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VENDIAN-EARLY ORDOVICIAN GEODYNAMIC EVOLUTION AND MODEL FOR EXHUMATION OF ULTRAHIGH- AND HIGH-PRESSURE ROCKS FROM THE KOKCHETAV SUBDUCTION-COLLISION ZONE (*northern Kazakhstan*)

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The Kokchetav subduction-collision zone (KSCZ) hosting ultrahigh- and high-pressure (UHP-HP) rocks underwent the multistage Vendian-Early Ordovician geodynamic evolution. The subduction of the Paleoasian oceanic lithosphere bearing blocks of continental crust and the collision of the Kokchetav microcontinent with the Vendian-Cambrian island-arc system ultimately led to the formation and exhumation of UHP-HP rocks. In the Vendian-Early Cambrian the margin of the Kokchetav microcontinent deeply subsided into the subduction zone (150–200 km), which led to UHP-HP metamorphism (the maximum at about 535 Ma) and to partial melting of its rocks. In next stage (535–528 Ma), the generated acidic melts including blocks of UHP-HP rocks quickly, at a rate of 1 m/year, ascended to depths of 90 km for 1 Myr. During subsequent 5 Myr, the UHP-HP rocks ascending at a rate of 0.6–1 cm/year reached the base of the accretionary prism (depths of 60–30 km). Then, in the period from 528 to 500 Ma, the UHP-HP rocks ascended along the faulting structures of the lower crust as a result of jamming the subduction zone by the Kokchetav microcontinent. During the period from 500 to 480 Ma, the UHP-HP rocks became part of the upper crust. This process led to the KSCZ, which comprises terranes of the Vendian-Early Arenigian subduction zone occurring at different depths, separated by zones of garnet-mica and mica schists, blastomylonites and mylonites. In the same period there was a jump of subduction zone, which led to the formation of the Ordovician Stepnyak island arc. As a result of the Late Arenigian-Early Caradocian microcontinent-island arc collisions (480–460 Ma), the KSCZ overrided upon the fore-arc trough of the Stepnyak island arc to form a thick accretion-collision orogen, which having experienced anatectic melting was intruded by collisional granites of the Zerenda complex 460–440 Ma in age.

Subduction, collision, diamond-coesite gneisses, eclogites, exhumation, olistostromes, overthrusts, tectonic nappes, Kokchetav microcontinent

INTRODUCTION

Northern Kazakhstan is part of the Caledonian accretion-collision zone of Central Asia, which lies between the East-European and Siberian Precambrian continents (Fig. 1). The evolution of the Caledonian structure in terms of lithosphere plate tectonics was considered elsewhere [1–5]. The largest suture zones of Central Asia harbor complexes of UHP-HP rocks (the Kyrgyz complex with coesite and the Kokchetav complex with coesite and diamond) as well as eclogites and glaucophane schists (Fig. 1).

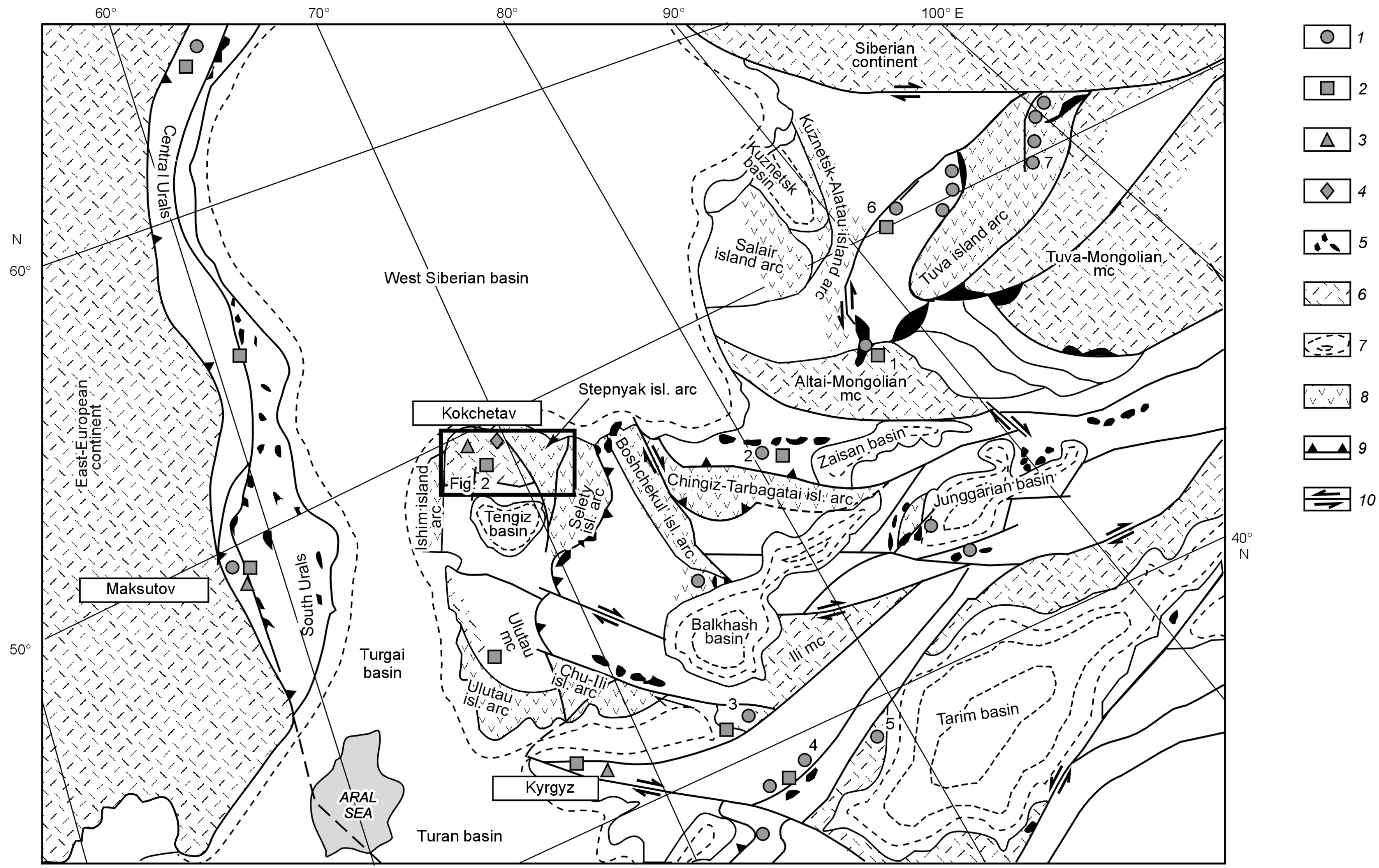

Fig. 1. Major tectonic structures of Central Asia, including the location of the Kokchetav subduction-collision zone, after [3] with modifications. ***1*** **— glaucophane schists,** ***2*** **— eclogites,** ***3*** **— coesites,** ***4*** **— diamonds,** ***5*** **— ophiolites,** ***6*** **— Precambrian continents and microcontinents (mc),** ***7*** **— Late-Paleozoic-Mesozoic basins,** ***8*** **— Vendian-Cambrian island arcs (isl. arc),** ***9*** **— overthrusts,** ***10*** **— strike-slip faults. Framed labels stand for ultrahigh-pressure rock complexes. Digits denote high-pressure rock complexes: 1 — Chagan-Uzun, 2 — Char, 3 — Aktyuz, 4 — Atbash, 5 — Aksui, 6 — Borus, 7 — Oka.**

Mineralogical and geochemical features, *P-T-t* paths of evolution of the Kokchetav UHP-HP rocks and associated rocks as well as datings of their formation and exhumation stages have been described in many publications [6–14]. It has been shown that the Cambrian UHP-HP rocks (coesite-diamondiferous gneisses and schists, eclogites) are structurally and genetically related to the Precambrian granite-gneisses and sedimentary rocks of the Kokchetav microcontinent. The UHP-HP rocks belong to eclogite-schist-gneiss high-pressure complexes, whose protolith is composed of rocks from the basement and cover of the microcontinent (carbonate-sand-schist and sand-schist rocks of the Sharyk and Kokchetav Formations, respectively) [6, 7, 9, 10]. Detailed studies of mineralogy, morphology of microdiamonds and paragenetic analysis of mineral assemblages suggest that the pressures under which diamond- and coesite-bearing rocks were formed exceeded 40 kbar [7–10] and, possibly, 60–70 kbar [11–13]. Most likely, the rocks were formed in the subduction zone at depths of 150–200 km. It is important to clear up why they came to the day and to explain the high rate of their uplift permitting preservation of high-pressure minerals and assemblages. To understand the mechanism and probable high rate of their uplift from depths of 150–200 km, different models have been derived, including the models bearing on the collision of a microcontinent with an island arc and reorganization of the subduction zone [9, 15, 16] as well as the formation of large thrusts [14] or squeezing of a subhorizontal wedge [11, 13].

