopyroxene manifests itself as a reference phase, the composition of which fixes both PT parameters of the Grt + Cpx + Pl + Qz equilibrium. However, the accuracy of these measurements largely depends on the stability of plagioclase and, as a rule, does not exceed ± 0.5 kb in pressure and ± 25°C in temperature.

Plagioclase is the most vulnerable to pressure estimation by Ab-Jd-Qz equilibrium. Losses of sodium during microprobe analysis, limited range of estimated pressure values, and the impact of metasomatic processes on the composition of Pl do not make it a sufficiently reliable sensor in the analysis of eclogitic mineral associations. Often, one has to be satisfied with only minimal pressure estimates within the stability field of the Ab-Jd-Qz paragenesis, allowing for some nonequilibrium with omphacite pyroxene.

But, since in Grt-Cpx equilibrium the pressure value has little effect on the determined temperatures, studies of relative temperature dependences are possible in the entire range of Pl and Cpx compositions coexisting in a given sample.

5.2 On Models of Formation of Contrasting Series of Rocks
Data on the composition of garnet and its accompanying minerals in eclogite inclusions and host rocks of the Maksyutov and Atbashi complexes support the idea of the formation of contrasting series of EBSC rocks as a result of tectonic mélange at an early stage of complex development (eclogite bodies, blocks, boudins) and coherent processes of formation of host strata on the regressive stages. However, the gradual transitions and merging of the stage of tectonic mélange and the stage of coherent development, noted in the Atbashi complex and in individual samples of the Maksyutov EBSK, showed that these processes proceed in the single line of the metamorphic events and are not always independent. On the other hand, temporary breaks between two independent processes are visible in the multistage Maksyutov complex when the direction of its development changes. Thus, the question of the continuity or independence of evolutionary processes according to the models of tectonic mélange or coherent development remains open. In any case, the transition of one process into another and its final consequences are practically not always visible and significant, and in the process of development of the complex, due to the involvement of previously formed rocks in subsequent metamorphic events, they are erased and become less noticeable and effective.

Metamorphism Parameters of Contrasting Series of Rocks
Nevertheless, as a result of the studies, in addition to the known structural and morphological features, petrological features have been established for contrasting series of rocks, which make it possible to unambiguously classify their belonging to one or another model of their formation. The rocks formed in the process of tectonic mélange are characterized by an order of magnitude higher level of metamorphism with a progressive direction of the PT trends of its development, prograde zoning of the main rock-forming phases - Grt, Cpx, Pl and the maximum values of their fundamentally important compositional parameters: XPrp - in garnet, XJd - in clinopyroxene, XAb. - in plagioclase.

The rocks of coherent development are characterized by signs of the opposite type: a reduced level of metamorphism with characteristic negative PT trends, regressive zoning of rock-forming phases, and relatively low values of their key compositional parameters. These signs should be supplemented by the synfolded relationships of the eclogite interlayer with other rocks of the host complex, by change in the direction of the PT trends in the development of the rocks of the complex of the "clockwise" type, and the formation of new phases of a fundamentally different composition: garnet, pyroxene, and albite, first of all.

In both studied complexes, the level of metamorphism of eclogite inclusions, boudins, and bodies is an order of magnitude higher than that of host rocks. It is with the maximum parameters of metamorphism up to 800–900°C and 3.2–3.5 GPa that the finds of high-pressure minerals (diamond, coesite, etc.) in the Maksyutov complex are associated. At the same time, the level of metamorphic development of the host gneiss-schist's strata of this complex at the regressive stage drops to the low of the greenschist facies. In the Atbashi EBSC, the maximum parameters of Grt-Cpx-Pl-Qz equilibrium in eclogite boudins and bodies reach 650–700°C and 13–15 kb. (sometimes up to P=18–19 kb.), while the host rock complex was formed under conditions of low-temperature metamorphism, the parameters of which are reduced to 300–350°C and 2–4 kb.

