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Thematic Article

Petrology and retrograde P–T path for eclogites of the Maksyutov Complex, Southern Ural Mountains, Russia

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Abstract The Maksyutov Complex, situated in the southern Ural Mountains of Russia, is the first location where quartz aggregates within garnets exhibiting radial fractures were identified as coesite pseudomorphs (Chesnokov & Popov 1965). The complex consists of two tectonic units: a structurally lower eclogite-bearing schist unit and an overlying meta-ophiolite unit. Both units show evidence for multiple stages of metamorphism and deformation. The high-pressure metamorphism of the eclogite-bearing schist unit, discussed in this report, is suspected to be related to a collision between the Russian platform and a fragment of the Siberian continent during the early Cambrian. At least three stages of metamorphism (M_{1-3}) and two stages of deformation (S_1 and S_2) were observed in thin sections: M_1) garnet (Alm_{55-60}, Prp_{22-28}, Grs_{16-20}) + omphacite (Jd_{46-56}) + phengite (Si ≈ 3.5) + rutile; M_2) garnet + glaucophane ± lawsonite + white mica; and M_3) epidote + chlorite ± albite ± actinolite + white mica. Observed mineral parageneses define a retrograde P–T path for the eclogite. Mineral assemblages within the most representative eclogite from the lower unit of the Maksyutov Complex indicate minimum peak pressures of 15 kbar at temperatures of approximately 600 °C. If the presence of coesite pseudomorph is confirmed, the peak ultrahigh-pressure metamorphism may be as high as 27 kbar at 615 °C.

Key words: coesite pseudomorphs, eclogite, P–T path, ultrahigh-pressure metamorphism, Ural Mountains.

INTRODUCTION

The Maksyutov Complex, situated in the southern Ural Mountains of Russia (Fig. 1), is the first location where quartz aggregates within garnets exhibiting radial fractures were recognized as pseudomorphs of coesite (Chesnokov & Popov 1965). The plausibility of this interpretation, however, was not realized until coesite and coesite pseudomorphs were described and documented in whiteschists and eclogites from the Dora Maira Massif of the western Alps (Chopin 1984) and from the Western Gneiss Region of Norway (Smith 1984). Coesite-bearing whiteschists and eclogites are significant because they indicate that crustal rocks underwent metamorphism at ultrahigh-pressures greater than 27 kbar (90 km) and then were returned to the surface.

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The Maksyutov Complex consists of an eclogite-bearing schist unit that underwent high- to ultrahigh-pressure metamorphism, and a structurally higher meta-ophiolite unit that underwent greenschist to blueschist facies metamorphism. The internal structure and petrology of the Maksyutov Complex have been investigated by Russian geologists (e.g. Lennykh 1977; Moscovchenko 1982; Dobretsov & Dobretsova 1988; Valizer & Lennykh 1988). This paper builds on the previous research and focuses on the mineral assemblages, mineral compositions, and P–T path of the eclogite-bearing schist unit.

TECTONIC SETTING

The Maksyutov Complex is a 15 km wide and 200 km long belt situated in the southern Ural

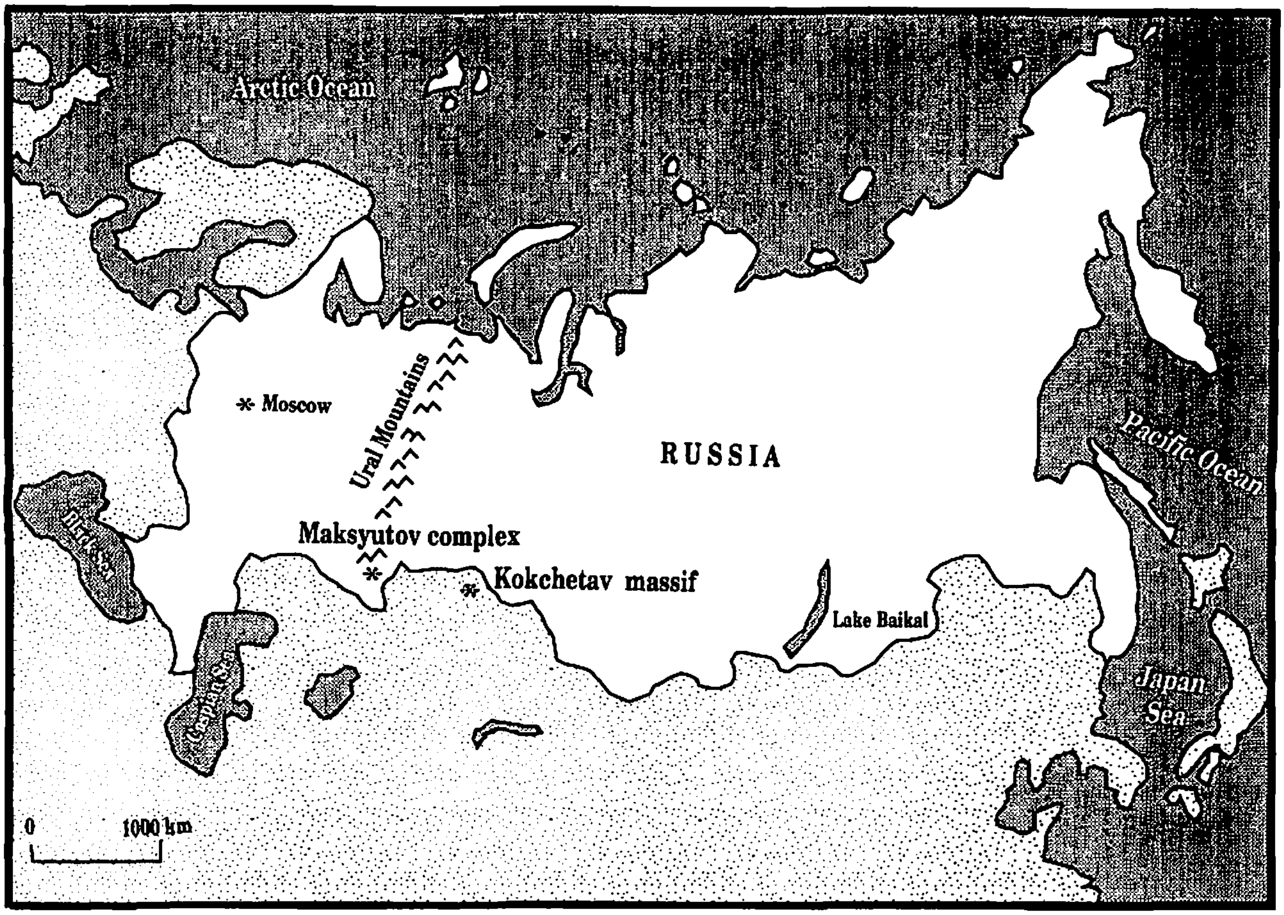

Fig. 1 Geographical location of the Maksyutov Complex and the Kokchetav Massif.