The Kokchetav metamorphic complex, sedimentary rocks of the Sharyk and Kokchetav Formations are well-known in the literature as the Kokchetav massif surrounded by low-grade metamorphosed Paleozoic rocks. Detailed structural study of the Kokchetav massif permitted us to interpret the metamorphic complex as megamelange [9, 14, 17] and the massif as a whole, as an intricately deformed Cambrian-Early Caradocian subduction-collision zone [14–17].

This work summarizes our earlier publications [9, 10, 14–17] and supplements them with detailed information on the tectonic evolution of the Kokchetav subduction-collision zone (KSCZ) in the Cambrian–Early Ordovician, comparing and correlating geological, geochronological, and petrologo-mineralogical data. In our opinion, study of tectonic evolution of the KSCZ can contribute very much to understanding of the subduction-collision processes that occur in the system of microcontinent-island arc interaction as well as exhumation of UHP-HP rocks.

The geological and structural ground for this study is provided by data of detailed geological mapping of some areas of the KSCZ performed from 2001 to 2005.

STRUCTURAL POSITION AND TECTONIC REGIONALIZATION OF THE KSCZ

The KSCZ (Fig. 2) is a tectonic collage of repeatedly deformed fragments of the Precambrian Kokchetav microcontinent, Vendian-Cambrian megamelange (terranes of the paleosubduction zone), and Early Ordovician accretionary wedge [14–17]. The features of the Vendian-Cambrian island arc, including volcanosedimentary sequences and accretionary wedges with tectonic lenses of ophiolites, olistostromes, and blocks of Precambrian rocks, occur (see Fig. 2) in a modern structure west of the KSCZ (the Ishim island arc) and are also widespread northeast and east of it, as part of the Selety island arc, where they partially enter the basement of the Ordovician Stepnyak island arc [18]. Poor denudation of the area where the Ishim island arc occurs and superimposed processes of the Late Paleozoic large-amplitude strike-slip tectonics accompanied by oroclinal folding and turns of blocks [1–5] hinder geodynamic interpretation of the Central Asian structure in general and northern Kazakhstan in particular. Therefore, it is difficult to reveal the direction of the Vendian-Cambrian subduction processes, which led to the collision of the Kokchetav microcontinent with the arc.

Nikolai L. Dobretsov believes that the variant with the Ishim island arc is the most likely, as supposed earlier [3, 4, 14, 17]. This is also confirmed by regional comparisons. Figure 1 shows that the Vendian-Cambrian Ishim island arc and its supposed continuation southward in the Ulutau, Kendyktas, and Chu-Ili Mountains over its entire extension (more than 1000 km) is in contact with microcontinents (Kokchetav, Ulutau, Moiynkum) hosting eclogites and occasionally UHP rocks.

In M.M. Buslov's opinion, the subduction proceeded beneath the Selety island arc as the KSCZ is thrust upon the Ordovician Stepnyak zone, which originated on the Selety arc [18]. This variant allows for the successive accretion and collision of the Kokchetav microcontinent with the successively developed Vendian-Early Ordovician Selety-Stepnyak island-arc system. Probably, both variants hold true on the assumption that the Ishim and Selety arcs separated by the Late Paleozoic strike-slip faults meet north of the KSCZ.

Slices and blocks of UHP-HP rocks occur in two structural units: (1) megamelange belt including terranes of metamorphic rocks of the paleosubduction zone formed at depths from 60 to 150–200 km and (2) accretionary prism (see Fig. 2), where eclogites are found, formed at depths of about 60 km juxtaposed with tectonic blocks of the microcontinent rocks, ophiolite and island-arc terranes alternating with the Early Ordovician turbidites harboring lenses of olistostromes [15, 16].

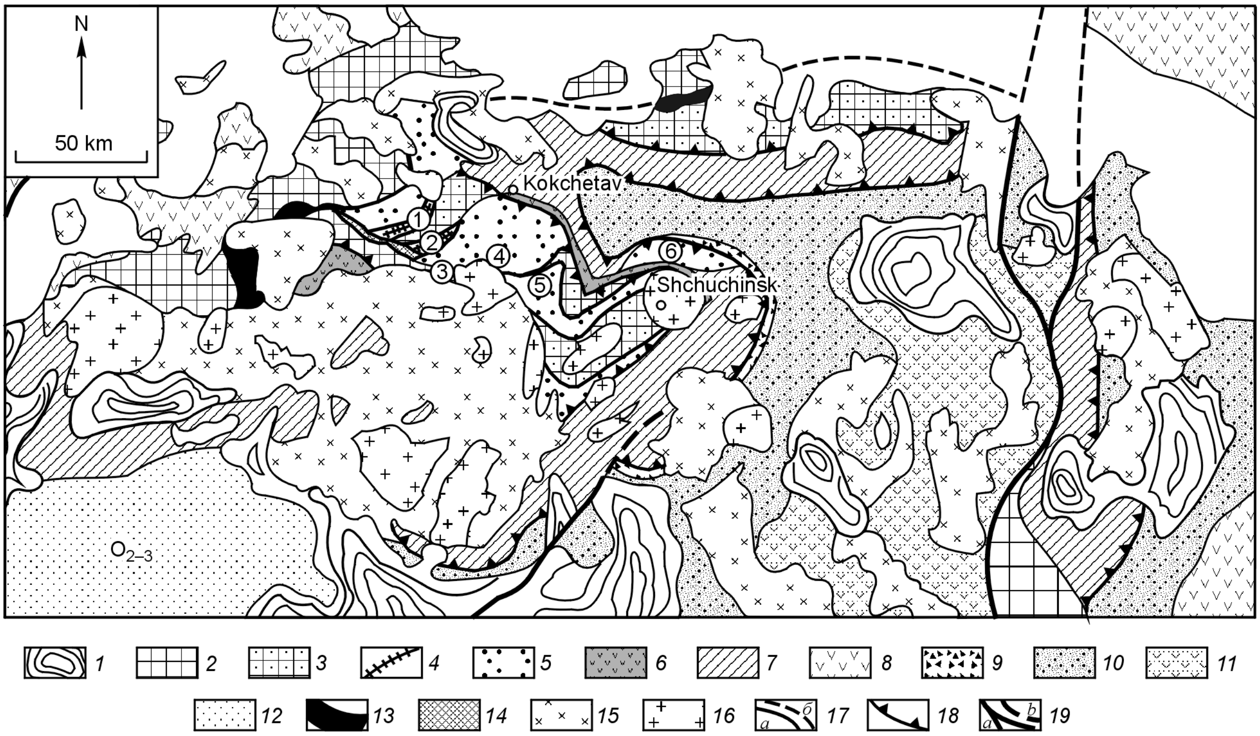

Fig. 2. A tectonic scheme of northern Kazakhstan. ***1*** **— Devonian-Late Paleozoic volcanosedimentary basins;** ***2*****,** ***3*** **— fragments of Kokchetav and Shat (northeast of Kokchetav) microcontinents:** ***2*** **— with retrograde metamorphism in greenschist facies,** ***3*** **— with sediments metamorphosed in subduction zone to amphibolite facies;** ***4*****,** ***5*** **— megamelange belt (terranes of paleosubduction zone):** ***4*** **— diamondiferous gneisses and coesite eclogites (encircled digits denote terranes: 1 — Barchi, 2 — Kumdy-Kol'),** ***5*** **— other terranes contained eclogites, garnet amphibolites, garnet peridotite within granite gneisses and micaceous schists (terranes: 3 — Sulu-Tobe, 4 — Enbek-Berlyk, 5 — Kulet, 6 — its analogs north of the town of Shchuchinsk);** ***6*** **— Vendian(?) volcanosedimentary rocks in accretionary prism;** ***7*** **— Early Ordovician accretionary prism;** ***8*** **— Vendian-Cambrian island-arc volcanosedimentary rocks (in west — Ishim arc, in east — Selety arc);** ***9*** **— Late-Arenigian syntectonic olistostrome;** ***10*** **— Ordovician volcanosedimentary rocks of Stepnyak trough;** ***11*** **— Ordovician volcanogenic units of Stepnyak island arc;** ***12*** **— Middle-Upper Ordovician shelf (?) deposits;** ***13*** **— Late Cambrian-Tremadocian ophiolites of Zlatogorsky complex;** ***14*** **— Middle-Late-Cambrian Krasnomaisky alkali-ultrabasic complex;** ***15*** **— Ordovician-Silurian granites;** ***16*** **— Devonian granites;** ***17*** **— deformed planes of Late Cambrian-Early Ordovician faults, established (*****a*****) and proposed (*****b*****);** ***18*** **— Late Arenigian-Early Caradocian frontal overthrust of Kokchetav subduction-collision complex upon Stepnyak trough;** ***19*** **— Late Paleozoic strike-slip faults:** ***a*** **— established,** ***b*** **— proposed.**

