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## Research Article

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# **Origin of diamond in high-pressure rocks of the Maksyutov eclogite-blueschist complex: setting, criteria, and indicators**

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## **Highlights:**

- The Maksyutov blueschist complex (MC) in the Southern Urals is not a high-pressure/ultra-high-pressure (HP/UHP) metamorphic complex. The grade of its progressive metamorphism does not reach the thermodynamic stability field of diamond and coesite—minerals that serve as indicators of high-pressure petrogenesis.
- Alone micro-inclusions of diamond and coesite found within garnet and omphacite in the rocks of the MC are unrelated to the complex's prograde metamorphism. Instead, they were incorporated into the terrane substrate as part of ancient, high-pressure rock inclusions and cannot be taken as evidence of HP/UHP conditions during the formation of the orogen as a whole.
- The ancient age of these inclusions, the high-pressure/high-temperature conditions of their formation, their specific geochemical signatures, and their geodynamic setting point to a distinct—earlier and deeper—origin, likely resulting from mantle–crust interaction between a mantle plume and the surrounding substrate.

## **Abstract**

The Maksyutov blueschist complex (MC) in the Southern Urals is recognized as a high-pressure/ultra-high-pressure (HP/UHP) complex due to the presence of diamond and coesite—index minerals for high-pressure metamorphic conditions—within its rocks. However, such index phases are extremely rare in the Maksyutov complex and have been confirmed by instrumental analysis in only a few alone instances. These occurrences, along with suspected quartz pseudomorphs after coesite and graphite cuboids after diamond, are found within specific high-pressure lithologies—appearing as boudins, inclusions, and blocks—situated within both the lower (eclogite–schist) and upper (ophiolite-like) structural-compositional units of the complex. These inclusions differ from the surrounding host rocks in their greater age, higher formation parameters, and distinct geochemical signatures in both their bulk-rock and mineral compositions. These characteristics suggest a different, earlier, and deeper origin, likely resulting from mantle–crust interaction between a mantle plume and the surrounding substrate. The metamorphic grade of the host Maksyutov complex, in terms of its P-T conditions, never reached the thermodynamic stability field of diamond or coesite. Consequently, the presence of these HP/UHP inclusions is unrelated to the prograde subduction-related metamorphism of the complex; therefore, the classification of the Maksyutov terrane as an HP/UHP complex cannot be considered substantiated.

## **1. Introduction**

The Maksyutov eclogite–blueschist complex (MC) in the Southern Urals is well known as a high-pressure (HP) to ultra-high-pressure (UHP) subduction complex of Middle to Late Paleozoic age (Dobretsov et al., 1996; Lennykh et al., 1995). Evidence for ultra-high-pressure conditions—including suspected quartz pseudomorphs after coesite (Chesnokov & Popov, 1965), graphite cuboids after diamond (Leech & Ernst, 1998), diamond micro-inclusions in garnet (Bostick et al., 2003), coesite inclusions within double-layered shells in garnet and omphacite (Rusin et al., 2021), and high metamorphic parameters frequently determined via thermobarometry—has established a firm consensus regarding the ultra-high-pressure (UHP) status of the Maksyutov complex.

The discovery of diamond within the rocks of the Maksyutov complex is undoubtedly its most significant petrological feature and a primary indicator of the physicochemical conditions of its formation. Its presence defines the Maksyutov terrane as an ultra-high-pressure (UHP) complex.

However, the origin of the diamond—whether it is metamorphic, having formed during prograde subduction metamorphism, or mantle-derived (mantle-crustal), having been captured and transported by a mantle plume—remains a key point of debate. Our recent studies of the metamorphic processes in the MC (Fedkin, 2020) and the testing of the new geodynamic concept

known as the "Subduction Initiation Rule" (Whattam & Stern, 2011)—using the Maksyutov complex as a case study (Fedkin & Shchipansky, 2026)—have demonstrated that the peak prograde metamorphic conditions of the terrane did not reach the diamond and coesite stability fields. These results have brought the question of the origin of diamonds within the complex's rocks into sharper focus and defined the primary objective of this study: to assess whether the MC is a high-pressure/ultra-high-pressure (HP/UHP) complex.

## **2. Geological Setting**

The Maksyutov eclogite-blueschist complex is situated in the south-eastern part of the western slope of the Southern Urals, within the Main Uralian Fault zone; it forms a narrow tectonic block 15–20 km wide and 180–200 km long (Lennykh et al., 1995). The complex is part of the Southern Ural fold belt, and its geotectonic position is illustrated in Fig. 1. Two structural-compositional units are traditionally distinguished within the complex (Valizer & Lennykh, 1988; Lennykh et al., 1995; Dobretsov et al., 1996).

The lower, "subcontinental" eclogite-blueschist unit comprises glaucophane schists, feldspar-mica schists, and quartzites containing lenses, boudins, and blocks of eclogites, garnet-pyroxene rocks, and—less frequently—mafic-ultramafic rocks.

The upper, "ophiolite-like" unit consists of metavolcanic rocks and greenschist-facies crystalline schists, with subordinate amounts of graphitic quartzites and metagraywackes; it locally contains bodies and lenses of serpentinites, marbles, and metabasaltic rocks, as well as lawsonite-bearing eclogites and meta-ultramafic rocks.

The intermediate, Yumaguzin unit—comprising metasedimentary rocks of uncertain origin—is part of the lower series and constitutes the bulk of it. It includes quartzites and mica schists, along with distal turbidites and rare occurrences of garnet-pyroxene rocks and eclogites.

The protolith is of Precambrian age; the oldest zircon dates—characteristic of continental-type crust—span an interval from the Early Proterozoic (2060–2084 Ma) to the late Precambrian (1.1–1.4 Ga) (Valizer et al., 2011; 2026). Two subsequent age milestones, derived from magmatic and metamorphic zircons, reflect the crystallization of oceanic basalt ( $517 \pm 7$  Ma) and an Early Devonian prograde metamorphic event ( $411 \pm 5$  Ma) (Valizer et al., 2026).

There are two competing hypotheses regarding the formation of the Maksyutov complex. According to one, the eclogites within the complex were formed during an intense ultra-high-pressure (UHP) metamorphic event 550–600 million years ago (Valizer & Lennykh, 1988). The final stage of high-pressure (HP) metamorphism (320–385 Ma) occurred contemporaneously with

the metamorphism of the ophiolitic part of the complex (Dobretsov, 1974). According to an alternative view, the eclogites formed from Middle Devonian oceanic basalts (370–380 Ma). Some specialists on the Urals interpret this as evidence of a two-stage evolution of the terrane (Dobretsov, 1996; Shatsky et al., 1997; Valizer et al., 2011). However, a consensus has recently emerged among researchers placing the age of the final HP metamorphic stage at ~390 Ma. Based on the discovery of diamond and coesite micro-inclusions in the complex's rocks (Bostick et al., 2003; Rusin, 2021), the majority of researchers estimate the eclogite-facies metamorphic conditions to be within the ranges of T up to 650–700°C and P up to 2.8–3.2 GPa (Lennykh & Valizer, 1999; Beane & Leech, 2007; Dobretsov et al., 1996; Valizer et al., 2011, 2013b, 2026, etc.). These parameters fall near in the diamond stability field, and the question of the ultra-high-pressure origin of the Maksyutov complex remains open.

