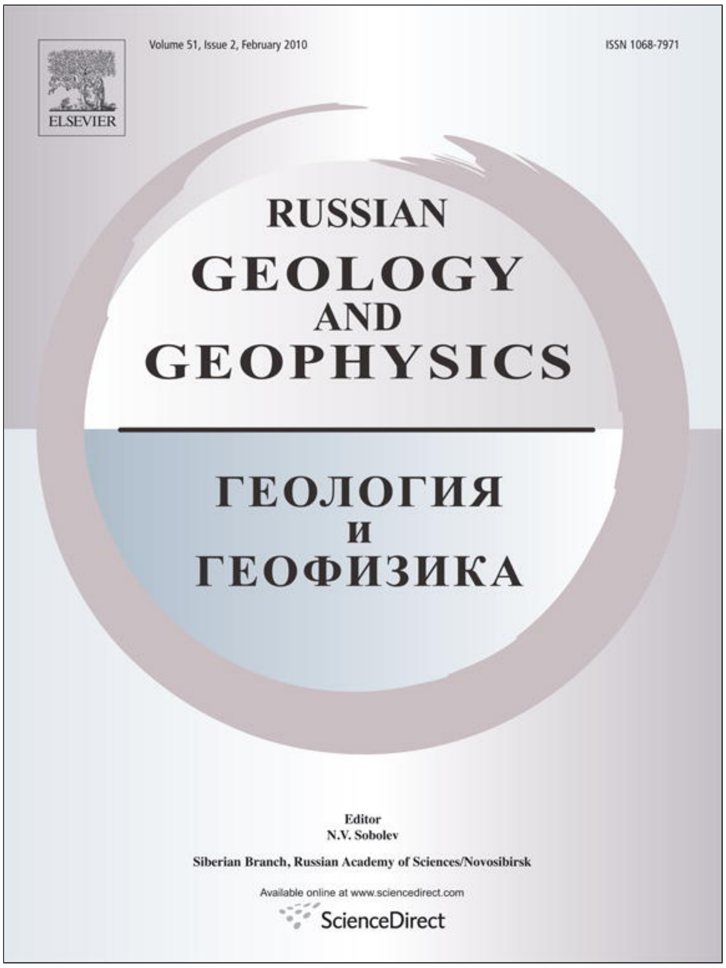
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Eclogites of the Late Cambrian–Early Ordovician North Kokchetav tectonic zone (*northern Kazakhstan*): structural position and petrology

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Abstract

We consider the structural position and petrology of eclogites in the North Kokchetav accretion-collision zone located north of the Kokchetav metamorphic belt formed by high- and ultrahigh-pressure rocks. In the Early Ordovician North Kokchetav tectonic zone, thin sheets of mylonite and diaphthoric gneisses with eclogites are tectonically conjugate with the volcanic and sedimentary rocks of the Stepnyak paleoisland-arc zone. Eclogites have been revealed at two sites of the North Kokchetav tectonic zone—Chaikino and Borovoe. The Chaikino eclogites formed at 800–850 ℃ and 18–20 kbar, and the Borovoe eclogites, at 750–800 ℃ and 17–18 kbar. Study of pyroxene-plagioclase symplectite replacing omphacite of the eclogites at both sites has recognized three stages of regressive magmatism: (1) formation of coarse-grained clinopyroxene-plagioclase symplectite at 760–790 ℃ and 11–12 kbar, (2) formation of fine-grained clinopyroxene-plagioclase symplectite at 700–730 ℃ and 7–8 kbar, and (3) amphibolization of pyroxene at 570–600 ℃ and 5–6 kbar. The Ar-Ar age of muscovite from the Borovoe mica schists hosting eclogites is 493 ± 5 Ma, which corresponds to the time of cooling of metamorphic rocks to <370 ℃. Hence, the peak of high-pressure metamorphism and all recognized stages of retrograde changes are dated to the Cambrian. The geological data evidence that eclogite-schist-gneiss sheets were localized in the accretion-collision zone and became conjugate with sedimentary and volcanic rocks no later than in the Middle Ordovician.

Keywords: eclogites; symplectites; Ar-Ar dating; tectonic sheets; North Kokchetav tectonic zone

Introduction

Eclogites are widespread in the Kokchetav region of northern Kazakhstan (Abdulkabirova, 1946; Korsakov et al., 1998; Massago, 2000; Okamoto et al., 2000; Shatsky et al., 1989, 1993; Udovkina, 1985). They occur as boudins among gneisses and mica schists of the Zerenda Group (Rozen and Bogoyavlenskaya, 1962). Outcrops of the Zerenda Group form a W–E-striking belt 150 km long and 10–30 km wide, known as the Kokchetav metamorphic belt (KMB). In recent time it has been regarded as a metamorphic melange (Dobrzhinetskaya et al., 1994) that formed in the Cambrian–Ordovician as a result of the subduction of the Kokchetav microcontinent into the mantle, the metamorphism of rocks of continental crust at depths of 150–200 km, and the subsequent exhumation of some blocks of metamorphosed rocks (Dobretsov et al., 1995, 2006). Fragments of melange composed of schists, gneisses, eclogites, marbles, and serpentinites were mapped at some sites of the belt (Dobretsov et al., 1998; Dobrzhinetskaya et al., 1994). Based on analysis of mineral assemblages and geologic-structure studies, which showed a significant change in the type of deformations in different parts of the belt (Theunissen et al., 2000a,b), Dobretsov et al. (1998) drew the conclusion about the block structure of the metamorphic belt and considered it to be a megamelange. In the south, the KMB is bounded by the Late Ordovician granitoid massifs of the Zerenda complex, which replaced the more ancient Cambrian–Ordovician tectonic structure at the southern edge of the belt. North of the KMB, there are Ordovician island-arc complexes of the Stepnyak zone (Stepnyak trough, Stepnyak synclinorium). The KMB joins the Stepnyak zone to form the North Kokchetav tectonic zone (NKTZ) (Dobretsov et al., 2006; Zhimulev, 2007). The latter stretches along the northern and eastern framing of the KMB—from the Chaglinka River to

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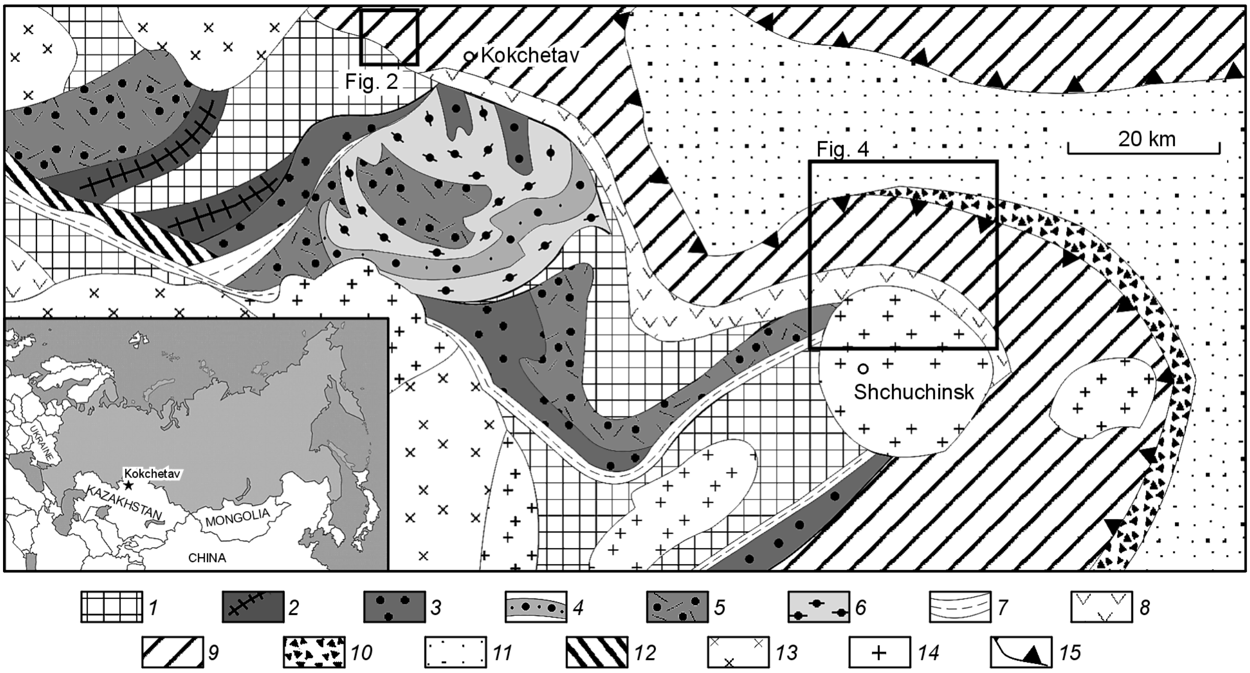