The megamelange belt is composed of rocks generated at different depths of the Vendian-Cambrian subduction zone. On the tectonic scheme of northern Kazakhstan it occurs between a weakly altered fragment of the Kokchetav microcontinent and Early Ordovician accretionary prism (see Fig. 2). The boundary between the fragment of the Kokchetav microcontinent and megamelange belt is traced by a chain of Late Cambrian–Early Ordovician ophiolites of the Zlatogorsky complex including a series of massifs: Dubrovsky, Novoselovsky, Shalkar, Zhanadaur, Shat, and Chekhov. Dobretsov et al. [19] described in detail the Shalkar suprasubduction ophiolite complex, geochemically characterized the basalts including the complex of parallel dikes, and reported data of U-Pb dating of zircons (485±6 Ma) from plagiogranites intruding the layered complex of gabbro-pyroxenites.

The megamelange belt is a contrasting structure composed of slices and blocks of UHP-HP rocks separated by tectonic sheets of the Kokchetav rocks metamorphosed to moderate pressures. Conventionally, five terranes can be recognized: (1) Barchi, (2) Kumdy-Kol', (3) Sulu-Tobe, (4) Enbek-Berlyk, and (5) Kulet, where UHP-HP and HP rocks are widespread (see Fig. 2). Terranes 1 and 2, 3 and 4 have the same suites of rocks. Therefore, terranes (1 + 2), (3 + 4), and (5) correspond to different levels of the paleosubduction zone, each of which is characterized by a certain suite of rocks and by its own evolution of pressure and temperature (Fig. 3). Diamondiferous rocks with P = 40–70 kbar and T = 1100–1200 °C were exposed or penetrated by boreholes in the Kumdy-Kol’ and Barchi terranes [7, 9–11, 13, 17]. In the Kulet and Sulu-Tobe terranes the rocks contain no diamonds but occasionally coesite occurs (in the area south of Lake Kulet). Unlike the Kumdy-Kol’ terrane, metacarbonate rocks are absent but there are interbeds of talc-garnet, talc-phengite, and other high-Mg rocks [14, 17, 20–22].

Some rocks in the above terranes are metasedimentary and have equivalents in the sedimentary cover of the Kokchetav microcontinent. In particular, diamondiferous metapelites and metacarbonate rocks might be analogs of black shales and dolomites enriched in bitumen and graphitic matter that occur at the bottom of the sedimentary cover of the microcontinent adjacent to the Kumdy-Kol’ terrane.

The above terranes also harbor metamorphosed analogs of the basement rocks of the microcontinent represented by mylonitized granite gneisses with lenses of eclogites. In the Kumdy-Kol’ terrane they are partly remelted and intruded by lenses, veins, injection migmatites of granites, and in the Sulu-Tobe and Kulet terranes, they are differently foliated and mylonitized. The granite gneisses could transformed in some garnet-mica schists with rounded bodies of eclogites, garnet amphibolites and amphibolites. An example is garnet-mica schists with bodies of eclogites and other rocks near Chaglinka Village, which separate the Kumdy-Kol’ terrane from the Sulu-Tobe terrane (see Fig. 2).

The terranes in question also differ in structural features and in stages of structural evolution [14, 17]. Thus, the Kumdy-Kol’ and Barchi terranes are structures of diamond-shaped horsts with the steep occurrence of metamorphic schistosity and linear NE strike, parallel to the horst-bounding faults, which is confirmed by exploring a drive and drilling boreholes to 800 m deep on the Kumdy-Kol’ terrane [14, 17, 23]. The structure of the Sulu-Tobe and Kulet terranes is represented by gentle lying folds and deformed overthrusts which appeared on transpression—simultaneous extrusion of the rocks up- and northeastward. The axes of folds and rock linearity in the Kulet terrane are chiefly of southeastern orientation [14, 17]. The Sulu-Tobe terrane is composed of eclogite blocks of varying size included into micaceous schists. The eclogites in marginal zones are transformed into foliated amphiboles. Between the Sulu-Tobe and Kulet terranes occur serpentinite schists, which separate them from tectonic sheets of granite gneisses of the microcontinent’s basement and mylonitized granite gneisses with eclogite bodies.

The Enbek-Berlyk terrane (Berlyk Formation) considerably differs from the other terranes in composition

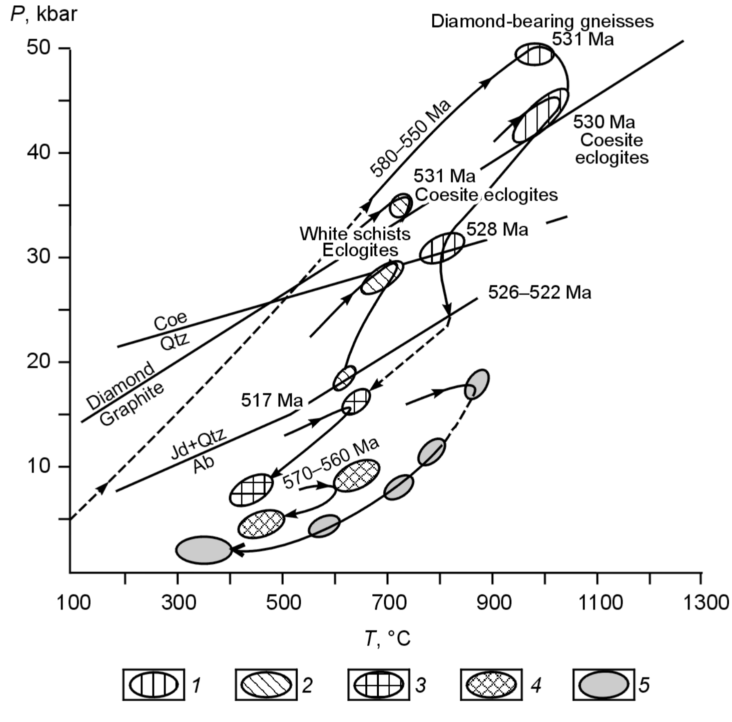

Fig. 3. *P-T* evolution of metamorphic rocks (modified after [21]). Terranes: *1* — Kumdy-Kol’, *2* — Kulet, *3* — Sulu-Tobe, *4* — Enbek-Berlyk, *5* — accretionary prism. Arrows show evolution of *P-T* conditions in time, digits near ellipses — estimated ages (see Table 1 and text). Coe — coesite, Ab — albite, Qtz — quartz, Jd — jadeite.

and age. It is represented by alternating tectonic sheets of three types separated by garnet-micaceous and micaceous schists and serpentinite melanges of: (1) mylonitized micaceous granite gneisses with boudins of eclogites and garnet amphibolites, (2) biotite-garnet-kyanite (±sillimanite) schists including boudinized bodies of coronites (with garnet coronas around clinopyroxene and plagioclase) and garnet amphibolites, and (3) alternating gabbro-amphibolites and garnet-pyroxene schists or, less frequently, peridotites. Fine-grained metamorphic schists of sheet 2 often display distinct mineral linearity due to very fine long grains of kyanite. This mineral linearity is usually normal to weakly developed fine-wave linearity [14, 17]. The linear structure is reoriented by later mesofolding. The predominant laminar structure is formed by fine small-wave folding but displays no intense shear deformations. Shear deformations are usually associated with wings of box folds, which abound in sillimanite crystals.

Thus, the metamorphic schists of the Enbek-Berlyk terrane experienced, at least, three stages of deformation: early stage stressed by mineral linearity, intermediate stage characterized by small-wave folding, and late stage with intense folding at wings of box folds and appearance of sillimanite [14, 17]. The detailed structure of the Enbek-Berlyk terrane and geochronological age of near-fault micaceous and garnet-micaceous schists are considered by De Grave et al. [24]. Worthy of note, however, is that Ar-Ar dating revealed only old (Vendian) and Early Ordovician generations of rocks (Fig. 4, Table 1). A Cambrian age of 531 Ma common in other terranes was established only in one case. Also, UHP rocks are absent, and eclogites in granite gneisses and micaceous schists are rare.

