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Neoproterozoic to Early Ordovician Evolution of the Paleo-Asian Ocean: Implications to the Break-up of Rodinia

Nikolay L. Dobretsov, Mikhail M. Buslov and Valery A. Vernikovsky

United Institute of Geology, Geophysics and Mineralogy, Siberian Branch of Russian Academy of Science,
prospect Koptyuga 3., Novosibirsk-90, 630090, Russia, E-mail: misha@uiggm.nsc.ru

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Abstract

The paper reviews and integrates the recent geological and geochronological data, which allow us to recognize three stages of the evolution of the Paleo-Asian Ocean.

The opening of the Paleo-Asian Ocean at 970–850 Ma is dated by the Nersin Complex in the Aldan shield, plagiogranites of the Sunuekit massif, enderbites of the Sludinsk Lake area, and passive margin sediments of the Patoma or Baikal series. The initial subduction (850–700 Ma) is marked by volcanic rocks, trondjemite and gabbro of the Sarkhoy island arc series. Collisions of microcontinents with Siberia at 660 to 620 Ma are evidenced by the exhumation of Muya eclogites (650 Ma), formation of migmatites and amphibolites of the Njurundukan belt (635 and 590 Ma), metamorphic units of the Near-Yenisei belt (640–600 Ma), and orogenic molasse (640–620 Ma). The Paleo-Asian Ocean maximally opened at 620–550 Ma, because at that time a long island arc composed of boninite volcanic rocks was formed. Primitive island arcs of that age have been reconstructed in Kazakhstan, Gorny Altai, West and East Sayan, and North Mongolia. HP and UHP rocks formed in two stages at 550–520 and 520–490 Ma. At 550–490 Ma oceanic islands and Gondwana-derived microcontinents (Kokchetav, Tuva-Mongolian, Central Mongolian and others) collided with the Cambrian-early Ordovician island arc of the Siberian continent. As a result, the island-arc system was extensively modified. Collision occurred twice at 550–520 and 520–490 Ma during which many HP and UHP rocks formed. At that time, the new oceans – the Junggar, Kazakhstan and Uralian – with an Ordovician island arc were formed.

Key words: Tectonic evolution, accretionary and orogenic belts, Rodinia, Paleo-Asian Ocean.

Introduction

Following the first paleomagnetic evidence for the existence of a Proterozoic supercontinent (Piper, 1976), and the SWEAT hypothesis proposing a south-western United States – East Antarctic tectonic connection was published (Moores, 1991), many studies have supported the concept of a Meso-Neoproterozoic supercontinent named Rodinia (Dalziel, 1991, 1992; Hoffman, 1991; Young, 1992, 1995; Powell et al., 1993, 1994; Karlstrom et al., 1999; Dalziel et al., 2000; Meert and Powell, 2001; Powell and Pisarevsky, 2002). The name "Rodinia" is derived from the Russian verb "rodit" meaning "to give birth" or "to beget", so Rodinia was regarded to be a mother supercontinent that gave birth to all subsequent continents (McMenamin and McMenamin, 1990; Meert and Powell, 2001).

Maruyama (1994) suggested that supercontinent break-up was initiated by a superplume situated in what now is the South Pacific. A triple-point junction over the superplume could have resulted in the opening of the North Pacific, South Pacific and Paleo-Asian oceans (Maruyama, 1994). Two stages of the Rodinia break-up have been suggested by Dobretsov et al. (1995a): (1) the first stage at 900–800 Ma resulted in the opening of the Paleo-Asian ocean, and (2) the second stage at 750–700 Ma resulted in the opening of the Paleo-Pacific.

This paper summarizes new data, which support this idea of two-step opening on the basis of additional data for South Siberia and Mongolia, and shows the main stages of the evolution of the Paleo-Asian Ocean and their correlation with the opening episodes of the North Pacific and South Pacific Oceans during Neoproterozoic to early Ordovician time.

Late Mesoproperozoic (Grenville-Age) Events in Siberia

Recent publications have reported a variety of data on late Mesoproterozoic (Grenville-age) events in the basement of the Siberian platform and associated orogenic belts. Possible early Grenville events (1380–1100 Ma) are recorded by diverse basic dykes and dyke belts in the Anabar and Aldan shields (Okrugin et al., 1990; Parfenov and Kuzmin, 2001). Unfortunately, most geochronological dates have been obtained with the K–Ar method, although in several cases they are supported by U–Pb baddeleyite isotopic data and geological data. For example, Middle Riphean ophiolitic basalts and basaltic tuffs are found in the Udzhinsky aulacogene and Olenek upland in association with extensive intrusions of dyke and sill. Of the same age are ultrahigh-K and high-Mg basic rocks of lamproite-type composing pipe-like and/or dyke-like bodies in the upper reaches of the Kuonamka (Anabar shield) (Okrugin et al., 1990). In one locality, they yield 1200±10 Ma K–Ar age. However, they show a wide range of ages in the second locality, the average being 1180 Ma. Rb–Sr ages for phlogopite-bearing lherzolite (1130±119 Ma) and lamproite (1268±12 Ma) of the Tumanshet and Urik grabens are interpreted to reflect the first stage of Pacific superplume activity (Maruyama, 1994), which led to the initiation of breakup of Rodinia. But their age, close to that of ultrahigh-K rocks of the Anabar shield and orogenic belt units, indicates a relation to Grenville events (Fig. 1).

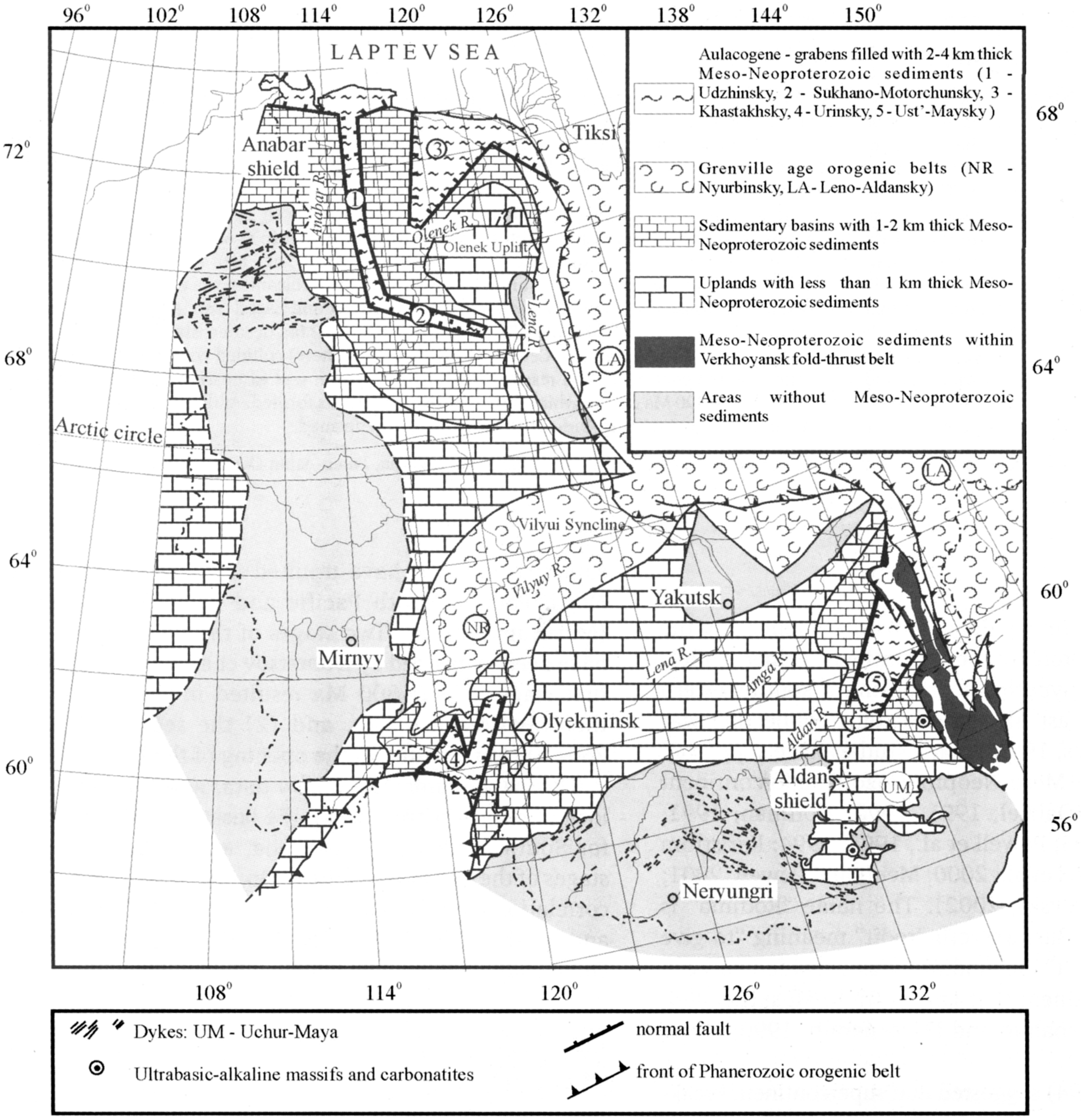

Fig. 1. Simplified geological map of the Siberian platform with Meso-Neo-Proterozoic structures (Parfenov and Kuzmin, 2001).