Fig. 1. Schematic geological map of the Kokchetav region with marked studied sites. *1*, fragments of the sedimentary cover of the Kokchetav microcontinent (Ilekta Group, Upper Riphean); *2–6*, Kokchetav metamorphic belt: *2*, diamond-bearing gneisses and coesite eclogites, *3*, coesite eclogites, eclogites, and garnet amphibolites in mica schists, *4*, garnet peridotites, eclogites, and amphibolites, *5*, eclogites and garnet amphibolites in granite gneisses, *6*, garnet-sillimanite-cordierite schists (mylonites and blastomylonites) with boudins of eclogites and garnet amphibolites; *7*, andalusite-cordierite-botite schists and gneisses (Daulet Formation); *8*, Vendian–Early Cambrian(?) volcanosedimentary rocks; *9*, North Kokchetav tectonic zone; *10*, Late Arenig–Middle Ordovician olistostrome; *11*, Ordovician volcanosedimentary rocks of the Stepnyak paleoisland arc zone; *12*, Cambrian Krasnyi Mai alkaline-ultrabasic complex; *13*, Ordovician garnets; *14*, Devonian garnets; *15*, frontal thrust of the North Kokchetav tectonic zone. The inset shows the locality of the study area.

the west from Kokchetav and then, via this city, to the east to Aleksandrovka Village, parallel to the Kylshakty River valley, and then to the northeast to Zhanatalap Village, where it makes a steep bend to the south (Fig. 1). The North Kokchetav tectonic zone nearly coincides with the Kokchetav fault zone recognized during 200,000 surveys in the areas mapped on sheets N-42-XXVIII and N-42-XXIX (Babichev et al., 1968; Rozen and Bogoyavlenskaya, 1962; Zhukov and Rakhimbaev, 1964). It is a zone of junction of the KMB and Ordovician island-arc complexes of the Stepnyak zone. In most papers, the geologic complexes that we recognized as the NKTZ were considered to be the northeastern margin of the Kokchetav massif (Abdulin, 1988b) but were not included into the KMB (Dobretsov et al., 1998). The NKTZ is formed by a group of tectonic plates composed of the complexes of the sedimentary cover of the Kokchetav microcontinent (quartz-sericite schists and dolomites of the Ilekta Group), rocks of its basement (granite-gneisses with amphibolite bodies), ophiolites of the Shchuch'e complex (gabbros, gabbro-diabases, basalts, serpentinite melanges, and schists), Early Ordovician siliceous-terrigenous deposits with olistostrome lenses, and pre-Ordovician andesite-basalt and rhyolite lavas and tuffs alternating with conglomerates and sandstones. Faults between the plates are filled with quartz-chlorite-muscovite schists (sometimes containing garnets). The Ar-Ar mica age of the schists is 490–476 Ma (Dobretsov et al., 2005b), which corresponds to the Early Ordovician and agrees with the Early Ordovician age of the zonal olistostromes determined by the paleontological method (Obut et al., 2006). The above peculiarities permit the NKTZ to be considered an Early Ordovician accretion-collision zone (Dobretsov et al., 2005a,b, 2006). Another complexes revealed in this zone are highly diaphthoric high-pressure eclogites localized in quartz-garnet-mica schists and mylonitized biotite gneisses. The finding of high-pressure rocks in the Cambrian–Ordovician accretion-collision zone, beyond the generally accepted KMB boundaries, proves that the regional high-pressure metamorphism was related to the Cambrian–Ordovician subduction-collision processes and is of great interest for clarifying the geodynamic evolution of the Kokchetav region. In the NKTZ, metamorphic rocks compose tectonic plates conjugate with igneous and sedimentary rocks that were not subjected to high-pressure metamorphism. This permits one to determine the time and conditions of the conjugation of high-pressure rocks with the upper-crust geologic complexes. In this work we for the first time describe the structural position and petrology of the NKTZ eclogites. They were studied at two sites—Chaikino and Borovoe. At the Chaikino site, such eclogites were found by us for the first time, whereas those at the Borovoe site have been long known (Kushev and Vinogradov, 1978; Zhukov and Rakhimbaev, 1964). The paper presents new data on the *PT*-conditions of eclogite metamorphism, the age of micas in the host schists, and the structural position of eclogites.

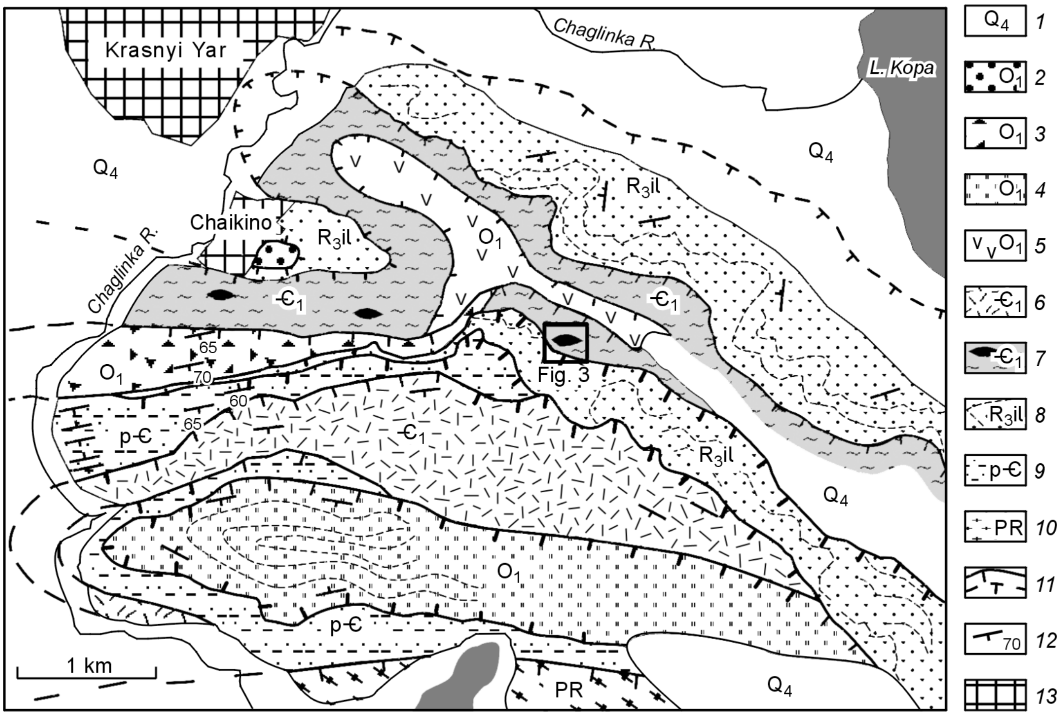

Fig. 2. Schematic geological map of the Chaikino site of the NKTZ (right bank of the Chaglinka River, region of Chaikino and Krasnyi Yar Villages). *1*, Quaternary deposits; *2–5*, Early Ordovician deposits: *2*, sandstones and conglomerates, *3*, Arenig siliceous-terrigenous deposits with olistostrome lenses, *4*, flints, siliceous mudstones, and jasperoids, *5*, andesite-basalts, tuffs, sandstones, and siltstones; *6*, Early Cambrian(?) quartz porphyry, lava breccias, and red-colored sandstones; *7*, greenschists developed after gneisses and relics of porphyroblastic gneisses with eclogites and garnet amphibolites; *8*, quartzites and quartz-sericite schists of the Ilekta Group; *9*, greenschists developed after metaterrigenous rocks of tentatively Precambrian age; *10*, mylonitized gneisses of the basement of the Kokchetav microcontinent (Uyaly Formation of the Zerenda Group); *11*, faults; *12*, dips and strikes of layering; *13*, human settlements.

The geologic structure of the Chaikino site

The Chaikino site (Fig. 2) is located on the right bank of the Chaglinka River, south of Chaikino and Krasnyi Yar Villages (5 km west of Kokchetav), where a series of folded tectonic plates was mapped. They are composed of quartz-sericite schists of the Ilekta Group (complex of the cover of the Kokchetav microcontinent), mylonitized gneisses (deformed basement of the Kokchetav microcontinent), metaterrigenous greenschist rocks of tentatively Precambrian age, tuffs, tuff breccias, quartz porphyry, and acid-normal lava breccias of tentatively Early Cambrian age (Rozen and Bogoyavlenskaya, 1962), Early Ordovician siliceous, volcanogenic, and terrigenous deposits similar to the complexes in the Stepnyak zone, and greenschist apogneiss strata with relics of porphyroblastic gneisses and boudin-like amphibolite and eclogite bodies. The Early Ordovician siliceous-terrigenous deposits contain olistostrome lenses. Dating of the complex of radiolarians and conodonts in these deposits showed its Arenig age (Obut et al., 2006; Tsai et al., 2001).

The tectonic nature of the contacts is determined by their cutting of the internal structure of the plates, the drastic thickness changes along the strike of tectonic plates, and different degrees of metamorphism of conjugate rocks. In the zones of contacts between tectonic plates, the rocks are ferruginized, brecciated, and enriched in mica, and quartzy sandstones of the Ilekta Group are transformed into quartz-muscovite dynamoschists. The $^{40}Ar/^{39}Ar$ age of muscovite from them is 476.5 ± 1.9 and 487.6 ± 3.5 Ma (Early Ordovician) (Dobretsov et al., 2005a), which is interpreted as the time of formation of the imbricated structure (Dobretsov et al., 2005b, 2006).