Mountains (Fig. 2). The high-pressure metamorphism of the complex may correspond to a collision between the Russian platform and a fragment of the Siberian continent at approximately 550 Ma, and may be correlated to the diamond-bearing Kokchetav Massif in northern Kazakhstan (Shatsky *et al.* 1995). Blueschist/greenschist facies metamorphism, at approximately 400 Ma, is believed to be contemporaneous with the accretion and subduction of intracontinental oceanic crust; deformation accompanying the metamorphism corresponds with large-scale left-lateral strike-slip movement along the Main Uralian fault (N. L. Dobretsov *et al.* unpubl. data, 1995).

Descriptions of the geologic and tectonic setting of the southern Ural Mountains are found in Zonenshain *et al.* (1984, 1990) and illustrated in the geodynamic map of the southern Ural Mountains (Fig. 2). The Russian platform forms the western boundary of the complex and is overlain by Late Ordovician to Early Carboniferous Sakmara clastic wedge sediments (Zonenshain *et al.* 1984). The Suvanjak terrane, composed of Ordovician continental margin sediments, is in fault contact with the western edge of the Maksyutov Complex. The Main Uralian thrust fault places Ordovician–Silurian ophiolites along the eastern margin of the Maksyutov Complex.

The Main Thrust ophiolites form the basement of the Magnitogorsk island arc. Most ophiolites are dismembered; some have been altered to serpentinite melanges. The Middle Devonian Magnitogorsk island-arc complex contains intra-arc basin sediments interlayered with calc–alkaline volcanic rocks (Zonenshain *et al.* 1984). The ophiolite and island-arc assemblage rocks are folded and metamorphosed to zeolite to low-grade greenschist facies. The eastern edge of the Magnitogorsk island-arc complex is overthrust by Vendian–Ordovician Mugodshar and Ilmen microcontinents (Zonenshain *et al.* 1990). The Mugodshar microcontinent, composed of migmatites and granulites, rifted from the Russian platform during the Early Ordovician (Zonenshain *et al.* 1990). Late Carboniferous–Permian granitic plutons intrude the Magnitogorsk island-arc and the microcontinents.

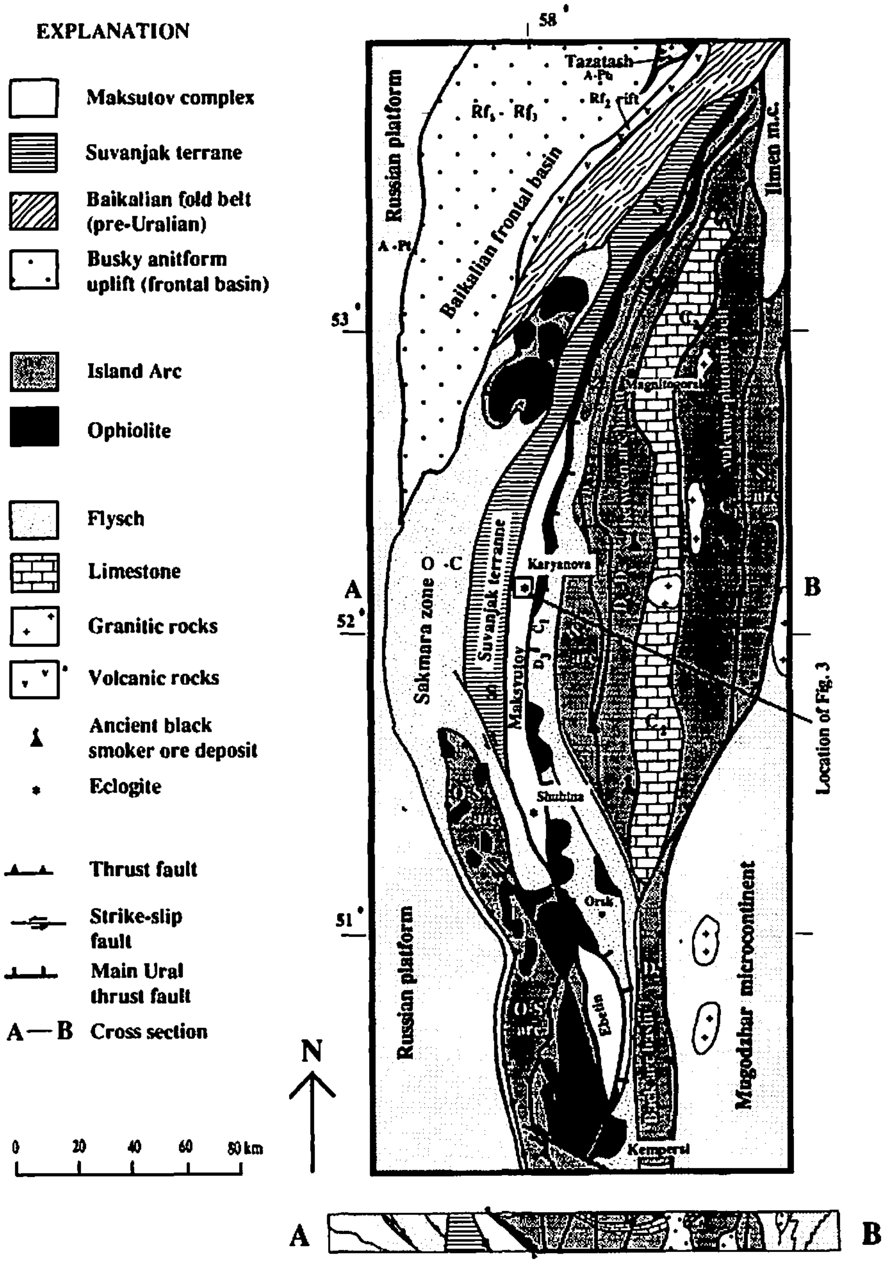

Fig. 2 Geodynamic map of the southern Ural Mountains (compiled by Coleman *et al.*, 1993 from Dobretsov & Dobretsova 1988; Lennykh 1977; Moscovchenko 1982; Peive *et al.* 1977 and Sobolev 1975). A-Pt, Archean-Proterozoic; Rf, Riphean; O, Ordovician; S, Silurian; D, Devonian; and C, Carboniferous. Samples described in this report were collected near Karyanova and Shubino villages in the Maksyutov Complex.