A Grenville-age basement in the Vilyui syncline and Verkhoyansk fold-thrust belt was suggested by Parfenov and Kuzmin (2001), and is supported by several Sm–Nd model dates for gabbro-diabase (1184 Ma) and biotite-muscovite microgneiss (987–1000 Ma) from deep drill holes (Parfenov and Kuzmin, 2001). Besides numerous K–Ar determinations, there is a 942±18 Ma Sm–Nd isochron age (Pavlov et al., 1992) and 1005±4 and 974±7 Ma U–Pb baddeleyite ages (Rainbird et al., 1998) for gabbroic sills in the southern part of the Verkhoyansk belt (Fig. 1).

Obviously, there are several records for Grenville-age events in the western margin of the Siberian craton. For example, the first determined Rb–Sr age of Isakov ophiolites in the Yenisey ridge was 1262±100 Ma (Vernikovsky et al., 1994a). Subsequently, U–Pb dating showed that the Isakov belt formed at 700 Ma, although the Nd model age of the source of Isakov ophiolites is close to the above mentioned value – 1270 Ma (Vernikovsky et al., 2001). The Rybinsk-Panimba ophiolitic belt in the Yenisey Ridge possibly formed in Grenville time. The evidence for this comes from geological data and ^{40}Ar-^{39}Ar amphibole and plagioclase ages for gabbro of 1050 and 960 Ma (Vernikovsky and Vernikovskaya, 2001a).

Stages of Paleo-Asian Ocean Evolution in Neoproterozoic-Early Ordovician Time

Figure 2 shows a revised paleogeodynamic reconstruction of the initial stages of Paleo-Asian and Paleo-Pacific opening. The positions of Siberia, Greenland, Baltica and Laurentia were estimated by Condie and Rosen (1994). The older dates of 800–900 Ma in the Siberian part of the Paleo-Asian Ocean correspond to figure 2. In the following discussion the ages (in Ma) of a Neoproterozoic island arc and rift-related magmatism in the Paleo-Pacific ocean are taken from Roots and Parrish (1988), Hoffman (1991), Cecile et al. (1991), Heaman et al. (1992), Patrick and McClelland (1995) for the western Laurentia margin and from Vernikovsky et al. (1994a, b) for the Siberian margin (Taimyr and Yenisey Ridges). The ages of the Southern Pacific Ocean (between Australia and Laurentia) are much older (780–730 Ma) than those of the Northern Pacific (740–680 Ma). Indeed, paleomagnetic data suggest that Laurentia and Australia had been separated by 755–780 Ma and then kept on moving independently (Wingate and Giddings, 2000; Buchan et al., 2001; Wingate et al., 2002).

Figure 2 demonstrates three possible successive stages of ocean opening: (1) opening of the Paleo-Asian Ocean at 900-830 Ma (see Fig. 3 and Table 1), (2) the South Paleo-Pacific ocean at 780–740 Ma (at nearly 780 Ma), and Table 3) the North Paleo-Pacific Ocean at 740–680 Ma (nearly 700 Ma).

The early stages of the Paleo-Asian Ocean Evolution are well correlated with four major stages during which different oceanic branches were opened (Table 1).

1. The first stage of the opening of the Paleo-Asian Ocean at 970–850 Ma, which is dated by the oldest dyke swarms, ophiolites, plagiogranites and enderbites (Table 1, Fig. 3).
2. The initial subduction at 850–700 Ma can be subdivided into two stages (a – 850–750 Ma, b – 750–700 Ma) which are well correlated with the opening of the South and North Pacific.
3. The first collisional stage of microcontinents with the Siberian continent at 650–620 Ma is correlated with the opening of the Iapetus Ocean between Laurentia and Baltica, which resulted in the final break-up of Rodinia and maximum opening of the Paleo-Asian Ocean.
4. The Vendian-early Ordovician subduction-collision.

Below, we discuss in detail the signature of these events starting from the rifting and initial opening stages of the Paleo-Asian Ocean in Siberia (Fig. 3).

Opening and early evolution of the Paleo-Asian Ocean

The first stage of the Paleo-Asian Ocean (opening) is fixed by a successive formation of dyke swarms in the Baikal region(Fig.4), the Aldan shield and the Uchur-Maya region (the Sette-Daban range, Fig.1). Figure 4 illustrates the dyke swarm in the Kocherikov area of the Northwest Baikal Zone (Sklyarov et al., 2003). Similar dyke swarm and sills of the Nersa complex are mapped in the early Precambrian rocks of the Sharyzhalgay salient in the southwestern Baikal corner (see inset in Fig. 4, area B). In both cases, dykes and sills are composed of tholeiitic and subalkaline diabase and gabbro-diabase. The compositional variations of investigated dolerites and gabbro-dolerites of the Nersa Complex can be explained by a combination of partial melting of a slightly depleted peridotite followed by fractional crystallization of the melt. The most primitive dolerites are similar to N-MORB (Sklyarov et al., 2003). Recently, the age of dolerites has been estimated at 853–886 Ma by the Ar-Ar method (Gladkochub et al., 2000), but this may represent metamorphic and metasomatic alteration, and the magmatic age may be near 900–950 Ma, as in the Aldan and Uchur-Maya dykes (Sette-Daban range, Fig.1) (Table 1). Smethurst et al. (1998) assumed that the Sette-Daban sills are about 730 Ma based on K–Ar dating, geologic considerations, and possible correlations with Franklin dykes in Laurentia, but recent geochronologic studies have yielded a U–Pb baddelyite age of 974±7 Ma (Rainbird et al., 1998) and a Sm–Nd age of 942±18 Ma (Pavlov et al., 1992).