Eclogites, garnet and garnet-free amphibolites occur in the strata composed of green (quartz-sericite-chlorite) schists. Relics of mylonitized augen gneisses in the strata suggest that the greenschists are diaphthorites developed after gneisses, which formed under greenschist facies conditions. The bodies of eclogites and garnet and garnet-free amphibolites are round and vary in size from few centimeters to few meters. Garnet amphibolites and eclogites were found at two sites of similar geologic structure, 100–150 m south of the southern margin of Chaikino Village (53º17′50″ N, 69º15′19″ E) and in the eastern part of the site (53º17′50″ N, 69º17′32″ E) (Fig. 3). At both sites, high-pressure rocks compose boudins oriented along the strike of the host-unit schistosity and the imbricated structure as a whole. With approach to eclogite bodies, the appearance of the host schists changes: K-feldspar porphyroclasts 2–3 to 10 mm in size appear among fine-grained quartz-chlorite-sericite aggregate. Their amount in the rock gradually increases, and schist gives way to blastomylonite developed after gneiss and then to typical augen gneiss. The latter consists of fine-grained quartz-biotite-microcline-plagioclase matrix and large (1–10 mm) microcline porphyroblasts. It is dark green and has a well-expressed banding, often with

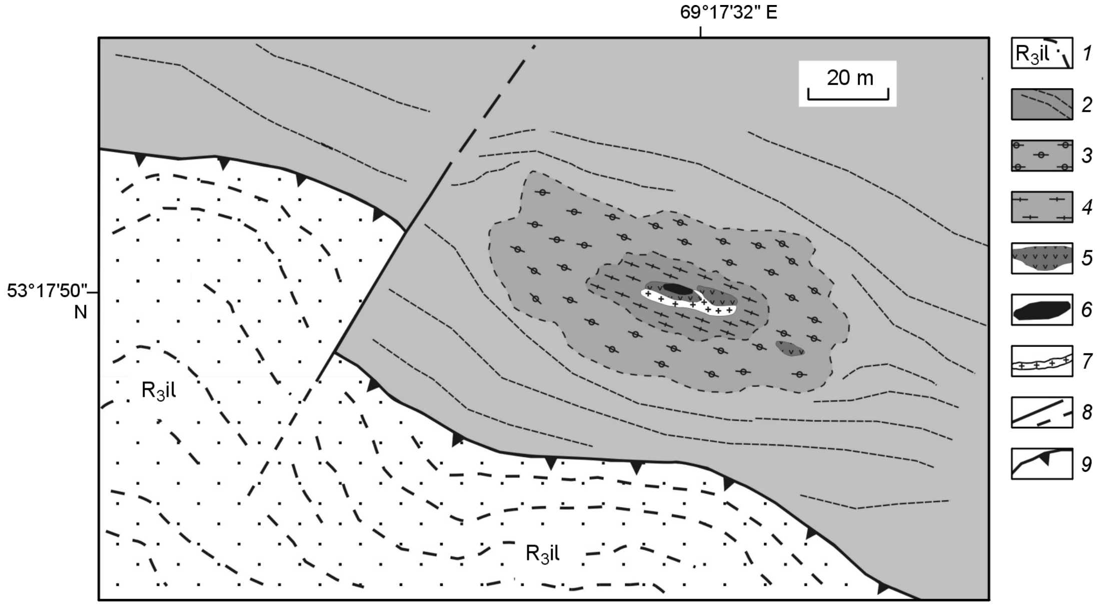

Fig. 3. Detailed geological map of the occurrence of eclogites at the Chaikino site. *1*, quartz-sericite schists of the Ilekta Group, *2*, quartz-chlorite-sericite schists (diaphthorites developed after gneisses), *3*, blastomylonites developed after gneisses, *4*, augen gneisses, *5*, garnet amphibolites, *6*, amphibolized eclogites, *7*, massive garnet-quartz rock, *8*, fault cutting the imbricated structure, *9*, thrust in the NKTZ.

microfolds. Such gneisses are one of the main host rocks for the eclogites of the Kokchetav metamorphic belt in both the Kumdykul' and Kulet blocks. Eclogites for study were sampled in the eastern part of the site.

The geologic structure of the Borovoe site

The Borovoe site is localized north of the Borovskie Mountains, 60 km southeast of Kokchetav (Fig. 4). Here, as at the Chaikino site, the NKTZ is formed by a series of tectonic plates. In passing from Lake Ul'ken-Sor in the north of the NKTZ to Lake Maibalyk in the south, the following sequence of plates is observed: quartz-sericite schists and dolomites of the Ilekta Group, mylonitized schists and gneisses with eclogite bodies, quartz-sericite schists and dolomites of the Ilekta Group (thin broken plate), and compositionally intricate pre-Ordovician strata including volcanomictic flysch, olistostrome-conglomerates, and plagioclase porphyrites.

The imbricated structure is intruded by Late Silurian (Shatagin, 1995; Shatagin et al., 1999) (Borovoe and Orlinaya Gora) massifs of the Borovoe complex. The isometric shape of the plutons and the sharply cutting contacts evidence that the above plates aligned before the intrusion of granites. The structure is ended with the Late Ordovician (Abdulin, 1988a; Letnikov et al., 2009) plutons of the Krykkuduk complex, which suggests that it is older than not only the Late Silurian but also the Late Ordovician.

At the Borovoe site, the contact between the NKTZ and the Stepnyak zone is exposed and is ubiquitously of tectonic nature. A complex of dynamoschists occurs in the contact zone. North of the NKTZ, the Stepnyak zone is composed of folded volcanogenic and sedimentary rocks of Early–Middle Ordovician age (Obut et al., 2006). On the regional scale, the folds of the northewestern Stepnyak zone are conformal to the boundaries of the Borovoe block of the Kokchetav massif, but the detailed examination shows that the frontal fault of the NKTZ cuts the folded structure of the zone. North of Lakes Maloe Chebach'e and Bol'shoe Chebach'e, the NKTZ is of W–E strike, and the members of Ordovician volcanomictic sandstones of the folded structure in the Stepnyak zone are of NE strike, i.e., approach the frontal fault at an angle and are cut by it. These relationships with the Early–Middle Ordovician folded complexes of the Stepnyak zone indicate that the regional tectonic activity took place no earlier than in the Middle Ordovician.

High-pressure rocks of the Borovoe site are eclogites, whose boudin-like bodies occur among quartz-garnet-muscovite schists (sometimes, almost monomineral glimmerites). A plate of mica schists bearing eclogites is traceable for at least 25 km (including the zones where the schists are overlain by Quaternary deposits and water basins), from Lake Maibalyk via the isthmus between Lakes Bol'shoe Chebach'e and Akkol' to the area east of Lake Zhainak (Fig. 4). The plate is 500 m to 1 km in width. It is in contact with the plates composed of gneisses and quartz-sericite schists of the Ilekta Group and pre-Ordovician volcanogenic and sedimentary deposits. Eclogites were sampled 5 km east of Lake Zhainak.

Zircons from granite-gneisses near the contact of the eclogite-glimmerite and amphibolite-gneiss plates at the Maibalyk site were dated by Letnikov and Khalilov (1994). All zircons fall onto the discordia, whose upper intersection marks an age of 1.2 Ga, and the lower one, ~450 Ma (Late Ordovician), which is interpreted as the time of K-Si-metaso-