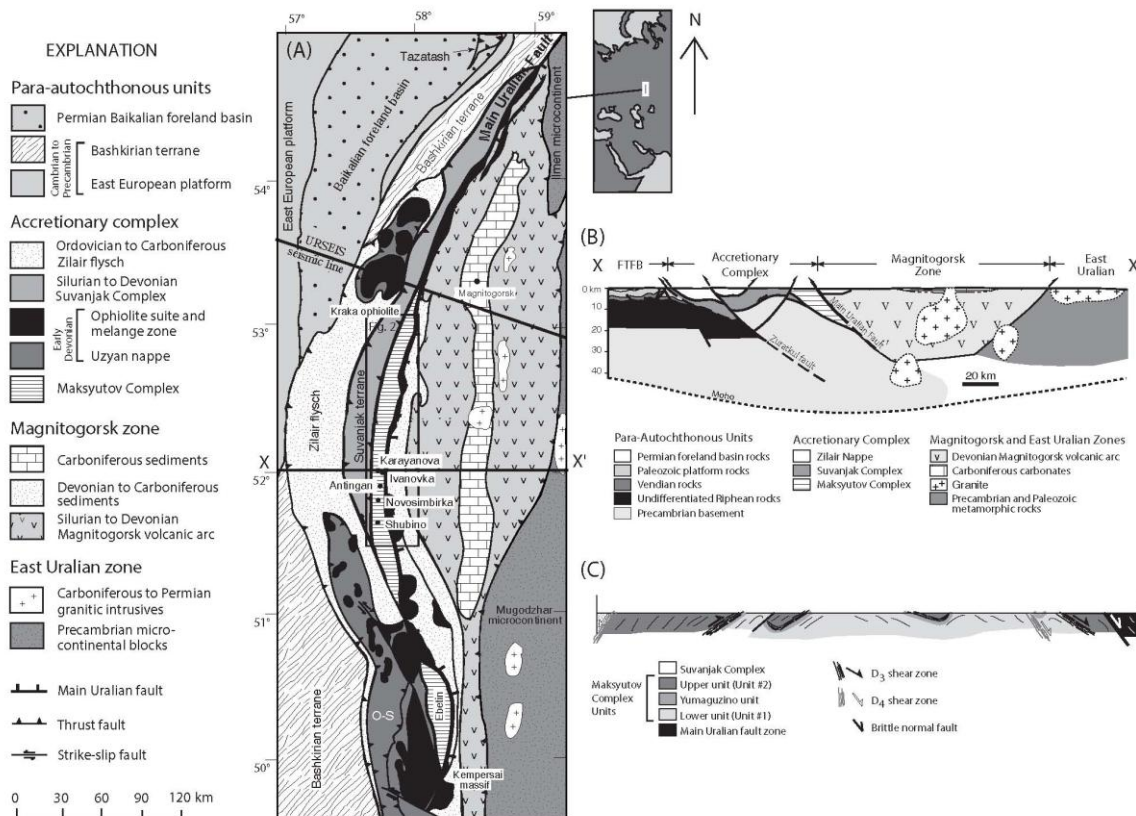


Figure 1

**Fig. 1.** Geotectonic map of the South Ural Mountains, Russia, adapted from (Leech and Stockli, 2000).

URSEIS (Urals Reflection Seismic Experiment and Integrated Studies) transect that provides important depth control for the South Ural Mountains.

### 3. Object and Methods

The study focused on the most thoroughly investigated and informative sections of the southern part of the MC, extending from the village of Shubino in the south to the former village of Karayanova

in the north. Eighteen representative samples of HP/UHP rocks from the complex's lower tectono-stratigraphic unit were analyzed for major, trace, and rare-earth elements using XRF and ICP-MS techniques at the Washington State University Geo-Analytical Laboratory. Data from the XRF and ICP-MS rock analyses, as well as calculated mineral compositions, were previously published in the context of a petrotectonic overview and a study on the metamorphism of mafic rocks within the MC (Fedkin, 2020; Fedkin et al., 2021). In the present study, these data are utilized for an independent geochemical analysis of the rock and mineral compositions, interpreted in light of the new concept of subduction initiation (Whattam & Stern, 2011) and the geodynamic classification of oceanic basalts (Pearce, 2008); this approach allows for an assessment of the role and degree of involvement of large crustal fragments in the subduction process. To estimate the P-T conditions of formation for eclogites and other Grt-Cpx rocks, the Grt-Cpx geothermometer (Powell, 1985) and the refined Grt-Cpx-Pl-Qz geobarometer (Perchuk, 1992) were employed. Mineral chemical composition, homogeneity, and zoning were investigated using electron probe microanalysis (EPMA) at the Institute of Experimental Mineralogy, Russian Academy of Sciences. The methodology and instrumentation for the microprobe analysis are described in the author's earlier publications (Fedkin, 2020; Fedkin et al., 2021).

**3.1. Garnet.** The primary focus was on studying the complex, multidirectional zoning of garnet, which serves as the most informative mineral—and the one most sensitive to changes in metamorphic parameters. A comprehensive analysis of the chemical heterogeneity of rock-forming minerals in the MC (metamorphic complex) rocks revealed that garnet is the key mineral for determining the P-T trends of metamorphic conditions within specific mineral assemblages. The study encompassed large porphyroblastic grains, smaller newly formed crystals within the rock matrix, grains exhibiting normal or reverse zoning, and various types of complex/inversion zoning (Fedkin, 2024). In some instances, evidence of these zoning patterns is preserved within a single sample, or even within a single mineral grain.

**3.2. Clinopyroxene occurs** in the rock matrix as small (0.1–0.4 mm) short-prismatic crystals and is rarely zoned. Within an individual grain, the jadeite component content typically varies by no more than 0.10–0.20 mole fraction. Pyroxene inclusions within garnet are compositionally identical to the grains found in the matrix; both are used to constrain the P-T parameters of the Grt-Cpx-Ab-Qz equilibrium. The composition of clinopyroxene in the MC rocks is close to omphacite and shows only minor variation within individual samples, with  $X_{\text{Jd}}$  values ranging from approximately 0.2 to 0.40. Observations of the phase composition in garnet-clinopyroxene (Grt-Cpx) pairs indicate

that the P-T trends for the formation of eclogitic assemblages are primarily determined by the chemical zoning of the garnet, while the omphacite remains essentially inert.

**3.3. Plagioclase**, which is necessary for estimating pressure in equilibrium with garnet and clinopyroxene, occurs only in the relatively low-pressure rocks of the complex that have undergone retrograde secondary alteration. The presence of plagioclase inclusions within large garnet grains significantly facilitates the interpretation of metamorphic conditions during the formation of the rock. The composition of this plagioclase ranges from nearly pure albite to a composition containing 5–7% of the anorthite component. Electron microprobe analysis of plagioclase typically yields an underestimated sodium content due to sodium loss during the analytical process; consequently, the measured anorthite content does not exceed 3–7%. This error naturally leads to an underestimation of the equilibrium pressure for the Grt-Cpx-Pl-Qz assemblage by approximately 0.1–0.2 GPa. Nevertheless, such deviations in plagioclase composition are not critically significant when comparing pressure values across different samples.

#### **4. Origin of high-pressure minerals and discussion**

The origin of high-pressure minerals—specifically diamond and coesite—within the rocks of the metamorphic complex (MC) is a highly controversial and debated topic. On one hand, the discovery of these index minerals suggests that the terrane may have been subjected to high- or ultra-high-pressure conditions during subduction. On the other hand, such occurrences in eclogites and gneisses are quite rare, and only a few have been confirmed through instrumental analysis. In one study, two or three nano-sized diamond grains—found as micro-inclusions within garnet in two eclogite samples—were identified using Raman spectroscopy (Bostick et al., 2003). Our own subsequent attempts to expand this search, using similar samples from the same area and comparable equipment at the University of San Francisco, proved unsuccessful. Cuboid graphite formations typically develop at low temperatures and are not the result of diamond graphitization (Korsakov et al., 2019), contrary to earlier hypotheses (Leech & Ernst, 1998). Isolated diamond grains found in heavy-mineral concentrates depend on the sediment source and cannot be definitively attributed to the metamorphic complex itself. Furthermore, the features interpreted as quartz pseudomorphs after coesite (Chesnokov & Popov, 1965; Dobretsov & Dobretsova, 1988) remain a subject of doubt and discussion. Coesite has been definitively identified only once—within a composite inclusion of garnet and omphacite in lawsonite-bearing eclogites from the Utarbaevo association—where its presence was confirmed by Raman spectra (Rusin et al., 2021).

Nevertheless, diamond and coesite do occur in the rocks of the MC, and the maximum formation parameters for the host rocks—derived by various authors using different methods across different parts of the complex—sometimes reach  $T = 800\text{--}910^\circ\text{C}$  and  $P \approx 3.5\text{--}4.5$  GPa (Valizer et al., 2011; 2013a; Fedkin et al., 2021). These values certainly appear to be overestimated, especially given that such parameters would lead one to expect the appearance of adakites—indicators of slab melting—which are absent from the MC. The parameters of the upper critical point in the basalt– $\text{H}_2\text{O}$  system ( $P = 3.4$  GPa,  $T = 760^\circ\text{C}$ ) explain the absence of adakites in the MC (Mibe et al., 2011), as the system's three-phase state (fluid, solid, and melt) lies outside the complex's evolutionary trend (Beane & Leech, 2007). However, these anomalous  $P$ – $T$  estimates may stem from a different cause: rather than reflecting metamorphism, they may indicate mantle–crust interaction during the complex's formation and the presence of deep-seated inclusions tectonically entrained by a rising mantle plume. Traditional methods of metamorphic petrology and geochemistry have been employed to address this issue.

## **5. The metamorphism of the Maksyutov complex**

The metamorphism of the Maksyutov complex has been studied by numerous researchers. The results of these studies are summarized in reviews and articles (Valizer et al., 2011, 2013a; Kovalev et al., 2015; Fedkin, 2020; Rusin et al., 2021; Lennykh et al., 1995; Dobretsov et al., 1996; Leech & Ernst, 2000; Brown et al., 2006; Beane & Leech, 2007; Fedkin et al., 2021). A very wide range of formation parameters has been determined for the complex's high-pressure rocks: from low-temperature greenschist-facies assemblages to the peak conditions of Ti-eclogites and mafic-ultramafic inclusions, with temperatures reaching  $700\text{--}910^\circ\text{C}$  and pressures of  $3.2\text{--}4.4$  GPa. Our research (Fedkin, 2020; Fedkin et al., 2021) and the work of Ural geologists (Valizer et al., 2011, 2013a; Kovalev et al., 2015; Rusin et al., 2021) confirm the peak formation parameters for the complex's high-pressure rocks: a prograde stage of  $800\text{--}900^\circ\text{C}$  and a retrograde stage of  $910\text{--}730^\circ\text{C}$  at pressures of  $3.2\text{--}3.4$  GPa. It has been established that the defining characteristic of the Maksyutov Complex (MC) is not extremely high metamorphic parameters, but rather its cyclic, oscillatory nature (Fedkin, 2020), wherein prograde and retrograde metamorphic events recur repeatedly, and  $P$ – $T$  trends—derived from the compositions of the Grt-Cpx-Pl-Qz paragenesis—form coupled pairs characterizing the regimes of distinct stages (cycles) of the terrane's evolution.