Contrasting series of rocks have a fundamentally different direction of development of metamorphic processes: prograde evolution in eclogite inclusions and reverse prograde-retrograde development in mineral associations of shale strata. As the distance from the central parts of the eclogite bodies moves away, the prograde PT trends gradually turn into "clockwise" trends, with the subsequent disappearance of clinopyroxene from the equilibrium and the appearance of Grt-Am, Grt-Gln, Grt-Chl associations, micaceous schist's and quartzites. Clockwise reversal of prograde PT trends in Grt-Cpx rocks is a characteristic sign of the initial stage of their coherent development in the host complex.

All critical phases (Grt, Cpx, Pl, etc.) of eclogite bodies have progressive zoning, the widest and most stable composition of key components: in garnet, the pyrope index XPrp varies from 0.108–0.113 - in the centers of grains to 0.533 at the edges; the content of XJd in Cpx reaches – 0.50–0.66; the proportion of albite in plagioclase reaches XAb = 0.40. In the retrograde rocks of the host complex, the composition and zoning of the coexisting phases are not constant and can vary from grain to grain; the regressive zoning of reference minerals predominates against the background of regressive PT trends of the host rocks.

At the end of the coherent stage of development of the complex, at the condition of regressive metamorphism and diaphthoresis, manifestations of metasomatic processes are characteristic: plagioclase albitization, carbonatization of clinopyroxene associations, and general silicification of rocks.

6. Conclusion

The study of the properties of garnet and its ability to fix in its composition the conditions of mineral formation in developing metamorphic systems was carried out on two diverse eclogite-blueschist complexes - the Maksyutov Complex (Southern Urals) and the Atbashi Complex (Southern Tien Shan). Both complexes belong to the Ural-Mongolian folded belt, have similar age characteristics and structural- tectonic position, but differ in the level and number of metamorphic transformations. These features are reflected in changes in the composition of garnet and make it possible to use the obtained regularities to solve a number of other problems, for example, the issue of the formation of contrasting series of rocks in eclogite complexes. As a result of the research, the following conclusions were obtained.

1. Garnet, originated in eclogite rock under high-pressure conditions, after its rise and possible boudination, remains as a stable phase in the process of further development of the complex. It goes through all stages of the terrane development from the UHP stage in field of stability of diamond and coesite to the rocks of the gneiss-schist complex of medium and low grades of metamorphism. In high- pressure rocks of eclogite-glaucophane schist complexes, garnet has unique properties to retain its original composition, reflecting the PT parameters of the initial stages of metamorphism, and simultaneously record changes in these parameters in subsequent metamorphic processes in new grains, outgrowths, and replacements.
High inertness to changes in its composition, formed at high parameters, and high activity towards crystallization of grains and outgrowths of a different composition under changed conditions of metamorphism are the most important properties of garnet of eclogite-glaucophane schist complexes.
2. The formation of contrasting series of rocks of eclogite complexes occurs as a result of tectonic mélange and a coherent stage of development of the enclosing gneiss-shale sequence. Boudins and small bodies of eclogites that appeared at the stage of tectonic mélange are involved in the processes of joint development of the complex at the next stages of the evolution of the complex. Garnet is a sensitive indicator of formation conditions and properties of contrasting series of rocks. The composition and zoning of the garnet show clear signs of tectonic mélange (progressive zoning of key minerals, prograde direction of PT trends in the evolution of metamorphism) and of coherent stage in the development of the complex (negative zoning of minerals, change in the direction of PT trends of the "clockwise" type). In the multistage history of the Maksyutov EBSC, these processes are separated in time and are sometimes repeated at the next stages of the development of the complex. In the one-stage Atbashi EBSC, both events occur sequentially in the same key of metamorphism evolution.
3. The phenomena of tectonic mélange and coherent development of EGS complexes can be considered as two independent phases of the general process of metamorphic evolution, differing in the level and nature (orientation) of metamorphism: prograde and much higher level for eclogite blocks and inclusions, and retrograde for the host complex. They also differ in the composition and zonation of rock-forming minerals: progressive, with the maximum parameters of key compositions in boudinaged eclogites, and regressive, in minerals from host rocks. A change in the direction of the PT trends of metamorphism of the "clockwise" type and the reverse (negative) zoning of critical minerals is a characteristic feature of the initial stage of the coherent development of Grt-Cpx rocks in the transition zone. However, one should not overestimate the significance of these differences, since in the process of development of the complex, due to the involvement of previously formed rocks in subsequent metamorphic events, they are erased and become less noticeable and effective.