FIELD RELATIONS

The Maksyutov Complex consists of two tectonic units: an eclogite-bearing schist unit and an overlying meta-ophiolite unit (Fig. 3). The eclogite-bearing schist unit underwent high to ultrahigh-pressure metamorphism and contains boudins and tectonic blocks of eclogite, enstatite–olivine rocks, and quartz–almandine–jadeite rocks in mica schist and quartzite host rocks that typically contain graphite, garnet, and sodic amphibole. Boudins of eclogite that occur within the mica schists varyfrom a few centimeters to two meters in length. Both eclogites and country schists are strongly foliated and have been subjected to multistage deformation and recrystallization. Details of the relationship between deformational events and metamorphic recrystallization remain to be investigated (N. L. Dobretsov *et al.* unpubl. data, 1995).

The meta-ophiolite unit was subjected to blueschist/greenschist facies metamorphism, and consists of serpentinite melanges, metabasalt, graphitic schist, and marble. The serpentinite melanges contain lawsonite-bearing metarodingites; lawsonite grains vary in size from a few millimeters to 5 cm in length and are pseudomorphosed by clinozoisite.

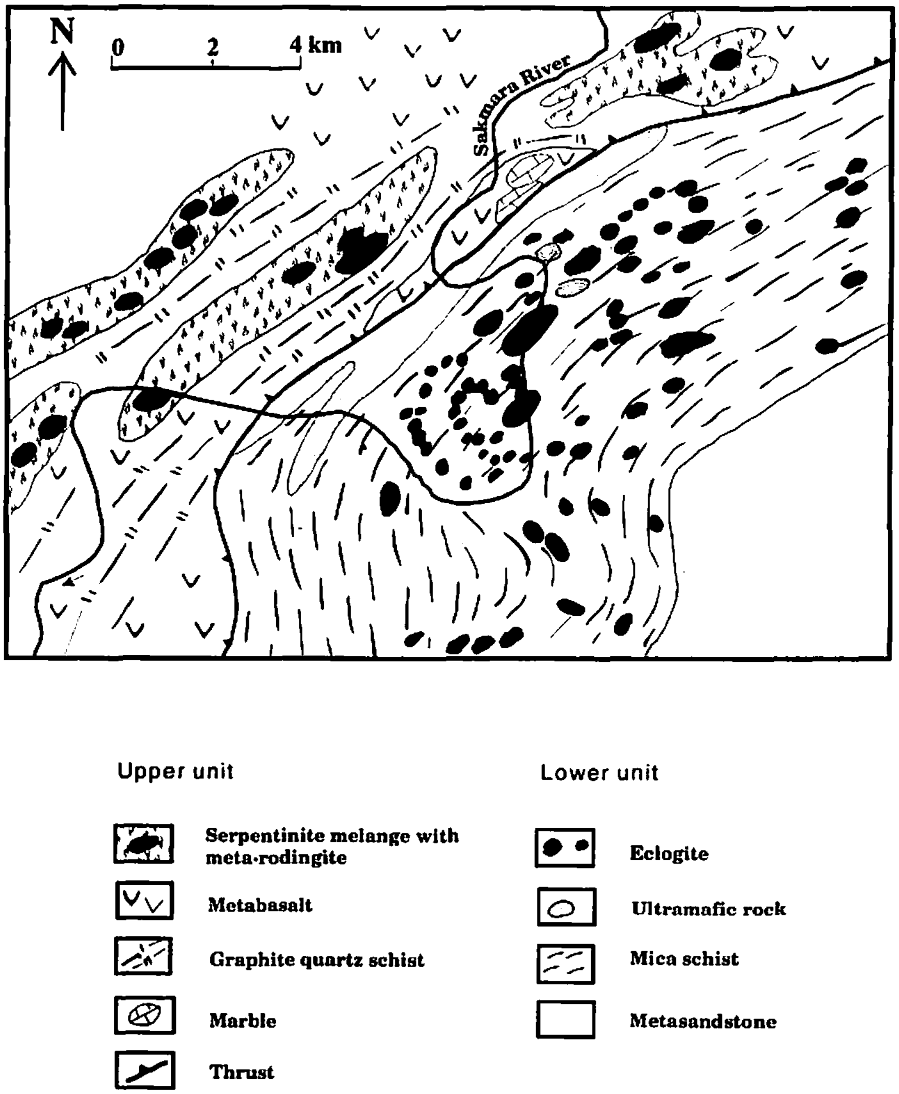

Fig. 3 Exposure of the Maksyutov Complex along the Sakmara River near Karyanova village (adapted from Valizer & Lennykh 1988)

Both the eclogite-bearing schist unit and the meta-ophiolite unit show evidence for multiple stages of deformation and metamorphism. Thrust contacts and recumbent folds of the early high-pressure stage of deformation are cut by steep left-lateral ductile shear zones that contain retrograde mineral assemblages (Coleman *et al.* 1993). The two units were thrust together after the high- to ultrahigh-pressure metamorphic event (M_1) that affected the eclogite-bearing schist unit, and then both were recrystallized simultaneously during blueschist and greenschist facies metamorphism ($M_{2\text{-}3}$).