Four such cycles have been identified based on microprobe analyses of coexisting phase compositions (Table 1). Collectively, they define the overall evolutionary trend of the complex (Fig. 2), characterized by similar  $P$ – $T$  parameters for the prograde and retrograde branches within each cycle, short time intervals ( $\sim 20\text{--}25$  Ma) between cycles, and recurrence across all five studied areas

of the complex (Table 2). The ratio of prograde to retrograde cycle branches in the studied MC samples (4:1) indicates that the complex's evolution was dominated by subduction processes, with only a minor component of retrograde changes—most of which were largely overprinted by subsequent prograde stages.

Table 1. Generalized P-T trends of prograde-retrograde stages (cycles) of development of the Maksyutov eclogite-blueschist complex (Fedkin, 2020).

| Stage No | Prograde Trends            | Retrograde Trends          | Age, Ma*                                           |
|----------|----------------------------|----------------------------|----------------------------------------------------|
| 1.       | T=800→900°C, P>3.5→4.4 GPa | T=910→730°C, P=3.4→3.1 GPa | 515-533±4,6 <sup>1)</sup>                          |
| 2.       | T=500→790°C, P=2.5→3.2 GPa | T=740→610°C, P=2.5→1.4 GPa | 360-385 <sup>1), 2)</sup><br>360-380 <sup>3)</sup> |
| 3.       | T=460→680°C, P=1.1→2.2 GPa | T=690→430°C, P=1.3→1.0 GPa | 335 <sup>2)</sup>                                  |
| 4.       | T=310→515°C, P=0.9→1.2 GPa | T=545→310°C, P=1.0→0.6 GPa | 310-315 <sup>2)</sup>                              |

\*) Age are given after: <sup>1)</sup> Vakizer et al., 2013a, <sup>2)</sup> Beane, Leech, 2007, <sup>3)</sup> Dobretsov et al., 1996.

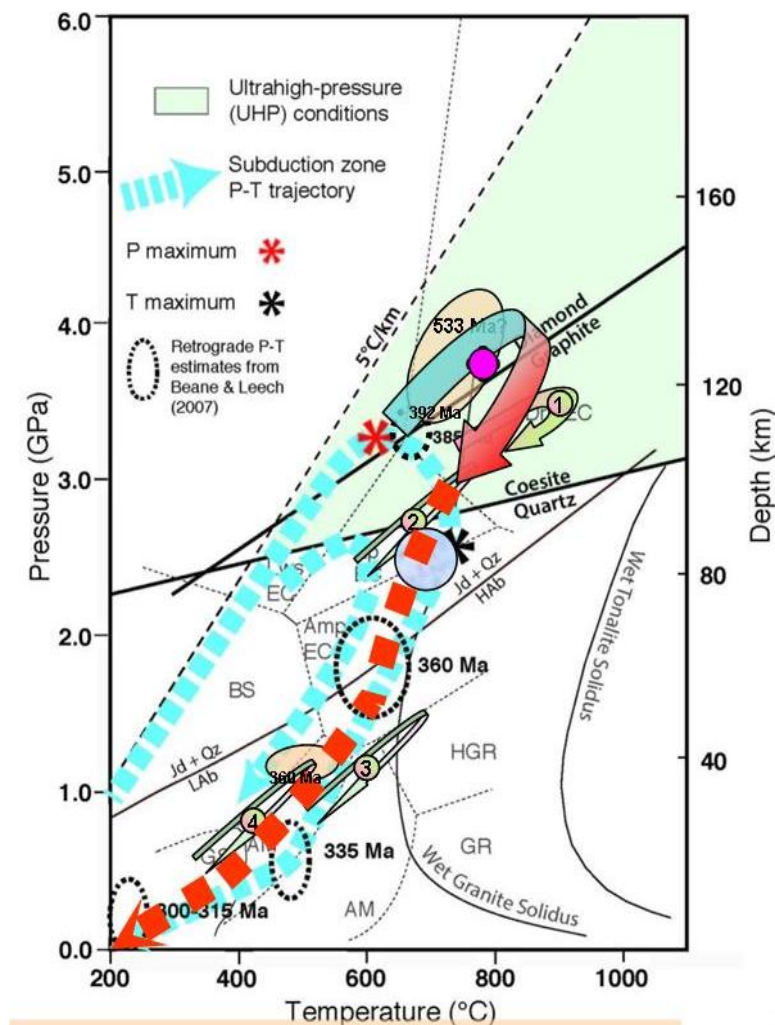


**Fig. 2.** Four episodes of coupled prograde and retrograde metamorphism (Fedkin, 2020).

● - The upper critical point (3.4 GPa and 760°C) in the H<sub>2</sub>O–basalt system explains the absence of melt in the subducting slab (Mibe et al., 2011).

The peak formation parameters for the mafic rocks of the complex, determined via mineralogical thermobarometry, were identified in titanium eclogites near the village of Shubino and at the Karayanovo site; here, the peak (diamond-coesite) stage of the first cycle is clearly manifested, showing a prograde trend (800–900°C at  $P = 3.5$  GPa) and a retrograde branch ( $T = 910$ – $730$ °C,  $P = 3.4$ – $3.1$  GPa). The opposing P-T trends derived from these data virtually coincide in terms of parameters, forming a "consistent" pair that characterizes the peak formation conditions of the complex's high-pressure mafic-ultramafic inclusions (see Cycle 1 in Tables 1 and 2). The co-occurrence of high-pressure rocks and samples reflecting lower metamorphic grades at these sites indicates a close structural-genetic relationship with the matrix Ti-eclogites, with the original parameters being preserved.

**Table 2. Prograde–retrograde trends of the Maksyutov complex in different areas (Fedkin, 2020)**

| Cycle number                                                                    | Shubino        | Novosimbirka   | Antingan       | Karayanovo      | Ivanovla       | Mineralogical Thermobarometry, T °C / P, GPa | P-T-metry and cycle age (literature date) |
|---------------------------------------------------------------------------------|----------------|----------------|----------------|-----------------|----------------|----------------------------------------------|-------------------------------------------|
| (1)                                                                             | 1 pr. 800-900  |                |                | 1 pr. 460-910   |                | >800/3.5                                     | >700/>4.4 <sup>1)</sup>                   |
|                                                                                 | 1 rtr. 910-730 |                |                |                 |                | 910-730/3.5                                  | 533±4.6 Ma <sup>1)</sup>                  |
| <b>1 – P-T parameters of high-pressure mantle-crustal clusters of the MC</b>    |                |                |                |                 |                |                                              |                                           |
| <b>2-4 – Prograde subduction metamorphism cycles of the Maksyutov complex ▼</b> |                |                |                |                 |                |                                              |                                           |
| (2)                                                                             |                | 2a pr. 640-790 |                | 2a pr. 550-790  |                | 550-790/3.2                                  |                                           |
|                                                                                 | 2b pr. 540-720 |                |                | 2b pr. 500-750  |                | 500-750/2.5                                  | 392-385 Ma <sup>2,3)</sup>                |
|                                                                                 |                |                |                | 2 rtr. 740-610  |                | 740-610/2.5-1.4                              | 740-630/3.1 <sup>1)</sup>                 |
| (3)                                                                             |                | 2c pr. 560-680 |                | 2c pr. 560-690  |                | 560-690/1.1-1.5                              |                                           |
|                                                                                 |                | 3a pr. 470-630 | 3a pr. 470-660 | 3a pr. 470-640  | 3a pr. 460-680 | 460-680/0.7-1.3                              | 360±3 <sup>1,2)</sup>                     |
|                                                                                 |                | 3 rtr. 690-450 |                | 3 rtr. 690-550  | 3 rtr. 690-430 | 690-430/1.3-1.0                              | 360-335 Ma <sup>2)</sup>                  |
|                                                                                 | 3b pr. 410-630 |                | 3b pr. 430-570 |                 | 3b pr. 420-620 | 410-630/1.1-1.3                              | 450-550/1.1 <sup>1)</sup>                 |
| (4)                                                                             |                | 4 pr. 380-450  |                | 4th pr. 310-515 |                | 310-515/1.0-1.2                              | 320-335 Ma <sup>2)</sup>                  |
|                                                                                 |                | 4 rtr. 540-310 |                |                 |                | 540-310/1.2-1.0                              | 300-420/0.8-1.2                           |

Note. References for the ages of the cycles are from: 1) Valizer et al., 2011, 2013a; 2) Leech, Ernst 2000; 3) Beane & Leech, 2007;

pr – prograde trends, rtr – retrograde trends;

## 6. Geochemical characteristics of high-pressure rocks from the Maksyutov complex

**6.1. The most significant (long-recognized) general geochemical features** of the mafic rocks in the Maksyutov complex are fairly conventional (Fedkin, 2020); however, only some of these can be linked to the origin of the rocks containing diamond and/or coesite. These include:

1. A unified evolutionary trend for the basalts, ranging from tholeiitic to calc-alkaline series and encompassing both depleted and enriched compositions (Fig. 3a). This trend is characterized by a progressive depletion in coherent elements—from tholeiites to andesite-basalts—driven by fluid influx and an increase in the oxidation state (Whattam, 2023).
2. A wide range of compositions and source materials (Fig. 3b, c). The formation of high-pressure rocks in the Maksyutov complex requires at least a three-component source: enriched mantle (OIB-type), depleted mantle (N-MORB and E-MORB types), and a contribution from a subduction-related component (crustal contamination).
3. Distinct rare-earth element (REE) patterns: enrichment in large-ion lithophile elements (LILE) in intraplate basalts and high-pressure inclusions, contrasted with depletion in high-field-strength elements (HFSE) in the host complex (Fig. 3d).