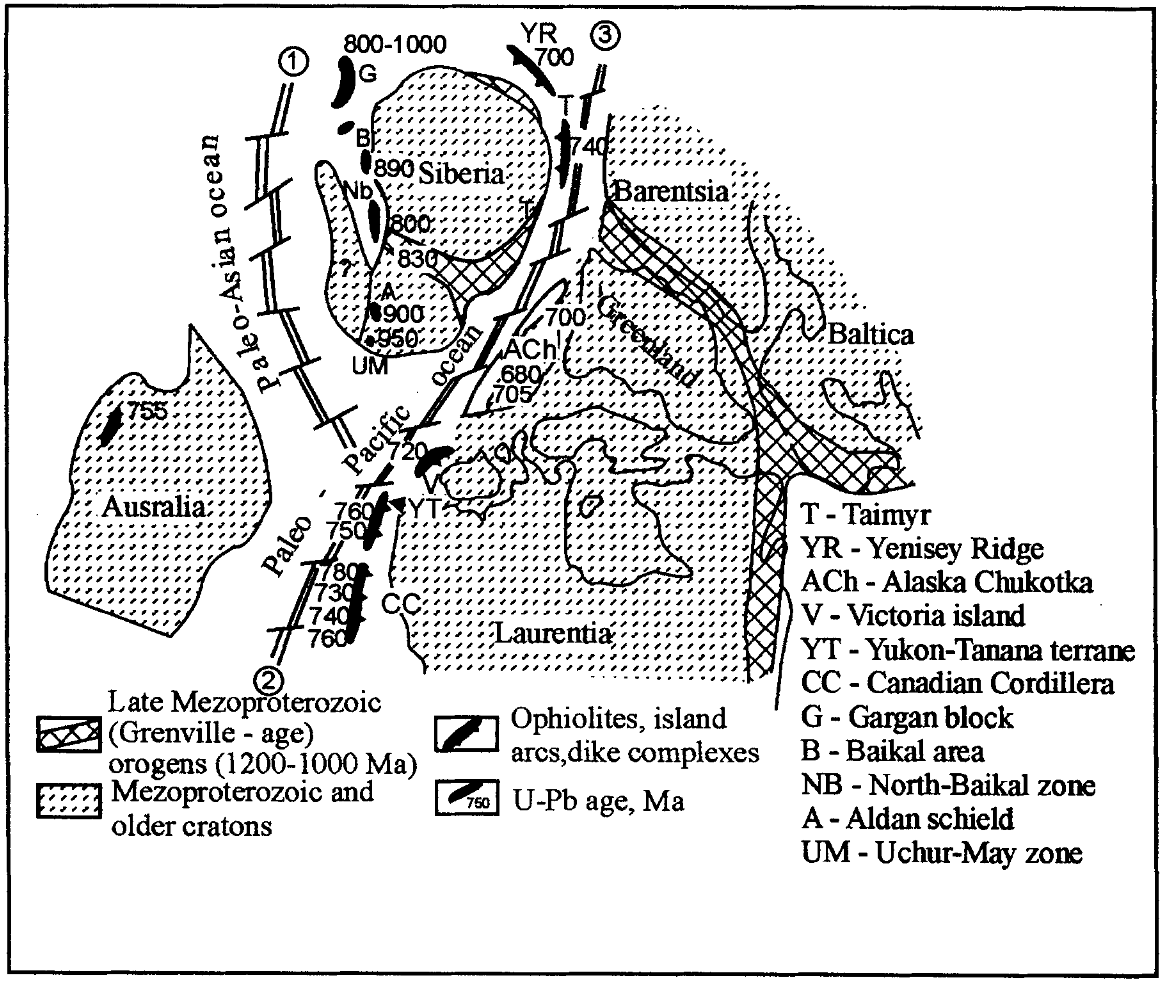

Fig. 2. Proposed paleogeographic reconstruction of the three stages (1, 2, 3 in circles) of the Paleo-Asian and Paleo-Pacific Ocean opening at 900–700 Ma.

We suggest an age of 950–900 Ma for the rifting stage of Paleo-Asian Ocean opening and that the southern margin (present coordinates) of the Siberian continent occupied low latitudes at that time.

The 1000–800 Ma ophiolites

The oldest ophiolites, dated at 850–900 Ma, possibly back to 1000 Ma, are located in North Baikal (Nurundukan and Baikal-Muya, Fig. 3) and in Eastern Sayan, to the northwest of South Baikal (Dunzhugur in figure 3).

The Nurundukan and Baikal-Muya ophiolite belts have been traditionally regarded as parts of the same belt, but in figure 3 they are shown separately and with different ages ca. 900 Ma for the Nurundukan belt and 830 Ma for the Baikal-Muya belt. Nurundukan metabasalts yielded a Sm–Nd whole-rock isochron of 1035±92 Ma (Konnikov et al., 1994; Rytsk et al., 2001), whereas other determinations show 900–850 Ma.

A near-complete ophiolite pseudostratigraphic section was identified in the Baikal-Muya Complex near Taksimo village (Fig. 5). It includes an ultramafic restite, layered gabbro, pyroxenite, a dyke complex, pillow lavas with N-MORB affinities (in ascending order) and sea-floor sediments (Dobretsov et al., 1992a; Konnikov et al., 1994). These ophiolites have tectonic contacts with island-arc volcanic rocks intruded by plagiogranites (Fig. 5). The Sunuekit plagiogranites yielded a Rb–Sr age of 880 Ma (Konnikov et al., 1999).

The Param ophiolitic massif is located at the eastern margin of the Muya block (Fig. 3) and is composed of peridotites, gabbro-amphibolites, sheeted dykes and metabasalts (Dobretsov et al., 1992a; Konnikov et al., 1999). The Param peridotitic body is thrust over the Kamensk terrane, which is a 'macro-mélange' consisting of a nappe stack of fore-arc sediments, island-arc volcanic rocks, and fragments of ophiolites (Konnikov et al., 1999). In general, this section is similar to that shown in figure 5, but there are no isotopic dates available.

The oldest dates have been obtained for metamorphic rocks of the Slyudyanka granulite-charnokite complex in

Table 1. The stages of evolution of the Paleo-Asian ocean (PAO).

N	Age, Ma	Interpretation	Examples from North Asia with isotopic ages, Ma
0	1430–1000	The Grenville and Rodinia stages	a) Fragmented metamorphic rocks b) Platform type sediments in the Siberian and Russian cratons
1	970–850	Opening of PAO	a) Dykes in the Baikal region (886–853), Aldan shield (950–900), Sette-Daban (974–942) b) Sunuekit plagiogranite (880) and Sludinsk Lake enderbite (905–860) c) The oldest passive margin sediments of the Baikal series (900–850)
2	850–750 (a) 750–700 (b)	Initial subduction in PAO and opening of the North (a) and South (b) Pacifics	a) Kelyana metabasalts of the Namakan block (850–840), rhyolites (850 or 923±72) b) Trondjemite (790±5) and gabbro (774–733) c) Dunzhugur island arc (850–760) d) Sarkhoy island arc, volcanic series (745–709) e) Porozhny plagioporphyry granites of the Yenisey ridge (710–700), Chelyuskin (Taimyr) plagiogranite (740–700)
3	660–620	The first collisional stage of microcontinents with the Siberian continent and the opening of Yapetus between Laurentia and Baltica	a) Muya eclogites (650), Hugein blueschists (640–620), Yenisey garnet amphibolites (630–620) b) Migmatites and amphibolites of the Nurundukan belt (667–623) c) Metamorphic units of the Near-Yenisey belt (640–620), Derba block d) Orogenic molasse (Vendian)
4	620–550	Reconstruction and maximal opening of PAO with primitive island-arc volcanism	a) Boninitic island-arc series (620–550) in Mongolia, West Sayan, Gorny Altai b) Mongolia, Tuva, West Sayan ophiolites (593–570)
5	550–520 (a) 520–490 (b)	Early Caledonian collisions and local origin of new island arcs	a) Eclogites and related metamorphic rocks in Kokchetav (540–520), Gorny Altay (550–520), etc. b) Two stages of granitic magmatism (520–510 and 500–480) c) New formed island arcs (520–490)
6	490–310	New formed Ordovician-early Devonian oceans (Junggar, Uralian) and their island arcs	a) Ordovician ophiolites in Junggar, Kazakhstan etc. b) Ordovician-Silurian island arcs in Junggar, Kazakhstan, Transbaikalia, etc.

the NW Baikal area, which is a part of the Nurundukan belt (Fig. 3). The Pb–Pb age of zircon from amphibole-two-pyroxene schist is 905±30 Ma (Makrygina et al., 1993), although a 570±15 zircon age from migmatite corresponds to the Rb–Sr bulk rock age of 588±30 Ma (Konnikov et al., 1999). These metamorphic rocks are intruded by high-Mg gabbro: the Sm–Nd ages of the Chuya massif and the Narrow Cape massif are, correspondingly, 667±26 Ma and 585±22 Ma (Makrygina et al., 1993; Konnikov et al., 1999). We propose that the metamorphic rocks of the Slyudyanka-Nurundukan belt and the intrusions are a part of the North-Baikal collisional belt, which formed in two stages at 667–623 Ma and 588–570 Ma.

Gargan-Darhat region and Dunzhugur ophiolites

The second example of early Neoproterozoic ophiolites is located in East Sayan, within the Tuva-Mongolian microcontinent (Figs. 3 and 6). The northern part of this microcontinent consists of several units or terranes (Fig. 6).