GEOCHRONOLOGY

Ages of the metamorphic events in the Maksyutov Complex are not well established. Protoliths of the eclogites are approximately 1200 Ma based on U–Th–Pb age determination of zircon from metavolcanics (Dobretsov & Sobolev 1984). Matte *et al.* (1993) dated phengite from eclogite, 373 ± 4 Ma, and from micaschist, 388 ± 4 Ma, using the $^{40}Ar/^{39}Ar$ stepwise heating method; they interpret these dates as the age of high-pressure metamorphism. Dobretsov *et al.* (unpubl. data, 1995) believe the blueschist/greenschist facies metamorphism, not the high-pressure metamorphism, occurred ~ 400 Ma, contemporaneous with the accretion and subduction of intracontinental oceanic crust. This interpretation corresponds with Edwards & Wasserburg's (1985) 397 ± 20 Ma determination of the igneous crystallization age for oceanic crust to the west of Maksyutov based on the Sm–Nd isochron. Dobretsov *et al.* (unpubl. data, 1995) suggest the high-pressure metamorphic event occurred during the early Cambrian based on a 589 Ma age obtained by a Sm–Nd garnet–omphacite–whole rock isochron from eclogite. The early Cambrian age of high-pressure metamorphism is related to the collision between the Russian and Siberian platforms, and is similar to the 530 Ma ultrahigh-pressure event of the Kokchetav Massif (Shatsky *et al.* 1995).

PETROGRAPHY

Representative eclogite, blueschist, mica schist, and quartzite were selected for petrologic investigation to evaluate the P–T path and metamorphic evolution. Samples described in this report were collected near Karyanova and Shubino villages (for location see Fig. 2).

ECLOGITE

Eclogite occurs near the villages of Shubino and Karyanova as tectonic blocks and boudins (10 cm to 2 m in length) within host mica schists and quartzites. Chesnokov and Popov (1965) reported inclusions of coesite pseudomorphs in garnet from eclogite near Shubino village. However, no coesite pseudomorphs have yet been observed by us in thin sections of eclogites from Shubino and other localities in the Maksyutov Complex to confirm Chesnokov and Popov's report.

Eclogite (sample #UM-21) from Shubino village contains 68% omphacite, 24% garnet, 5% white mica, 2% quartz, and 1% rutile. Garnet and omphacite grew synchronous with deformation. Pyroxene grains are aligned in the S_1 foliation plane and occasionally wrap around garnet. Small grains of pyroxene are included in or have grown over the grain boundaries of coarser-grained pyroxene, providing evidence for two stages of growth. White micas in the S_1 foliation plane wrap slightly around garnet suggesting the mica grew synchronous with and continued to grow after the completion of garnet growth. Quartz and white mica grew in pressure shadows around garnet. Garnets contain quartz and pyroxene inclusions which are aligned with the S_1 foliation. Garnet is fractured, probably by the later S_2 deformation, and partly replaced by chlorite.

Some eclogitic garnets exhibit atoll forms (Fig. 4a); the cores contain mica, pyroxene, and quartz, whereas the rims are relatively free of inclusions. The atoll garnets most likely formed through replacement of the cores of zoned garnets. This interpretation is supported by the descriptions of atoll garnets by Massonne & Chopin (1989) and Ushakova and Usova (1990). Ushakova and Usova (1990) analyzed atoll garnets from Tuva, south central Siberia, and concluded the cores of initially zoned garnets were subsequently replaced, leading to the observed atoll shape. Furthermore, Massonne and Chopin (1989) suggested that atoll garnets from metagranites in the Alps formed by decomposition of the grossular component in garnet within the high-pressure stability field.

BLUESCHIST

Blueschist exposed near Shubino village occurs as tectonic blocks on the scale of tens of meters. A representative blueschist (#MC-37) consists of 40% sodic amphibole (1–3 mm in length), 23% chlorite, 18% garnet (1–2 mm in diameter), 7% white mica, 5% quartz, 5% plagioclase, 2% calcite, 2% zoisite, and 2% iron oxide minerals (Fig. 4b). Crenulation cleavage in the blueschist is defined by the subparallel alignment of white mica and sodic amphibole. In addition to aligned white mica and sodic amphibole, the S_1 cleavage is also defined by aligned blades of zoisite. The S_2 crenulating cleavage cuts the early cleavage at a high angle.

Two stages of garnet growth can be differentiated in the blueschist. Many garnets are pulled apart subperpendicular to the S_1 cleavage indicating they grew before deformation; garnet fractures are filled with white mica, quartz, calcite, and plagioclase. Several garnets have straight aligned inclusions of quartz, white mica and zoisite that are subparallel to parallel to the S_1 cleavage indicating garnet grew synchronous with S_1 deformation, and were not rotated during the later S_2 deformational event. Some garnet porphyroblasts have a slight 'S' fabric to the inclusions further indicating syntectonic growth with respect to the S_1 cleavage.

Pressure shadows around garnet contain white mica and chlorite. White mica aligned in the plane of the S_2 cleavage wraps around garnet. Chlorite growth along the rims and fractures of garnets and occasional replacement of garnet by chlorite indicate a greenschist facies overprint of the blueschists.

MICA SCHIST

Mica schist is exposed throughout the Maksyutov Complex and includes boudins of eclogite (10 cm to 2 m in length) and quartz veins (2–5 cm in width). A representative amphibole-bearing mica schist (#MC-29) contains 41% white mica, 32% quartz, 15% sodic amphibole, 8% chlorite, 3% garnet (from < 1 mm to 1.5 cm in diameter) and 1% iron oxides. Two cleavages are defined by aligned white mica,