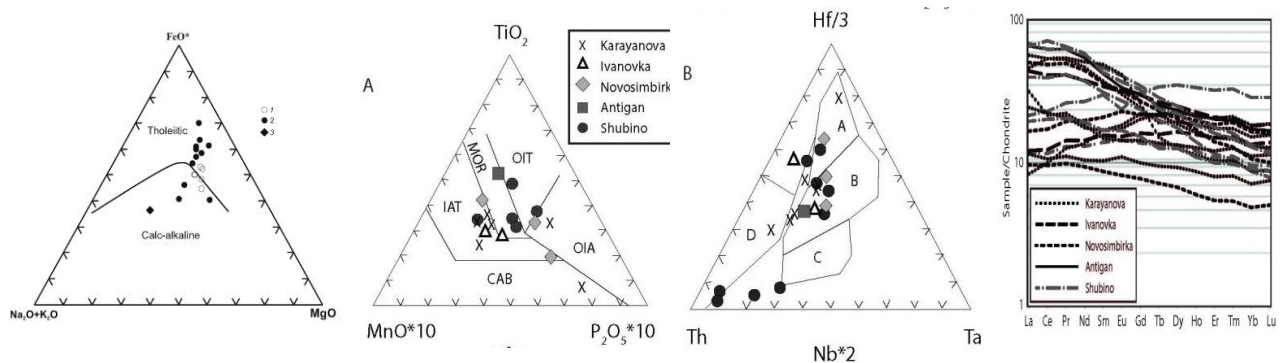


**Fig. 3.** Compositions of eclogites from the Maksyutov complex, shown on discrimination diagrams for rare, trace, and rare-earth elements.

**6.2. Trace element composition of high-pressure rocks and the host matrix.** New geochemical data on the rare and trace element composition of HP/UHP rocks from the Maksyutov complex (Fedkin et al., 2021), interpreted in light of model calculations (Pearce, 2008), have made it possible to identify more significant diagnostic features that distinguish high-pressure inclusions from progressively metamorphosed eclogites and schists.

A detailed comparison of the composition of rocks from high-pressure inclusions and the host complex reveals a number of additional, yet equally significant, geochemical differences between these units. The most significant findings are as follows:

- in eclogites from UHP inclusions, the ratio of depleted to enriched rock varieties (D/E) is 1:5, whereas the prograde metamorphic rocks of the matrix show a D/E ratio of ~1:3 (Fedkin, 2021);
- La/Yb ratios in enriched and depleted high-pressure rocks range from 5.15–4.39 (E) and 2.14–1.62 (D), respectively, while for the host gneisses and schists, the values are 3.81–1.90 (E) and 1.24–0.46 (D);
- a similar pattern is observed for the Nb/Th ratio: 1.84–1.17 (E) in prograde ultramafic rocks versus 1.12–0.14 (E) in retrograde diaphorites.

**6.3. Niobium-enriched basalts of the Maksyutov complex.** Of particular significance is the enrichment of ultra-high-pressure rocks in niobium—the so-called "niobium-enriched basalts" (NEB)—which serves as an indicator of the subduction of oceanic ridges. The link between these samples (typically depleted in other elements) and an oceanic substrate (of N-MORB and E-MORB types) is clearly evident in the diagrams (Figs. 4, 5) (Pearce, 2008), raising a number of geodynamic questions.

**6.3.1. First, this necessitates a re-evaluation of the subduction polarity of the Maksyutov complex,** as suggested by the NEBs. The need to revise the subduction polarity in the Maksyutov complex—from eastward to westward—arose in the vicinity of the Guberlya island arc (Ryazantsev et al., 2008; Ryazantsev & Tolmacheva, 2016). Such a shift may be related to the upwelling of a mantle wedge and fundamentally alters the developmental scenario for the entire orogen. Within this revised geodynamic model, the key event becomes the underthrusting of the Paleo-Asian Ocean's oceanic crust beneath the continent, rather than the subduction of the East European Craton margin beneath the Magnitogorsk island arc (Puchkov, 2010). Nevertheless, these studies do not dispute the occurrence of eastward subduction of the continent beneath the Devonian Magnitogorsk island arc, a fact that confirms the oscillatory nature of the metamorphism within the Maksyutov complex.

**6.3.2. Secondly, there arises the question of the role of a subduction-related component** (crustal contamination) in the formation of the complex. Geochemical data on the composition of the complex's mafic rocks—both depleted and enriched (Fedkin et al., 2021)—have allowed the contribution of a subduction-related component to the rocks of the Maksyutovo Complex (MC) to

be estimated at 1–4% (Fig. 4). For Paleozoic subduction structures, this is a relatively small proportion. Nevertheless, in the Maksyutov complex, Th/Nb ratios in the zone of peak metamorphism (near the settlement of Shubino) reach 2.38–7.11, which is more than three times the values observed in young subduction complexes (1.54; Whattam, 2023).

Crustal contamination is typically associated with mantle-crust interaction—a process in which mantle rocks (both depleted and enriched) acquire a subduction-related component, resulting in the formation of high-pressure hybrid rocks. Elevated values of these parameters serve as strong evidence for intense mantle-crust interaction; this process may have led to the formation of clusters and inclusions of high-pressure ( $T > 700^{\circ}\text{C}$  and  $P > 3.5\text{--}4.4\text{ GPa}$ ) ultramafic-eclogitic rocks within the lower structural-lithological unit of the MC (Valizer et al., 2011; 2013a).

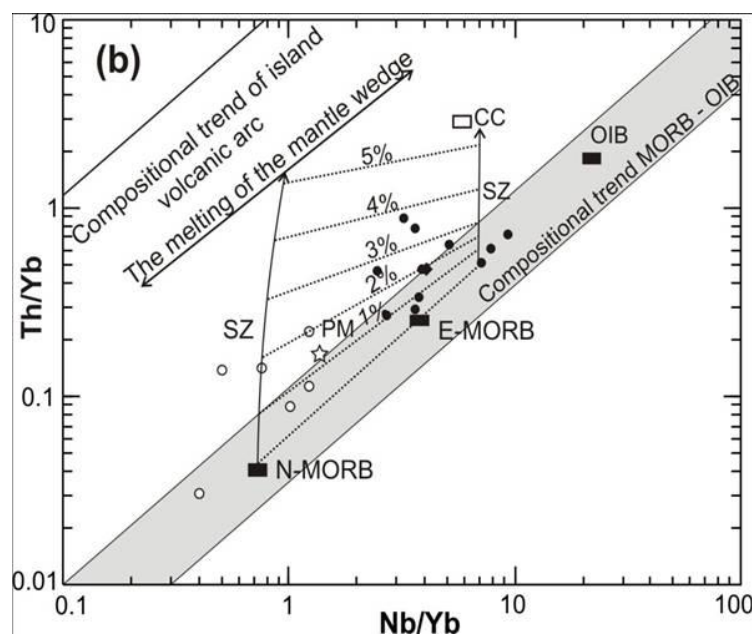


**Fig. 4.** Contribution of the subduction component in high-pressure rocks of the MC. Compositions of eclogites of the Maksyutov complex (Fedkin et al., 2021) on the Th/Yb – Nb/Yb diagram (Pearce, 2008).

This is a relatively low percentage for Paleozoic subduction structures. Nevertheless, in the Maksyutov complex, values of the Th/Nb ratio in the zone of peak metamorphism (near the village of Shubino) reach 2.38–7.11; this is more than three times higher than the corresponding values in young subduction complexes (1.54; Whattam, 2023). Crustal contamination is typically associated with mantle-crust interaction, a process wherein mantle rock compositions (both depleted and enriched) inherit a subduction component contribution, resulting in the formation of high-pressure

hybrid rocks. Elevated values of these parameters serve as compelling evidence of intensified mantle-crust interaction; this process may have led to the formation of clusters and inclusions of high-pressure ( $T > 700^{\circ}\text{C}$  and  $P > 3.5\text{--}4.4\text{ GPa}$ ) ultramafic-eclogitic rocks within the lower structural-compositional unit of the MC (Valizer et al., 2011; 2013a).

