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Late Cambrian-Ordovician tectonics and geodynamics of Central Asia

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Abstract

In the Late Cambrian-Ordovician, Gondwana-derived microcontinents such as Kokchetav, Altai-Mongolian, Tuva-Mongolian, and Barguzin, as well as the Kazakhstan-Tuva-Mongolian island arc or a system of island arcs were involved in intense accretion-collision processes in similar geodynamic settings on a vast territory of Central Asia — from West Kazakhstan to Lake Baikal. The processes were likely to be the result of a large rebuilding of the Earth's crust possibly related to the increased mantle impact on the lithosphere as they were simultaneous to the opening of the Uralian and Mongolian-Okhotsk (Turkestan) Oceans. The 970–850 Ma breakup of Rodinia and the 760–700 Ma important tectonic events were followed by the Late Cambrian-Early Ordovician plume magmatism impulse at 500–480 Ma, which led to the opening of new oceans and accelerated the accretion of the Gondwana-derived blocks to the island arc and subsequent formation of an extended — more than 6000 km long — Kazakhstan-Baikal orogenic belt.

Keywords: accretion-collision processes, Gondwana-derived microcontinents, island arc, orogen, mantle plume

Introduction

The Late Cambrian-Ordovician accretion-collision events widely revealed themselves in Central Asia (Fig. 1), resulting in the formation of four important tectonic structures. From west to east, these structures are as follows: 1. The Kokchetav subduction-collision belt, which was formed in two stages: Vendian-Cambrian subduction of the Kokchetav microcontinent and Late Cambrian-Ordovician subduction of this microcontinent followed by its collision with an island arc (Dobretsov et al., 2005, 2006). Analogs of the belt have been found in West Kazakhstan and in the basement of the West Siberian Plate. 2. The thrust-strike-slip fold belt of central Altai-Sayan Folded Area (ASFA), whose formation also proceeded in two stages: Late Cambrian-Ordovician subduction of oceanic crust beneath the Altai-Mongolian microcontinent and its Late Devonian collision with the Siberian continent (Buslov, 1988; Buslov et al., 2003; Buslov et al., 2004). 3. The thrust-strike-slip fold belt extending from Tuva and Buryatia to northern Mongolia, which was formed by the Vendian-Cambrian subduction and Late Cambrian-Ordovician collision of the Tuva-Mongolian microcontinent with an island arc (Kuzmichev, 2004; Vladimirov et al., 2000, 2004). 4. The thrust-strike-slip fold belt of Transbaikalia formed during the Vendian-Cambrian subduction of the Barguzin microcontinent and its Late Cambrian-Ordovician collision with an active margin of the Siberian continent (Fedorovsky, 1997; Fedorovsky et al., 1993, 1995; Fedorovsky et al., 2005; Sklyarov et al., 2001).

These accretion-collision structures were oroclinally folded and cut by transverse and lengthwise strike-slip faults of Middle Paleozoic and Mesozoic age. With late deformations taken into account, they can be regarded as a single belt of more than 6000 km long. Supposedly, the Kokchetav, Altai-Mongolian, Tuva-Mongolian, Barguzin and other microcontinents were accreted to the Kazakhstan-Tuva-Mongolian island-arc system and formed a single thrust-folded structure, the Kazakhstan-Baikalian orogenic belt. In the Middle-Late Ordovician the territory under consideration experienced post-collisional granitoid magmatism with subsequent accumulation of molasses and flysch and final formation of the Kazakhstan-Baikalian composite continent — an important part of the Central Asian folded system formed as a result of evolution of the Paleoasian Ocean (Didenko et al., 1994; Dobretsov, 2003; Dobretsov et al., 2003; Zonenshain et al., 1990).

What are the factors that initiated the Late Cambrian-Ordovician subduction-collision events synchronously over a huge territory of Central Asia? How important are they for understanding tectonics and geodynamics of Central Asia and evolution of the Paleoasian Ocean? This paper is an attempt

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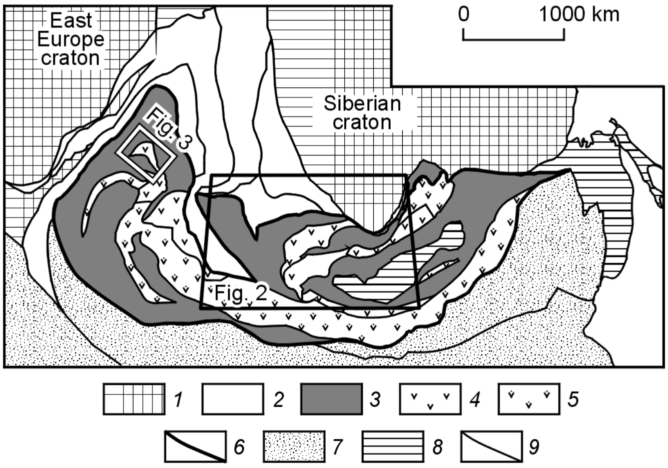

Fig. 1. Position of the Kazakhstan-Baikalian orogenic belt in the structure of Central Asia. *1* — Laurasia-derived cratons; *2* — continent margin fragments of the Siberian and East European cratons; *3–6* — Late Cambrian-Early Ordovician Kazakhstan-Baikalian orogenic belt: *3* — Gondwana-derived microcontinents, *4*, *5* — Kazakhstan-Tuva-Mongolian island arc: *4* — igneous rocks, *5* — rocks of accretionary prisms and fore-arc troughs, *6* — boundary of the Kazakhstan-Baikal orogen; *7* — Late Paleozoic-Early Mesozoic accretion-collison belt comprising Gondwana-derived continents and microcontinents; *8* — Mesozoic rocks; *9* — boundaries of terranes.

to answer these questions by characterizing and comparing the Late Cambrian-Ordovician accretion-collision events that resulted in the formation of these four large folded structures.

The knowledge of the scale and geodynamic origin of the Late Cambrian subduction-collision events is very important for clearing up the Vendian-Paleozoic history of Central Asia and for understanding the Paleoasian Ocean geodynamics. As far as most interpretations are still disputable, the next reviewing section will give the reader an idea about the proposed succession of tectonic events.

A short review of ideas about the tectonics and geodynamics of Central Asia

The folded structures of Central Asia have recently been characterized as Vendian-Paleozoic accretion-collision belts formed during the evolution of the Paleoasian Ocean (Berzin et al., 1994; Berzin and Dobretsov, 1993; Didenko et al., 1994; Dobretsov, 2003; Mossakovsky et al., 1993; Parfenov et al., 2003; Zonenshain et al., 1990). Maruyama (1994) believed that the opening of the Paleoasian Ocean was induced by a superplume which broke the supercontinent Rodinia into several continents, including Siberia and East Europe (Scandinavia). The breakup of Gondwana in the Late Precambrian formed several microcontinents and blocks which were later incorporated into the crust of the Paleoasian Ocean (Didenko et al., 1994; Mossakovsky et al., 1993). The further evolution of the Paleoasian Ocean was involved with the interaction of the Siberian and East European continents and Gondwana-derived microcontinents. Dobretsov et al. (2003) reported in detail about the Neoproterozoic-Early Ordovician history of the Paleoasian Ocean and showed that the 970–850 Ma opening of the ocean was recorded in mafic dikes within Rodinia blocks as well as in coeval ophiolites. The lithosphere of the Paleoasian Ocean was subducting beneath the Siberian continent during two periods from 850 to 750 Ma and from 750 to 700 Ma, which are correlated with the opening of the Northern and Southern Pacific, respectively. The final stage of Rodinia breakup was the 650–620 Ma opening of the Iapetus Ocean, which existed between Laurentia and Baltica, and the maximum opening of the Paleoasian Ocean occurred at 620–550 Ma, in the period of formation of island-arc systems along the margin of the Siberian continent.