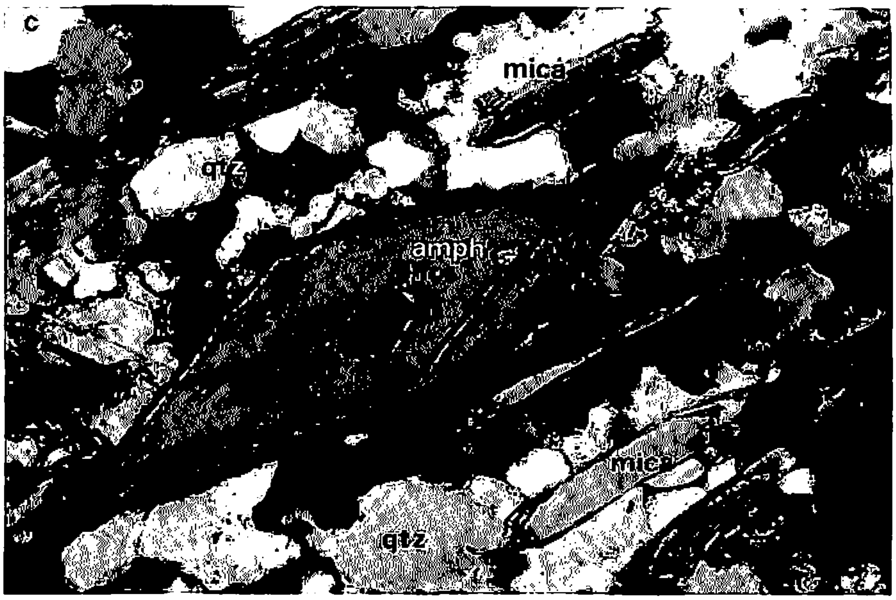

Fig. 4 a) Photomicrograph of atoll garnet in eclogite (Sample #UM-13k). Garnet rim surrounds mica and quartz. b) Photomicrograph of blueschist (Sample # UM-36a) showing crenulation cleavage (S_1 & S_2) defined by white mica and amphibole. c) Photomicrograph of quartzite (Sample #UM-15b) with aligned white mica and amphibole. Samples collected near Karyanova village. Field of view is 2 mm in each photo.

elongate quartz grains, sodic amphibole, and chlorite; the S_2 cleavage crenulates the S_1 cleavage. Some white mica grains are kinked indicating they grew synchronous with the development of the S_1 cleavage and were later rotated during S_2 deformation. Quartz is somewhat elongate and displays undulatory extinction. Garnet is highly fractured and partially replaced by chlorite; inclusions in garnet are aligned subparallel to the S_1 cleavage. Pressure shadows containing white mica, quartz, sodic amphibole, and chlorite have developed around garnet.

Some atoll garnets (sample #M-13) have single white mica crystals extending from the core of the garnet, across the rim into the matrix of the schist. This relationship suggests atoll garnets in mica schist formed by later recrystallization of the garnet cores; the same explanation proposed for the development of atoll garnets in eclogites from the Maksyutov Complex.

Graphite-bearing mica schist sample (#M-16) from near Karyanova village consists of 40% white mica, 38% graphite, 19% quartz, 1% calcite and <1% of feldspar, iron oxide and zircon. The one observable cleavage is defined by aligned white mica and elongate graphite grains and wraps around large graphite aggregates (up to 1.3 × 1 cm). Graphite grains have straight aligned inclusions of white mica and quartz that are subparallel to the cleavage; graphite may preserve a crenulation cleavage in the aligned inclusions. Pressure shadows containing quartz and coarse-grained white mica have developed around graphite grains. Quartz is relatively equigranular and displays undulatory extinction.

QUARTZITE

Quartzite is exposed throughout the Maksyutov Complex and is a host rock to the eclogites (Fig. 4c). A representative quartzite (#MC-32) contains 73% quartz, 20% phengite, 5% sodic amphibole, 1% garnet (from < 1 mm to 4 mm in diameter), and 1% chlorite. Some samples also contain abundant graphite; others have considerable amounts of jadeite ± kyanite (Dobretsov *et al.* unpubl. data, 1995).

Quartz is deformed and shows undulatory extinction, serrated grain boundaries, and subgrain boundary development. Quartz grains exhibit preferred crystallographic orientations.

Quartzites show one cleavage as defined by aligned phengite and sodic amphibole. Phengite is strongly aligned within the S_2 cleavage, suggesting it grew during deformation. Sodic amphibole (riebeckite–crossite) appears to have grown synchronous with the growth of phengite. The phengite and amphibole define the foliation and wrap around the garnet porphyroblasts. Garnet grew prior to S_2 deformation and is highly fractured. Quartz is found in pressure shadows around garnet. A few garnets have straight aligned inclusions of quartz and phengite that suggest syntectonic growth during the S_1 deformation event that has since been completely transposed. Chlorite partially replaces garnet.

In contrast to the more typical quartzite, rose-colored quartzite (sample #UM-13m) from near Karyanova village is composed of 45% quartz, 40% garnet, 12% white mica and 3% chlorite. Quartz is recrystallized with no preferred crystallographic orientation. White mica is weakly aligned, probably growing during the last stages of deformation. Abundant fine-grained garnet post-dates the S_1 deformation and is partially replaced by chlorite.

MINERAL CHEMISTRY

Mineral compositions of representative eclogite and quartzite samples were analyzed with the five-spectrometer JEOL 733 Superprobe at Stanford University under the operating conditions 15 kV accelerating voltage, 15 nA beam current and 1 μm beam diameter. Count rates were corrected for dead time using ratio data, and counts were corrected using CITZAF. Results are precise to 1% for major elements. Various mineral standards were selected from the Stanford University geology set of natural minerals. Standards were analyzed before and after each microprobe session to account for drift effects and to confirm the accuracy of instrument performance. Data consistency was verified by analyzing a secondary mineral standard similar to the composition of the minerals under investigation. The mineral abbreviations used in this paper are after Kretz (1983).

GARNET

Garnets of selected eclogite samples were analyzed; representative analyses are shown in Table 1 and plotted in Fig. 5. Iron was assumed to be exclusively ferrous. Garnets are characterized by a high almandine component (Alm_{55-60} Prp_{22-28} Grs_{16-22}). The pyrope component of analyzed garnet decreases slightly from the core to rim. Garnets plot in the Group C eclogite field of the Grossular–Almandine–Pyrope diagram where Group A represents deep-seated eclogites, Group B, eclogites from migmatic gneisses, and Group C, eclogites from glaucophane schists (Coleman 1965).

CLINOPYROXENE

Clinopyroxene (Jd_{46-56}) in eclogites is omphacite in composition (Fig. 6); representative analyses of clinopyroxene inclusions and matrix grains are shown in Table 2. End-member components were calculated according to $Jd = Al^{VI}$, $Aug = Ca$, and $Acm = Fe^{3+}$. Ferric iron was estimated according to $Fe^{3+} = Na - Al^{VI}$; titanium contents of these clinopyroxenes are minor. Omphacites show no significant zoning. Omphacite inclusions within garnet tend to be slightly enriched in Fe compared to matrix grains. Some clinopyroxenes are replaced by secondary pyroxene with high augite content together with albitic plagioclase.