**6.4. Mantle–crust interaction and magma generation.** Geochemical data on the trace and rare-earth element composition of rocks within the complex indicate that the interaction between a mantle plume and depleted mantle occurred at pressures ranging from 1.5 to 3.5 GPa (Fig. 5). This study provides the first evidence for mantle–crust interaction and magma generation within a mantle plume for this complex. A decrease in pressure to 1.5–2.0 GPa leads to an increase in the degree of partial melting—from 5% for an OIB-type source to 20% in the region where N-MORB and E-MORB compositions are formed; under these conditions, diamond becomes unstable due to the drop in pressure. Thus, geochemical data on the bulk composition of the rocks impose significant constraints on the potential presence of diamond, limiting its existence to pressure conditions below 3.3–3.5 GPa (Fedkin & Shchipansky, 2026).

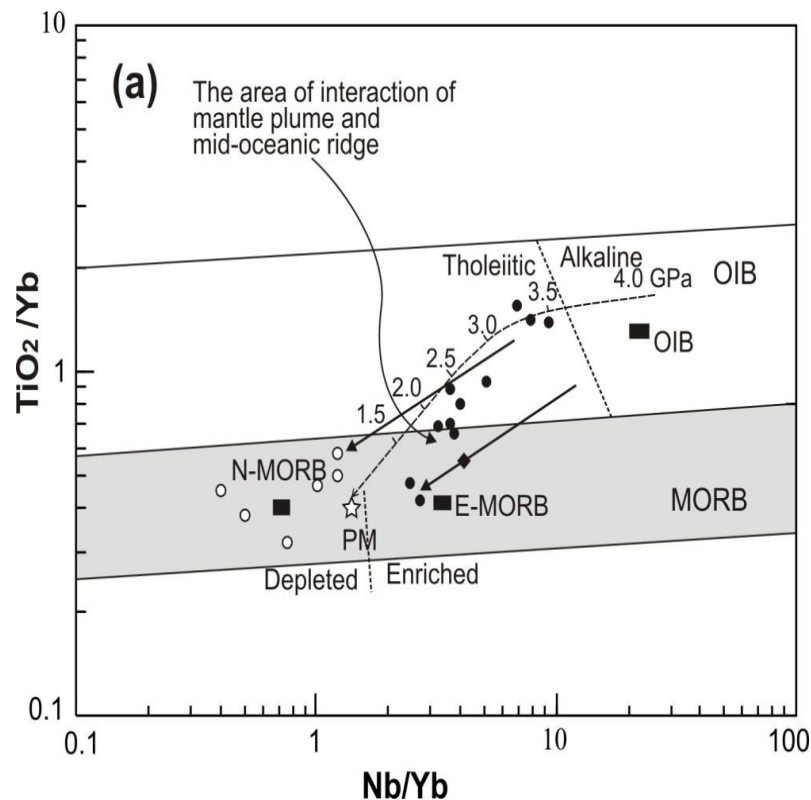


**Fig. 5.** Interaction between an OIB-type mantle plume and MORB-type depleted mantle. Data from Fedkin et al. (2021) interpreted within the framework of the Pearce (2008) model.

The geochemical differences cited between the rocks of the first cycle (No. 1) and those of the complex's subsequent evolutionary cycles leave no doubt as to its distinct nature. These differences reinforce the unique characteristics of this period in the complex's history—regarding parameters, age, and rock composition—thereby setting it apart from the general sequence of subduction events and indicating that it is unrelated to the processes of prograde subduction metamorphism.

## **7. Geodynamic criteria for the formation of high-pressure rock clusters in the Maksyutov complex**

The most significant and characteristic occurrences of high-pressure rocks—potentially associated with the indicator minerals diamond and coesite—have been studied in both structural-compositional units of the complex.

**7.1. Mafic–ultramafic rocks in the lower eclogite–schist unit of the (MC).** Ancient ( $533 \pm 4.6$  Ma) mafic–ultramafic (olivine–enstatite) rocks, which are structurally and genetically associated with jadeite–garnet eclogites, have been described within the lower eclogite–schist unit of the Maksyutov complex. Their formation parameters ( $T > 700^\circ\text{C}$  and  $P > 3.5\text{--}4.4$  GPa) suggest that these associations are fragments of the deep zone of a continental rift, tectonically exhumed to the surface within an ascending mantle wedge (Ivanov & Rusin, 1997; Valizer et al., 2011, 2013a). The hybrid composition of the rocks, their age and formation parameters, as well as the geochemical signature of the ultramafics and their geodynamic setting, collectively indicate a local (independent) origin distinct from the conditions under which the host substrate formed during prograde metamorphism. It is hypothesized that, as a result of mantle–crust interaction at the peak of subduction, these ultramafics were juxtaposed with fragments of continental crust (Jd–Grs eclogites) and subsequently exhumed to the continental crust level (at  $P \approx 3.2\text{--}3.3$  GPa) by an ascending mantle plume, becoming part of the complex's lower structural-compositional unit. It was previously shown (Fig. 5) that the interaction between a mantle plume and the depleted mantle occurred within a pressure range of 1.5 to 3.5 GPa (Fedkin & Shchipansky, 2026). A decrease in pressure to 1.5–2.0 GPa increases the degree of partial melting of the slab—from 5% (characteristic of an OIB source) to 20%—shifting the process toward the formation of N-MORB and E-MORB compositions, a regime in which diamond is no longer stable. Thus, geochemical data on the composition of mafic rocks within the metamorphic complex (MC) indicate that the potential occurrence of diamond in the eclogites of the lower MC unit is strictly limited to pressures of up to 3.3–3.5 GPa.

**7.2. Garnet–pyroxene and lawsonite-bearing rocks in the ophiolitic part of the complex:** in the transition zone between the eclogite–schist rocks of the lower block and the greenschist and schistose rocks of the upper (ophiolitic) block, rare garnet–clinopyroxene (Grt–Cpx) and lawsonite-bearing rocks occur, characterized by a unique paragenesis involving Fe–Ca garnet (Valizer et al., 2013b). Their formation is dated to the interval of 470–440 Ma. These rocks are also interpreted as high-pressure formations originating from the deep-seated zone of a continental rift and are even classified as a distinct "mafic-ultramafic" unit.

According to experimental data, the range of crystallization parameters for lawsonite-zoisite (Lws-Zo) rocks is quite broad: 620–760 °C and 2.5–4.0 GPa (Schmidt and Poli, 1994). However, during the retrograde replacement of lawsonite ( $\text{Lws} \rightarrow \text{CZo} + \text{Ms} + \text{Cpx} + \text{Ab}$ ) at temperatures of 380–460 °C and pressures of 0.7–1.1 GPa, diamond is not preserved, and the probability of its presence in association with lawsonite decreases sharply. Nevertheless, given the maximum parameters of their mineral assemblages, this group of rocks—found within the upper ophiolitic unit of the complex—could potentially support the stability of at least coesite, a mineral commonly encountered in lawsonite-bearing schists.

**7.3. Lawsonite-bearing eclogites from the Utarbaevo association.** At nearly the same P–T conditions, coesite micro-inclusions—encased in a double shell of garnet and omphacite—have been discovered in lawsonite-bearing eclogites from the Utarbaevo association of the metamorphic complex (Rusin et al., 2021). The age of these rocks (471–444 Ma) and their relatively high formation parameters ( $T = 495\text{--}622\text{ °C}$ ,  $P = 2.2\text{--}2.4\text{ GPa}$ ) suggest that this association belongs either to the category of pre-subduction mantle-crustal inclusions (of the Ol–En type) from the lower part of the metamorphic complex (Valizer et al., 2011) or to the group of garnet-clinopyroxene (Grt–Cpx) and lawsonite-bearing rocks derived from the ophiolitic sequence (Valizer et al., 2013b).

**7.4. Antigorite metasomatites of the upper block of the Maksyutov complex.** In terms of formation parameters, another occurrence of high-pressure exotic metasomatites—antigorite-bearing metaharzburgites and meta-orthopyroxenite sampled from rock dumps of the upper unit of the Maksyutov complex (MC) near the village of Karayanovo—shares similarities with the aforementioned rocks (Perchuk et al., 2024). It is hypothesized that they formed during the same time interval as the lawsonite-bearing rocks of the Utarbaevo association (470–440 Ma) as a result of high-pressure Si–Al metasomatism at  $T = 630\text{ °C}$  and  $P = 2.0\text{ GPa}$ . The authors interpret these meta-ultramafic rocks as fragments of supra-subduction mantle that were tectonically juxtaposed with eclogites and metasedimentary rocks of the subducting slab. Given the absence of metasomatic

features in the lower structural-compositional unit, the authors conclude that the Si-Al metasomatism of the antigorite-bearing meta-ultramafic rocks occurred within the subduction channel prior to their tectonic juxtaposition with the crustal rocks of the complex's upper unit during the Early Devonian.