The recognition of island-arc systems, especially their number and polarity, is important for understanding the tectonics and geodynamics of Central Asia and reconstructing the evolution of the Paleoasian Ocean. Sengör et al. (1993, 1994) proposed a single Vendian-Paleozoic subduction boundary with the related Tuva-Mongolian and Kipchak island arcs. The Paleozoic migration and rotation of the Siberian and East European continents resulted in the deformation of the island arcs, which was accompanied by oroclinal folding and multiple slipping of their fragments along the strike. The most important episodes in the formation of the Central Asian accretionary collage were Late Carboniferous dextral and Late Permian sinistral strike-slip displacements caused by the drift of the East European continent towards the Siberian continent and rotation of the former relative to the latter.

On the basis of structural, geochronological and paleogeographic data Buslov et al. (2000, 2003, 2004) supposed the Late Paleozoic large-scale strike-slip displacement in ASFA and East Kazakhstan, which were related to the closure of the Paleoasian Ocean and had formed the final tectonic zoning of both regions. The authors showed that the Late Paleozoic strike-slipping displacements for a distance of more than 1000 km significantly changed the older tectonic zoning. The Late Devonian-Early Carboniferous collision of the Kazakhstan (or composite Kazakhstan-Baikal) and Siberian continents and the Late Carboniferous-Permian collision of the East European, Kazakhstan and Siberian continents led to strike-slip deformation, which formed a collage of terranes. As a result of both collisions, the accretion-collision margins of the Siberian and East European continents and the Kazakhstan composite continent (in this paper we regard it as the Kazakhstan-Baikalian continent) were broken by strike-slip faults and related thrusts into numerous terranes. For this reason the reconstruction of the pre-Late Paleozoic tectonic zoning of Central Asia is faced with difficulties.

Figure 2 shows the most important structural elements and segments in eastern Central Asia.

1. Southern segment (southern ASFA, Tuva, Mongolia, Transbaikalia) consists of Vendian-Paleozoic island arc units and accretion-collision belts comprising fragments of Gondwana-derived microcontinents of Precambrian age such as Kokchetav, Altai-Mongolian, Tuva-Mongolian, Barguzin, etc. (Belichenko et al., 1994; Berzin et al., 1994; Berzin and Dobretsov, 1994; Buslov, 1998; Dobretsov et al., 2003).

2. Northern segment (northern ASFA) consists of the active

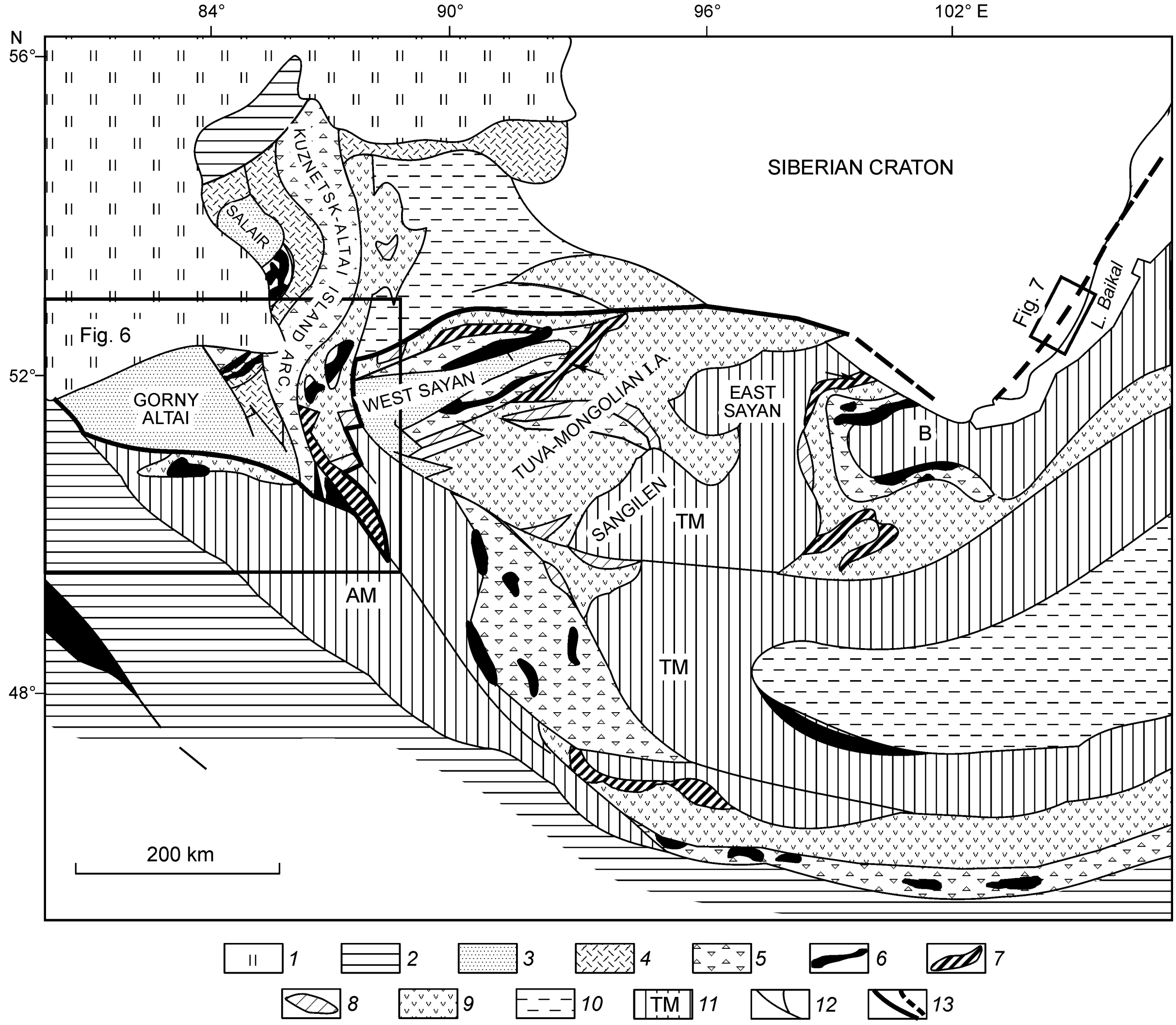

Fig. 2. Tectonic scheme of Altai-Sayan folded area, Tuva, Mongolia and Transbaikalia. *1* — Cenozoic sediments of the Biya-Barnaul basin; *2* — Hercynides; *3* — Cambrian turbidites; *4* — Cambrian island-arc calc-alkaline volcanic series; *5* — Vendian-Cambrian accretionary prisms; *6* — Vendian-Cambrian oceanic ophiolites; *7* — Vendian ophiolites of primitive island arcs; *8* — Vendian-Cambrian ophiolites and oceanic seamount basalts; *9* — Vendian- Cambrian island-arc calc-alkaline volcanic series; *10* — Middle-Late Paleozoic volcanosedimentary basins; *11* — Gondwana-derived microcontinents: AM — Altai-Mongolian, TM — Tuva-Mongolian, B — Barguzin; *12* — Late Paleozoic strike-slip faults; *13* — Charysh-Terekta-Sayan suture zone.

margin units of the Siberian continent which comprise the Kuznetsk-Altai island arc of Vendian-Cambrian age, Ordovician-Silurian passive margin units and Devonian-Carboniferous island-arc (or active margin) units. The accretionary wedges of the island arcs contain fragments of the Vendian-Paleozoic oceanic crust consisting of ophiolites and paleo-oceanic seamount rocks. The northern segments have no Gondwana-derived microcontinents (Buslov, 1998; Buslov et al., 2003, 2004; Dobretsov et al., 2004).

3. The Charysh-Terekta-Sayan suture zone separated the northern and southern segments and comprises fragments of the Late Cambrian-Early Ordovician oceanic crust and Ordovician-Silurian blueschists (Buslov, 1998; Buslov et al., 2003, 2004; Volkova et al., 2005).