Funding:
The work was financially supported by the governmental projects FMUF-2022-0004, No. 1021051302305-5-1.5.2; 1.5.4 of the D.S. Korzhinskii Institute of Experimental Mineralogy, grant RFBR 05- 05-64561, and the Program Fulbright of the Institute of International Education, 2015.

Acknowledgments: Authors thank three anonymous reviewers for their constructive suggestions.

Conflicts of Interest: The authors declare no conflict of interests.

References
1. Perchuk, L. L. (1977). *Equilibria of rock forming minerals.* Saad Publications, Translations Division.
2. Powell, R. (1985). Regression diagnostics and robust regression in geothermometer/geobarometer calibration: the garnet-clinopyroxene geothermometer revisited. *Journal of metamorphic Geology, 3*(3), 231-243.
3. Kotova, L. S. (1989). Petrochemical evolution of the eclogite-glaucophane schist complex of the Atbashi Ridge (Southern Tien Shan). In: Geochemistry of igneous and metamorphic formations of the Tien Shan. Fr.: Ilim, 110-127.
4. Perchuk, A. L., (1992). New variant of the omphacite–albite–quartz geobarometer taking into account the structural states of omphacite and albite. *Dokl. Akad. Nauk 324*(6), 1286-1189.
5. Lennykh, V. I., Valizer, P. M., Beane, R., Leech, M., & Ernst, W. G. (1995). Petrotectonic evolution of the Maksyutov Complex, Southern Urals, Russia: implications for ultrahigh-pressure metamorphism. *International Geology Review, 37*(7), 584-600.
6. Dobretsov, N. L., Shatsky, V. S., Coleman, R. G., Lennykh, V. I., Valizer, P. M., Liou, J., ... & Beane, R. J. (1996). Tectonic setting and petrology of ultrahigh-pressure metamorphic rocks in the Maksyutov Complex, Ural Mountains, Russia. *International Geology Review, 38*(2), 136-160.
7. Leech, M. L., & Ernst, W. G. (2000). Petrotectonic evolution of the high-to ultrahigh-pressure Maksyutov Complex, Karayanova area, south Ural Mountains: structural and oxygen isotope constraints. *Lithos, 52*(1-4), 235-252.
8. Fedkin, V.V. (2004). Mineralogical Geothermobarometry in Developing Metamorphic Systems. In: "Experimental mineralogy: some results on the century's frontier". Moscow: "Nauka Publ." Vol. II 172- 187.
9. Fedkin, V. V. (2020). Four stages of the thermal evolution of