WHITE MICA

White mica occurs both as matrix minerals and as inclusions within garnet. Representative analyses of white micas from eclogites (samples #UM-1a, 3a, 21 & 35) and quartzite (#UM-15b) are shown in Table 3. Iron was assumed to be exclusively ferrous. Phengites from eclogites and quartzites have high Si values between 3.3 and 3.6 per formula unit. Paragonite (sample #UM-35f) occurs as inclusions in garnet and as matrix minerals.

AMPHIBOLE

Sodic amphiboles were analyzed from eclogite and quartzite. Representative analyses for sodic amphibole are shown in Table 4. Amphibole from quartzite was zoned riebeckite–crossite in composition with the rims more enriched in riebeckite. Amphibole from eclogite was glaucophane–crossite to barroisite in composition. In addition, actinolite

Table 1 Representative analyses of garnet.

Sample #	UM1a	UM3a	UM3a	UM35f	UM35f	UM21
Rock name	eclogite	eclogite	eclogite	grt-px-qtz	grt-px-qtz	eclogite
Location	Karyanova	Karyanova	Karyanova	Karyanova	Karyanova	Shubino
	core	core	rim	core	rim	core
SiO_2	38.88	38.64	38.71	38.38	38.48	38.83
TiO_2	0.10	0.00	0.09	0.16	0.07	0.17
Al_2O_3	20.81	21.48	22.02	21.73	21.52	20.84
Cr_2O_3		0.00	0.00	0.00	0.03	
FeO_T	26.68	26.78	25.90	25.91	27.55	25.02
MnO	0.10	0.70	0.85	0.59	0.52	1.66
MgO	3.85	4.58	5.54	3.72	4.87	3.90
CaO	10.53	9.74	8.29	10.30	8.01	10.13
Na_2O	0.07	0.03	0.04	0.07	0.05	0.06
K_2O	0.00	0.00	0.00	0.00	0.01	0.01
Total	101.01	101.94	101.44	100.86	101.10	100.61
Si	3.03	2.96	2.98	2.99	2.99	3.03
Ti	0.01	0.00	0.01	0.01	0.00	0.01
Al	1.91	1.99	2.00	1.99	1.97	1.92
Cr	0.00	0.00	0.00	0.00	0.00	0.00
Fe	1.74	1.70	1.67	1.69	1.79	1.63
Mn	0.01	0.06	0.06	0.04	0.03	0.11
Mg	0.45	0.51	0.69	0.43	0.56	0.45
Ca	0.88	0.81	0.68	0.86	0.67	0.85
Na	0.01	0.01	0.01	0.01	0.01	0.01
K	0.00	0.00	0.00	0.00	0.00	0.00
Total	8.04	8.04	8.04	8.01	8.03	8.01
Alm	56.7	56.3	55.0	56.6	59.2	55.6
Prp	28.7	26.8	22.3	28.9	22.1	29.0
Grs	14.7	16.9	22.7	14.5	18.7	15.4

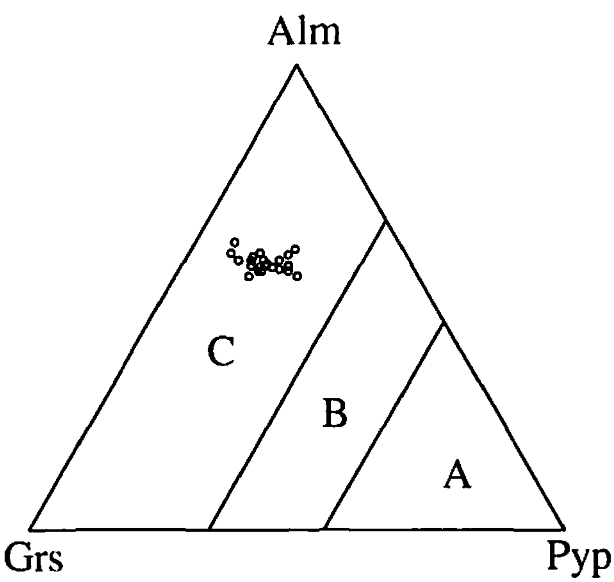

Fig. 5 Compositions of garnet from eclogite. Group A represents deep seated eclogites, Group B, the eclogites from migmatic gneisses and Group C, the eclogites from glaucophane schists (Coleman *et al.* 1965).

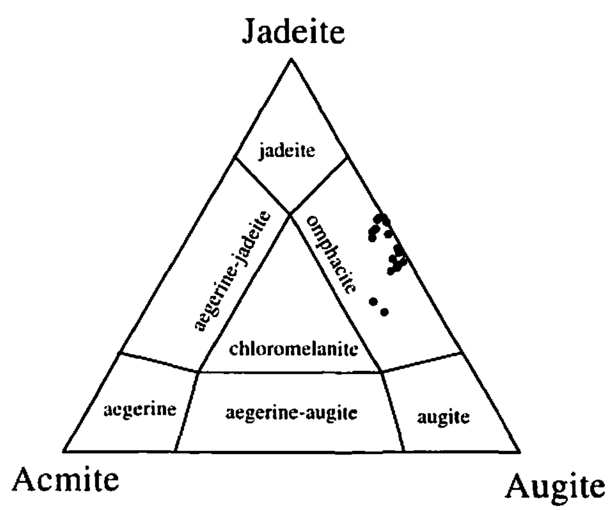

Fig. 6 Compositions of clinopyroxene from eclogite.

amphibole has been previously reported (Lennykh 1977; Dobretsov & Dobretsova 1988). Ferrous-ferric iron ratios were determined with the program Minform by calculating the minimum and maximum Fe_2O_3 contents and using the mean value allowing for crystal chemical consistency according to the method of Papike *et al.* (1974).

METAMORPHIC EVOLUTION

Mineralogical and microtextural analyses indicate eclogites of the Maksyutov Complex underwent

Table 2 Representative analyses of clinopyroxene.