4. The strike-slip faults transverse or parallel relative to the suture zones are of Middle-Late Ordovician, Late Devonian, Early Carboniferous and Late Carboniferous-Permian, Permian-Triassic and Triassic-Jurassic ages. The strike-slip faults have formed the present-day mosaic-blocky structural pattern of Central Asia (Berzin et al., 1994; Berzin and Dobretsov, 1993; Buslov, 1998; Buslov et al., 2003, 2004).

The most intense were the faults formed by the Late Carboniferous-Permian collision of the East European, Kazakhstan and Siberian continents which definitely changed the structural pattern created in previous geodynamic settings. The fragments of Vendian-Cambrian (Ordovician?) island arcs and their associated microcontinents have been identified in East Kazakhstan, southern ASFA, Tuva, and Mongolia (Fig. 2). No microcontinents have been found in the Vendian-Paleozoic fold belts of NE Kazakhstan and northern ASFA. All fold belts are characterized by a specific succession of environments that existed at the margin of the Siberian continent: 1) Vendian-Cambrian island arcs with accretionary prisms and their incorporated fragments of ophiolite sections, oceanic plateaus and seamounts, eclogites and blueschists; 2) Ordovician-Silurian passive margin; 3) Devonian-Early

Carboniferous active margin (Buslov, 1998; Dobretsov et al., 2003; Buslov et al., 2003, 2004).

The widely expressed Late Cambrian-Ordovician subduction-collision events and the related high-pressure (HP) belts and ophiolites have been recognized in ASFA during the last decade (Iwata et al., 1997; Buslov et al., 2000, 2003, 2004; Volkova et al., 2005), though no good explanation for their occurrence has been given yet. We believe that the HP belts and ophiolites compose the Charysh-Terekta-Sayan suture zone, which separates the Vendian-Early Paleozoic Siberian continental margin and the Kazakhstan-Baikalian continent consisting of Precambrian Gondwana-derived microcontinents and Kazakhstan-Tuva-Mongolian island arc units (Figs. 1 and 2).

Late Cambrian-Ordovician subduction-collision events in Central Asia

Kazakhstan. There are a lot of accretion-collision belts in Kazakhstan, which comprise fragments of Vendian-Ordovician island arcs and Gondwana-derived microcontinents. The Late Cambrian-Ordovician evolution of this territory structure has been better studied within the Kokchetav subduction-collision belt in Northern Kazakhstan (Figs. 1 and 3). The structure and composition of Kokchetav rock units and their geochronology indicate an important role of Late Cambrian-Early Ordovician tectonic processes in the evolution of the Kokchetav belt (Dobretsov et al., 2005, 2006; De Grave et al., 2006). The belt consists of: (i) terranes of the Precambrian Kokchetav microcontinent; (ii) Cambrian subduction-related metamorphic rocks formed at different depths; and (iii) Late Cambrian-Early Ordovician accretionary prism with island-arc rocks, ophiolites, mylonitized granite-gneiss with eclogite boudins, olistostromes and turbidites (Figs. 3 and 4). In the Early Ordovician the Kokchetav microcontinent collided with the newly formed Stepnyak island arc. The two-stage subduction (Vendian-Cambrian and Ordovician) and the Late Cambrian-Early Ordovician collision formed the thrust-sliced (or imbricated) structure of the Kokchetav subduction-collision belt (Fig. 5).

The Kokchetav subduction-collision belt consists of two large structural elements (Dobretsov et al., 2005, 2006) (Figs. 3 and 4): (1) a megamelange belt comprising fragments of a Cambrian subduction zone formed at different depths: from 150–200 to 60–30 km, and (2) an Ordovician accretionary prism formed at 0 to 60–30 km. Figure 5 shows the ages of the megamelange belt and interpretation of its early

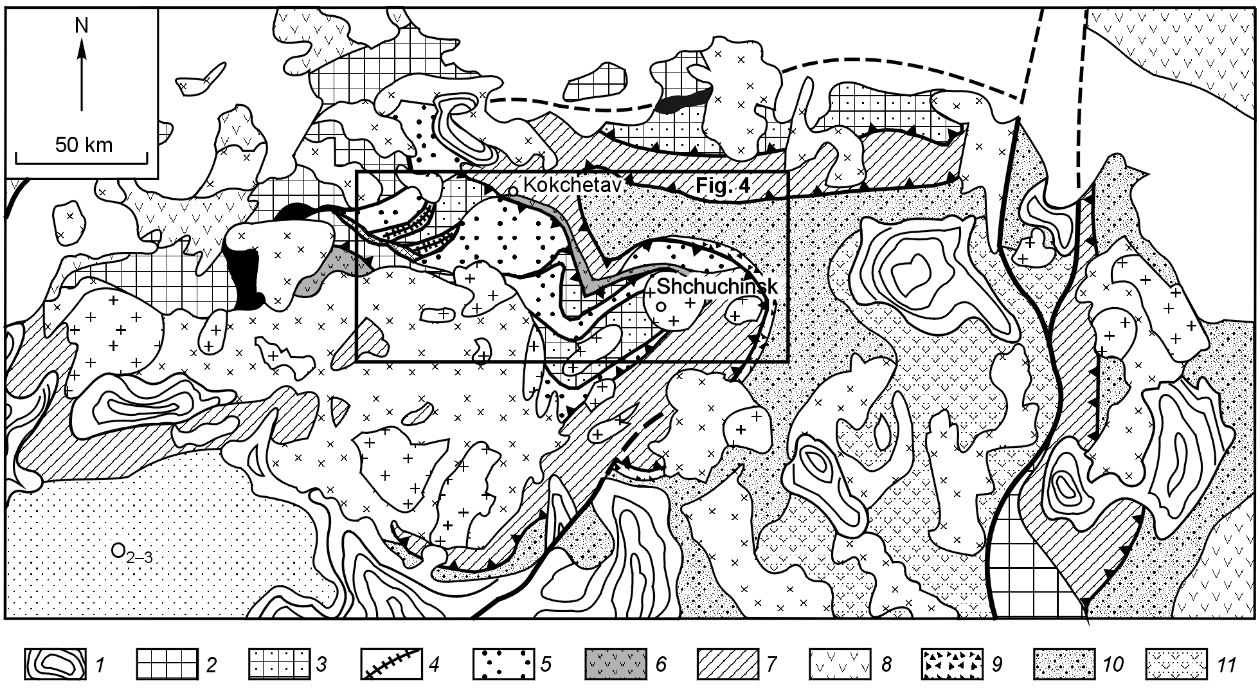

Fig. 3. Tectonic scheme of northern Kazakhstan (Dobretsov et al., 2006). *1* — Devonian-Late Paleozoic volcanosedimentary basins; *2*, *3* — fragments of the Kokchetav and Shatsky (NE of Kokchetav) microcontinents: *2* — greenschist diaphthorized rocks and *3* — sediments metamorphosed up to the amphibolite facies in subduction zone; *4*, *5* — megamelange belt (paleosubduction zone terranes): *4* — diamondiferous gneisses and coesite-bearing eclogites, *5* — other terranes composed of eclogites, garnet amphibolites, and garnet peridotites hosted by granitic gneisses and mica schists; *6* — Vendian(?) accretionary prism; *7* — Early Ordovician accretionary prism; *8* — Vendian-Cambrian island-arc volcanosedimentary rocks (Ishim island arc in the west and Seletin island arc in the east); *9* — Early Ordovician syntectonic olistostrome; *10* — Ordovician volcanosedimentary rocks of the Stepnyak trough; *11* — Ordovician volcanic rocks of the Stepnyak island arc; *12* — Middle and Late Paleozoic shelf sediments; *13* — Late Neoproterozoic-Tremadocian ophiolites of the Zlatogorsky complex; *14* — Late and Middle Cambrian Krasnomaisky alkaline-ultramafic complex; *15* — Silurian-Ordovician granites; *16* — Devonian granites; *17* — deformed Late Cambrian-Early Ordovician faults; *18* — Early Ordovician frontal thrust of the Kokchetav massif over the Stepnyak trough; *19* — Late Paleozoic strike-slip faults.