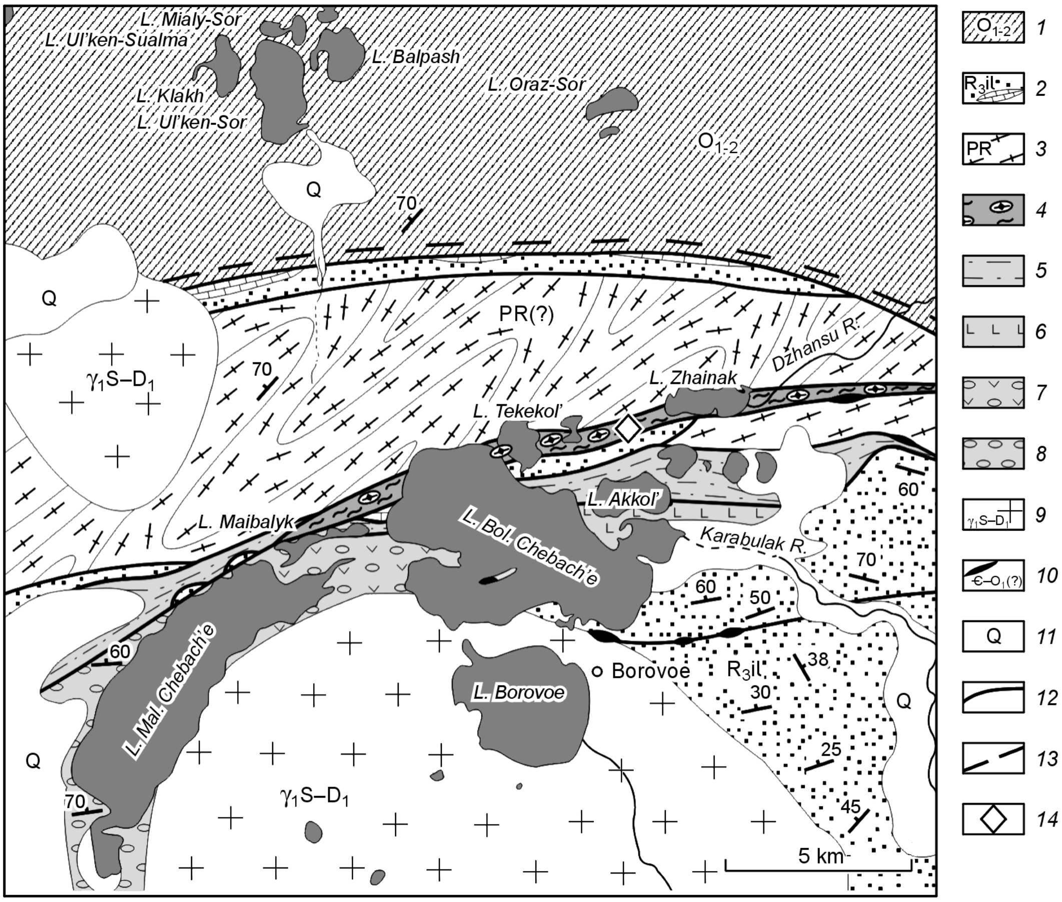

Fig. 4. Schematic geological map of the Borovoe site of the NKTZ. *1*, Ordovician sedimentary and volcanosedimentary deposits of the Stepnyak paleoisland arc zone; *2*, quartzy sandstones and dolomites of the Ilekta Group (Late Riphean, cover of the Kokchetav microcontinent); *3*, gneisses, schists, migmatites, and blastomylonites developed after Proterozoic gneisses (basement of the Kokchetav microcontinent); *4*, garnet-muscovite glimmerites and gneisses with eclogite bodies; *5–8*, volcanosedimentary complexes of the pre-Ordovician island arc(?): *5*, siltstones, mudstones, and sandstones (flysch deposits), *6*, basaltic porphyrites, *7*, agglomerates of andesite composition, *8*, boulder conglomerates (olistostrome-conglomerates); *9*, Silurian–Early Devonian hornblende-biotite granites of the Borovoe complex; *10*, serpentinites of the Shchuch'e ophiolite belts; *11*, Quaternary deposits; *12*, faults; *13*, mylonitization zone tracing the frontal thrust of the NKTZ; *14*, locality of sampling (sample F-06-22) for Ar/Ar dating.

matism and the formation of muscovite schists. Dating of zircons from granodiorite veins cutting the gneiss plate yielded an age of 1128 ± 12 Ma (Letnikov et al., 2007).

We performed $^{40}Ar/^{39}Ar$ dating of muscovite from quartz-garnet-muscovite schists hosting the eclogites of the Borovoe site (sample F-06-22, 53°08′49.5″ N, 70°19′9.6″ E, H = 325 m).

Petrography and mineralogy of eclogites

Eclogites of both sites are dark green and brown-green fine-grained rocks. They are composed of garnet (40–50%), clinopyroxene (30–40%), and quartz (5–10%). The secondary minerals are amphibole, plagioclase, epidote, biotite, and calcite, and the accessory minerals are rutile, zircon, apatite, sphene, and ilmenite. The rocks are of porphyroblastic texture and massive structure.

Garnet occurs as pale-pink and colorless grains of both isometric and irregular shapes. It is optically homogeneous. The largest garnets bear solid inclusions: quartz, pyroxene, and rutile. Often, case-like (atoll) garnets with a quartz core are found.

Clinopyroxene occurs as pale-greenish and colorless grains without a distinct crystal habit. Studying the thin sections, we recognized two generations of the mineral. Pale-greenish and colorless porphyroblasts without a distinct crystal habit were assigned to generation I (Cpx-I). These clinopyroxene grains are replaced by clinopyroxene-plagioclase symplectite (Fig. 5). Earlier, similar symplectites were found in the eclogites of the Kumdykol' microdiamond placer (Shatskii and Sobolev, 1985). Relics of clinopyroxene of generation I have been preserved mainly at the contact with garnet. Pyroxene-plagioclase symplectite (clinopyroxene of generation II (Cpx-II) is developed along the contacts of clinopyroxene with quartz or plagioclase. By the size of Cpx-II and Pl segregations, several morphological types are recognized among pyroxene-plagioclase symplectites: ultrafine-grained, fine-grained, and coarse-grained. The most coarse-grained symplectite replaces the edges of clinopyroxene crystals, forming a rim around Cpx-I. Toward the core, coarse-grained symplectite is changed by fine-grained and then ultrafine-grained one.

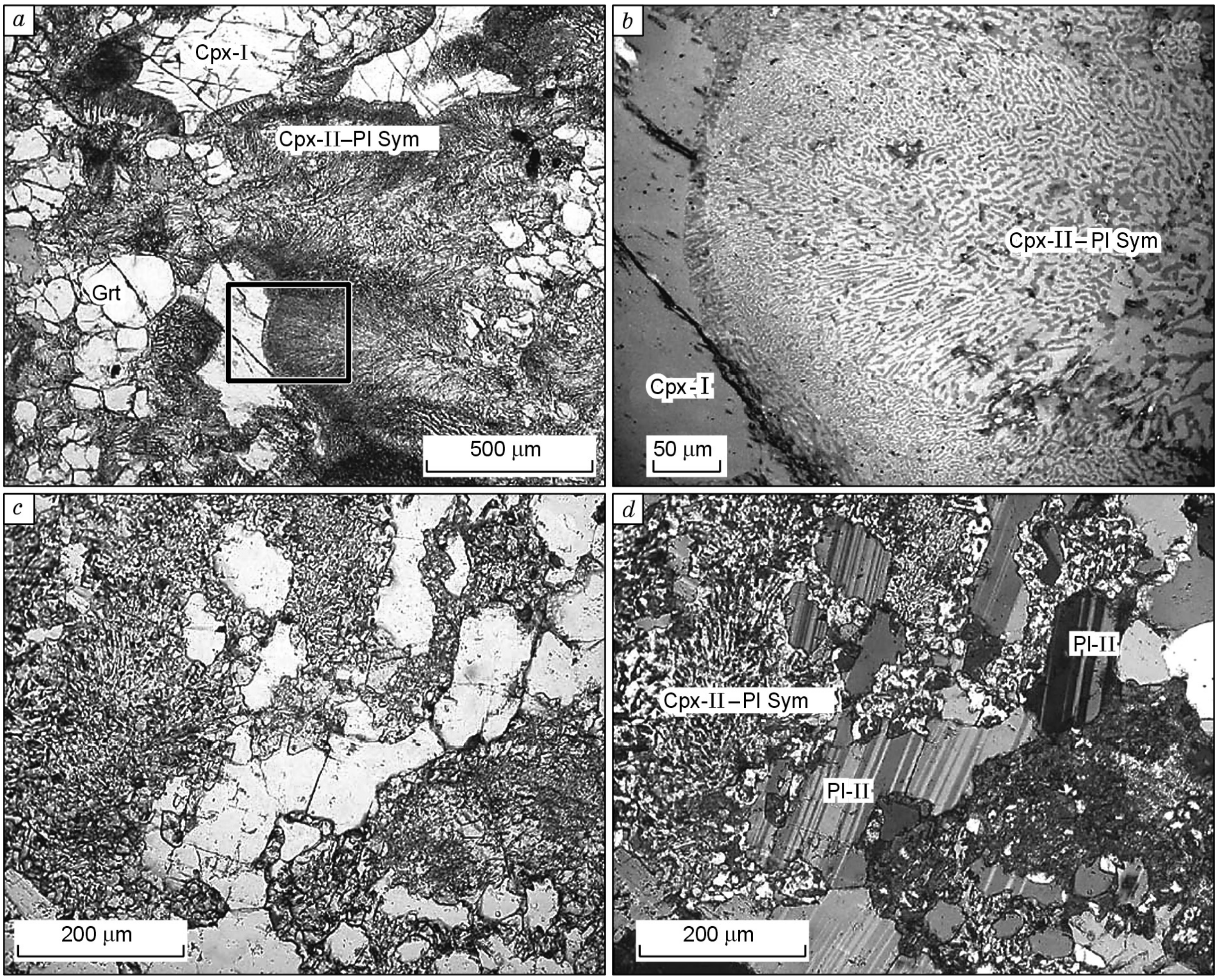

Fig. 5. Photomicrographs of amphibolized eclogite from the Chaikino site (sample Ch-03-01). *a*, Omphacite and garnet (Grt) relics; *b*, clinopyroxene-plagioclase symplectites at the contact with omphacite porphyroblast (its position is shown in Fig. 5, *a*); *c*, *d*, clinopyroxene-plagioclase symplectite (Cpx-Pl Sym) and euhedral plagioclase crystals of generation II (Pl-II) (*c*, nicols ||, *d*, crossed nicols).

Quartz occurs as irregular-shaped grains with normal (not undulatory) extinction in small veins, along with amphibole and epidote. It is unevenly distributed within a thin section. No polycrystalline pseudomorphs after coesite were found in the studied thin sections.

Amphibole occurs as small crystals and large porphyroblasts; the latter bear crystals of garnet, pyroxene, Cpx-Pl symplectite, quartz, epidote, and rutile. Amphibole is also present in garnet cracks. In one of the studied thin sections we revealed amphibole-plagioclase symplectite developed after clinopyroxene and garnet and recognized different stages of its evolution: (1) formation as a result of the partial replacement of pyroxene and garnet and (2) complete replacement of these minerals. This symplectite is of two morphologic types: ultrafine- and fine-grained.

Plagioclase is also of two morphologic types: worm-like grains in clinopyroxene-plagioclase symplectite (Pl-I) and euhedral plagioclase crystals (Pl-II) (Fig. 5, *d*).

Epidote occurs as flattened prismatic colorless crystals. In the studied thin sections it is highly unevenly distributed and is scarce. It is also present in small veins.

The main accessory minerals are rutile and ilmenite. They occur both in the matrix and as inclusions in garnet. In some thin sections, there are also apatite (<1%), sphene, and zircon (both >1.5%).