The accretionary complex bounds the Kokchetav metamorphic belt in the east (see Fig. 2) and is represented by contorted tectonic sheets and slices made up of the Early Arenigian olistostrome, Vendian-Early Cambrian(?) volcanosedimentary rocks of island-arc composition, amphibolized gabbros and gneisses, quartz-muscovite-microcline gneisses (with bodies of garnet amphibolites and eclogites), micaceous quartzites, serpentinite schists, ophiolite gabbros and basalts of Vendian–Early Cambrian age. The sheets and slices are outlined by blastomylonites, mylonites, and micaceous schists with an age of 500–485 Ma [15, 16].

In our opinion, it is important that the Kokchetav massif harbors an association of the above rocks formed under the conditions of accretionary wedge in the Early Ordovician, which is inferred from the age of formation of olistostromes, turbidites, and micas from metamorphic schists of fault zones.

P-T EVOLUTION AND AGE OF FORMATION OF KSCZ ROCKS

To determine *P-T* evolution of UHP-HP rocks, we used mineralogical thermobarometers for carbonate rocks, eclogites and Ti-clinohumite-garnet-olivine rocks as well as *P-T* estimate of the early retrograde stage for metacarbonate rocks, granite gneisses, and micaceous schists (see Fig. 3) [13, 17–19]. The published and new ages (see Table 1, Figs. 4 and 5) are summarized and compared with the geodynamic stages of formation of the rocks of the KSCZ (Fig. 6).

As noted, the UHP-HP rocks of the Kumdy-Kol' terrane were formed at 40–70 kbar and 1100–1200 °C, which corresponds to depths of 150–200 km. To date UHP-HP and host rocks (see Table 1), the SHRIMP method was applied to zircons from gneisses [29], the Sm-Nd method to eclogites [17, 29], the U-Pb dating to zircons from host gneiss granites [30], and the Ar-Ar method to micas from schists and gneisses [31, 32]. Study of zircons by cathodoluminescence and SHRIMP [28, 33] demonstrated their distinct zoning. The cores of zircon grains from diamond-bearing gneisses and coesite eclogites, which characterize the prograde stage metamorphism have an age of 537±7 Ma, while the rim containing low-pressure minerals of amphibolite facies — 507±7 Ma [33]. A close age of high-pressure metamorphism was obtained by the Sm-Nd method for eclogites — 535±3 Ma [29]. Earlier [27], in the diamond-bearing rims of zircons an age of 530±7 Ma was established, while in the cores different ages were established: from 580 to 2000 Ma. The zircon rims with HP mineral inclusions [28] show an age of 527±5 Ma, with inclusions of a granulite facies — 528±8 Ma, and with inclusions of amphibolite facies, 526±5 Ma. Only narrow margins in these zircons show an age of 518±8 and 517±9 Ma. The directed and regular pattern of zoning in all grains of zircons and change in composition of mineral inclusions suggested [28] that before 526±3 Ma the UHP-HP rocks were exhumed to the conditions of amphibolite facies (5–8 kbar and 600–650 °C, about 35 km deep). The period of exhumation from depths of more than 140 km to a depth of 35 km is estimated at 6 Myr and the rate, more than 1.8 cm/year. The critical age is 522 Ma determined for zircons from migmatites (oral communication of A.V. Korsakov). This means that the crystallization of the "jacket" of the melts transporting the diamondiferous rocks to the crust continued within the interval 526–522 Ma.

Ages of zircon rims of 517–518 Ma coincide with the lower limit of Ar-Ar ages of micas from granite gneisses, gneisses, and schists hosting and associated with the UHP-HP rocks of the Kumdy-Kol' terrane (517–499 Ma) (see Table 1). The U-Pb ages of zircons [23] from the diamond-hosting granite gneisses are within 505–510±5 Ma. Supposedly, in the period from 522 to 499 Ma, the Kumdy-Kol' terrane was in the conditions of

Table 1

Results of Geochronological Dating of Rocks of the Kokchetav Massif

No.	Rock	Coordinates	Mineral	Method	Age (Ma), reference
1	2	3	4	5	6
		Kumdy-Kol’ terrane			
1	Amphibolized eclogite	N53°08′13″, E68°57′40″	Hornblende	Ar/Ar isochron	664 ± 2 [34]
2	»	»	»	Ar/Ar plateau	~651 ± 7 [34]
3	Quartz eclogite	»	»	Ar/Ar isochron	643.4 ± 1.1 [32]
4	Ti-clinohumite-bearing garnet peridotite	»	Metamorphosed part of zircon	U/Pb SHRIMP	554–494 [33]
5	Diamond-bearing gneisses and coesite-bearing eclogites	»	Zircon	»	537 ± 7 [33]
6	Eclogite	»	Garnet-pyroxene	Sm-Nd isochron	535 ± 3 [21]
7	»	»	»	»	533 ± 20 [38]
8	Diamondiferous gneiss	»	Zircon, core Metamorphic rim	U/Pb SHRIMP	2000–580 [27] 530 ± 7 [27]
9	Garnet-muscovite-kyanite-quartz schist	»	Muscovite	Ar/Ar plateau	529.4 ± 1.0 [36]
10	Biotite-bearing amphibolized eclogite	»	Biotite	»	528.3 ± 0.9 [34]
11	High-temperature eclogites	»	Garnet-pyroxene	Sm-Nd isochron	528 ± 7 [29]
12	Diamondiferous gneiss	»	Zircon rim with granulite facies minerals inclusions	U/Pb SHRIMP	528 ± 8 [28]
13	»	»	Zircon rim with HP-mineral inclusions	»	527 ± 5 [28]
14	»	»	Zircon rim supposedly of amphibolite facies	»	526 ± 5 [28]
15	Quartz-muscovite-plagioclase gneiss	»	Muscovite	Ar/Ar plateau	525.3 ± 0.9 [34]
16	Diamondiferous gneiss	»	»	»	517.1 ± 5.4 [31]
17	»	»	»	»	515 ± 5 [21]
18	Garnet-biotite-quartz schist	»	Biotite	»	511.4 ± 0.9 [34]
19	Diamondiferous gneiss (garnet, biotite, quartz, plagioclase, muscovite)	»	»	»	510.8 ± 0.9 [36]
20	Granite gneiss included diamond-bearing blocks	»	Zircon	U/Pb	505–510 ± 5 [30]
21	Garnet-biotite gneiss	»	Biotite	Ar/Ar plateau	510.3 ± 0.9 [34]
22	Garnet-mucovite-kyanite-quartz schist	»	Muscovite	»	509.4 ± 0.9 [36]
23	Garnet-kyanite-muscovite-biotite rock	»	»	»	508.9 ± 0.9 [34]
24	Diamondiferous gneisses	»	Zircon rims contained low-pressure minerals (amphibolite facies)	U/Pb SHRIMP	507 ± 8 [33]
25	Garnet-biotite gneiss	»	Muscovite	Ar/Ar plateau	506.6 ± 0.9 [34]
26	Garnet-muscovite-plagio-clase-quartz orthogneiss	»	»	»	506.9 ± 0.9 [34]
27	Garnet-biotite gneiss	»	Biotite	Ar-Ar isochron	483.9 ± 0.9 [34]