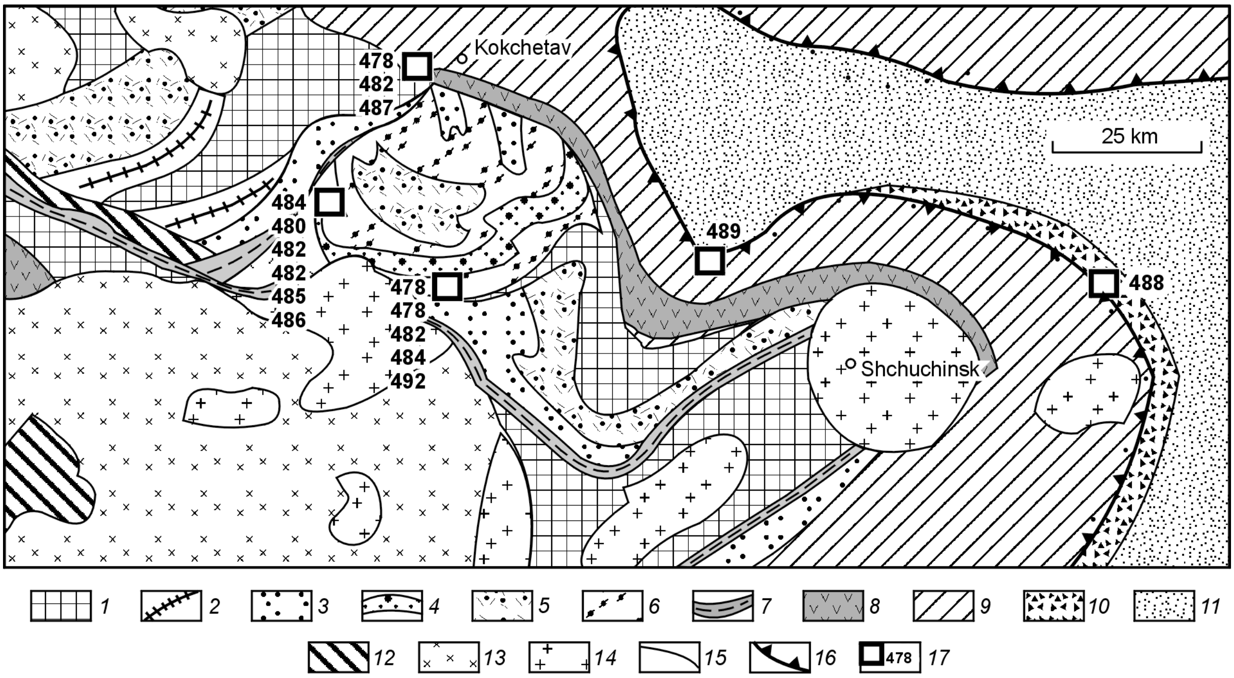

Fig. 4. Structural elements of the Kokchetav subduction-collision zone of Late Cambrian-Early Ordovician age and location of Ar-Ar dated samples. *1* — fragments of the sedimentary cover of the Kokchetav microcontinent; *2–6* — megamelange belt (paleosubduction terranes): *2* — diamondiferous gneisses and coesite-bearing eclogites, *3* — coesite eclogite, eclogite, and garnet amphibolite hosted by mica schists, *4* — eclogite, amphibolite, garnet peridotite, *5* — eclogites and garnet amphibolites hosted by granitic gneisses, *6* — garnet-sillimanite-cordierite schists (mylonites and blastomylonites) with boudins of eclogite and garnet amphibolite; *7* — garnet-cordierite-biotite schists and gneisses (Daulet Formation); *8* — Vendian(?) volcanosedimentary rocks; *9* — Early Ordovician accretionary prism; *10* — Early Ordovician syntectonic olistostrome; *11* — Ordovician volcanosedimentary rocks of the Stepnyak trough; *12* — Late-Middle Cambrian Krasnomaisky alkaline-ultramafic complex; *13* — Ordovician granites; *14* — Devonian granites; *15* — deformed Late Cambrian-Early Ordovician faults; *16* — Early Ordovician frontal thrust of the Kokchetav massif; *17* — location and age of garnet-mica and mica schists from fault zones (Ma).

evolution at 550–527, 520–515, and 507–500 Ma. We interpret these dates as corresponding to the following stages: formation of UHP rocks, their exhumation, and intracollisional deformation (for more detail see Dobretsov et al., 1998, 2005, 2006; Dobretsov, Shatsky, 2004; Hacker et al., 2002; Theunissen et al., 2000). The present paper discusses the later evolution of the belt correlating with the data on other collision-subduction events.

The fault zones separating the fragments of the subduction zone and the tectonic slices of the accretionary prism are marked by garnet-quartz-muscovite and quartz-muscovite schists, which are isoclinally folded dipping to SW. The $^{40}Ar/^{39}Ar$ dating of muscovite from mica-rich rocks of the near-fault zones both in the megamelange belt and in the accretionary prism showed close values of age plateaus corresponding to 490–480 Ma. A syntectonic olistostrome is located at the base of the thrust-sliced structure of the Kokchetav belt. The age of the siliceous rocks from the matrix of accretionary prism and syntectonic olistostromes associated with island-arc volcanic rocks is Early Ordovician (conodont *O. evae*, *B. navis*-lower *Par. originalis* Zones). It was the time of tectonic rebuilding of the accretionary wedge and thrusting of the Kokchetav subduction-collision belt over the Stepnyak fore-arc trough (Obut et al., 2006).

Thus, the available geological, paleontological and geochronological data constrain the Late Cambrian-Early Ordovician tectonic stage of formation of the thrust-sliced structure of the Kokchetav belt as a result of microcontinent–island arc collision. The collision led to the thrusting of complexes of the microcontinent, paleosubduction zone and accretionary prism over the fore-arc trough and formation of a thrust-sliced structure. At the base of that thick structure the rocks were then melted to form the Zerenda complex of collisional granites at 460–440 Ma. In the Late Ordovician the uplifting and subsequent denudation of the orogenic structures resulted in molasse formation (Fig. 5).

Altai-Sayan Folded Area (ASFA). In ASFA the Late Cambrian-Ordovician accretion-collision events were more intense at the junction zone between the Altai-Mongolian microcontinent and Siberian continent (Figs. 2 and 6). The zone consists of fragments of the Late Cambrian-Early Ordovician oceanic crust comprising a serpentinitic melange with blocks of massive serpentinite and gabbro, sheets of basalt-siliceous rocks of ophiolitic origin plus oceanic island basalts, siliceous-carbonate-terrigenous and carbonate rocks. In the Ordovician the sedimentary-basaltic units were metamorphosed in the greenschist and blueschist facies (Buslov et al., 2003; Volkova et al., 2005). The siliceous rocks contain numerous remnants of radiolarians and conodonts of Late Cambrian-Early Ordovician age (Buslov et al., 2000, 2003; Iwata et al., 1997).