eclogites from the Maksyutov Complex (South Urals). *Russian Geology and Geophysics, 61*(5-6), 543-558.
10. Dobretsov, N. L., Sobolev, N.V. (1977). Glaucophane-schist belts. In: Metamorphic complexes of Asia. N: Nauka, 283-288.
11. Dobretsov, N. L., & Dobretsova, L. V. (1988). New mineralogic data on the Maksyutovo eclogite-glaucophane schist complex, southern Urals.
12. Meyer, M., Klemd, R., Hegner, E., & Konopelko, D. (2014). Subduction and exhumation mechanisms of ultra-high and high-pressure oceanic and continental crust at Makbal (Tianshan, Kazakhstan and Kyrgyzstan). *Journal of Metamorphic Geology, 32*(8), 861-884.
13. Liu, F., Xu, Z., Yang, J., Maruyama, S., Liou, J. G., Katayama, I., & Masago, H. (2001). Mineral inclusions of zircon and UHP metamorphic evidence from paragneiss and orthogneiss of pre-pilot drillhole CCSD-PP2 in north Jiangsu Province, China. *Chinese Science Bulletin, 46,* 1038-1042.
14. Hacker, B. R., Andersen, T. B., Johnston, S., Kylander-Clark, A. R., Peterman, E. M., Walsh, E. O., & Young, D. (2010). High-temperature deformation during continental-margin subduction & exhumation: The ultrahigh-pressure Western Gneiss Region of Norway. *Tectonophysics, 480*(1-4), 149-171.
15. Miyashiro, A. (1974). Volcanic rock series in island arcs and active continental margins. *American journal of science, 274*(4), 321-355.
16. Chesnokov, B. V. (1965). Increasing of volume of quartz grains in eclogites of the South Urals. *Doklady Akademii Nauk SSSR, 162,* 176-178.
17. Leech, M., & Ernst, W. G. (1998). Graphite pseudomorphs after diamond? A carbon isotope and spectroscopic study of graphite cuboids from the Maksyutov Complex, south Ural Mountains, Russia. *Geochimica et Cosmochimica Acta, 62*(12), 2143-2154.
18. Beane, R., & Leech, M. (2007). The Maksyutov Complex: The first UHP terrane 40 years later.
19. Fedkin, V.V., Kotova, L.S. (2002). Are P-T paths caprices of experiment or peculiar features of the metamorphic evolution ? /*Experiment in Geosciences,* 10, (1), 39-46.
20. Fedkin, V.V., Novikov, G.V., Sipavina, L.V., Fedkin, A.V. (2007). Geochemical features of eclogite-glaucophane schist rocks of the Maksyutov (Southern Urals) and Atbashy (Southern Tien Shan) complexes. Mineralogy of the Urals. Collection of scientific papers. Miass-Yekaterinburg, 116-122.
21. Lü, Z., & Bucher, K. (2018). The coherent ultrahigh-pressure terrane of the Tianshan meta-ophiolite belt, NW China. *Lithos, 314,* 260-273.
22. Perchuk, L. L., Aranovich, L. Y., Podlesskii, K. K., Lavrant'eva, I., Gerasimov, V. Y., Fed'Kin, V. V., ... & Berdnikov, N. V. (1985). Precambrian granulites of the Aldan shield, eastern Siberia, USSR. *Journal of metamorphic Geology, 3*(3), 265-310.
23. Korzhinsky, D.S. (1973). Theoretical foundations for the analysis of mineral paragenesis M., Nauka, 288.
24. Ellis, D. J., & Green, D. H. (1979). An experimental study of the effect of Ca upon garnet-clinopyroxene Fe-Mg exchange equilibria. *Contributions to Mineralogy and Petrology, 71*(1), 13-22.
25. Ganguly, J. (1979). Garnet and clinopyroxene solid solutions, and geothermometry based on Fe-Mg distribution coefficient. *Geochimica et Cosmochimica Acta, 43*(7), 1021-1029.
26. Ai, Y. (1994). A revision of the garnet-clinopyroxene Fe2+-Mg exchange geothermometer. *Contributions to Mineralogy and Petrology, 115*(4), 467-473.
27. Ravna, K. (2000). The garnet–clinopyroxene Fe2+–Mg geothermometer: an updated calibration. *Journal of metamorphic Geology, 18*(2), 211-219.
28. Fedkin, V. V., Burlick, T. D., Leech, M. L., Shchipansky, A. A., Valizer, P. M., & Ernst, W. G. (2021). Petrotectonic origin of mafic eclogites from the Maksyutov subduction complex, south Ural Mountains, Russia.
29. Fedkin, V.V., (2022). Origin of Contrast Series Of Rocks In The Crust Eclogite-Blueschist Complexes. *Experiment in Geosciences, 28*(1), 5-9.
30. Fedkin, V.V. (1986) Geothermobarometry for Metamorphic Complexes and the Problem of Metamorphism Evolution. In: “Experiment in Solving of the Actual Geological Problems”. Moscow: “Nauka Publ.” 183- 200.