At the Chaikino site, along the contact of eclogite and the host rocks, there is a zone composed of fine-grained leucocratic rock. Microscopic studies showed a predominance of quartz and garnet (a total of 80%) in it, the rest being plagioclase and K-feldspar.

The chemical composition of minerals from eclogites

According to microprobe analysis data, the rock-forming garnets at both sites are a series of pyrope-grossular-almandine solid solutions (Fig. 6). All garnets are poor in MnO (0.3–0.7 wt.%).

Most garnets are nonzonal or have a homogeneous core and a <50 μm thick marginal zone with minor compositional variations. Garnets from eclogites of the Chaikino site are characterized by compositional variations in the core and

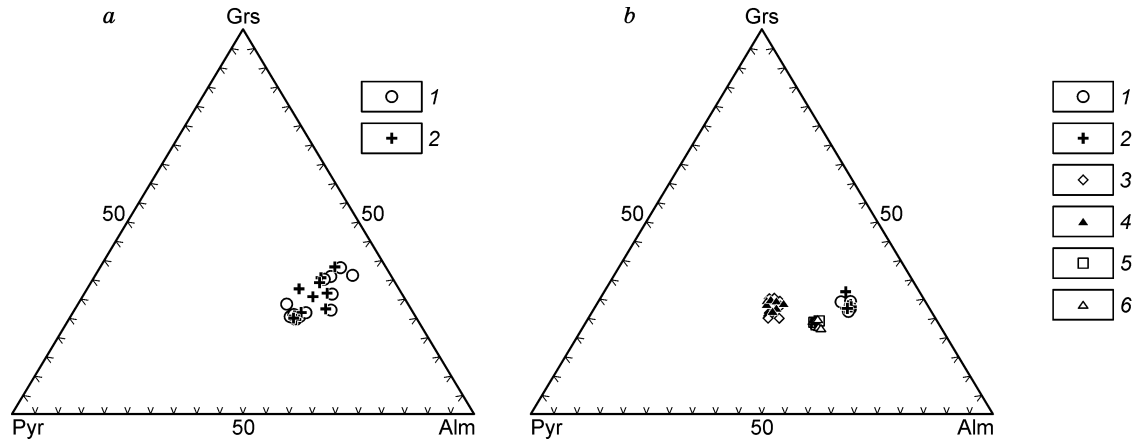

Fig. 6. Compositions of garnets from eclogites (mol.%). *a*, Chaikino site: *1*, Grt(c) (samples Ch-03-1 and Ch-03-4); *2*, Grt(r) (Ch-03-1 and Ch-03-4); *b*, Borovoe site: *1*, Grt(c) (G-01-3); *2*, Grt(r) (G-01-3); *3*, Grt(c) (S-01-1); *4*, Grt(r) (S-01-1); *5*, Grt(c) (G-01-4); *6*, Grt(r) (G-01-4). Grs, grossular, Alm, almandine, Pyr, pyrope.

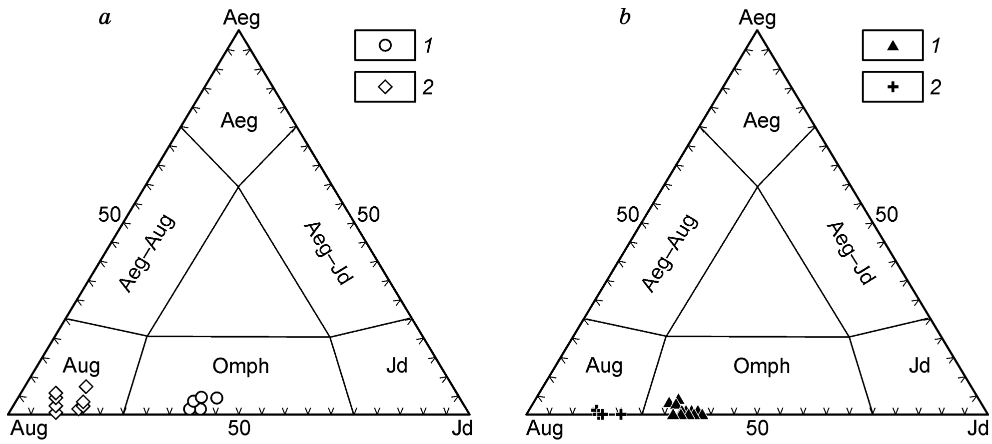

Fig. 7. Compositions of clinopyroxenes from eclogites (mol. %). *a*: Chaikino site: *1*, Cpx-I (samples Ch-03-1 and Ch-03-4), *2*, Cpx-II (Ch-03-1 and Ch-03-4); *b*, Borovoe site: *1*, Cpx-I (G-01-3 and S-01-1), *2*, Cpx-II (G-01-3 and S-01-1). Aeg, aegirine, Aug, augite, Jd, jadeite, Omph, omphacite.

marginal zones. The core compositions vary from $Pyr_{13–15}Alm_{50–51}Grs_{35–36}$ to $Pyr_{22–27}Alm_{48–56}Grs_{24–26}$, and those of the marginal zones, from $Pyr_{11–12}Alm_{49–50}Grs_{31–36}$ to $Pyr_{20–26}Alm_{49–51}Grs_{25–26}$. Note that the amount of pyrope component in grains decreases on approaching the leucocratic rocks localized at the contact of eclogite with the host gneisses. The different behavior of elements in garnets might be due to the local compositional inhomogeneities in the eclogite protolith. A similar phenomenon was earlier established in the eclogites of the Kokchetav massif (Korsakov et al., 1998).

Garnets from the Borovoe site eclogites lack zoning; the core and periphery of grains of the sample $Pyr_{17–18}Alm_{54–55}Grs_{28–29}$ are of identical composition.

Clinopyroxenes of generation I from the Chaikino site eclogites are omphacites with 37–40% jadeite component. Calcium-Eskola (Ca-Esk) and calcium-Tschermak's (Ca-Tsch) molecules are lacking. Clinopyroxenes of generation II from the symplectites contain 5–14% jadeite component. Note that the coarse-grained symplectites contain 12–14% jadeite end-member and the fine-grained ones, 5–10%. The amount of Ca-Tsch in both types of symplectites is 4–7%.

Clinopyroxenes of generation I from the Borovoe site are omphacites with 33–38% jadeite component. None of the analyzed clinopyroxene samples contains Ca-Esk molecule, whereas Ca-Tsch amounts to 2%. Clinopyroxenes of generation II from the symplectites contain 14–20% jadeite component and 4–7% Ca-Tsch. The compositions of Cpx-I and Cpx-II are shown in Fig. 7.

Plagioclases from the Chaikino site eclogites contain up to 4 wt.% CaO, and those from the Borovoe site eclogites, 3–3.5 wt.%. Amphiboles are characterized by $(Na + K) > 0.50$ f.u. and $(Ca + Na) > 1.0$ f.u., which permits them to be considered Na-K-amphiboles according to Leake's classification (1997). The compositions of minerals from the Chaikino and Borovoe eclogites are given in Tables 1, 2, and 3.

The rutiles from the Chaikino site are enriched in Zr (up to 2000 ppm) as compared with the rutiles from the Borovoe

Table 1. Compositions of minerals from eclogites from the Chaikino site, sample Ch-03-4

Mineral	Grt1(c)	Grt1(r)	Grt7(c)	Grt7(r)	Grt9(c)	Grt9(r)	Cpx-I(c)	Cpx-I(r)	Cpx-I(c)	Cpx-I(r)	CPX-Inc
SiO_2, wt.%	38.1	38.0	38.1	38.7	38.4	38.3	56.3	56.0	56.7	56.8	56.7
TiO_2	0.08	0.06	0.14	0.15	0.17	0.17	0.16	0.10	0.11	0.12	0.11
Al_2O_3	21.1	21.2	20.9	21.1	21.1	20.8	9.07	9.42	9.03	8.77	9.03
FeO	24.4	24.0	25.2	24.2	24.7	23.1	6.12	5.78	5.80	5.66	5.80
MnO	0.56	0.52	0.58	0.47	0.48	0.58	0.03	0.01	0.05	0.04	0.05
MgO	4.68	4.64	2.12	4.17	3.91	2.84	8.58	8.55	8.65	8.79	8.65
CaO	10.0	10.6	12.7	11.2	11.1	13.6	15.2	14.3	14.4	14.7	14.4
Na_2O	0.04	0.05	0.07	0.04	0.06	0.08	5.73	6.32	5.92	5.92	5.92
K_2O	0.00	0.02	0.01	0.01	0.00	0.01	0.00	0.02	0.00	0.01	0.00
Total	99.03	99.13	99.75	100.08	99.89	99.46	101.17	100.53	100.74	100.84	100.74
Si, f.u.	3.00	2.99	3.02	3.02	3.01	3.02	2.04	2.04	2.05	2.06	2.05
Ti	0.00	0.00	0.01	0.01	0.01	0.01	0.00	0.00	0.00	0.00	0.00
Al	1.96	1.96	1.95	1.94	1.95	1.94	0.39	0.40	0.39	0.37	0.39
Fe	1.61	1.58	1.66	1.58	1.62	1.52	0.19	0.18	0.18	0.17	0.18
Mn	0.04	0.03	0.04	0.03	0.03	0.04	0.00	0.00	0.00	0.00	0.00
Mg	0.55	0.54	0.25	0.48	0.46	0.33	0.46	0.46	0.47	0.47	0.47
Ca	0.85	0.90	1.07	0.94	0.93	1.14	0.59	0.56	0.56	0.57	0.56
Na	0.01	0.01	0.01	0.01	0.01	0.01	0.40	0.45	0.42	0.42	0.42
K	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
Total	8.02	8.01	8.01	8.01	8.02	8.01	4.07	4.09	4.07	4.06	4.07