1. The Gargan continental block consists of a crystalline basement of 2160 Ma age (Fig. 3) and a sedimentary cover of 800 Ma age. The basement is composed of mafic granulites, amphibolites and gneisses with relicts of granulite facies mineral assemblages. They are comparable with enderbite gneisses of the Baydrag block of 2409±0, 4 Ma (Kröner et al., 2001). The sedimentary cover is composed of marbles of the lower unit (Irkut Formation) and metasandstones and metashales of the upper unit (Ilchir and Ospa Formations) with an olistostrome subunit.

2. The Gargan block is tectonically overlapped by an allochthonous terrane with ophiolite pseudostratigraphy section. The ophiolite was tectonically dismembered and is associated with sedimentary and volcanic units of the Dunzhugur island arc of 850–800 Ma age (Kuzmichev et al., 2001a). The Dunzhugur plagiogranites yielded an U–Pb age of 1020 Ma (Khain et al., 2002). The first model for the structure of the region regarding tectonic sheets of ophiolites and their related olistostromes and mélanges was proposed by Dobretsov (1985). The

0.1–1 km thick serpentinite mélange contains boudins of peridotite, pyroxenite, metagabbro, metadiabase, and rodingite, which in places are intercalated with olistostrome layers.

3. The third unit consists of Sumsunur tonalites (U-Pb zircon age is 785±11 and Rb-Sr mineral isochron age is 812±18 Ma), Sarkhoy-Darhat volcanic rocks (760–700 Ma) and Oka-Hugein fore-arc units, which were later transformed into an accretionary prism with blueschist-bearing tectonic sheets, which have a mineral Rb–Sr age of 620–640 Ma (Kuzmichev et al., 2001a, b). This complex is interpreted as a continental arc that resulted from the collision of the Dunzhugur island arc with the Tuva-Mongolian microcontinent.

4. The Shishkhid ophiolites and associated fore-arc units are the relicts of a late Neoproterozoic island arc, located between the Oka-Sarkhoy arc and the Sangilen microcontinent (Figs. 3 and 6). The time of collision of the Shishkhid and Sarkhoy island arcs (or the Sangilen and Khamar-Daban microcontinents – Fig. 3) is determined by the ages of blueschist tectonic sheets, which were exhumed from a subduction zone at 640–620 Ma (Kuzmichev et al., 2001a).

5. Contemporaneous with the Shishkhid arc are carbonate rocks of the Khubsugul-Bokson Series of Vendian-early Cambrian age (640-530 Ma). The Bokson Series includes dolomites and limestones with bauxite and phosphorite layers and overlaps the Sarkhoy-Darhat Series in the Darhat depression. However, the Bokson Series tectonically overlies all older rocks in the Bokson-Durzhugur area, and is the uppermost member of the nappe structure (Dobretsov, 1985). This suggestion is discussed in Kuzmichev et al. (2001), who interpret the tectonic mélange in the base of the Bokson nappe as tilloids.

The complete reconstructed section of the Dunzhugur ophiolites (Fig. 7) includes serpentinized harzburgite at the base, layered complex (alternating pyroxenite and gabbro, and pyroxenite and gabbro veins), gabbro complex

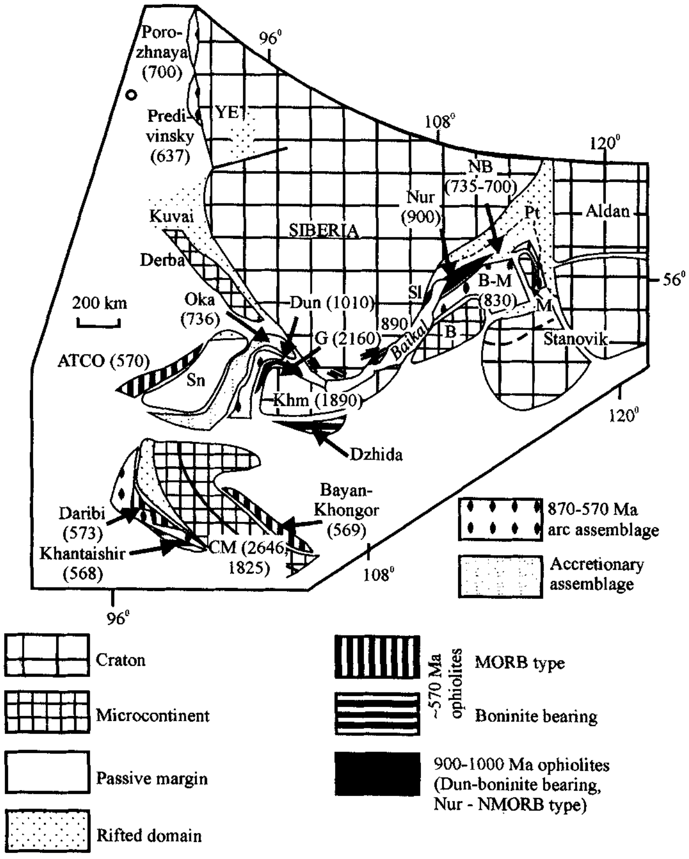

Fig. 3. Principal units of Paleo-Asian Ocean (present reference frame) at 1000–570 Ma. For 670–570 Ma ophiolite complexes alone are shown. Compiled by E.V. Khain et al. (2001). ATCO-Agardagh-Tes Chem ophiolite, B-Barguzin, BM-Baikal-Muya, CM–Central Mongolia, Dun-Dunjugur, G-Gargan, Khm-Khamar-Daban, M-Muya block, NB-North-Baikalian, Nur- Nyurundukan, Sn-Sangilen, Pt-Patom, YE-Yenisey. Numerals indicate radiometric age, Ma.

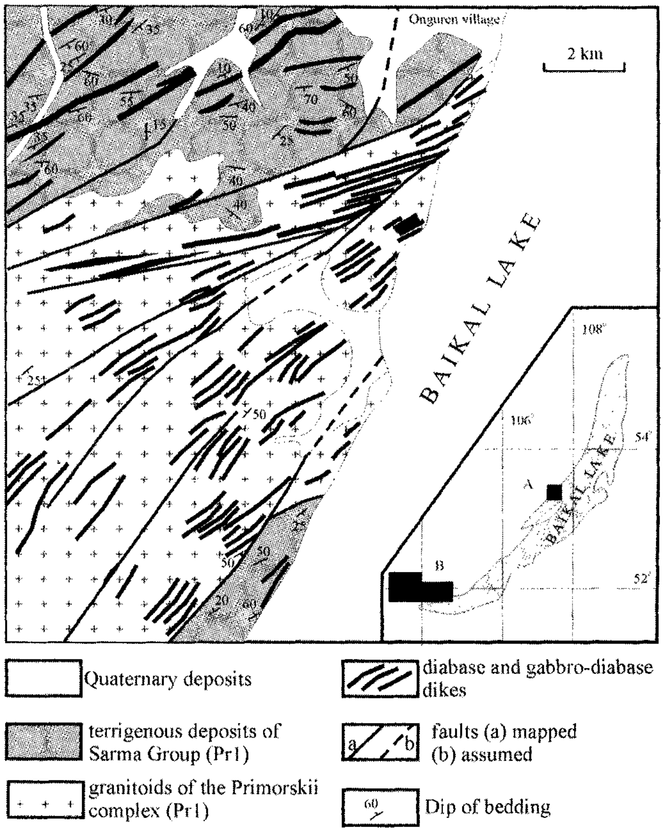

Fig. 4. Simplified sketch map of the Kocherikov area of the Northwest Baikal Zone (Sklyarov et al., 2001) showing dyke swarm. The location of dyke swarm is shown in the index map at right bottom, area A (this figure). In the area B (Nersa complex of Sharyzhalgaj salient) a similar dyke swarm is also present.