## **Conclusions**

A comprehensive analysis of petrological, geochemical, geodynamic, and geochronological data for the Maksyutovo eclogite-glaucophane schist complex has revealed specific features of its formation. These features clarify the nature and degree of its tectono-petrological transformation—specifically, whether the terrane represents a high-pressure (HP) to ultra-high-pressure (UHP) complex, or one that formed under the intermediate pressure-temperature (P-T) conditions typical of crustal eclogites.

1. The cyclic, pulsatory nature of metamorphism within the Maksyutov complex, combined with results from mineralogical thermobarometry, indicates that the peak subduction-related metamorphism did not reach the thermodynamic stability fields of diamond or coesite—the diagnostic minerals for high-pressure/ultra-high-pressure (HP/UHP) conditions.
2. The presence of diamond and coesite within the rocks of the Maksyutov complex is not a product of its prograde subduction-related metamorphism. Instead, it results from the tectonic incorporation of distinct, ancient, high-pressure rock clusters—containing diamond and/or coesite—into the surrounding terrigenous-schist sequence.
3. These clusters differ from the host rocks in their greater age, higher formation P-T conditions, and various geochemical characteristics of their constituent rocks and minerals. These features point to a distinct origin—one that is both earlier and deeper—arising from mantle-crust interaction between the mantle wedge and the complex's terrigenous-schist substrate.
4. Thus, the presence of diamond and coesite inclusions in the rocks of the Maksyutov complex (MC) is not an indicator of high-pressure or ultra-high-pressure (HP/UHP) metamorphism; their occurrence is unrelated to the subduction-related metamorphism of the terrane and is instead attributable to deep-seated, mantle-derived processes.
5. Given the insufficient degree of crustal metamorphism and the mantle origin of the diamond and coesite found in the rocks of the Maksyutov complex, it can be concluded that the Maksyutov

eclogite–blueschist complex cannot be classified as a high-pressure or ultra-high-pressure (HP/UHP) complex.

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## Figure Captions

**Figure 1.** Geotectonic map of the South Ural Mountains, Russia, adapted from (Leech and Stockli, 2000). URSEIS (Urals Reflection Seismic Experiment and Integrated Studies) transect that provides important depth control for the South Ural Mountains.

**Figure 2.** Four episodes of coupled prograde and retrograde metamorphism (Fedkin, 2020).

● - The upper critical point (3.4 GPa and 760°C) in the H<sub>2</sub>O–basalt system explains the absence of melt in the subducting slab (Mibe et al., 2011).

**Figure 3.** Compositions of eclogites from the Maksyutov complex, shown on discrimination diagrams for rare, trace, and rare-earth elements.

**Figure 4.** Contribution of the subduction component in high-pressure rocks of the MC. Compositions of eclogites of the Maksyutov complex (Fedkin et al., 2021) on the Th/Yb – Nb/Yb diagram (Pearce, 2008).

**Figure 5.** Interaction between an OIB-type mantle plume and MORB-type depleted mantle. Data from Fedkin et al. (2021) interpreted within the framework of the Pearce (2008) model.

## **Table Captions**

**Table 1.** GENERALIZED P-T TRENDS OF PROGRADE-RETROGRADE STAGES (CYCLES) OF DEVELOPMENT OF THE MAKSYUTOV ECLOGITE-BLUESCHIST COMPLEX (FEDKIN, 2020).

**Table 2.** PROGRADE-RETROGRADE TRENDS OF THE MAKSYUTOV COMPLEX IN DIFFERENT AREAS (FEDKIN, 2020)

**APPENDIX-1.** ON THE HISTORY OF THE FORMATION OF THE MAKSYUTOV COMPLEX

Table 1. Generalized P-T trends of prograde-retrograde stages (cycles) of development of the Maksyutov eclogite-blueschist complex (Fedkin, 2020).

| Stage No | Prograde Trends            | Retrograde Trends          | Age, Ma*                                           |
|----------|----------------------------|----------------------------|----------------------------------------------------|
| 1.       | T=800→900°C, P>3.5→4.4 GPa | T=910→730°C, P=3.4→3.1 GPa | 515-533±4,6 <sup>1)</sup>                          |
| 2.       | T=500→790°C, P=2.5→3.2 GPa | T=740→610°C, P=2.5→1.4 GPa | 360-385 <sup>1), 2)</sup><br>360-380 <sup>3)</sup> |
| 3.       | T=460→680°C, P=1.1→2.2 GPa | T=690→430°C, P=1.3→1.0 GPa | 335 <sup>2)</sup>                                  |
| 4.       | T=310→515°C, P=0.9→1.2 GPa | T=545→310°C, P=1.0→0.6 GPa | 310-315 <sup>2)</sup>                              |

\*) Age are given after: <sup>1)</sup> Vakizer et al., 2013a, <sup>2)</sup> Beane, Leech, 2007, <sup>3)</sup> Dobretsov et al., 1996.

**Table 2. Prograde–retrograde trends of the Maksyutov complex in different areas (Fedkin, 2020)**

| Cycle number                                                                    | Shubino        | Novosimbirka   | Antingan       | Karayanovo      | Ivanovla       | Mineralogical Thermobarometry, T °C / P, GPa | P-T-metry and cycle age (literature date) |
|---------------------------------------------------------------------------------|----------------|----------------|----------------|-----------------|----------------|----------------------------------------------|-------------------------------------------|
| (1)                                                                             | 1 pr. 800-900  |                |                | 1 pr. 460-910   |                | >800/3.5                                     | >700/>4.4 <sup>1)</sup>                   |
|                                                                                 | 1 rtr. 910-730 |                |                |                 |                | 910-730/3.5                                  | 533±4.6 Ma <sup>1)</sup>                  |
| <b>1 – P-T parameters of high-pressure mantle-crustal clusters of the MC</b>    |                |                |                |                 |                |                                              |                                           |
| <b>2-4 – Prograde subduction metamorphism cycles of the Maksyutov complex ▼</b> |                |                |                |                 |                |                                              |                                           |
| (2)                                                                             |                | 2a pr. 640-790 |                | 2a pr. 550-790  |                | 550-790/3.2                                  |                                           |
|                                                                                 | 2b pr. 540-720 |                |                | 2b pr. 500-750  |                | 500-750/2.5                                  | 392-385 Ma <sup>2,3)</sup>                |
|                                                                                 |                |                |                | 2 rtr. 740-610  |                | 740-610/2.5-1.4                              | 740-630/3.1 <sup>1)</sup>                 |
| (3)                                                                             |                | 2c pr. 560-680 |                | 2c pr. 560-690  |                | 560-690/1.1-1.5                              |                                           |
|                                                                                 |                | 3a pr. 470-630 | 3a pr. 470-660 | 3a pr. 470-640  | 3a pr. 460-680 | 460-680/0.7-1.3                              | 360±3 <sup>1,2)</sup>                     |
|                                                                                 |                | 3 rtr. 690-450 |                | 3 rtr. 690-550  | 3 rtr. 690-430 | 690-430/1.3-1.0                              | 360-335 Ma <sup>2)</sup>                  |
|                                                                                 | 3b pr. 410-630 |                | 3b pr. 430-570 |                 | 3b pr. 420-620 | 410-630/1.1-1.3                              | 450-550/1.1 <sup>1)</sup>                 |
| (4)                                                                             |                | 4 pr. 380-450  |                | 4th pr. 310-515 |                | 310-515/1.0-1.2                              | 320-335 Ma <sup>2)</sup>                  |
|                                                                                 |                | 4 rtr. 540-310 |                |                 |                | 540-310/1.2-1.0                              | 300-420/0.8-1.2                           |

Note. References for the ages of the cycles are from: 1) Valizer et al., 2011, 2013a; 2) Leech, Ernst 2000; 3) Beane & Leech, 2007;

pr – prograde trends, rtr – retrograde trends;