Sample #	UM1a	UM3a	UM3a	UM35f	UM21
Rock name	eclogite	eclogite	eclogite	grt-px-qtz	eclogite
Location	Karyanova matrix	Karyanova inclusion	Karyanova matrix	Karyanova matrix	Shubino inclusion
SiO_2	57.82	55.98	56.34	55.90	55.42
TiO_2	0.10	0.02	0.04	0.00	0.09
Al_2O_3	13.14	10.73	11.44	13.34	8.12
Cr_2O_3	0.00	0.00	0.00	0.00	0.00
FeO_T	4.10	5.48	3.91	4.02	8.86
MnO	0.00	0.03	0.01	0.04	0.07
MgO	6.53	7.71	7.82	6.54	7.67
CaO	11.59	12.94	13.01	10.70	13.69
Na_2O	8.09	7.33	7.32	8.58	6.73
K_2O	0.01	0.00	0.01	0.03	0.02
Total	101.38	100.21	99.90	99.13	100.68
Si	2.01	2.00	2.00	1.99	2.01
Ti	0.00	0.00	0.00	0.00	0.00
Al	0.54	0.45	0.48	0.57	0.35
Cr	0.00	0.00	0.00	0.00	0.00
Fe^{+3}	0.01	0.05	0.03	0.03	0.12
Fe^{+2}	0.11	0.11	0.09	0.09	0.15
Mn	0.00	0.00	0.00	0.00	0.00
Mg	0.34	0.41	0.42	0.33	0.41
Ca	0.43	0.49	0.50	0.40	0.53
Na	0.55	0.51	0.50	0.61	0.47
K	0.00	0.00	0.00	0.00	0.00
Total	3.99	4.02	4.01	4.01	4.04
Jd	55.1	45.7	48.3	56.7	35.0
Acm	1.0	5.2	1.2	2.9	12.0
Aug	43.9	49.1	50.5	40.4	53.0

Table 3 Representative analyses of white mica.

Sample #	UM1a	UM3a	UM35	UM15b	UM21
Rock name	eclogite	eclogite	grt-px-qtz	quartzite	eclogite
Location	Karyanova phengite	Karyanova phengite	Karyanova paragonite	Karyanova phengite	Shubino phengite
SiO_2	51.16	49.90	46.46	51.01	51.77
TiO_2	0.32	0.44	0.11	0.32	0.11
Al_2O_3	28.13	28.05	39.80	21.31	24.84
Cr_2O_3	0.00	0.06	0.03	0.06	0.00
FeO	1.72	1.41	0.40	7.53	2.05
MnO	0.03	0.00	0.00	0.05	0.01
MgO	3.11	3.47	0.19	2.69	3.90
CaO	0.01	0.02	0.19	0.00	0.03
Na_2O	0.89	0.75	7.76	0.14	0.26
K_2O	10.05	9.81	0.82	11.09	10.20
Total	95.42	93.90	95.76	94.20	93.17
Si	3.39	3.36	2.97	3.56	3.52
Ti	0.02	0.02	0.01	0.02	0.01
Al	2.20	2.23	2.99	1.75	1.99
Cr	0.00	0.00	0.00	0.00	0.00
Fe	0.10	0.08	0.02	0.44	0.12
Mn	0.00	0.00	0.00	0.00	0.00
Mg	0.31	0.35	0.02	0.28	0.39
Ca	0.00	0.00	0.00	0.00	0.00
Na	0.11	0.10	0.96	0.02	0.03
K	0.85	0.84	0.07	0.99	0.88
Total	6.13	6.13	7.05	7.05	6.06

Table 4 Representative analyses of sodic amphibole.

Sample #	UM15b	UM15b	UM21	UM21
Rock name	quartzite	quartzite	eclogite	eclogite
Location	Karyanova	Karyanova	Shubino	Shubino
	rim	core	inclusion	matrix
SiO_2	54.36	53.55	57.32	52.42
TiO_2	0.04	0.10	0.05	0.14
Al_2O_3	7.32	1.99	9.68	8.43
Cr_2O_3	0.00	0.04	0.00	0.00
FeO	18.06	16.86	11.55	9.65
Fe_2O_3	5.28	13.88	1.79	1.77
MnO	0.05	0.01	0.06	0.00
MgO	4.52	4.70	9.89	13.61
CaO	0.21	0.09	1.63	6.97
Na_2O	7.16	6.95	6.78	4.57
K_2O	0.05	0.03	0.02	0.24
Total	97.03	98.17	98.77	97.80
Si	7.97	7.97	7.91	7.43
Ti	0.00	0.01	0.01	0.02
Al	1.27	0.35	1.58	1.41
Cr	0.00	0.01	0.00	0.00
Fe^{+2}	2.22	2.10	1.33	1.14
Fe^{+3}	0.58	1.56	0.19	0.19
Mn	0.01	0.00	0.01	0.00
Mg	0.99	1.04	2.03	2.87
Ca	0.03	0.01	0.24	1.06
Na	2.04	2.01	1.82	1.26
K	0.01	0.01	0.00	0.04
Total	15.12	15.06	15.12	15.38

multiple stages of deformation and recrystallization. At least three stages of metamorphism (M_{1-3}) and two stages of deformation (S_1 and S_2) were observed from examination of more than 70 thin sections (Fig. 7). Field observations suggest there may be as many as six stages of deformation (Moskovchenko 1982). Furthermore, if the occurrence of coesite pseudomorphs (Chesnokov and Popov 1965) is confirmed, at least four stages of metamorphic recrystallization could be established for the eclogitic rocks of the Maksyutov Complex.

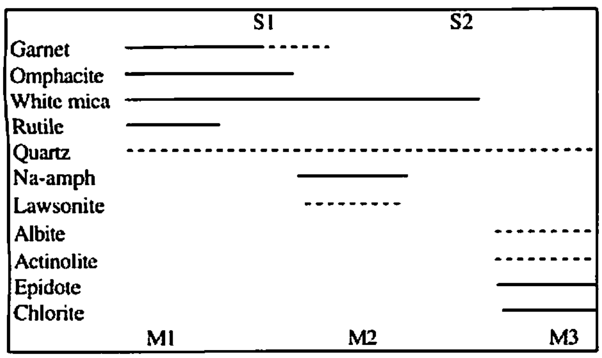

Fig. 7 Mineral growth with respect to deformation for eclogites.

Stage M_1: Grt + Cpx + Phn + Rut

The high-pressure metamorphic stage is recognized by the assemblage almandine garnet + omphacitic clinopyroxene + phengite + rutile. Phengite has a silica value of ~ 3.5 per formula unit. The peak-stage eclogitic assemblage is well preserved in some eclogites. Only minor symplectic intergrowth of sodic amphibole and plagioclase after omphacite and amphibole rimmed around garnet occur.