The previous structural, geochronological and paleomagnetic data showed that an open ocean (Altai-Sayan oceanic basin) existed between the Altai-Mongolian microcontinent

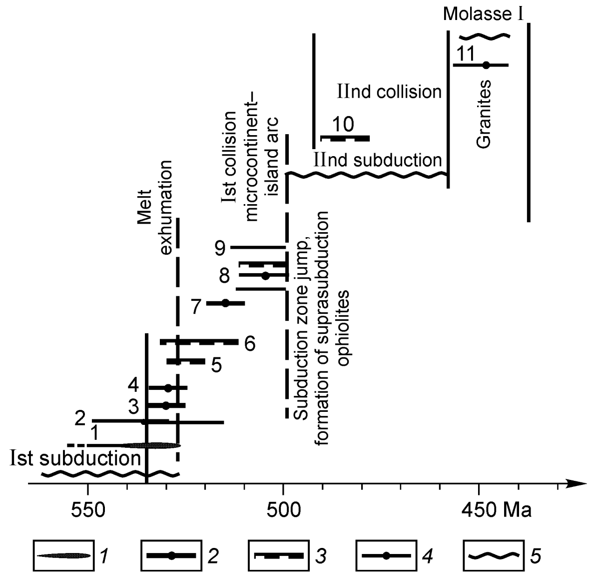

Fig. 5. Correlation of main geodynamic stages and geochronological dates for the Kokchetav subduction-collision zone after (Dobretsov et al., 2006) with modification. 1–11 — age intervals for: 1 — eclogite, Sm-Nd (Shatsky et al., 1993); 2 — diamond-coesite gneiss, U-Pb, SHRIMP (Katayama et al., 2002; Herman et al., 2006); 3 — gneiss, U-Pb, SHRIMP (Claoue-Long et al., 1991); 4 — gneiss, U-Pb, SHRIMP-zoned zircons, core (Herman et al., 2001); 5 — gneiss, Ar-Ar on biotite and muscovite (Hacker et al., 2003); 6 — granites hosting UHP-HP rocks, Ar-Ar on biotite and amphibole (Hacker et al., 2003); 7 — UHP-HP rocks, U-Pb, SHRIMP-zoned zircons, outer rim (Katayama et al., 2002); 8 — granites hosting UHP-HP rocks, U-Pb (Borisova et al., 1995); 9 — gneiss, K-Ar on mica (Hacker et al., 2003); 10 — thrust zone schists, Ar-Ar and K-Ar on mica (De Grave et al., 2006; Dobretsov et al., 2006); 11 — Zerenda granites, Rb-Sr (Shatygin, 1994). Methods of dating: *1* — Sm-Nd, *2* — U-Pb, *3* — Ar-Ar, *4* — K-Ar and Rb-Sr, *5* — geological.

and Siberian continent from Late Cambrian to Silurian (locally up to the Middle Devonian) (Buslov et al., 2003, 2004). The Late Cambrian-Ordovician island arcs were accreted to the Altai-Mongolian microcontinent during the same time interval (Windley, 1994; Windley et al., 2002).

The Late Devonian collision of the Siberian continent and the Altai-Mongolian microcontinent with its accreted island arcs resulted in the formation of EW-trending strike-slip and thrust fault zones including the Charysh-Terekta dextral strike-slip zone, Kurai, Ulagan and North Sayan oblique thrust zones (Fig. 6). The structure of the collision zone has been better studied in the Charysh-Terekta strike-slip zone (Buslov et al., 2003).

The generalized section of the strike-slip zone in the Uimon zone of central Gorny Altai consists of the following units (NW–SE):

1. Metavolcanic, carbonate and terrigenous rocks of the Terekta Formation of Ordovician(?) age: epidote-quartz-albite-chlorite and chlorite-albite-carbonate schists, quartzite schists, marble and metabasalts.

2. Highly metamorphosed gneisses and mafic rocks of the Turgunda complex dated at 415±3, 418±3, 418±2 Ma (i.e. Early Silurian; Ar-Ar amphibole).

3. The blueschists of the Uimon Formation are variably diaphthorized and metamorphosed to porphyroblastic albite-chlorite+phengite+quartz schists. The blueschist metamorphism is dated at 491–484 and 455–444 Ma with the K-Ar and Ar-Ar methods after phengite and amphibole. The lithology of the Uimon and Terekta Formations and the geochemical features of metabasalts suggest that basalts, siliceous-carbonate terrigenous rocks and carbonates were formed in an oceanic island environment (Buslov et al., 2003; Volkova et al., 2005).

4. The Cambrian-Ordovician ophiolitic melange consisting of siliceous-basaltic units and ultramafic rocks. The ultramafics are generally altered to serpentinitic schists with oval blocks of massive serpentinite, serpentinitized dunite, pyroxenite, gabbro and rhodingite.

5. Cambrian volcanogenic, Late Cambrian-Early Ordovician siliceous, and Early-Middle Ordovician tuff-sedimentary units. The volcanogenic andesitic-basaltic unit consists of intercalating diabase, pyroxene and plagioclase porphyrites, mafic variolitic lavas, their tuffs, dikes and sills of diabase, diabase-porphyrite and gabbro-diabase as well as graywacke sandstones and siltstones. The volcanic rocks have island-arc calc-alkaline affinities. The siliceous unit consists of bedded red cherts with deformed remnants of radiolarians, which are similar to the Late Cambrian-Early Ordovician siliceous rocks of Zasur'ya Formation of NW Altai within the Charysh-Terekta fault zone.

Figure 6 illustrates the structure of NW Altai comprising a series of tectonic nappes including fragments of the Late Cambrian-Early Ordovician oceanic crust, which is of special interest. The fragments of the oceanic crust occur as tectonic slices, which consist of variegated sandstones, grey, green, lilac, and dark-red siliceous rocks (mainly cherts), pillow-lavas of variolitic, aphyric, and porphyric basalts, their tuffs, gabbro and diabase dikes. The dark-red and green bedded cherts contain numerous conodonts and radiolarians of Late Cambrian-Early Ordovician (Tremadocian) age. The basalts of the Zasur'ya Formation have MORB and OIB affinities (Buslov et al., 2000; Safonova, Buslov, 2005).

Tuva, Buryatia, Mongolia and the Baikal region (the territory south of the Siberian craton) are characterized by the occurrence of highly metamorphosed rocks previously regarded as the basement rocks of Precambrian Laurasia- and Gondwana-derived microcontinents (Berzin and Dobretsov, 1993; Mossakovsky et al., 1993; Zonenshain et al., 1990). Their detailed structural and geochronological study showed that the rocks in the granulite and amphibole facies of regional metamorphism were formed at 500 to 450 Ma in oblique-thrust faulting setting (Donskaya et al., 2000; Fedorovsky et al., 1995; Fedorovsky et al., 2005; Kuzmichev, 2004; Vladimirov et al., 2000). The findings of zircons of Early Precambrian age in some metamorphic rocks suggest that at least some of granulitic and amphibolitic rocks originated from the metamorphic and igneous rocks of microcontinent basements.

The metamorphic rocks alternate with tectonic slices of the Late Neoproterozoic-Early Cambrian rocks of microcontinent terrigenous-carbonate covers, tholeiitic and calc-alkaline island-arc series, and accretionary wedges including ophiolites, HP rocks and turbidites. These rock units collectively form a