Table 1 **(continued)**

1	2	3	4	5	6
		Kulet terrane			
28	Garnet-kyanite-micaceous schist with coesite	N53°00′36″, E69°30′38″	Phengite (Fig. 4, Ku 98-8)	Ar/Ar plateau Ar/Ar isochron	634.8 ± 1.1 [22] 635.1 ± 6.6 [22]
29	Garnet-biotite schist	»	Biotite (Fig. 4, 17A)	Ar/Ar plateau Ar/Ar isochron	612 ± 0.9 [22] 517 ± 36 [22]
30	Garnet-kyanite-micaceous schist	»	Phengite (Fig. 4, 25E)	Ar/Ar plateau Ar/Ar isochron	569.8 ± 1.3 [22] 565.2 ± 9.8 [22]
31	»	»	» (Fig. 4, 26C)	Ar/Ar plateau Ar/Ar isochron	565.1±1.5 [22] 494.4± 13.9 [22]
32	Amphibole-garnet-zoisite rock	»	»	Sm-Nd isochron	522 ± 5 [29]
33	Granite gneiss	»	Biotite	Ar/Ar plateau	521.5 ± 3.9 [22]
34	Garnet-kyanite-micaceous schist	»	Phengite	Ar-Ar plateau	519.3 ± 1.8 [29]
35	Pyrope-talc-kyanite-biotite schist	»	Biotite	»	504.7 ± 1 [34]
36	Garnet-muscovite-biotite-quartz schist	»	Muscovite	»	499 ± 3 [34]
		Sulu-Tobe terrane			
37	Zoisite amphibolite of eclogite	N53°04′52″, E69°11′53″	Amphibole	Ar/Ar plateau	512 ± 0.9 [34]
38	Micaceous granite gneiss	»	Phengite	»	469 ± 1.8 [37]
39	Eclogite	»	Garnet-pyroxene	Sm-Nd isochron	465 ± 32 [31]
40	Amphibolized eclogite	»	Amphibole	Ar/Ar plateau	435 [37]
		Enbek-Berlyk terrane			
41	Garnet amphibolites with corona texture	N53°04′14″, E69°20′30″	Amphibole (Fig. 4, E98/62)	Ar/Ar plateau Ar/Ar isochron	623 ± 21 [37] 553 ± 26 [37]
42	Granite gneiss	»	Biotite	Ar/Ar plateau	531 ± 21 [37]
43	Garnet-mica schist from fault zone	N53°08′08″, E69°11′38″	Muscovite (Fig. 5, 03-136)	Ar/Ar plateau Ar/Ar isochron	492.3 ± 4.8 New data 495.5 ± 6.0 New data
44	Quartz-garnet-mica rock from fault zone	N53°08′32″, E69°12′38″	» (Fig. 5, 3-17)	Ar/Ar plateau Ar/Ar isochron	486.3 ± 4.6 New data 473.7 ± 7.2 New data
45	Granite gneiss	N53°04′14″, E69°20′30″	Muscovite	Ar/Ar plateau	486 ± 9 [39]
46	Mica schist from fault zone	N53°08′36″, E69°12′38″	» (Fig. 5, 3-16)	Ar/Ar plateau Ar/Ar isochron	485.3 ± 4.9 New data 484.6 ± 5.5 New data
47	K-feldspar blastomylonite of gneiss	N53°03′19″, E69°23′31″	Biotite (Fig. 5, 3-108)	Ar/Ar plateau Ar/Ar isochron	484.8 ± 4.5 New data 446 ± 35 New data
48	Garnet-quartz-muscovite schist from fault zone	N53°08′12″, E69°11′44″	Muscovite	Ar/Ar plateau Ar/Ar isochron	484.2 ± 4 [24] 484.4 ± 3.9 [24]

Table 1 (continued)

1	2	3	4	5	6
49	Quartz-muscovite schist from fault zone	N53°08′24″, E69°12′47″	»	Ar/Ar plateau	481.9 ± 4.0 [24]
50	Mica schist of gneiss	N53°04′59″, E69°16′52″	» (Fig. 5, 3-63)	Ar/Ar plateau	481.9 ± 4.7 New data
				Ar/Ar isochron	483.3 ± 5.8 New data
51	Quartz-muscovite schist from fault zone	N53°08′16″, E69°14′49″	Muscovite	Ar/Ar plateau Ar/Ar isochron	481.6 ± 4.0 [24] 481.2 ± 2.8 [24]
52	Garnet-quartz-muscovite schist from fault zone	N53°08′50″, E69°12′40″	»	Ar/Ar plateau Ar/Ar isochron	480.4 ± 3.9 [24] 479.2 ± 2.9 [24]
53	Quartz-muscovite schist from fault zone	N53°04′24″, E69°20′13″	»	Ar/Ar plateau Ar/Ar isochron	478.9 ± 3.9 [24] 475.9 ± 9.0 [24]
54	Quartz-garnet-kyanite schist	N53°04′14″, E69°20′30″	»	Ar/Ar plateau	477.8 ± 5.3 [37]
	Daulet Formation				
55	Quartz-garnet-sillimanite-muscovite schist	N53°00′36″, E69°30′38″	Zircon	U/Pb SHRIMP	516–461 [33]
56	Biotite-cordierite schist	»	Biotite	Ar/Ar plateau	402 ± 5.1 [39]
57	Biotite schist	N53°04′52″, E69°11′53″	»	»	396 ± 6 [37]
	Fragment of Kokchetav microcontinent				
58	Micaceous granite gneisses from Chaglinka water reservoir	N53°13′43″, E69°15′13″	Phengite	»	498 ± 2.2 [37]
59	Amphibolites from these granite gneisses	»	Amphibole	»	516.6 ± 6.2 [37]
	Accretionary prism				
60	Mica schists of quartzites of Kokchetav Formation near Chaikino Village	N53°17′27″, E69°15′45″	Muscovite	»	487.6 ± 3.5 [15]
61	The same	N53°16′42″, E69°20′50″	»	»	478 ± 4.4 [15]
62	Mica schists in fault zone between quartzites of Kokchetav Formation and Early Ordovician siliceous deposits near Aleksandrovka Village	N53°06′45″, E69°52′10″	»	»	489.7 ± 3.1 [15]
63	Mica schists of quartzites of Kokchetav Formation near Zhanatalap Village	N53°08′52″, E70°36′11″	»	»	488.7 ± 3.5 [15]
64	Granite gneisses in fault zone near amphibolized eclogites	Near Maibalyk Lake	Zircon	U/Pb	~450 [39]

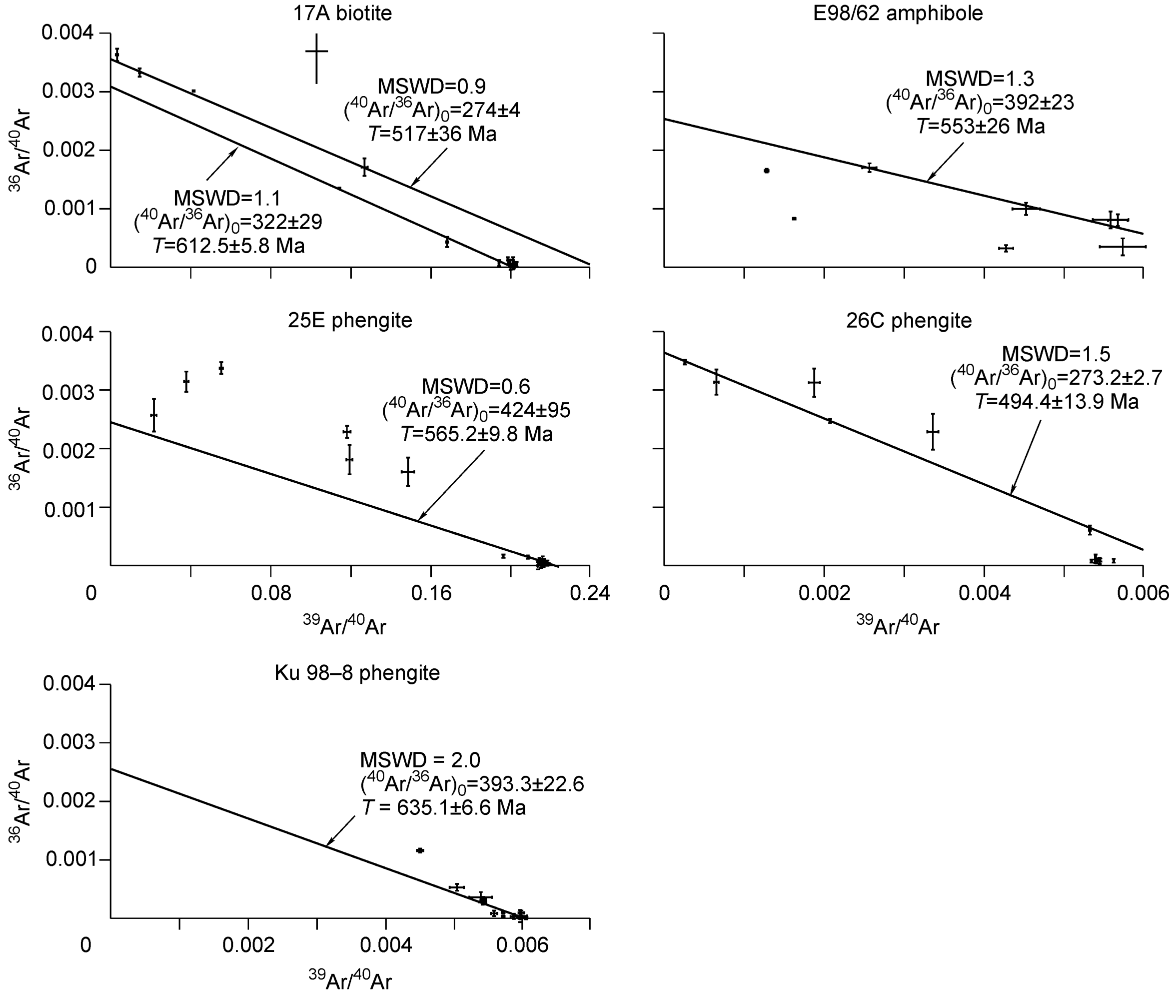

Fig. 4. The oldest Ar/Ar ages of minerals from rocks of the Kulet (sp. 17A, 25E, Ku 98-8, 26C) and Enbek-Berlyk (E98/62) terranes (see Table 1, nos. 28, 29, 30, 31, and 41, respectively).

intense tectonic deformations, which was accompanied by the formation of garnet-mica and mica schists, mylonitization, partial melting, or crystallization of late portions of melt.