Mineral	Cpx-IIa	Cpx-IIa	Cpx-IIb	Cpx-IIb	Pl-Ia	Pl-Ia	Pl-Ib	Pl-Ib	Pl-Ib	Amp2	Amp4	Amp4
SiO_2, wt.%	51.8	53.2	52.3	52.2	67.5	67.9	64.6	66.4	63.5	42.7	42.1	45.3
TiO_2	0.28	0.20	0.21	0.28	0.02	0.00	0.01	0.01	0.03	1.23	1.29	1.27
Al_2O_3	4.54	4.50	4.48	3.28	22.5	23.1	22.1	22.2	21.8	13.1	12.8	10.9
FeO	9.27	8.31	10.60	8.83	0.18	0.15	0.71	0.21	0.38	15.9	16.3	14.9
MnO	0.09	0.05	0.11	0.11	0.03	0.02	0.04	0.01	0.00	0.14	0.09	0.09
MgO	10.8	11.2	11.7	12.0	0.02	0.01	0.48	0.09	0.52	10.0	10.0	11.1
CaO	19.8	20.2	19.0	21.2	2.91	3.03	3.45	2.73	4.20	11.2	11.2	11.5
Na_2O	2.34	2.10	1.33	1.40	6.22	4.97	8.97	7.49	8.83	2.16	2.17	1.81
K_2O	0.00	0.00	0.15	0.00	0.08	0.10	0.11	0.12	0.08	0.99	1.13	0.50
Total	98.96	99.87	99.81	99.33	99.44	99.31	100.50	99.32	99.28	97.36	97.10	97.49
Si, f.u.	1.96	1.98	1.96	1.97	2.98	2.98	2.91	2.97	2.90	6.46	6.42	6.75
Ti	0.01	0.01	0.01	0.01	0.00	0.00	0.00	0.00	0.00	0.14	0.15	0.14
Al	0.20	0.20	0.20	0.15	1.17	1.19	1.17	1.17	1.17	2.33	2.31	1.92
Fe	0.29	0.26	0.33	0.28	0.01	0.01	0.03	0.01	0.01	2.01	2.08	1.86
Mn	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.02	0.01	0.01
Mg	0.61	0.62	0.65	0.67	0.00	0.00	0.03	0.01	0.04	2.26	2.26	2.47
Ca	0.80	0.81	0.76	0.85	0.14	0.14	0.17	0.13	0.21	1.81	1.83	1.84
Na	0.17	0.15	0.10	0.10	0.53	0.42	0.78	0.65	0.78	0.63	0.64	0.52
K	0.00	0.00	0.01	0.00	0.00	0.01	0.01	0.01	0.00	0.19	0.22	0.09
Total	4.04	4.03	4.02	4.03	4.83	4.75	5.1	4.95	5.11	15.85	15.92	15.60

Note. Hereafter, c, grain core; r, grain rim. Amp, amphibole; Cpx-I, clinopyroxene porphyroblasts; Cpx-IIa and Pl-Ia, Cpx-IIb and Pl-Ib, clinopyroxene and plagioclase from coarse- and fine-grained symplectites, respectively; CPX-Inc, clinopyroxene inclusions in garnet. All iron as FeO. Analyses were carried out at the V.S. Sobolev Institute of Geology and Mineralogy, Novosibirsk, analyst E.N. Nigmatulina.

Table 2. Compositions of minerals from eclogites from the Borovoe site, sample G-01-4

Component	Grt6(c)	Grt6(r)	Cpx-I	Cpx-I	Cpx-IIa	Cpx-IIa	Pl-Ia	Amp5	Amp6
SiO_2, wt.%	38.2	38.2	54.7	54.6	54.8	53.3	68.6	42.5	50.8
TiO_2	0.06	0.05	0.17	0.12	0.20	0.12	0.01	0.63	0.12
Al_2O_3	21.0	21.0	9.12	8.79	9.59	6.04	20.0	12.7	3.64
FeO	24.5	25.3	6.44	6.27	6.25	9.06	0.13	15.7	18.6
MnO	0.45	0.48	0.02	0.03	0.02	0.05	0.00	0.06	0.25
MgO	4.08	4.53	8.52	8.65	8.04	10.69	0.00	10.94	10.52
CaO	11.8	10.2	15.1	15.1	18.2	18.5	0.24	10.3	12.2
Na2O	0.02	0.02	5.45	5.45	2.88	2.00	11.2	2.67	0.37
K2O	0.04	0.01	0.02	0.01	0.03	0.16	0.08	1.06	0.20
Total	100.15	99.83	99.57	99.09	99.95	99.91	100.17	96.51	96.76
Si, f.u.	2.99	3.00	2.02	2.02	1.99	1.98	3.08	6.50	7.63
Ti	0.00	0.00	0.00	0.00	0.01	0.00	0.00	0.07	0.01
Al	1.94	1.94	0.40	0.38	0.41	0.26	1.06	2.28	0.64
Fe	1.61	1.66	0.20	0.19	0.19	0.28	0.00	2.00	2.34
Mn	0.03	0.03	0.00	0.00	0.00	0.00	0.00	0.01	0.03
Mg	0.48	0.53	0.47	0.48	0.44	0.59	0.00	2.49	2.36
Ca	0.99	0.86	0.60	0.60	0.71	0.73	0.01	1.69	1.97
Na	0.00	0.00	0.39	0.39	0.20	0.14	0.97	0.79	0.11
K	0.00	0.00	0.00	0.00	0.00	0.01	0.00	0.21	0.04
Total	8.04	8.02	4.08	4.06	3.95	3.99	5.12	16.04	15.13

Table 3. Compositions of minerals from eclogites from the Borovoe site, sample S-01-1

Component	Grt6(c)	Grt6(r)	Grt7(c)	Grt7(r)	Cpx3(c)	Cpx 3(r)	Cpx5(c)	Cpx 5(r)	Cpx-IIb	Cpx-IIa	Pl-Ia	Amp2
SiO_2, wt.%	39.4	38.6	39.1	39.3	55.6	54.8	54.6	55.4	52.3	53.4	64.8	41.0
TiO_2	0.06	0.17	0.07	0.07	0.12	0.14	0.10	0.40	0.22	0.28	0.02	0.51
Al_2O_3	21.6	21.3	21.7	21.8	9.32	9.14	9.21	9.41	1.94	3.26	20.7	15.2
FeO	18.9	18.8	19.2	18.8	2.69	2.89	2.84	2.51	8.63	8.12	0.13	15.0
MnO	0.35	0.39	0.43	0.40	0.02	0.03	0.01	0.01	0.13	0.09	0.03	0.07
MgO	9.68	8.52	8.63	9.20	10.7	10.6	10.8	10.5	12.4	11.7	0.01	10.4
CaO	9.67	11.4	10.5	10.1	16.6	16.7	16.9	16.0	22.7	21.7	3.17	10.2
Na2O	0.01	0.05	0.05	0.04	4.96	4.85	5.00	5.27	1.00	1.51	10.13	2.74
K2O	0.00	0.00	0.00	0.02	0.01	0.00	0.01	0.00	0.00	0.02	0.09	1.23
Total	99.75	99.31	99.79	99.89	100.12	99.31	99.55	100.13	99.34	100.06	99.09	96.31
Si, f.u.	2.99	2.97	2.98	2.99	2.01	2.00	1.99	2.01	1.97	1.99	2.97	6.27
Ti	0.00	0.01	0.00	0.00	0.00	0.00	0.00	0.01	0.01	0.01	0.00	0.06
Al	1.93	1.93	1.95	1.95	0.40	0.39	0.40	0.40	0.09	0.14	1.12	2.73
Fe	1.20	1.21	1.22	1.19	0.08	0.09	0.09	0.08	0.27	0.25	0.00	1.92
Mn	0.02	0.03	0.03	0.03	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.01
Mg	1.10	0.98	0.98	1.04	0.58	0.58	0.59	0.57	0.70	0.65	0.00	2.37
Ca	0.79	0.94	0.86	0.82	0.64	0.65	0.66	0.62	0.92	0.86	0.16	1.67
Na	0.00	0.01	0.01	0.01	0.35	0.34	0.35	0.37	0.07	0.11	0.90	0.81
K	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.01	0.24
Total	8.03	8.08	8.03	8.03	4.06	4.05	4.08	4.06	4.03	4.01	5.16	16.08

site (up to 450 ppm). Note that the compositions of rutile inclusions and matrix rutiles in the samples from both sites are identical.