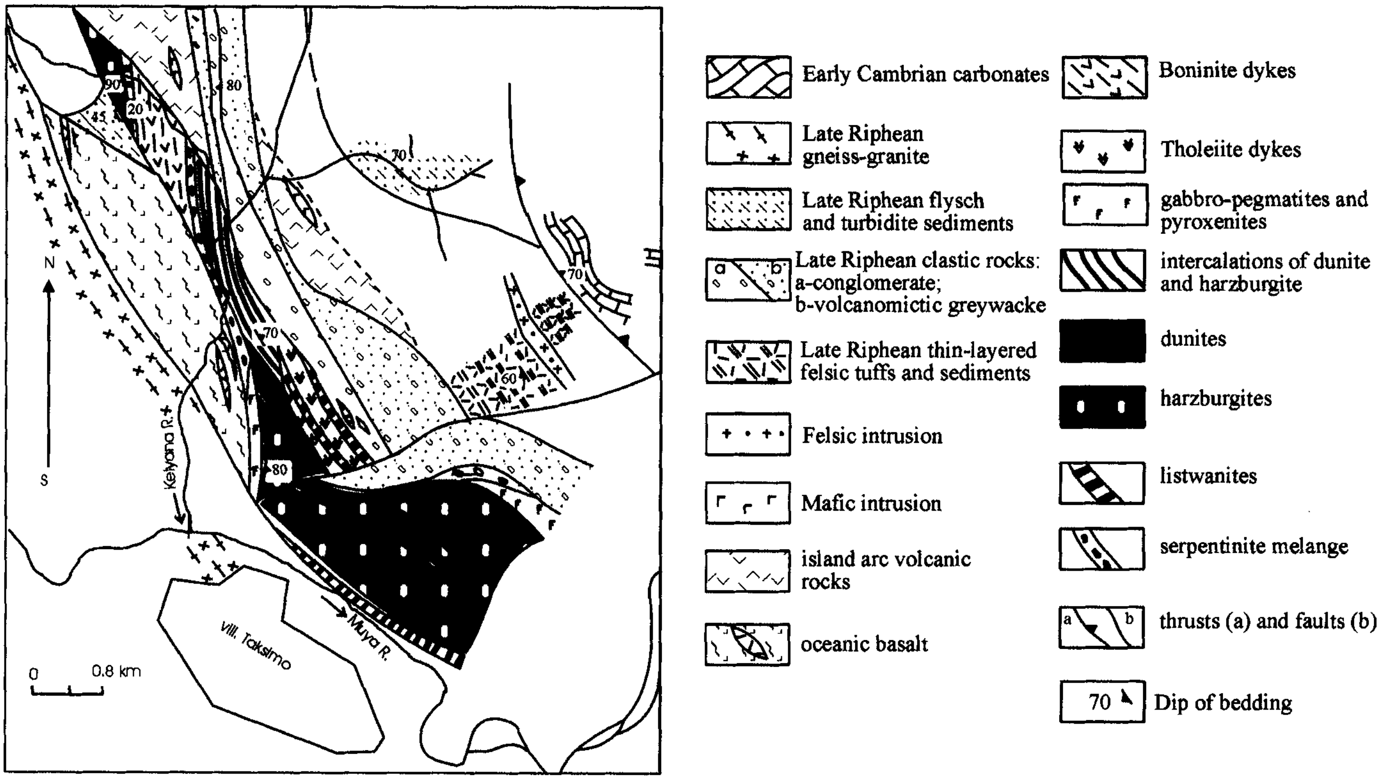

Fig. 5. Geologic map of the NW part of the Baikal-Muya ophiolite belt (Konnikov et al., 1994). For location of the region see figure 3.

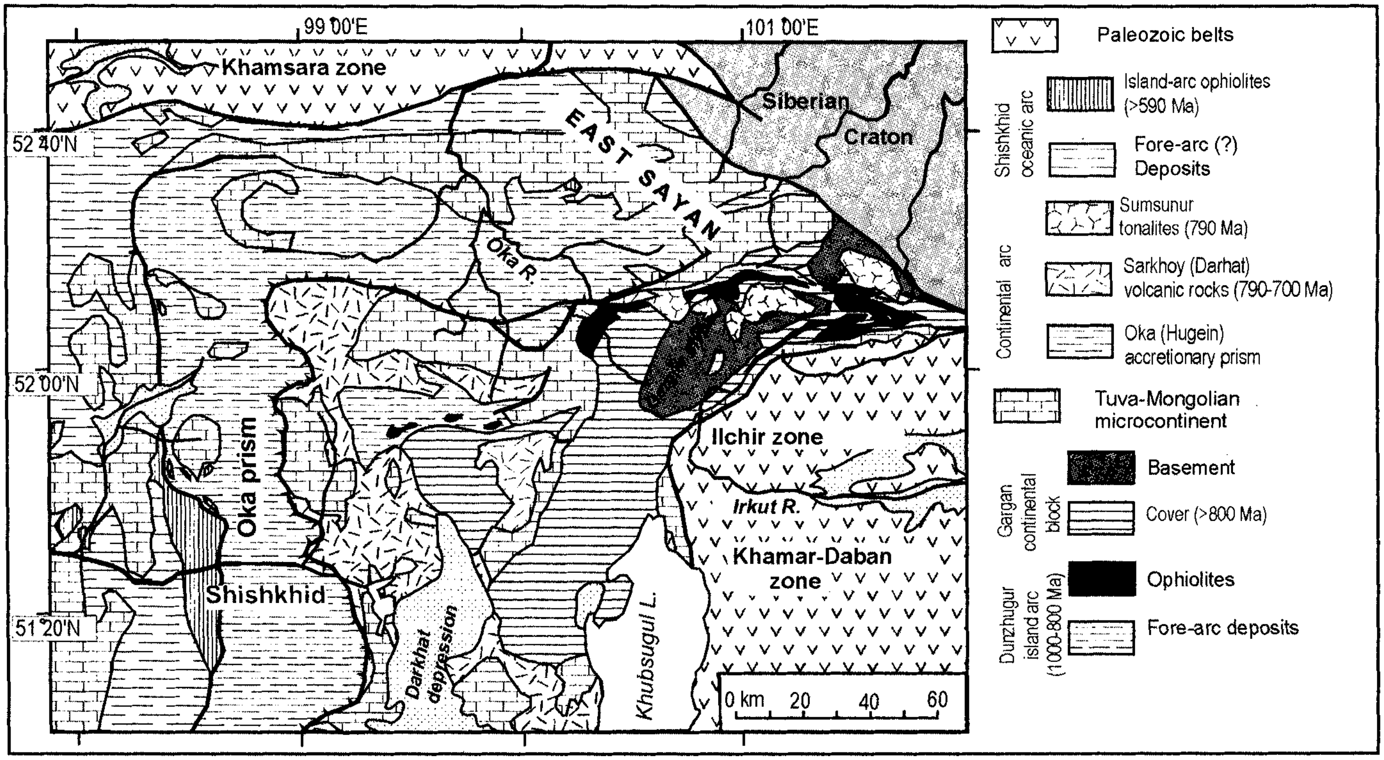

Fig. 6. Tectonic scheme of the Tuva-Mongolian microcontinent (Kuzmichev et al., 2001a). Paleozoic granites and Cenozoic sediments and volcanic rocks (except for large depressions) are not shown.