The Kulet terrane is composed [20, 22] of coesite garnet-phengite, garnet-phengite-kyanite schists, talc-phengite and other mica schists, biotite-kyanite-garnet gneisses containing blocks of eclogites and garnet amphibolites. The Kulet eclogites were formed at 28–31 kbar and 660–740 °C, and garnet amphibolites, at 7–13 kbar and 540–720 °C [20]. The existing Ar-Ar ages (see Table 1) of the Kulet and Enbek-Berlyk terranes show two generations. Thus, the phengites from mica schists are dated at 565±1.5 and 519.3±1.8 Ma, and the biotite from gneisses — 521±3.9 Ma. The old ages, 634.8±1.1, 569.8±1.3 and 612±0.9 Ma, were obtained for phengite from coesite garnet-kyanite-mica and garnet-kyanite-phengite schists and for biotite from biotite-garnet-kyanite schist, respectively.

The Sulu-Tobe terrane consists of mylonitized phengite gneisses with bodies of eclogites and garnet amphibolites. Geochronological study of terrane is rather poor (see Table 1). Eclogites of this terrane (14–16.5 kbar and 700–860 °C) [19] were formed in the subduction zone at depths of about 50–40 km.

The metamorphic schists of the Enbek-Berlyk unit were formed under crustal conditions at 7 kbar and 650–700 °C, which corresponds to depths of 20–25 km. Similarity with the curve of evolution of the accretionary wedge (see Fig. 3) may evidence that the Enbek-Berlyk schists were also formed in the collision setting. New Ar-Ar ages of 490–485 Ma for the micas that were formed in the near-fault zones of the Enbek-Berlyk terrane (see Fig. 5) [24]) can mark the time of juxtaposition of the Sulu-Tobe and Enbek-Berlyk terranes. The latter

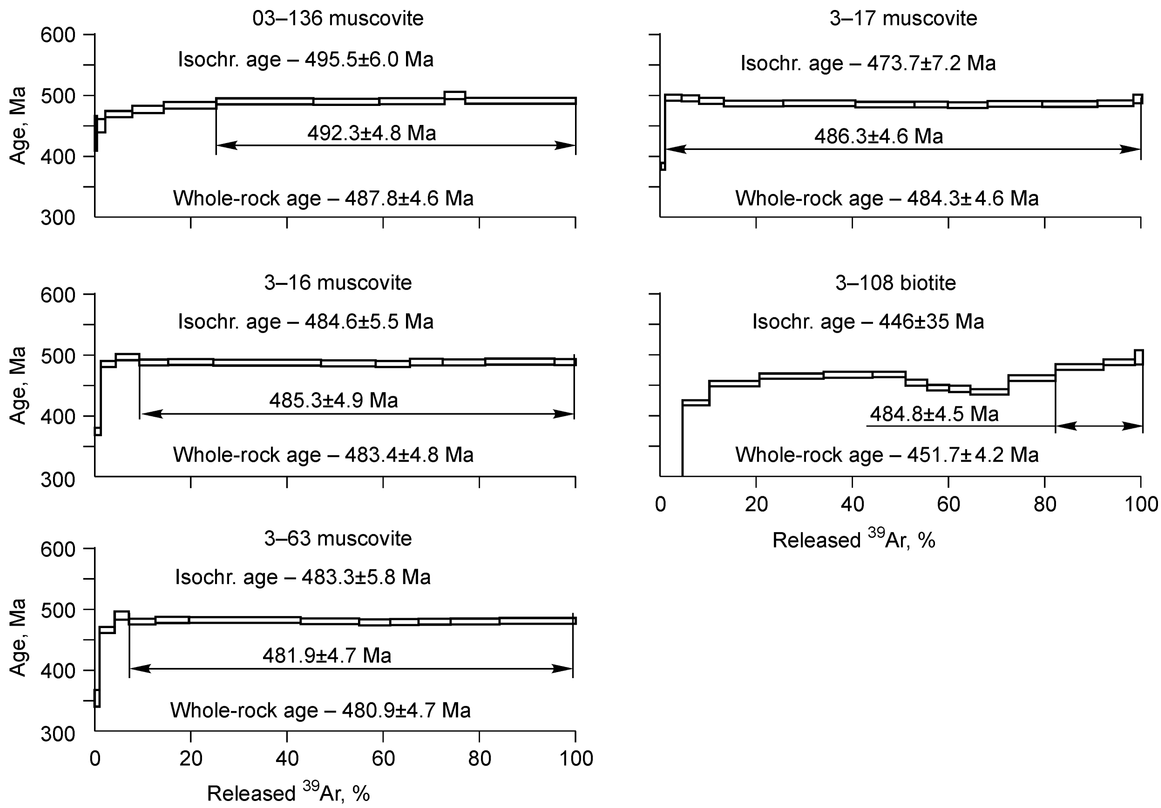

Fig. 5. Results of Ar/Ar dating of micas from the Enbek-Berlyk rocks (see Table 1 and text).

contains lenses of the rocks with Precambrian Ar-Ar ages (623–565 Ma) of micas (see Fig. 4, Table 1) as in the Kulet terrane.

Isochrons of the oldest datings of metamorphic rocks of the Kulet and Enbek-Berlyk terranes are given in Fig. 4. Worthy of note, in all cases the ages calculated by isochron regression are as a rule in agreement with the age of the plateau. Thus, the internal criteria of the Ar-Ar method do not permit recognition in minerals of trapped extra ^{40}Ar. The different plateau and isochron ages (623 and 553 Ma) of sp. E98/62 can be explained by two-stage metamorphism (see Table 1 and Fig. 4).

The reconstructed *P-T* evolution of the KSCZ rocks (see Fig. 3) is based on the above datings. Remarkably, the *P-T* evolution and rock age (531–525 Ma) of the Kumdy-Kol' terrane differ from other terranes, and only one Ar-Ar dating from the Enbek-Berlyk terrane yields 531 Ma. The *P-T* trend of eclogites of the Kulet terrane is close to that of the Kumdy-Kol' terrane but is distinguished by lower values. The ages 565–580 Ma established in different terranes coincide with the youngest ages (580 Ma) of zircon cores from diamondiferous gneisses [27] and can fix the manifestation of the Vendian subduction. It is not clear yet what is the meaning of old ages (635–565 Ma) in the Kulet and Enbek-Berlyk terranes. Probably, they correspond to the early stage of subduction of the Kokchetav microcontinent or reflect extra argon in minerals.

If we suppose that the K/Ar isotope system of minerals retained the memory on the age of their formation during subduction, we can estimate the intensity of late thermal effect using numerical modeling. At a temperature of superimposed metamorphism of 600 °C heating should not last for more than 1 Myr to minimize the loss of radiogenic argon by the mineral as a result of volume diffusion. This should be taken into account when choosing the model for tectonothermal evolution of the terrane.

Faulting planes of the accretionary wedge are traced by zones of mylonites, blastomylonites, low-temperature (300–400 °C) muscovite-chlorite schists with an age of 500–485 Ma [15, 16]. This age corresponds to the final stage of formation of accretionary prism and retrograde metamorphism of eclogites in their transportation to the day.