Solid-phase inclusions in zircons. As was established earlier (Hermann et al., 2001; Korsakov et al., 1998, 2002; Shatsky et al., 1999; Sobolev et al., 1994), relicts of high-pressure parageneses are best preserved as inclusions in zircons. Therefore, we extracted 200 zircons from the eclogite sample Ch-03-1 and analyzed 35 solid inclusions. In contrast to the earlier described zircons from the Barchinskii site eclogites (Korsakov et al., 1998), the above ones are elongate (elongation index 1.2–2) and have an oscillating zoning typical of

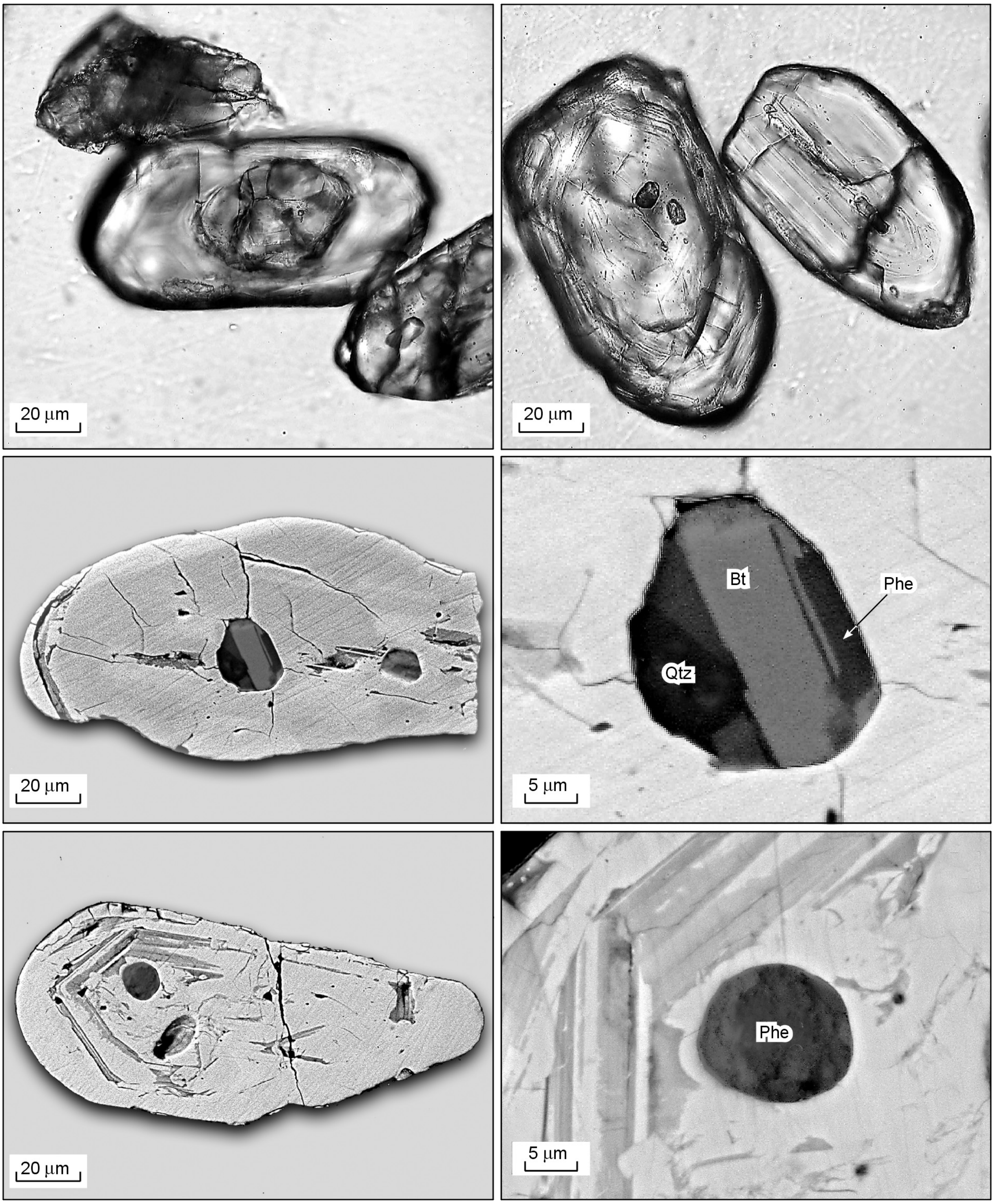

Fig. 8. Morphology and internal structure of zircons from the zone of contact of eclogite and augen gneisses. Qtz, quartz, Bt, biotite, Phe, phengite.

zircons from igneous rocks (Fig. 8). The solid inclusions are both one-phase and multiphase and include biotite, K-feldspar, plagioclase, phengite, quartz, epidote, sphene, and apatite. The mineral compositions of inclusions are presented in Table 4. Note that minerals of eclogite paragenesis have not been found in the inclusions.

Estimation of the *PT*-conditions of formation and alteration of eclogites

The absence of both coesite relics and quartz pseudomorphs after coesite from the studied samples suggests that the pressure during the metamorphism peak was no higher than

Table 4. Analyses of solid-phase inclusions identified in zircons from eclogite of the sample Ch-03-1

Component	Pl	Kfs	Bt	Phe	Ep	Ttn
SiO_2, wt.%	62.07	64.82	37.38	50.16	39.15	33.81
TiO_2	0.09	0.01	3.37	2.28	0.22	30.90
Al_2O_3	24.16	18.19	17.65	31.25	26.35	5.15
FeO	0.19	0.00	20.01	1.03	7.99	0.62
MnO	0.01	0.00	0.00	0.01	0.14	0.03
MgO	0.05	0.01	8.54	2.24	0.00	0.00
CaO	4.39	0.33	0.02	0.04	23.32	28.13
Na_2O	8.08	0.15	0.07	0.08	0.01	0.06
K_2O	0.80	16.60	9.63	8.18	0.02	0.01
Total	99.84	100.11	96.67	95.27	97.20	98.71
Si, f.u.	2.82	3.09	2.86	3.33	3.12	1.10
Ti	0.00	0.00	0.19	0.11	0.01	0.75
Al	1.29	1.02	1.59	2.44	2.47	0.20
Fe	0.01	0.00	1.28	0.06	0.53	0.02
Mn	0.00	0.00	0.00	0.00	0.01	0.00
Mg	0.00	0.00	0.97	0.22	0.00	0.00
Ca	0.21	0.02	0.00	0.00	1.99	0.98
Na	0.71	0.01	0.01	0.01	0.00	0.00
K	0.05	1.01	0.94	0.69	0.00	0.00
Total	5.09	5.15	7.84	6.86	8.13	3.05

Note. Kfs, K-feldspar; Ep, epidote; Ttn, sphene.

20 kbar. The pressures and temperatures of different stages of magmatism were evaluated using the THERMOCALC program (Holland and Powel, 1998). The temperatures of the metamorphism peak were estimated from the Grt–Cpx-I equilibria, using the Ellis–Green geothermometer (1979) and the geothermometer based on the solubility of Zr in rutile (Watson et al., 2006; Zack et al., 2004). We chose these geothermometers since they yield the closest estimates as compared to garnet-clinopyroxene thermometers of other calibrations (Krogh-Ravna, 2000). We have established the following *PT*-conditions of eclogite formation: 800–850 °C and 18–20 kbar at the Chaikino site and 750–800 °C and 17–18 kbar at the Borovoe site, which corresponds to depths of about 55–60 km.

For the Chaikino site eclogites, the highest temperatures were determined for the leucocratic part of the sample (from the zone of contact of eclogites with the host gneisses), whereas at a distance from the contact the eclogite is characterized by T = 650–800 °C. This can be explained in two ways. On the one hand, a change in the bulk composition of the system in the near-contact zone inevitably leads to a change in garnet composition there. Therefore, the higher temperatures in the contact zone might be due to the interaction between the chemically inhomogeneous media. On the other hand, at the exhumation stage, the gneisses might have been partly melted (Dobretsov and Shatsky, 2004). In this case, the rheologic difference might have caused a significant difference in the rates of gneiss and eclogite exhumation at the early stage (before the crystallization of acid melts in crust). Because of the specific hydrodynamic conditions, partly melted rocks from great depths (of higher temperatures) might have been in contact with colder eclogites. The short thermal effect of the hot host rocks might have led to the formation of an intermediate zone with higher temperatures as compared with the temperatures of eclogite formation during the metamorphism peak. The latter is supported by the fact that zircons from the host rocks and intermediate zone have morphology and internal structure typical of igneous rocks. The polyphase inclusions in them are interpreted as a product of recrystallization of trapped melt drops (Hermann et al., 2001; Hwang et al., 2001; Korsakov and Hermann, 2006; Perchuk et al., 2008).

The *PT*-conditions of formation of clinopyroxene-plagioclase symplectite permitted estimation of the conditions at the regressive stage of metamorphism from the equlibria Jd + Qtz = Ab (Holland, 1980; Perchuk, 1992). For the Chaikino site, two substages were recognized, based on the contents of jadeite component in pyroxenes from the above symplectite (Cpx-II): (1) formation of coarse-grained clinopyroxene-plagioclase symplectite at 760–790 °C and 11–12 kbar and (2) formation of fine-grained clinopyroxene-plagioclase symplectite at 700–730 °C and 7–8 kbar. Similar pressures and temperatures (750–780 °C, 11–14 kbar) were obtained using the Pl-Hbl geothermometer (Holland and Blundy, 1994) and Cpx-Pl-Hbl barometer (Holland and Powell, 1998).