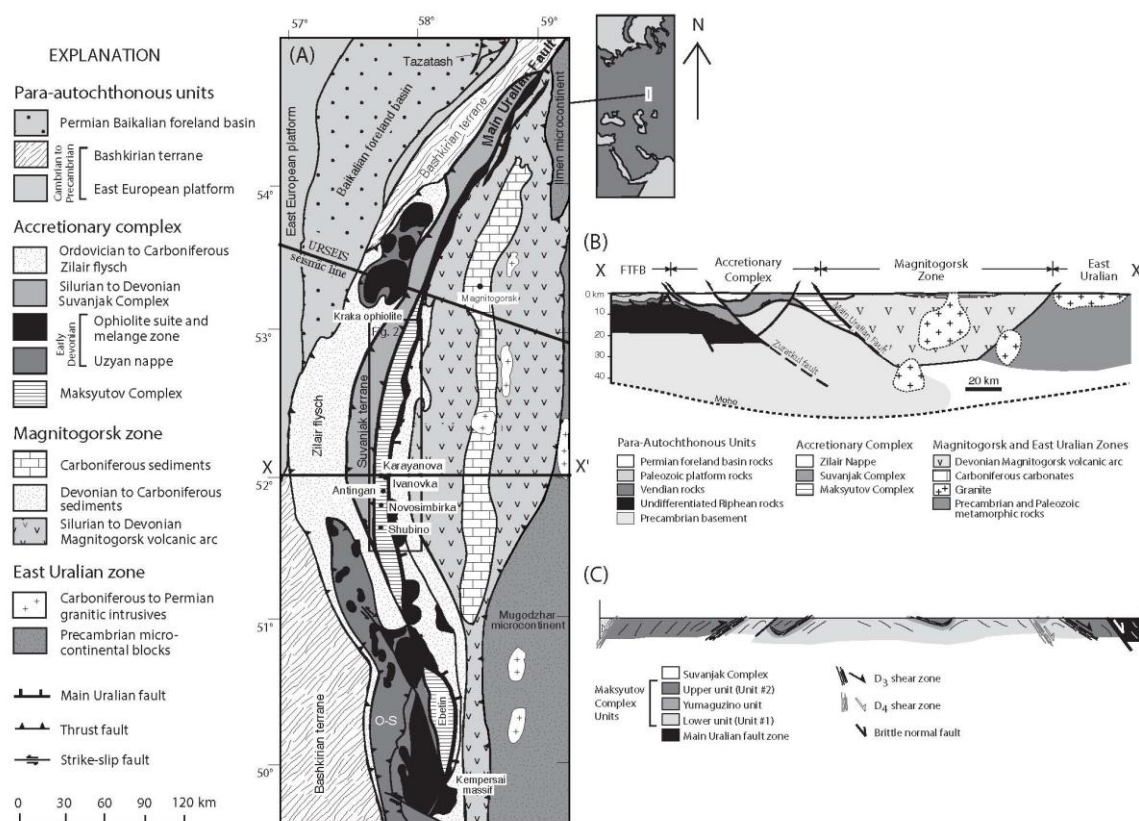


Figure 1

Figure 1

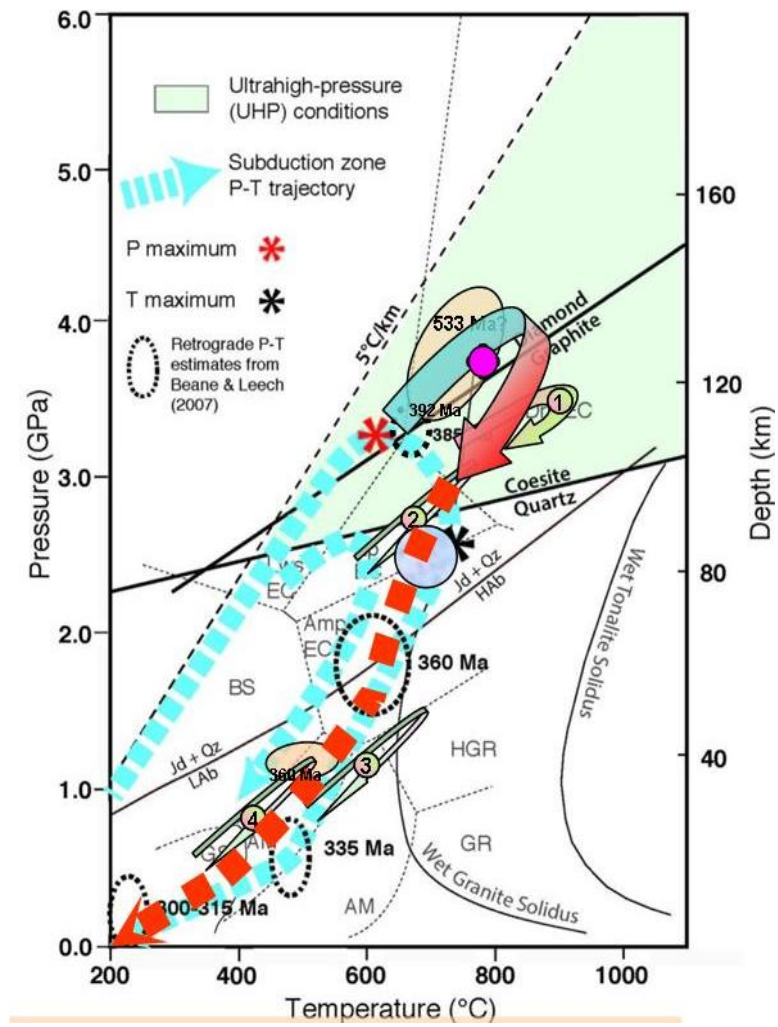


Figure 2

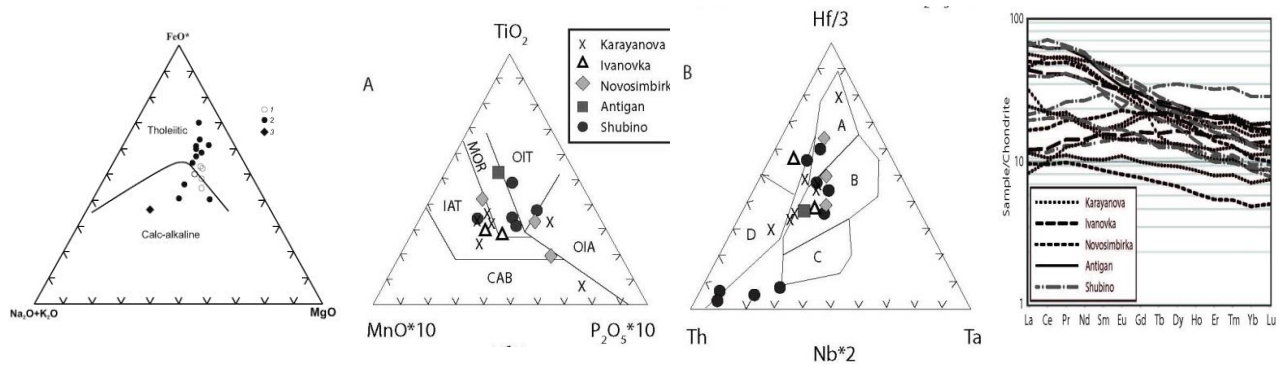


Figure 3

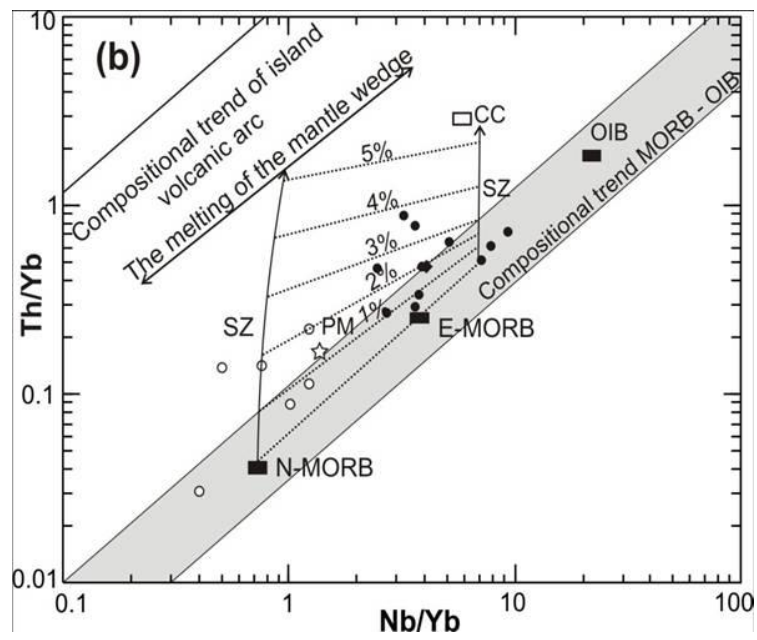


Figure 4

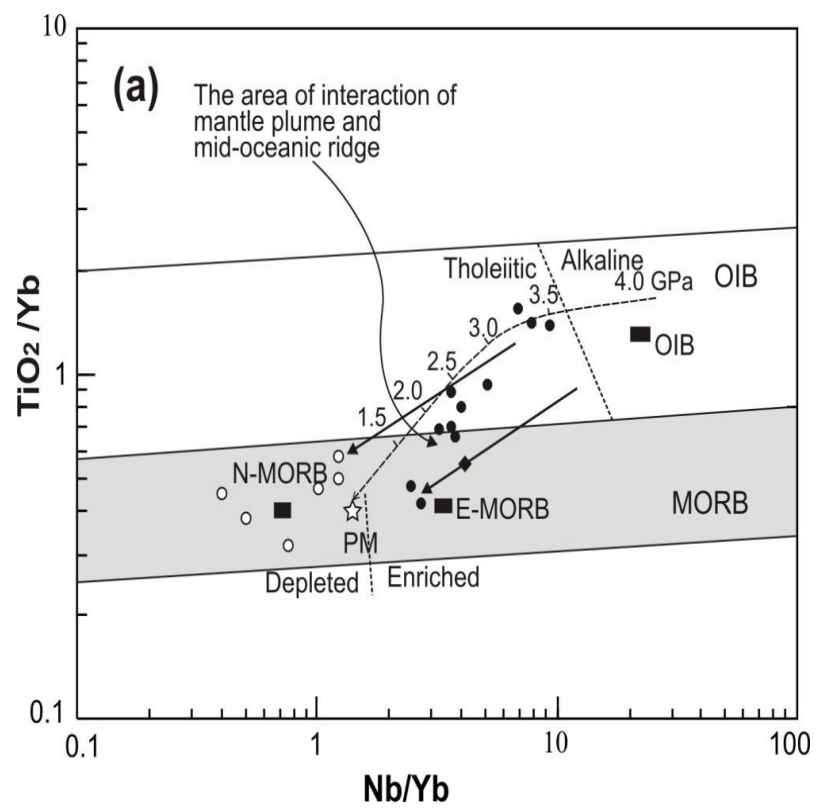


Figure 5

## APPENDIX-1. ON THE HISTORY OF THE FORMATION OF THE MAKSYUTOV COMPLEX

The history of the formation of the Maksyutov eclogite–blueschist complex begins long before its subduction in the Early Devonian. It encompasses at least a prolonged pre-subduction developmental phase of its protolith during the Early Paleozoic—dating back 550–600 million years (Valizer & Lennykh, 1988)—followed by the primary subduction stage in the Devonian, and a subsequent exhumation phase during the Devonian–Carboniferous.

Ancient high-pressure inclusions found within the rocks of the Maksyutov complex document a long pre-subduction history for the terrane, spanning from 533 to 440–390 Ma. The earliest evidence of such high-pressure formations dates to  $533 \pm 4.6$  Ma. These ultramafic–eclogitic inclusions—characterized by temperatures ( $T$ )  $> 700^\circ\text{C}$  and pressures ( $P$ )  $> 3.5$ – $4.4$  GPa—originated within a deep continental rift zone of the East European Craton (Valizer et al., 2011, 2013a). New age data derived from zircons in metavolcanic rocks from the upper tectonic block (Valizer et al., 2016) have allowed for a more precise definition of the key stages in the Early Paleozoic history of the Maksyutov complex. At approximately  $517 \pm 7$  Ma, the crystallization of the terrane’s oceanic basalts began—a process that coincides, in terms of timing, with the emergence of an association of mafic–ultramafic rocks and eclogites within the MC protolith ( $533 \pm 4.6$  Ma). These rocks formed under thermodynamic conditions corresponding to the diamond stability field: at temperatures ( $T$ )  $> 700^\circ\text{C}$  and pressures ( $P$ )  $> 3.5$ – $4.4$  GPa (Valizer et al., 2011, 2013a). The authors attribute this event to the activation of a deep continental rift along the eastern margin of the East European Craton (Ivanov & Rusin, 1997; Valizer et al., 2013) and to the initial stage of the formation of a subduction channel. During the pre-subduction evolution of the terrane, the interaction between the mantle and the crust within this rift structure brought deep-seated mafic-ultramafic (olivine–enstatite) rocks into proximity with fragments of continental crust (jadeite–grossular eclogites). At the peak of subduction, these complexes were exhumed to the level of the continental crust (at  $P \sim 3.2$ – $3.3$  GPa) and incorporated into the lower structural–lithological unit of the Maksyutov complex under conditions at the very limit of diamond stability.

As the East European Platform and the West Siberian paleo-ocean converged, high-pressure associations of rare garnet–clinopyroxene (Grt–Cpx) and lawsonite-bearing rocks—characterized by a unique paragenesis of Fe–Ca garnet—formed in the continent–ocean transition zone between 470 and 440 Ma, within a similar range of P–T conditions ( $620$ – $760^\circ\text{C}$  and  $2.5$ – $4.0$  GPa, based on earlier experimental data) (Valizer et al., 2013b). The presence of lawsonite—a high-pressure hydrous mineral—is extremely... ..unstable during retrograde metamorphism (diaphoresis)—

indicates a gradual decrease in pressure and an increase in the fluid saturation of the system. These changes affect the stability of diamond and coesite, which become unstable as metamorphic parameters decline and metasomatic processes intensify.

The pre-subduction evolution of the upper ophiolitic block of the complex during the Ordovician (440–490 Ma) coincides with the appearance of conodonts in the carbonate deposits of the paleo-ocean and the development of supra-subduction alterations within the oceanic lithosphere (Ryazantsev et al., 2008; Rusin et al., 2021). Intense metasomatic processes at the base of the metabasite complex led to the formation of lawsonite-bearing rocks containing coesite within the serpentinite mélange (Rusin et al., 2021), as well as antigorite-bearing metasomatites derived from oceanic crustal rocks (Perchuk et al., 2024). The age (444–470 Ma) and P–T conditions ( $T \sim 500\text{--}630\text{ }^{\circ}\text{C}$ ,  $P \sim 2.0\text{ GPa}$ ) of these inclusions are similar; however, they do not correspond to the lower-grade parameters of the subsequent subduction process.