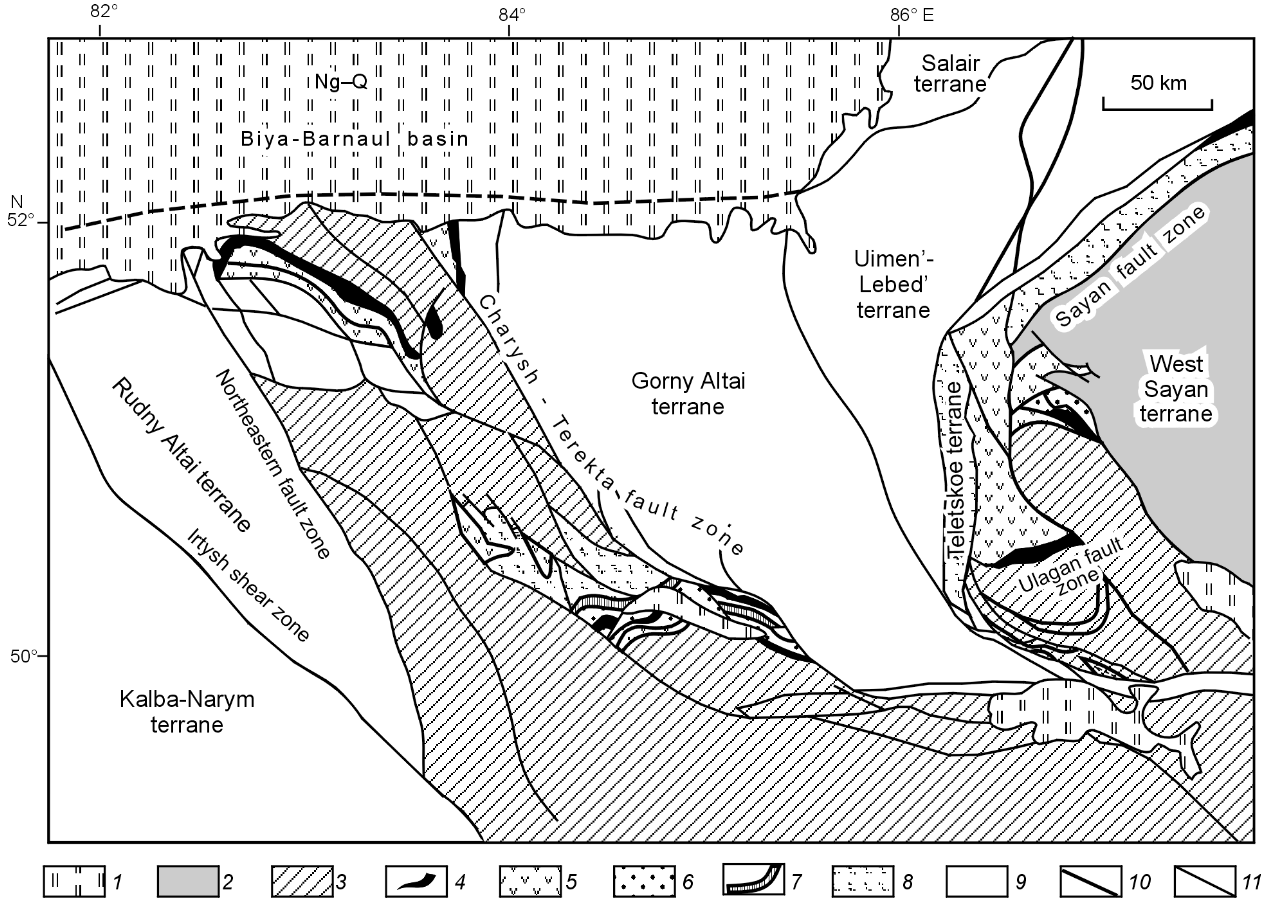

Fig. 6. Tectonic scheme of the junction zone between the Altai-Mongolian and Siberian continent. *1* — Neogene-Quaternary basins; *2*, *3* — fragments of the Kazakhstan-Baikalian orogenic belt: *2* — West Sayan turbiditic terrane, 3 — Altai-Mongolian microcontinent; *4–9* — terranes of the Charysh-Terekta-Sayan suture zone: *4* — Late Cambrian-Early Ordovician oceanic crust, *5* — Late Cambrian-Ordovician(?) island arc, *6* — Ordovician-Silurian blueschists, *7* — granitic gneisses, *8* — Terekta Formation (Turgunda complex) of metamorphic rocks of greenschist and amphibolite facies of metamorphism; *9* — terranes located at the margin of the Siberian continents: Kalba-Naryn; Rudny Altai — Devonian-Early Carboniferous island arcs; Gorny Altai — Vendian-Cambrian normal island arc, Ordovician-Silurian passive continental margin and Devonian island arc; Uimen-Lebed — Vendian primitive island arc, Ordovician-Silurian passive margin and Devonian back-arc basin; Salair — Cambrian island arc; *10* — Late Cambrian-Ordovician thrust faults separating terranes of Charysh-Terekta-Sayan suture zone; *11* — Late Paleozoic-Early Mesozoic strike-slip faults.

wide orogenic belt of Late Cambrian-Ordovician age (Figs. 1 and 2) extending from Sangilen (southern Tuva) to Transbaikalia. This orogenic belt is regarded as accretion-collision structure formed by the accretion of Tuva-Mongolian, Barguzin, and Muya-Vitim microcontinents to the Siberian continent (Berzin and Dobretsov, 1993; Donskaya et al., 2000; Fedorovsky et al., 1995; Fedorovsky et al., 2005; Zonenshain et al., 1990).

The Tuva-Mongolian microcontinent is bounded in the west and north (Figs. 1 and 2) by zones of thrusts and strike-slip faults of Late Cambrian and Middle-Late Ordovician ages, respectively (e.g., Kuzmichev, 2004).

The best studied Middle-Late Ordovician oblique thrust structure formed at the margin of the Tuva-Mongolian microcontinent occurs in southern Tuva (Sangilen). Vladimirov et al. (2000, 2004) suppose that this structure is the result of the collision between the Tuva-Mongolian microcontinent and the Tannu-Ola island arc (a fragment of the Tuva-Mongolian island arc). The collision led to the formation of highly metamorphosed series at 525–490 Ma and then to epidote-amphibolite and greenschist metamorphism (490–430 Ma) related to dextral strike-slip faulting. The strike-slip faulting was recorded in the metamorphic rocks of the Teskhem-Mugur complex and the overlying Late Neoproterozoic-Cambrian terrigenous-carbonate sediments. According to Vladimirov et al. (2000, 2004) strike-slip zones are associated with zones of extension injected by diorite-granodiorite sills of the Tannu-Ola complex dated at 451±15 Ma and by granite dikes and veins of the Chzhargalant complex dated at 442±21 Ma.

In the northern Baikal region the collision events led to the formation of the Ol'khon zone at the southern margin of the Siberian craton (Figs. 2 and 7), NW of Baikal. The Ol'khon zone is a collage of terranes composed of metamorphosed volcanosedimentary rocks and ophiolites separated by Early Paleozoic thrusts and strike-slip faults (Fedorovsky, 1997; Fedorovsky et al., 1993, 1995; 2005).

The Ol'khon zone consists of eight structural units (NW–SE; Fig. 7):

1. Paleoproterozoic metamorphic rocks and granites of the Siberian craton.

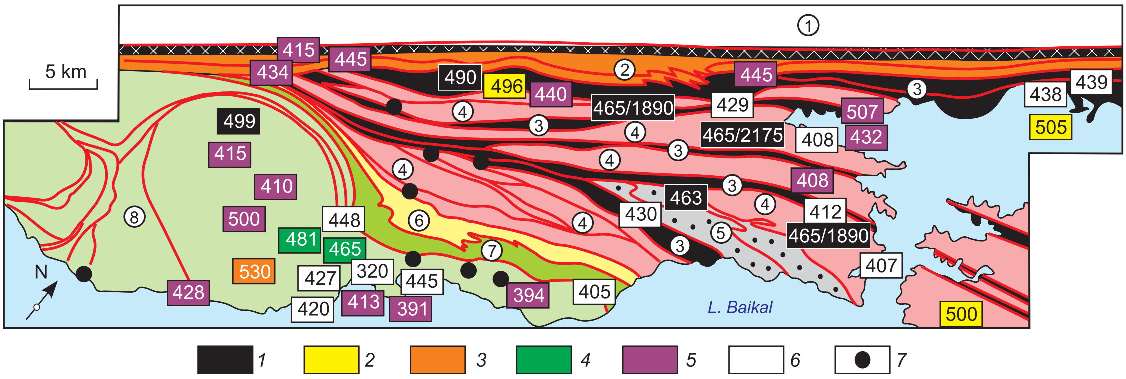

Fig. 7. Tectonic scheme of the SW Ol'khon collision zone including geochronological dates (Ma) (Fedorovsky, 1995; Fedorovsky et al., 2005). Encircled numbers: 1 — Siberian Craton; 2 — collisional suture separating the Siberian Craton and the Ol'khon zone; 3 — metamorphosed rocks of island-arc and back-arc basin including tholeiitic series and ophiolites; 4 — granite-gneiss domes (the Paleoproterozoic crust remobilized in the Early Paleozoic); 5 — gneissic domes tectonically overlapped by island-arc and accretionary prism sheets; 6 — microgneiss and amphibolite; 7 — marble, siliceous-carbonate rocks, amphibolite; 8 — metamorphosed island-arc rocks: subalkaline gabbro and dolerite, volcanosedimentary rocks. See comments in the text. Methods of dating: *1* — U-Pb (zircon, fuzion), *2* — U-Pb, SHRIMP, *3* — Sm-Nd, *4* — Rb-Sr, *5* — Ar-Ar, *6* — K-Ar, *7* — U-Pb (izircon, on dating).