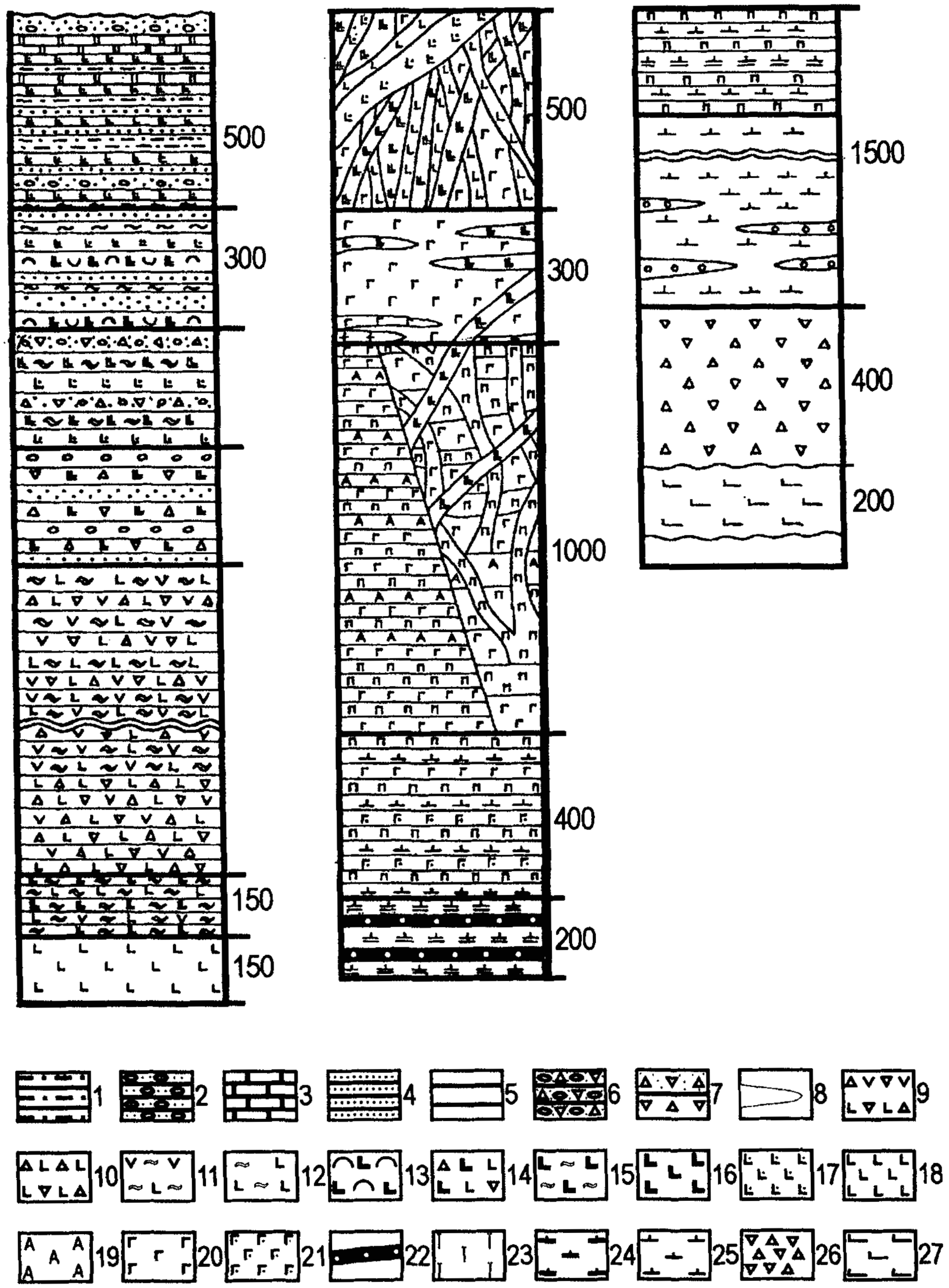

Fig. 7. Compiled ophiolitic sequence (Gladkochub et al., 2000). 1-cherts; 2-aleurolites and sands; 3-dolomites; 4-sandstones; 5-schists; 6-aleurolites with tuff material; 7-sandstones with tuff material; 8-dikes of plagiogranites; 9-brecciated lavas of andesite-basaltic composition; 10-brecciated lavas of basic composition; 11-lavas of andesite-basalts; 12-pillow lavas of basic composition; 13-boninite tuffs; 14-boninite lavas (brecciated); 15-boninite lavas; 16-boninite dikes; 17-gabbro-diabases; 18-massive diabases; 19-anorthosites; 20-gabbro; 21-olivine gabbro; 22-lenses of chromite; 23-orthopyroxenites; 24-dunites; 25-peridotites; 26-melange; 27-amphibolites.

(amphibolitized gabbro, gabbro-norite, and norite), sheeted dike complex and lavas. The sheeted dykes and lavas include boninites, which were first described by Sklyarov and Dobretsov (1987) and Dobretsov et al. (1992b). The boninitic rocks possess Cr-rich chromite, diopside relicts, pseudomorphs after orthopyroxene, and V-shaped REE patterns, which are typical of boninitic series of the present primitive island arcs, e.g. the Mariana fore-arc and others. Detailed geochemical data on ophiolitic rocks are available in Kuzmichev et al. (2001). There are two typical rock series: (1) calc-alkaline and (2) boninitic. No MORB-type rocks have been found.

Initial subduction (850–700 Ma)

The sediments associated with the ophiolites are poorly sorted and angular and they may have been deposited at the bottom of a steep slope in a relatively deep-water setting, possibly in a fore-arc trough in front of the Dunzhugur island arc. Abundant diabase dykes and sills, which intruded a non-consolidated sedimentary sequence, are evidence for an extensional regime. Compositionally, diabases correspond to high-Ti/Fe/P subalkaline tholeiites (Kuzmichev et al., 2001a).

The age of the Dunzhugur igneous rocks is defined by the U–Pb mineral isochron for gabbro-diabase sills (760±16 Ma) and SHRIMP zircon age of plagiogranites (850 Ma) (Khain et al., 2001). We suggest that the evolution of the Dunzhugur arc continued during 850–760 Ma and was followed by the formation of the Sarkhoy-Darhat island arc at 760–700 Ma.

The First collisional stages (microcontinent – Siberian continent) and re-organization of the Paleo-Asian Ocean (660–620 Ma)

Evidence for the collision/re-organization stages of the evolution of the Paleo-Asian Ocean comes from the relicts of wide oceans found near the Lake Baikal (see above the events of 667-570 Ma) and in the Yenisey region, such as Isakov and Predivinsky ophiolites (Vernikovsky et al., 1999, 2001), Porozny plagioporphyry granites of 700–710 Ma age, and Predivinsky ophiolites (metarhyolites of 637 Ma age) to the south (Fig. 3). The collision of all the early complexes resulted in their amalgamation into the Muya-Barguzin, Tuva-Mongolian, Derba-Kuvai and Angara microcontinents, each consisting of several blocks. For example, the Tuva-Mongolian microcontinent consists of the Khamar-Daban, Sangilen, and Central Mongolian blocks (Fig. 3).

Evidence for the first collisional stage comes mainly from the Muya eclogite, Oka-Hugein blueschists, and Yenisey garnet amphibolites (Table 1).

The Muya eclogites and garnet peridotites are found in association with the gneisses of the North and South Muya blocks. Eclogites occur as blocks and boudins up to 200 m in diameter in gneisses and mica-rich blastomylonitic schists. Blastomylonites with inclusions of eclogite, garnet amphibolite and garnet peridotite compose a tectonic mélange. Fresh eclogites consist of Ca-rich pyrope-almandine, omphacite, kyanite, rutile, and mica. P-T estimates for co-existing garnet and omphacite are 700–800°C and 16–17 kbar (Gabov et al., 1984). The Sm-Nd age of garnet, omphacite, and bulk rock is 650 Ma (Shatsky et al., 1996).

The Oka-Hugein belt contains blueschist rocks which are in the transitional glaucophane-greenschist subfacies of metamorphism and formed at 400–540°C and 7–9 kbar. Blueschists compose several tectonic sheets surrounded by terrigenous rocks of the Oka Series. The Rb–Sr ages show that the metamorphism and exhumation of rocks could have occurred at 640-620 Ma (Sklyarov et al., 1996b).

The exhumation of eclogites and blueschists from the subduction zone took place during the first stage of the collision. The main collisional stage is recorded by the intrusion of granites, syncollisional metamorphism, and deposition of post-orogenic molasse (Dobretsov, 2000). These events are well documented in the North Baikal area. The formation of Muya eclogites (650 Ma) was followed by a two-stage syn-orogenic metamorphism of the Nurundukan belt at 667–623 and 588–570 Ma (migmatites, gabbro and amphibolites; Makrygina et al., 1993), intrusion of Muya granites at 620 Ma, and accumulation of orogenic molasse in Vendian time (Padrokan and Kholodnensk Formation, 640-600 Ma), overlain by shallow-water cap-limestones (Konnikov et al., 1994, 1999; Neimark et al., 1995). Similar episodes of metamorphism and accumulation of orogenic mollasse in Vendian time can be recognized in the Yenisey ridge (640-600 Ma) (Vernikovsky et al., 1994a, 2001). Vendian molasse occurs in the Patoma Zone (Anangria and Dogaldyn Formations), Pribaikalia (Ushakovka Formation), and in many other places close to the Siberian craton margin (Stanevich et al., 2001; Khomentovsky, 2001).