For the Borovoe site eclogites, the following *PT*-conditions were obtained: 670–700 °C, 8–10 kbar. The reaction eclogite structures from the western part of the same plate (in the region of Lake Maibalyk) are described by Larikova and Shershakova (2005). These authors established that omphacite

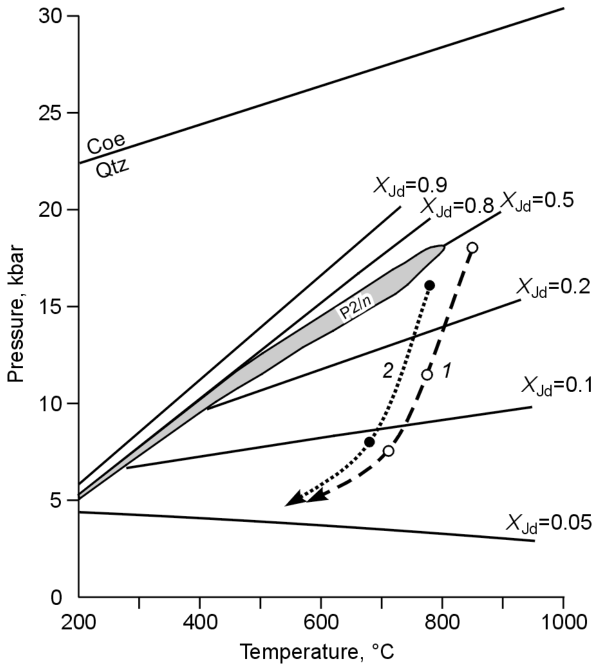

Fig. 9. PT-trend of the metamorphic evolution of eclogites from the Chaikino (*1*) and Borovoe (*2*) sites. The trend of the polymorphous transition quartz (Qtz)–coesite (Coe), the content of jadeite component (X_{Jd}, mol.%), the region of regular clinopyroxenes of structure P2/*n* (Holland, 1980) in pyroxene at different pressures, and the field of broken miscibility in jadeite-augite solid solution are shown.

was replaced by clinopyroxene-plagioclase symplectite at 700–720 ℃ and 8.5–9.5 kbar and garnet grains were crowned with plagioclase and hornblende at 670–680 ℃ and 4–6 kbar.

The *PT*-conditions at the third stage, diaphthoresis, are the most difficult to estimate. But the vast replacement of high-pressure mineral assemblages by sericite and chlorite suggests the greenschist facies conditions of metamorphism at one of the final stages. It is, most likely, at this stage that the host rocks (blastomylonites) were transformed into quartz-sericite-chlorite schists at the Chaikino site and quartz-garnet-muscovite schists formed at the Borovoe site. Since kyanite was identified in some quartz-garnet-muscovite schists, the pressure at this stage is estimated at 4–6 kbar. Thus, the NKTZ eclogites formed at moderate temperatures (eclogites of the Kulet type) (Shatsky and Sobolev, 1985); the *PT*-trends of eclogites from both sites are much similar (Fig. 9).

$^{40}Ar/^{39}Ar$ dating

A weight of muscovite (scales 0.2–0.5 mm in size) from quartz-garnet-muscovite schists (sample F-06-22) hosting the eclogites of the Borovoe site, together with weights of biotite MSA-11 (Standard Sample 129-88) used as a reference sample, was wrapped in aluminum foil and placed into a quartz ampoule, which was then evacuated and soldered. Biotite MSA-11, prepared as a standard K/Ar sample at VIMS, Moscow, in 1988, was tested as an Ar/Ar reference sample using the International Standard Samples of muscovite (Bern 4m) and biotite (LP-6). The integral age of the biotite MSA-11 was taken as an average of calibration results, 311.0 ± 1.5 Ma. The quartz ampoule with the sample was irradiated in the channel of a VVR-K reactor at the Tomsk Polytechnical Institute. Neutron flux gradient was no more than 0.5% of the sample volume. Stepwise heating was performed in a quartz reactor with an external-hearing furnace. The blank sample contained no more than 5×10^{-10} ncm^3 ^{40}Ar (10 min, 1200 ℃). Argon was purified using Ti and ZrAl SAES getters. The isotopic composition of Ar was measured on a Noble Gas 5400 (Micromass) mass spectrometer. The errors of measurements were within ± 1σ.

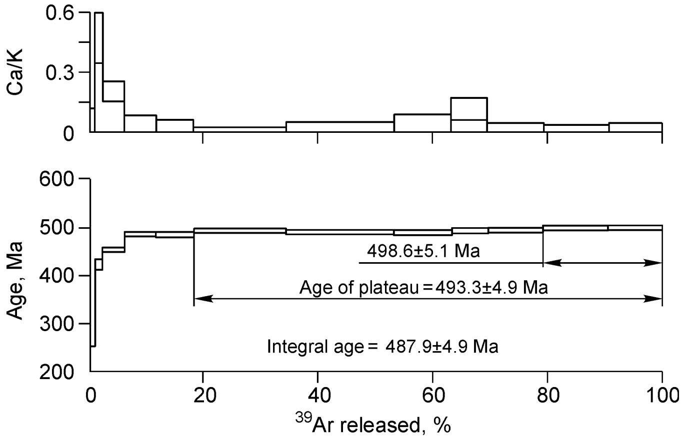

Fig. 10. Ca/K and ^{40}Ar/^{39}Ar spectra of muscovite F-06-22.

The age spectrum of muscovite has a well-expressed plateau corresponding to an age of 493 ± 4.9 Ma (Fig. 10). In the high-temperature region the age somewhat increases. The average over two last steps is 499 ± 5 Ma. Probably, the older ages correspond to large muscovite grains or grain cores, whose isotopic system was closed earlier.

Note that the obtained age is somewhat older than those for muscovite from quartz-muscovite dynamoschists (490–478 Ma) (Dobretsov et al., 2005b), which are interpreted as the time of formation of the imbricated structure in the North Kokchetav tectonic zone.

Discussion and conclusions

In petrography, petrochemistry, and mineralogy the described rocks are similar to the eclogites of the Kokchetav metamorphic belt. Like the KMB eclogites, they occur as boudins in porphyroblastic biotite gneisses or garnet-muscovite dynamoschists. The high-pressure metamorphism of eclogites at the Chaikino and Borovoe sites proceeded at 800–850 ℃, 18–20 kbar and 750–800 ℃, 17–18 kbar, respectively, which corresponds to depths of 55–60 km. The symplectite structures revealed in the eclogites are the result of the rapid rise of the latter in the crust. The early stages of exhumation in the eclogites are reflected as the formation of two generations of clinopyroxene-plagioclase symplectites during the granulite facies metamorphism, probably, in the lower crust. At shallow depths, high-pressure rocks underwent an intense diaphthoresis under the epidote-amphibole and greenschist facies conditions. The host gneisses were transformed into blastomylonites and then quartz-chlorite-sericite schists.

In the imbricated structure of the NKTZ, some plates of the eclogite-gneiss complex of the Kokchetav region join the weakly metamorphosed deposits of the subsurface levels of the Earth's crust. Dating of the structure is of crucial importance, because there are no literature data on the final stage of exhumation of high-pressure rocks (from the lower and middle crust).

The time of the tectonic activity of the accretion-collision zone was determined by three independent methods: Ar/Ar dating of syntectonic muscovite from dynamoschists from various fault zones, paleontological dating of syntectonic olistostromes, and study of the relationship between complexes of different ages during geological mapping (Dobretsov et al., 2005a,b; Obut et al., 2006; Zhimulev, 2007). Most ages of muscovite from the dynamoschists from different parts of the NKTZ fall into the range of 492–487 Ma, which corresponds to the Late Cambrian–Early Ordovician. The olistostromes are also of Early Ordovician age but younger (mainly Arenig). The geological data show that tectonic movements also took place in the Middle Ordovician. The isotope dates seem to reflect the earlier great-depth deformations that gave rise to dynamoschists. The Arenig–Middle Ordovician tectonic movements along the same fault zones proceeded in subsurface conditions and resulted in olistostromes, melanges, and tectonic breccias.

The K-Ar isotopic system of muscovite (1 mm grains) was closed at ~370 °C (Hodges, 2004). The last stage of the regressive magmatism of eclogites under greenschist facies conditions took place at ~500 °C, the scales of muscovite in the studied sample are smaller than 1 mm, and the effective temperature of the closure of its isotopic system is not higher than 370 °C. This suggests that all recognized stages of regressive metamorphism of eclogites preceded the cooling of the host schists and the closure of the isotopic system of muscovite that occurred at 493 Myr BP. With regard to the age in the high-temperature region of the spectrum, the regressive metamorphism took place no later than at 499 Myr BP. Thus, the eclogites reached the upper crust in the Middle Cambrian, and their subsequent rise, not detected by isotope-geochronological methods, continued in the Late Cambrian and Early and Middle Ordovician and led to their conjugation with the sedimentary and volcanic rocks of the Stepnyak island arc.

The Late Cambrian–Early Ordovician tectonometamorphic stage is also well expressed in the KMB rocks. Numerous dates of 490 to 480 Ma were obtained for the micas from dynamoschists bounding blocks of different compositions and from gneisses and high-alumina schists in the KMB (De Grave et al., 2006; Dobretsov et al., 2006; Travin, 1999). The Early Ordovician tectonometamorphic events are related to the collision of the Kokchetav microcontinent with the Late Cambrian–Early Ordovician island arc and conjugation of different fragments of the subduction zone, which led to the formation of the Kokchetav metamorphic complex and the North Kokchetav tectonic zone (Dobretsov and Buslov, 2007; Dobretsov et al., 2006).

The structural association of eclogite-gneiss and eclogite-schist plates with ophiolites, olistostromes, and deformed fragments of the metamorphic basement and sedimentary cover of the microcontinent in the Late Cambrian–Ordovician accretion-collision zone evidences the formation and exhumation of eclogites in the Kokchetav zone during the Cambrian-Ordovician subduction-collision processes.

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