2. Collisional-suture blastomylonites separating the Siberian craton from the Ol'khon collage of terranes.

3. Intercalating island-arc and back-arc metasedimentary rocks, metatholeiites and metaophiolites.

4. Granite-gneiss domes of the Chernorudnaya zone, which were formed as a result of the Early Paleozoic metamorphism of Precambrian rocks of, possibly, the Barguzin microcontinent within obducted allochthons.

5. Gneissic domes tectonically overlain by island-arc and accretionary wedge units.

6. Microgneiss and amphibolite allochthonous slices which are possibly fragments of a back-arc basin.

7. Marbles, siliceous-carbonate rocks, island-arc metasubalkaline volcanics (amphibolites).

8. Metavolcanogenicic-sedimentary rocks, dikes and massifs of island-arc subalkaline gabbro and diorite.

Units 3–5 belong to the Anga-Sakhyurt accretionary prism; unit 8 is part of the Krestovaya zone, a Cambrian island-arc terrane whose marginal NE part together with unit 7 belongs to the Pravaya Anga strike-slip fault zone.

The structural units were formed during four subsequent deformation stages: 1) Late Cambrian thrusting; 2) Early Ordovician doming (500–480 Ma); 3) Middle Ordovician strike-slip faulting (460–445 Ma); 4) Early Silurian strike-slip faulting (445–430 Ma). The deformation resulted in formation of structural-metamorphic parageneses and syncollisional magmatic and metamorphic rocks. The thrusts are traced by the zones of granulites and by the marble melange consisting of marble matrix and fragments of metasiliceous rocks. The older strike-slip faults zones include marble melange, blastomylonites and low-amphibolite schists. The younger strike-slip faults are marked by lower-grade metamorphic schists and rocks. The formation of the granite-gneiss domes is was structurally linked to thrusting and later strike-slip faulting (Fedorovsky, 1997; Fedorovsky et al., 1995, 2005).

The thrusts were formed in three stages during a period from 500 to 480 Ma. The thrust deformation and subsequent doming resulted in amphibolite and granulite metamorphism and formation of garnet-biotite, muscovite-biotite and hypersthene granites. The U-Pb zircon ages of the granulitic rocks deformed at several stages are 490±10, 505±10 and 494±16 Ma (Gladkochub, 2004; Fedorovsky et al., 2005; Khromykh et al., 2004).

The domes consist of granite-gneisses and later granitic veins diaphthorized and migmatized at the strike-slip faulting stage. The ages 434±5 and 437±5 Ma (Ar-Ar, amphibole in amphibolites), 431±5 Ma (Ar-Ar, biotite in plagiogneisses), 431±6 Ma (Ar-Ar, biotite in garnet-amphibole-biotite gneisses), 405±4 Ma (Ar-Ar biotite in migmatized gneisses), and 431±6 and 392±4 Ma (Ar-Ar biotite in granitic veins) constrain the stages of superimposed deformation (Bibikova et al., 1990; Fedorovsky et al., 2005).

The older strike-slip faults (460–465 Ma) are accompanied by the formation of granite mingling-dikes and tholeiitic dolerites (Fedorovsky et al., 2005; Sklyarov et al., 2001). The dikes are dated at 461±2 and 463±3 Ma (U-Pb zircon dating).

The younger strike-slip faulting (447–420 Ma) led to the formation of the blastomylonitic zone at the boundary with the Siberian craton with incorporated blocks of Neoproterozoic rocks of the latter. The Ar-Ar plateau age of biotite from the blastomylonite zone is 434±2 and 447±3 Ma.

The post-metamorphic granites of low amphibolite facies occur within the Pravaya Anga zone and are dated at 410±380 Ma, whereas the mica-rich schists from the younger strike-slip zones are older. The Ar-Ar age (biotite) is 413±4 Ma (Yudin et al., 2005).

Thus, the available geochronological data of granite-gneisses from the domes and of metamorphic rocks from the thrust and strike-slip zones provide a sequence of deformations decreasing from granulitic to amphibolitic facies. The thrust structures were formed at the subduction-collision stage of the granulitic and greenschist metamorphism, which led to the uplifting of the domes at 510–480 Ma. The strike-slip faulting occurred in periods of 465–445 and 440–420 Ma. The ages and scenarios of thrusting in the Ol'khon zone of the Baikal region and Kokchetav zone of northern Kazakhstan (Fig. 5)

(Dobretsov et al., 1998) are mutually correlated and both are consequent on the collision of microcontinents with island arcs in the Early Ordovician.

The island-arc related rocks in the Ol'khon zone are tholeiitic basalts of the Krestovaya zone, metavolcanic-terrigenous and volcanic rocks, subalkaline gabbros and diorites of the Anga zone, marbles, metasiliceous-terrigenous and metavolcanic rocks of the Pravaya Anga zone. The largest Birkhinsky gabbro massif is 12–13 km across. The age of crystallization of the massif is 530±23 Ma (Sm-Nd isochron) (Bibikova et al., 1990; Rosen and Fedorovsky, 2001) and the age of amphibolization in the superimposed strike-slip zones is 485 ± 5 Ma (U-Pb). Metamorphism related to strike-slip faulting and granitic veins was responsible for the formation of amphibolites. According to other data (Fedorovsky et al., 2005) the age of crystallization of gabbro is 499 ± 2 Ma (U-Pb). All the data taken as a whole allowed us to accept the Cambrian age for the island-arc system and the Early Ordovician age of the superimposed strike-slip faulting.

The ophiolites occur mainly in the Anga-Sakhyura zone as thin oval-shaped bodies up to 500 m across and include ultramafic rocks, gabbros and metabasalts (amphibolites) (Fedorovsky et al., 2005; Mekhonoshin et al., 2004). The age the ophiolites is probably Middle Cambrian as the phlogopites from plagiogranitic veins cutting dunites are dated at 497 ± 1.5 Ma (Ar-Ar) (Yudin et al., 2005). They could be analogs of the ophiolites marking the Charysh-Terekta-Sayan suture zone in central ASFA (Fig. 2).

Discussion and conclusions

Table 1 shows geochronological data on the igneous and metamorphic rocks from Caledonian belts of ASFA, Tuva, Mongolia, Mongolia, and Baikal. The geochronological dates characterize the ages of ophiolites, high-pressure rocks and accretion-collision events and can be grouped in six stages. Comparison with the above data (Figs. 4, 5, 7) shows that the main collision stages were synchronous within a vast territory from northern Kazakhstan to Baikal.

The 500–480 Ma events display the best correlation. We suggest that they reflect the collision of the Kokchetav, Tuva-Mongolian and Barguzin microcontinents, with island arcs being components of the single Kazakhstan-Tuva-Mongolian island arc. The collision zones are marked by high-pressure rocks (fragments of the microcontinent and Paleoasian Ocean crust rocks as protholith) formed in subduction zones (Dobretsov et al., 2005, 2006; Dobretsov and Buslov, 2004).