The Vendian-Early Ordovician Subduction-collision Stage (620–490 Ma)

Vendian-Cambrian subduction (620–550 Ma)

Vendian-early Cambrian ophiolites and island arcs occur mainly in South Siberia and Mongolia (Dobretsov et al., 1992a, 1995a; Berzin and Dobretsov, 1994; Al'mukhamedov et al., 2001; Gordienko and Mikhaltsov, 2001; Windley et al., 2001; Buslov et al., 2001). The Bayankhongor terrane, which is one of two major ophiolitic terranes in Mongolia (Fig. 3), contains a complete ophiolitic section and extends for more than 300 km. The Sm-Nd whole-rock age of basalts is 569±21 Ma (Windley et al., 2001). The ophiolite was thrust to the NE over deep-water sediments of probably a continental margin origin. The Khantaishirin terrane is another typical ophiolitic unit, which was first described by Zonenshain et al. (1985). The terrane includes typical boninitic sheeted dykes and lavas and has a clear suprasubduction origin. The zircon U–Pb age of plagiogranites is 568±4 Ma (Izokh et al., 1998; Kröner et al., 2001).

Daribi (Dariv) ophiolites (573±6 Ma) are located north of the Khantaishirin belt (Fig. 3) and are thrust onto the Daribi metamorphic complex containing dioritic gneisses dated at 1426, 4±1, 2 Ma (Kröner et al., 2001). The ophiolite is in tectonic contact with a volcanic-arc unit, which includes conglomerates with large fragments of quartz-porphyry dated at 539, 7±1 Ma and granite dated at 492±1 Ma (Kröner et al., 2001).

The Agardag-Tes Chem ophiolite is found in the vicinity of the Sangilen block and has a 569±1.1 Ma U-Pb zircon age (Pfander et al., 1999). Pillowed and massive metabasalts have flat REE patterns and MORB-like trace element concentrations. The initial +7.8 to +8.5 ε_{Nd} values are very close to the +8.5 value of the depleted mantle at 570 Ma. Another group of island-arc volcanic rocks is related to the melting in the subduction zone of a depleted mantle source with MORB characteristics, which was modified by the metasomatic fluid components separated from a subducted slab. Recent data from southern Tuva suggest that island-arcs and continental fragments collided at the same time as those in the Daribi and Bayankhongor terranes (Kröner et al., 2001; Pfander et al., 2001).

The Dzhida, Bayankhongor, Khantaishirin, Daribi and Agardag ophiolites are located around the marginal orogen of the Tuva-Mongolian continent (Fig. 3) and run parallel to the coeval subduction-accretion system. The Bayankhongor, Dzhida and Daribi ophiolites were thrust over the continental margins, and the Khantaishirin and Agardag ophiolites were thrust over island-arc terranes, suggesting variously - oriented polarity subduction (Windley et al., 2001).

The Vendian-Cambrian Kuznetsk-Altai-Khantaishirin boninitic island-arc units and related ophiolites are reconstructed in Gorny Altai, West Sayan, Kuznetsk Alatau and West Mongolia.

In figure 8 the outlines of the distribution of the following units are shown:

(1) the primitive Vendian-early Cambrian island arc with tholeiite-boninite rock series; (2) the early-Middle Cambrian accretionary prism with OIB and MORB (Fig. 9); (3) the early-Middle Cambrian normal island arc with calc-alkaline and shoshonitic rocks; (4) the fore-arc trough consisting of Middle-late Cambrian turbidites. (5) the back-arc basin.

Study of these units, which are best observed in the Katun (Cental Altai), Kurai (East Altai) and Salair Zones (Fig. 9), made possible the reconstruction of paleogeodynamic processes (subduction and accretion), which appear similar to those occurring in the present western Pacific active margin (Watanabe et al., 1993; Buslov and Watanabe, 1996).

As an oceanic plate is subducted, the thickened blocks of seamounts and/or fragments of seamount-top limestones are accreted to an island arc and buried in trench-related accretionary complexes. A Cambrian accretionary complex is exposed in Gorny Altai, near the Kurai island-arc terrane and Chagan Uzun ophiolitic terrane, which preserve large fragments incorporated in the accretionary complex. It involves Baratal basalt-limestone body of about 10 km-wide and Katun seamount-top-limestone body of 20 km across. The limestones are closely associated with greenstones and locally conformably overlie the basement pillow-basalts. Top-seamount limestones consist of micritic limestones and dolomitized limestones, containing ovoids and siliceous, calcitic, phosphatic, and carbonaceous shell microfossils (Uchio et al., 2001).

The Kurtushibin ophiolitic belt in West Sayan has a complete but slightly dismembered section of sheeted dykes, pillow-lavas and pillow-breccias. The first description of sheeted dykes and their relation to Precambrian ophiolitic gabbro and pillow-breccia of the PAO was made by Dobretsov and Ponomareva (1976) and Dobretsov et al. (1992a). Subsequently, they found boninitic dykes and identified zonal metamorphism in Kurtushibin ophiolites (Sklyarov and Dobretsov, 1987; Dobretsov et al., 1992b).

We obtained several isotopic dates for blocks included in serpentinitic mélange and metamorphic rocks of the Chagan-Uzun massif. The K-Ar phengite ages are 540±24 and 576±11 Ma (schists from serpentinitic mélange). The K-Ar amphibole age of Chagan-Uzun eclogite is 535±24 Ma and the Ar-Ar amphibole ages of eclogite are 562±10 Ma. The K-Ar amphibole age of the metamorphic basement is 523±23 Ma. These ages range in a wide time span, but may correspond to exhumation stages at 576-562, 540-535 and 523 Ma (Buslov and Watanabe, 1996; Buslov et al., 2001).

K-Ar amphibole ages of garnet amphibolites resulted from retrograde metamorphism of eclogites of the Chagan-Uzun massif are 473±13 and 487±22 Ma (Buslov and Watanabe, 1996), i.e. Ordovician. This suggests that the final stage of eclogite exhumation took place in Ordovician time and was accompanied by deformation and retrograde metamorphism.

The position of the Kuznezk-Altai-Khantaishirin island arc (including Kuznetsk Alatau, Gorny Altai, Kurtushibin, Dzhida and Khantaishirin segments) were reconstructed in the Paleo-Asian Ocean (PAO hereinafter) with respect to the Siberian craton according to paleomagnetic data, between the 20°N and 35°S (Fig.10). Since the beginning of the Cambrian, the studied fragments of Gorny Altai were the elements of the Kuznetsk-Altai island-arc system located within 14–35° S and outlining the northeastern (in the ancient coordinates) margin of the Siberian continent. By the beginning of the Ordovician, the island-