Stage M_2: Grt + Gl + Ab ± Lws + Mica

The development of a blueschist facies is recognized by the presence of sodic amphibole, chlorite, albite, lawsonite, and titanite. These phases define the dominant foliation of blueschist and retrograded eclogite. The sodic amphibole is glaucophane–crossite in composition and most likely derived from the alteration of omphacite. Second stage white mica is primarily paragonite. In blueschist-dominant meta-mafic rocks, only minor garnet relics occur, and omphacitic clinopyroxene is entirely replaced by sodic amphibole + lawsonite + chlorite ± albite.

Stage M_3: Ep + Chl ± Ab ± Act + Mica

The last stage of metamorphism is greenschist facies overprint. The development of the greenschist facies may have resulted from the reaction:

$$Gl + Lws = Ab + Chl + Act + Qtz + H_2O$$

The greenschist facies assemblage is minor in the investigated blueschist and eclogite samples; it is best developed along fractures and in strongly sheared rocks.

P-T ESTIMATES

Equilibrium temperature for the eclogites ranges from 560-680°C as calculated using Fe-Mg exchange geothermometry between clinopyroxene and garnet (Powell 1985; Krogh 1988). All iron in garnet was assumed to be ferrous for geothermometry calculations. Temperatures calculated using rims of garnets and adjacent clinopyroxene grains were indistinguishable from temperatures calculated with cores of garnets and clinopyroxene inclusions. Equilibrium temperature (680°C) for eclogite from Shubino village (sample #UM-21) was 40-120°C higher than equilibrium temperatures calculated for other eclogites in the Maksyutov Complex.

The minimum peak pressure for the eclogites is 12-16 kbar as determined by the jadeite content of omphacite (Jd_{46-56}) using the sliding equilibrium of Ab = Jd + Qtz (Holland 1983). Although the Si values (3.3-3.5) of phengites in eclogites suggest high-pressures during their formation (Massonne & Schreyer 1987), they cannot be used to evaluate equilibrium pressure because the samples lack the required limiting assemblage: phengite + K feldspar + phlogopite + quartz. For one eclogite sampled near Karyanova village (#UM-3a), the garnet-phengite barometry was attempted with the assumption that all iron in garnet and phengite was ferrous; the intersection of the $K_{D^{grt-cpx}}$ (Krogh 1988) and $K_{D^{grt-phe}}$ (Krogh & Raheim 1978) P-T curves defined a pressure of 22 kbar at a temperature of 614°C. If coesite relic is preserved, the peak ultrahigh-pressure may be as high as 27 kbar at 615°C.

P-T estimates and a comparison of observed mineral parageneses with experimentally determined stability fields were used to construct the retrograde P-T path for the eclogite (Fig. 8). The presence of coesite or coesite pseudomorphs would confirm the ultrahigh-pressure metamorphic stage that is presently shown with a ghost outline. Barring the confirmation of coesite, Stage M_1 is defined by the garnet-clinopyroxene P-T estimates. Stage M_2 is constrained by the stabilities of glaucophane and lawsonite. Stage M_3 is the greenschist facies overprint.

CONCLUSIONS

Observed mineral parageneses define a retrograde P-T path for eclogite: (M_1) eclogite facies, (M_2) blueschist facies, and (M_3) greenschist facies.

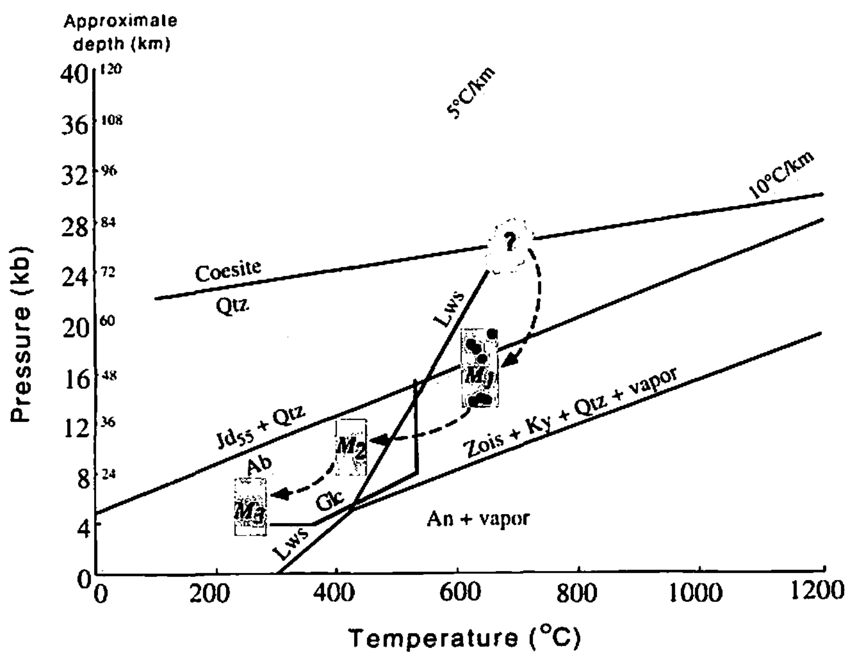

Fig. 8 Conjectured P-T path of eclogite from the Maksyutov Complex is based on observed mineral associations and analyzed compositions. Coesite stability from Bohlen and Boettcher (1982), glaucophane stability from Maresch (1977). Jd + Qtz = Ab after Holland (1983). Lws = Zois + Ky + Qtz + V from Newton and Kennedy (1963).

Mineral assemblages within the most representative eclogite from the Maksyutov Complex indicate minimum peak pressures of 15 kbar with temperatures of approximately 600 °C. We observed no coesite or coesite pseudomorphs in rocks from the Maksyutov Complex to confirm the initial report of coesite pseudomorphs by Chesnokov and Popov (1965).

Field observations suggest mafic-ultramafic rocks of unknown tectonic affinity were emplaced into continent-derived sediments; both the blocks and the matrix were then subjected to multi-stage deformation and metamorphism. The high-pressure metamorphism most likely occurred in the Early Cambrian as a result of a continent–continent collision between the Russian and Siberian platforms. Whether some eclogite blocks were recrystallized in the ultrahigh-pressure coesite stability field remains to be investigated.

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