In general, the folded tectonic plates of the megamelange belt and accretionary complex are thrust upon the

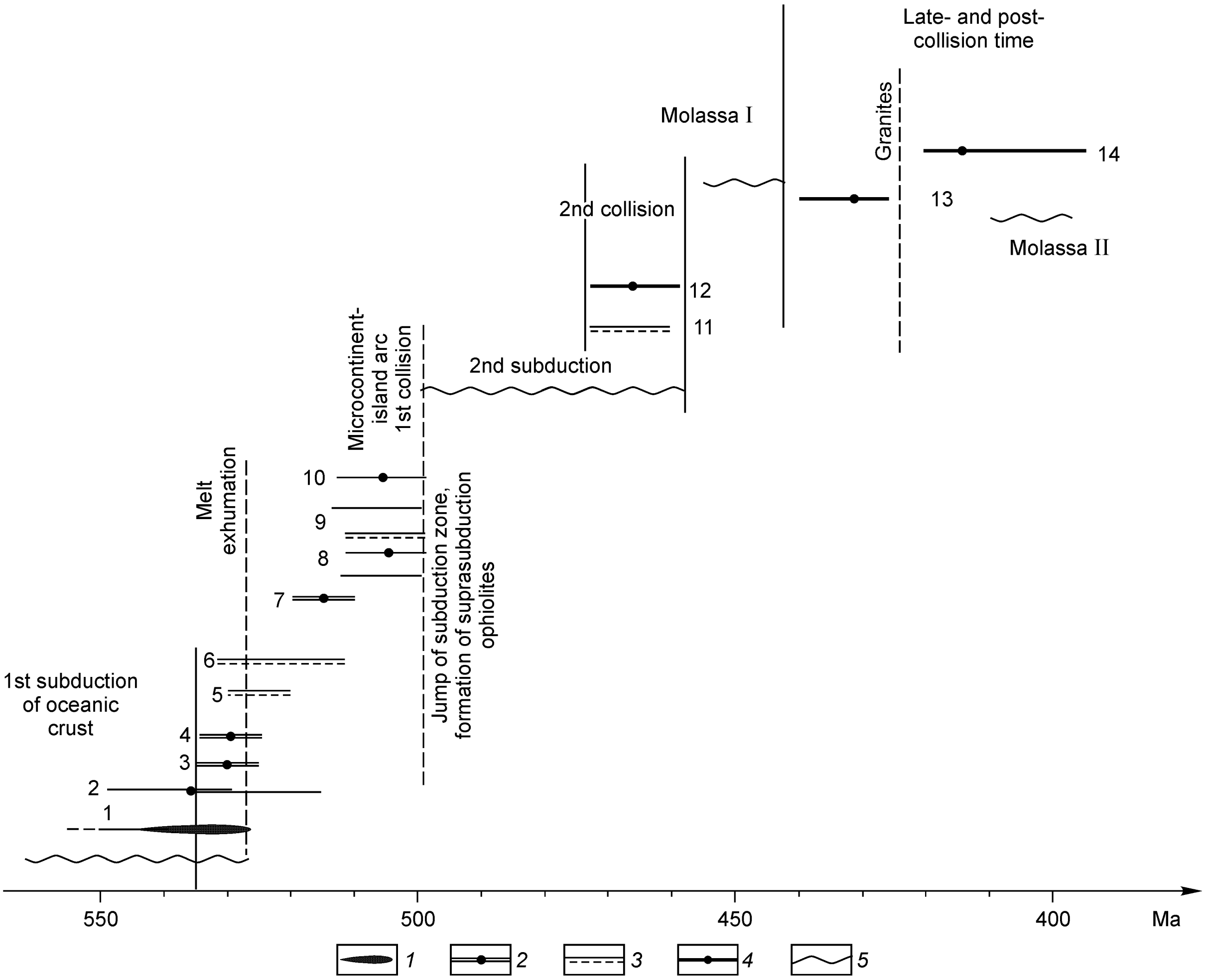

Fig. 6. Schematic comparison of geochronological datings (1–14) and geodynamic stages of the Kokchetav subduction-collision zone. 1 — Cpx-Gr from eclogites, Sm-Nd; 2 — zircons from diamond-coesite gneisses, SHRIMP; 3 — zircons from gneisses, SHRIMP; 4 — zonal zircons from gneisses, SHRIMP; 5 — Mu and Bi in gneisses, Ar-Ar; 6 — Bi and Hbl in granites hosting bodies of UHP-HP rocks, Ar-Ar; 7 — outer zones of zircons from UHP-HP rocks, SHRIMP; 8 — zircons from granites hosting UHP-HP rocks; 9 — Mu and Bi in retrograde gneisses, Ar-Ar; 10 — zircons of stage I of metamorphism in Daulet Formation, SHRIMP; 11 — Mu and Amph of overthrust zones, Ar-Ar and K-Ar; 12 — granites of Zerenda complex, K-Ar and Rb-Sr; 13, 14 — granites of Zolotonosha and Balkhash complexes, K-Ar and Rb-Sr. Dating methods: *1* — Sm-Nd, *2* — after zircons, *3* — Ar-Ar, *4* — K-Ar, *5* — geological.

northern Early Caradocian rocks of the Stepnyak trough and deform the structure of the autochthone. The forethrust is marked by a thin (few tens of meters) lenticular bodies of serpentinite melange and tectonic lenses of the Late Arenigian-Early Llanvirnian olistostrome (see Fig. 2).

VENDIAN–EARLY ORDOVICIAN GEODYNAMIC EVOLUTION OF THE KSCZ AND MODEL FOR UHP-HP ROCK EXHUMATION

The lithosphere plate of the Paleoasian ocean included microcontinents and terranes of the Gondwana origin, whose amalgamation in the Cambrian and then in the Middle Paleozoic ultimately led to the formation of the composite Kazakhstan continent [1–5]. A model for two-stage subduction of the crust of the Paleoasian ocean is proposed on the example of northern Kazakhstan. The reported new and published data permit us to distinguish several stages in the evolution of the Kokchetav massif which occurred on the background of the subduction of the Paleoasian oceanic crust, possibly, beneath the single Ishim-Selety island arc in the Vendian-Cambrian and beneath the Stepnyak island arc in the Ordovician (see Figs. 6 and 7). The onset of the subduction process (580–550 Ma) was recorded in the Vendian–Early Cambrian volcanosedimentary rocks and some datings of high-pressure rocks in the Kumdy-Kol', Kulet, and Enbek-Berlyk terranes (see Fig. 4, Table 1). In the Early Cambrian (with a peak at about 535 Ma) the Kokchetav microcontinent subsided to depths of 150–200 km, which led to the formation of UHP-HP rocks, acidic and carbonatite melts. It is likely that, together with the oceanic plate, the Kokchetav microcontinent was subsided to the greatest depth in the subduction zone at that time. The thinned margin of the microcontinent was subsided, which led to the metamorphism and partial melting of rocks. The UHP-HP rocks occur among migmatites and granite gneisses, making up few to 30% of their volume, which suggests the "fast" initial exhumation of diamondiferous high-alumina dolomite metasediments, gneisses, and eclogites in the "jacket" of acidic and carbonatite melts. As noted above, the directed and regular pattern of zoning in many zircon grains and change of the set of mineral inclusions suggested [23, 28] that the rocks of the Kumdy-Kol' terrane were exhumed from high-pressure metamorphism conditions (about 531±3–526±2 Ma) to amphibolite-facies conditions (about 526±3–522 Ma) for 3–6 Myr at a rate of more than 1.8 cm/year. To preserve high-pressure associations, zoning in minerals, and nitrogen aggregation in diamonds, the exhumation of ultrahigh-pressure eclogite-schist-gneiss complexes of rocks from the upper mantle should occur at a very high rate [23, 26]. At the initial stage it should reach 1 m/year [10, 23, 36]. Hence, the rocks ascended from the upper mantle depths of 200–150 km to 60 km along the subduction plane for the period of about 1 Myr. In the subsequent 5 Myr, when the UHP-HP blocks in the "jacket" of melts entered the crust, the rate fell down to 0.6–1.0 cm/year, and the uplift was 30 km (the depth interval from 60 to 30 km). This model is described in detail and substantiated elsewhere [23, 36].

The age of zircons, micas, and hornblende from the granite gneisses crystallized from the melts corresponds to the interval 522–500 Ma (see Table 1). In this period the collision of the Kokchetav microcontinent with the island arc was completed and a wedge-like structure composed of the Kumdy-Kol', Barchi, Kulet, and Sulu-Tobe terranes was extruded between them at a rate of about 0.2 cm/year (some phases could be extruded much faster). Then (500–480 Ma) a new island arc and accretionary prism began to form [15, 16], and then the Enbek-Berlyk terrane began to deform in the megamelange zone. The setting of compression coexisted with the setting of extension in the back-arc basin. As noted, this was preceded by the jump of subduction zone into the hinterland of the microcontinent, which led to the reorganization of the subduction zone and formation of suprasubduction ophiolites of the Zlatogorsky complex (see Fig. 7) and, in particular, Shalkar ophiolites [19].