Inclusions of high-pressure rocks within the Maksyutov complex demonstrate a gradual transition from continental crust to blocks derived from oceanic crust. This sequence—ranging from high-pressure ultramafic rocks to lawsonite eclogites and antigorite-bearing metasomatites—reflects both a shift in the nature of geological processes (from metamorphism to metasomatism) and an evolution in P–T conditions: from parameters typical of continental... ..rift, to conditions associated with deep-seated metasomatism within altered oceanic crust.

The data obtained suggest that the diamonds and coesite found in deep-seated ultramafic blocks were incorporated into the eclogite complex as a result of mantle-crust interaction that occurred prior to the onset of subduction. During the Early Devonian, at the peak of subduction ( $\sim 390\text{ Ma}$ ), these high-pressure rock inclusions were entrained by the ascending slab and brought to the surface of the terrane during exhumation. The episodic occurrence of these high-pressure inclusions within the Maksyutov complex points to the localized nature of thermal and fluid fluxes originating from mantle material, as well as a gradual decline in the intensity of these processes from the early Paleozoic to the present-day state of the complex.

**Chronological framework** for the key developmental stages of the Maksyutov terrane substrate and the retrograde metamorphism of the Maksyutov complex (MC).

533 ± 4.6 Ma: Formation of the oldest ultramafic-eclogitic inclusions—characterized by temperatures (T) > 700°C and pressures (P) > 3.5–4.4 GPa—within a deep-seated continental rift zone of the East European Craton (Valizer et al., 2011, 2013a).

470–440 Ma: Formation of rare garnet-clinopyroxene (Grt-Cpx) and lawsonite-bearing rocks under similar P–T conditions (620–760°C and 2.5–4.0 GPa, based on earlier experimental data) (Valizer et al., 2013b).

471–444 Ma: Formation of lawsonite eclogites containing coesite within the Utarbaevo association (T = 495–622°C; P = 2.2–2.4 GPa) (Rusin et al., 2021).

470–444 Ma: Formation of exotic Si–Al metasomatites within the upper ophiolitic series of the MC (T ~ 500–630°C; P ~ 2.0 GPa) (Perchuk et al., 2024). The presence of ancient, high-pressure mafic rock inclusions within the Maksyutov complex is not related to the prograde metamorphism associated with the complex's Early Devonian subduction (390–310 Ma). Instead, it resulted from the intrusion of a mantle plume into the substrate of the Maksyutov complex—a plume that may have carried rock fragments containing previously entrapped diamond and/or coesite.

#### **Age and P–T parameters of prograde subduction-related metamorphism:**

411 ± 5.0 Ma: Prograde subduction-related metamorphism at T = 395–418 °C (Valizer et al., 2026); 1st cycle of prograde–retrograde metamorphism (740–790 °C / 2.5–3.2 GPa)\*

392–385 Ma: 2nd cycle of prograde–retrograde metamorphism (630–740 °C / 3.1 GPa)\*

360–335 Ma: 3rd cycle of prograde–retrograde metamorphism (335–360 °C / 1.5 GPa)\*

335–300 Ma: 4th cycle of prograde–retrograde metamorphism (300–335 °C / 1.0–1.2 GPa)\*

Mineralogical thermobarometry data indicate that the peak P–T conditions of the prograde metamorphism affecting the mafic rocks of the Maksyutov complex (750 °C and 3.1–3.2 GPa) did not reach the stability fields of diamond or coesite. Consequently, the presence of high-pressure phases within these inclusions does not serve as evidence for ultra-high-pressure (UHP) conditions during the formation of the complex as a whole. The tectonic setting of the pre-subduction state of the continental crust, age and petrological criteria, as well as the geochemical characteristics of the

embedded inclusions and the host rocks, suggest that **the Maksyutov eclogite–blueschist complex is not an ultra-high-pressure complex.**

## Supplementary Files

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- [Table1.doc](#)
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