Thus, the available geological information and representative geochronological data support the idea about a Late Cambrian-Ordovician accretion-collision event, which led to the formation of a more than 6000 km long orogenic belt in Central Asia. The western segment (Kazakhstan) consists of Middle-Late Cambrian tectonic nappes, Early Ordovician oblique thrusts, fragments of microcontinents, accretionary prisms (with laterally juxtaposed turbiditic and ophiolitic terranes), and subduction zone fragments (with vertically juxtaposed terranes in the diamond-coesite to the epidote-amphibolite facies of metamorphism). The central segment (Altai-Sayan Folded Area) displays Late Cambrian-Ordovician thrusting, Late Devonian strike-slip faulting, oblique thrusting and is characterized by the occurrence of Ordovician blueschists and fragments of the Cambrian-Early Ordovician oceanic crust. The eastern segment (Tuva, Buryatia, Baikal) witnessed the Middle-Late Ordovician strike-slip deformation, which broke the Late Cambrian-Early Ordovician thrust structure preserved fragmentally.

Most likely, in the Late Cambrian-Early Ordovician a large territory of Central Asia experienced intense accretion-collision processes in the same active-margin geodynamic environment with participation of Gondwana-derived microcontinents. It is interesting that Gondwana-derived microcontinents or blocks have not been found in Vendian-Paleozoic accretion-collision belts of northern ASFA, i.e. at the SW margin of the Siberian continent (Figs. 1 and 2). In Late Cambrian-Early Ordovician time, the subduction of the Paleoasian Ocean crust and the subsequent collision of the microcontinents with the active margin led to the formation of the Kazakhstan-Baikal accretion-collision orogenic belt. The eastern segment of the orogenic belt — the Ol'khon zone (Figs. 1 and 7) — was formed close to the Siberian continent. Other segments of the belt (western and central) were separated from the continent by the Altai-Sayan (or Ob'-Zaisan) oceanic basin, whose relics occur within the Charysh-Terekta-Sayan junction zone of the Altai-Mongolian microcontinent and Siberian continent (Figs. 1, 2, and 6). In the Middle-Late Ordovician and Late Devonian, the central segment of the orogenic belt was accreted to the Siberian continent and the Altai-Sayan oceanic basin closed. Westwards (in modern coordinates) this oceanic basin probably communicated with the Uralian Ocean, which separated the Kazakhstan-Baikalian continent from the East European continent.

The Late Cambrian-Early Ordovician orogenic belt was formed simultaneously with the opening of the Uralian and Mongol-Okhotsk (Turkestan) Oceans. This allows us to consider both events a result of a large rearrangement in the Earth's history, possibly, related to an increasing effect of the mantle on the lithosphere. After the breakup of Rodinia at 970–850 Ma and manifestations of the superplume at 760–700 Ma (Dobretsov et al., 2003; Maruyama, 1994) the next Late Cambrian-Early Ordovician impulse of the mantle magmatism (500–480 Ma) resulted in the opening of the Uralian and Mongol-Okhotsk Oceans and accelerated the amalgamation of Gondwana-derived blocks. The Kazakhstan-Baikalian orogenic belt was formed by the end of the Ordovician and possibly represented a composite continent separated from the East European and Siberian continents by oceanic basins. The further history of Central Asia included the closure of the Uralian, Altai-Sayan and Mongol-Okhotsk Oceans and collision of the continents. The Late Paleozoic closure of the oceans resulted in the formation of the North European block which incorporated the Late Cambrian-Ordovician

Table 1
Main Stages of Evolution of Vendian-Paleozoic Structures of Mongolia, Gorny Altai, Tuva, and Baikal Region and Corresponding Magmatic and Metamorphic Events

Stage, Ma	Events, Ma		Reference
	magmatic	metamorphic	
I, 570±20	573±6, Daribin ophiolites	562±11, eclogites, Chagan-Uzun massif, Gorny Altai	Pfander et al., 2002 Gibsher et al., 2001
	570±2, Agardag ophiolites		Kepezhinskas et al.
	568±4, Han-Taishiri ophiolites 569±21, Bayan-Hongor ophiolites	562±2, metamorphics, Bayan-Hongor ophiolites	Kepezhinskas et al., 1999 Dobretsov, Buslov, 2004
II, 540±5	546±3, andesites and dacites of Lake zone, Mongolia 545±2, granulites of Bayan-Hongor zone, Mongolia 539±5, the same	536±6, Moren complex 529±5, eclogites, Chagan-Uzun massif, Gorny Altai	Yarmolyuk et al., 2003 Sal'nikova et al., 2001 Buslov et al., 2002
III, 515±10	512±2, plagiogranites, Sangilen 523±2, plagiogranites, Mainar massif, Sangilen 515±7, the same 517±3, the same 506±2, tonalites, Dzhida zone, Tuva	510±4, granulites, Daribin zone 505±5, blastomylonites, Ol'khon zone	Kozakov et al., 2003 Gladkochub, 2004 Kovalenko et al., 2004 Fedorovsy et al., 2005
IV, 490±10	495±5, tonalites, Lake zone, Mongolia 497±4, granitoids, Sangilen 489±3, granitoids, Sangilen 490±4, tonalites, Daribin massif 484±2, gabbros, Mazhalyk massif 485±5, ophiolites of Shalkar massif (Zlatogorsky complex, Kokchetav)	490±4, metamorphites of amphibolite facies, Daribin zone 494±1, granulites, Erzin complex, Sangilen 490±4, metaschists, Narym complex 485±2, blueschists, Uimon zone 483±9, the same 485±5, metaschists, Ol'khon zone 445±10, mylonites, Ol'khon zone	Borodina et al., 2004 Volkova et al., 2005 Bibikova et al., 1990 Kovalenko et al., 2004 Fedorovsky et al., 2005 Dobretsov et al., 2006
V, 465±10	465±10, tonalites, Lake zone, Mongolia 457±3, granites, Tannu-Ola complex, Tuva 451±3, the same	461±2, granulites, Ol'khon zone 463±3, the same 450±4, blueschists, Chara belt, Kazakhstan	Kozakov et al., 2003 Volkova et al., 2005 Buslov et al., 2004
	463±7, granites, East Sayan	445–450, blueschists, Uimon zone	Khain et al., 1995 Kovalenko et al., 2004 Fedorovsky et al., 2005
VI, 440±20	451±15, 442±21, granites, Tuva	434±5, amphibolites, Ol'khon zone 437±5, the same 431±6, gneisses, Ol'khon zone	Ar-Ar Buslov et al.., 2004 Vladimirov et al., 2000 Fedorovsky et al., 2005
		447±3, mylonites, Ol'khon zone 434±2, the same 430–435, phengite schists of Uimon zone	

Kazakhstan-Baikalian orogenic belt later strongly deformed by strike-slip faulting.

It is quite possible that the Late Cambrian-Early Ordovician is the time of initiation of the North Asian superplume, which, according to Yarmolyuk et al. (2000), was active throughout the Phanerozoic. We suggest independent impacts of several superplumes (Dobretsov et al., 2003b). A special study of alkaline rocks — e.g. Late Cambrian-Early Ordovician granites and syenites, layered gabbro and gabbro-peridotite plutons, nepheline syenite massifs of Central Asia (e.g., Dovgal' et al., 2004; Vladimirov et al., 1999; Yarmolyuk et al., 2000) is necessary to prove the existence of a Late Cambrian-Early Ordovician superplume.

Thus, answering the questions posed in the Introduction we can suppose the following: 1) in Vendian-Cambrian time the Paleoasian Ocean included two island-arc systems. The Kuznetsk-Altai island arc was located at the margin of the Siberian continent. The Kazakhstan-Tuva-Mongolian island arc was separated from the continent by an open ocean and probably was located closer to Gondwana. A more detailed subdivision of island arcs of different ages is quite possible but this does not change the situation. 2) The Late Cambrian-Ordovician subduction-collision events and orogenic processes in Central Asia could be related to plume activity which resulted in the opening of new oceans — Uralian and Mongol-Okhotsk — and in the accretion of the Gondwana-derived microcontinents to the Kazakhstan-Tuva-Mongolian island arc to form the extended Kazakhstan-Baikalian orogenic belt.

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