The deepening of the subduction zone (480–460 Ma) led to the Ordovician Stepnyak island arc with a complete rhyolite-dacite-andesite-basalt series, then to the closure of the Zlatogorsky zone of extension and microcontinent-island arc collision. Since the part of the microcontinent subsided into the subduction zone was already rather thick, it wedged out and terranes of varying levels of the paleosubduction zone were extruded along the retrothrust zones, heaped and thrust in the accretionary prism to form the KSCZ. As a result of the collision, the KSCZ overrided upon the Stepnyak fore-arc trough and a thick collisional orogen formed, which led to the melting of 460–440 Ma granites of the Zerenda complex at its root [41], i.e., the granites are 20 Myr younger than the deformations in question related to the microcontinent–island arc collision. As estimated by Rosen and Fedorovsky [42], the period of 25–20 Myr is a time interval necessary for thermal relaxation leading to self-heating and melting of collisional anatectic granites in the thickened collisional structure.

DISCUSSION

The new data and summarized information permit us to consider the tectonics and geodynamics of northern Kazakhstan as multistage manifestation of subduction and collision events that occurred in the Vendian–Early Ordovician after a large continental block had entered the subduction zone. It is shown that the KSCZ is composed of heterochronous terranes of the paleosubduction zone that rose from depths of 150–200 km and were juxtaposed at different times from 520 to 480 Ma. Widely developed Late Cambrian–Early Ordovician garnet-micaceous and micaceous rocks that trace the levels of fault zones as well as Early Ordovician subsurface formations such as olistrostromes suggest that the terrane structure of the KSCZ was ultimately formed in the Early Ordovician.

On the basis of reported data, the following model is proposed for the Vendian–Early Ordovician tectonic evolution and exhumation of the Kokchetav UHP-HP rocks (Fig. 7). The subduction of the lithosphere of the Paleoasian ocean containing blocks of continental crust and the collision of the Kokchetav microcontinent with the Vendian-Ordovician island-arc system ultimately determined the formation and exhumation of UHP-HP rocks. The process of subduction began in the Vendian. In the Early Cambrian (with a peak at about 535 Ma), the margin of the Kokchetav microcontinent was deeply submerged into the subduction zone (150–200 km), which led to

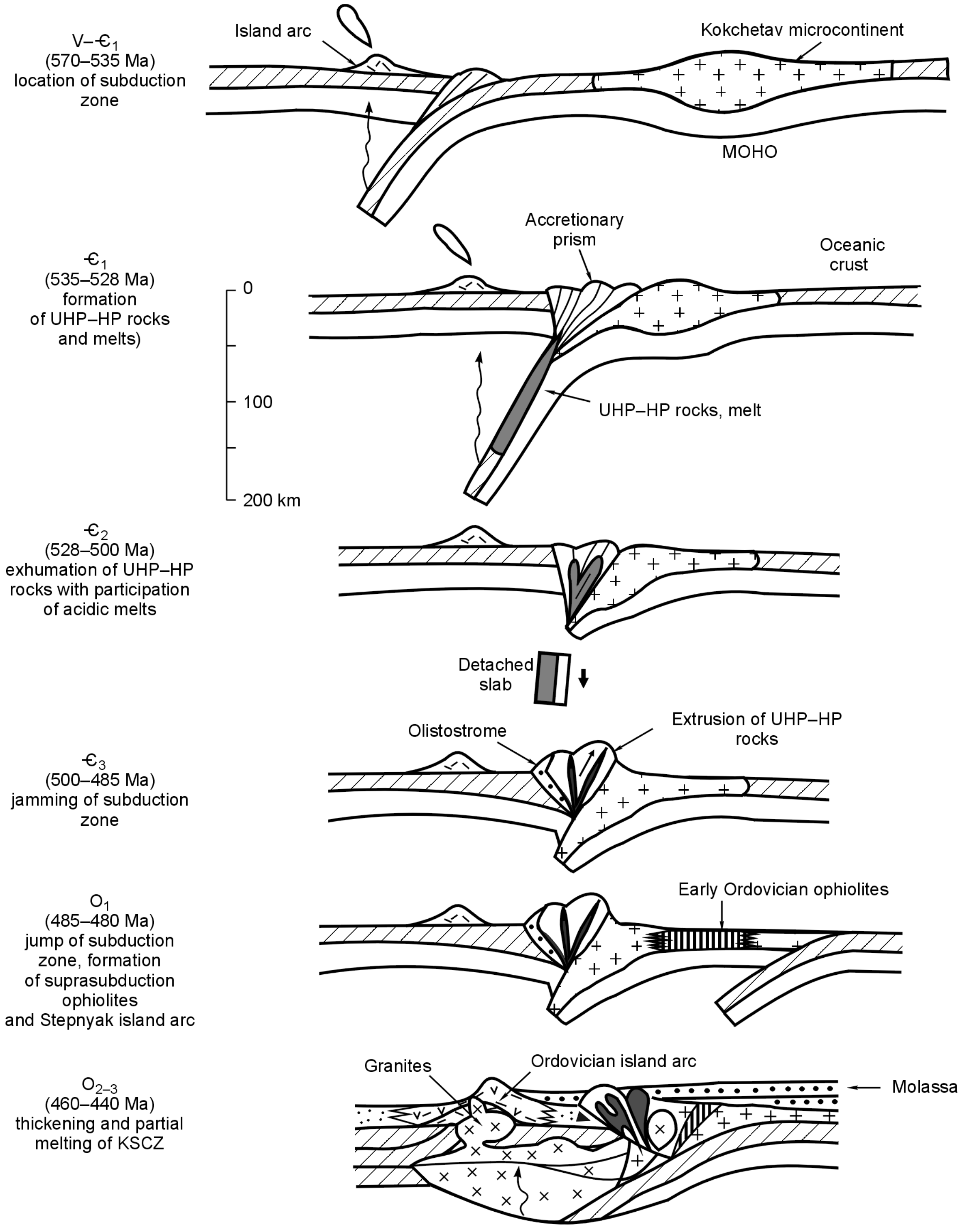

Fig. 7. Schematic two-stage microcontinent-island arc collision.

UHP-HP metamorphism as well as to partial melting of its rocks. In the following stage (535–528 Ma) the acidic and carbonatite melts containing blocks of UHP-HP rocks ascended first very fast (for 1 Myr) at a rate of 1 m/year to a depth of 90 km, which permitted the high-pressure associations to preserve. In the next 5 Myr, the UHP-HP rocks rising at a rate of 0.6–1 cm/year reached the level of the base of the accretionary prism (depths of 60–30 km). Then, in the period from 528–500 Ma, the UHP-HP rocks ascended along the fault structures as a result of jamming the subduction zone by the Kokchetav microcontinent. This process led to the formation of a megamelange belt, which represents different depths of occurrence of the Vendian-Cambrian subduction zone. In the period from 500–485 Ma the main tectonic movements were concentrated in the accretionary prism and partly in the megamelange zone. At the same time (500–480 Ma) a jump of subduction zone occurred, leading to the formation of the Stepnyak island arc. The jump of subduction zone also led to the formation of suprasubduction(?) Early Ordovician ophiolites of the Zlatogorsky complex (485–480 Ma). The Late Arenigian-Early Caradocian microcontinent–island arc collision processes (490–460 Ma) led to the overriding of allochthones made up of the rocks of megamelange belt and accretionary prism upon the fore-arc trough of the Stepnyak island arc, formation of olistostromes and final appearance of the collision-accretionary orogen, which as a consequence of thickening experienced intense granitization in the period from 460 to 440 Ma.

Our model for exhumation of UHP-HP rocks is controversial to the model for extrusion of hot mantle wedge [12, 13] and is close to the interpretation presented in [32, 34].

One of the unsolved questions is the geodynamic nature of metamorphism of the Daulet Formation made up of quartz-garnet-sillimanite-muscovite, biotite-cordierite, and biotite schists. It is important to carry out additional dating of the formation in different structural conditions. According to Japanese authors [12, 13], the Daulet Formation is the metamorphosed sole of hot covers made up of UHP-HP rocks. We consider the Daulet Formation metamorphism multistage. In our opinion, the first stage (515–460 Ma [33]) is linked to the formation of schists after the rocks of paleosubduction zone at the final stage of the microcontinent-island arc collision. It preceded the heating of a thick nappe-imbricated structure, which led to low-pressure metamorphism and then to the formation of granites of the Zerenda complex (460–440 Ma) and, possibly, of the Zolotonosha complex and its age analogs with an age of about 400 Ma [43]. The thermal effect of granites was expressed in datings of biotite from the Daulet Formation (402–396 Ma) [37].

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