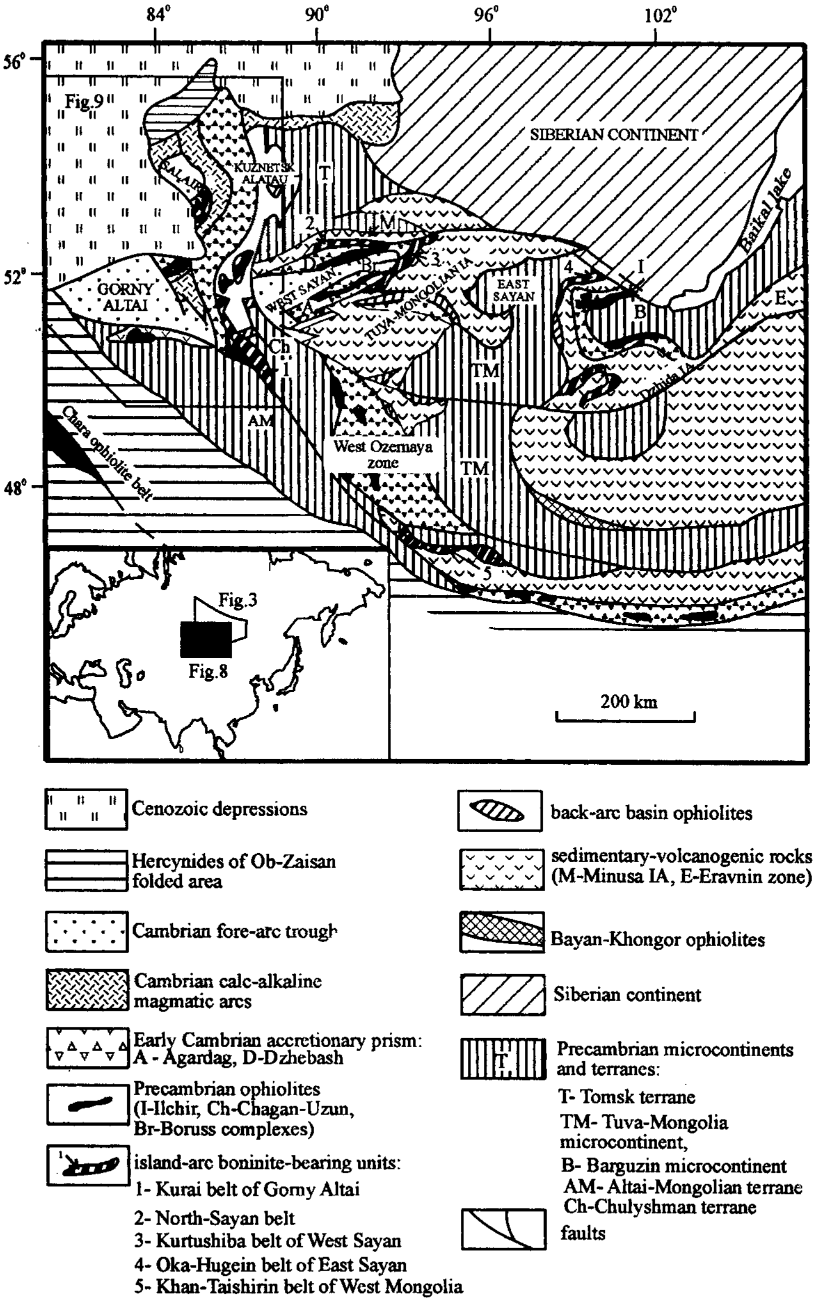

Fig. 8. Distribution of the Pre-Hercynian accretion-collision zones and microcontinents of the Gondwana and Laurasia groups in the southern side of the Siberian continent (Dobretsov et al., 1995).

arc system was attached to the continent. At that time the system moved northward to 7–18° S and turned 30–40° anti-clockwise (Kazansky et al., 1998; Metelkin, 1998; Gordienko and Mikhalsov, 2001).

Such a position accords well with the situation of the present island arcs containing boninitic series, such as Idzu-Bonin, Mariana, Tonga, etc. It is more difficult to define the position of older island arcs in the Paleo-Asian Ocean because they are present only as fragments in the mosaic of amalgamated microcontinents, which were rotated and repeatedly displaced before being finally accreted to the Siberian continent in Cambrian-Ordovician time. The older island arcs could be located closer to the Siberian craton, than estimated here, because the latter possibly migrated to the southern polar latitudes at 850 Ma and then moved back to the equator in the late Neoproterozoic (Dobretsov et al., 1995a; Young, 1995; Buchan et al., 2001).

Cambrian–early Ordovician collision (550–490 Ma)

This collisional stage can be divided into two substages (Table 1): (a) Early–Middle Cambrian at 550–520 Ma and

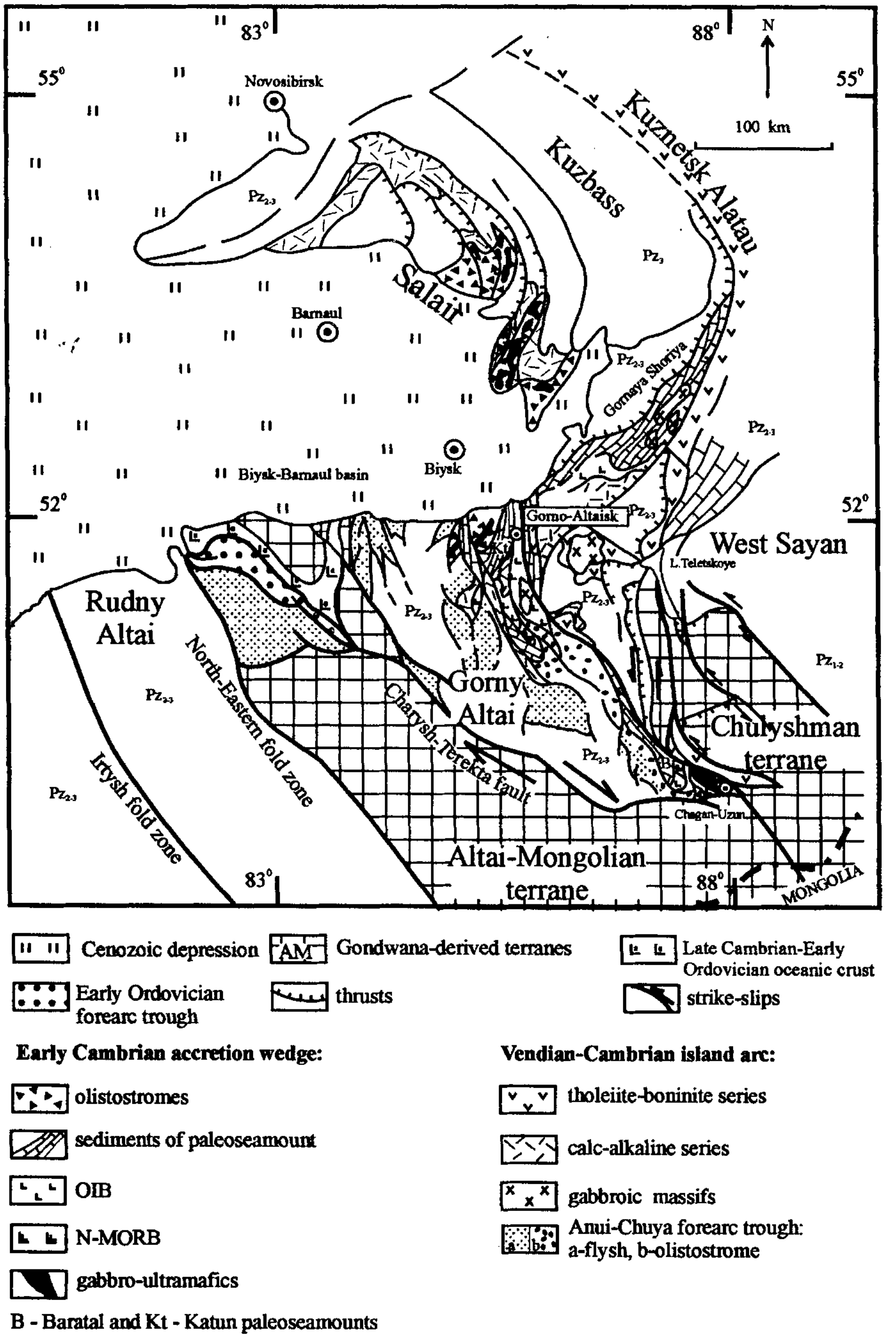

Fig. 9. Vendian–Cambrian Kuznetsk-Altai island arc units in Gorny Altai and Kuznetsk Alatau (Buslov et al., 2001).

(b) late Cambrian–early Ordovician at 520–490 Ma. The evidence for the first substage comes from the ages of eclogites and associated rocks in the mélange of the Chagan-Uzun ophiolitic massif in Altai (540–520 Ma) (Buslov and Watanabe, 1996; Buslov et al., 2001). Blueschists and eclogites of similar ages occur in the Kurtushibin ophiolitic belt in West Sayan, in the mélange of the Chara ophiolitic belt in Eastern Kazakhstan, and in the Kokchetav massif in Northern Kazakhstan (Dobretsov and Kirdyahskin, 1994; Dobretsov et al., 1995b, 1998).

A complex tectonic evolution, including a two-phase collision, was reconstructed for Gorny Altai (Buslov et al., 1993; Dobretsov et al., 1992b; Buslov and Watanabe, 1996; Buslov et al., 2001). Collision of paleooceanic islands and the Kurai island arc resulted in oceanward jumping of subduction zone. The jumping of the subduction zone led to the formation of a new island arc in the Middle-late Cambrian. This new formed island arc was active until the late Cambrian and subsequently collided with the Siberian craton in early Ordovician time.

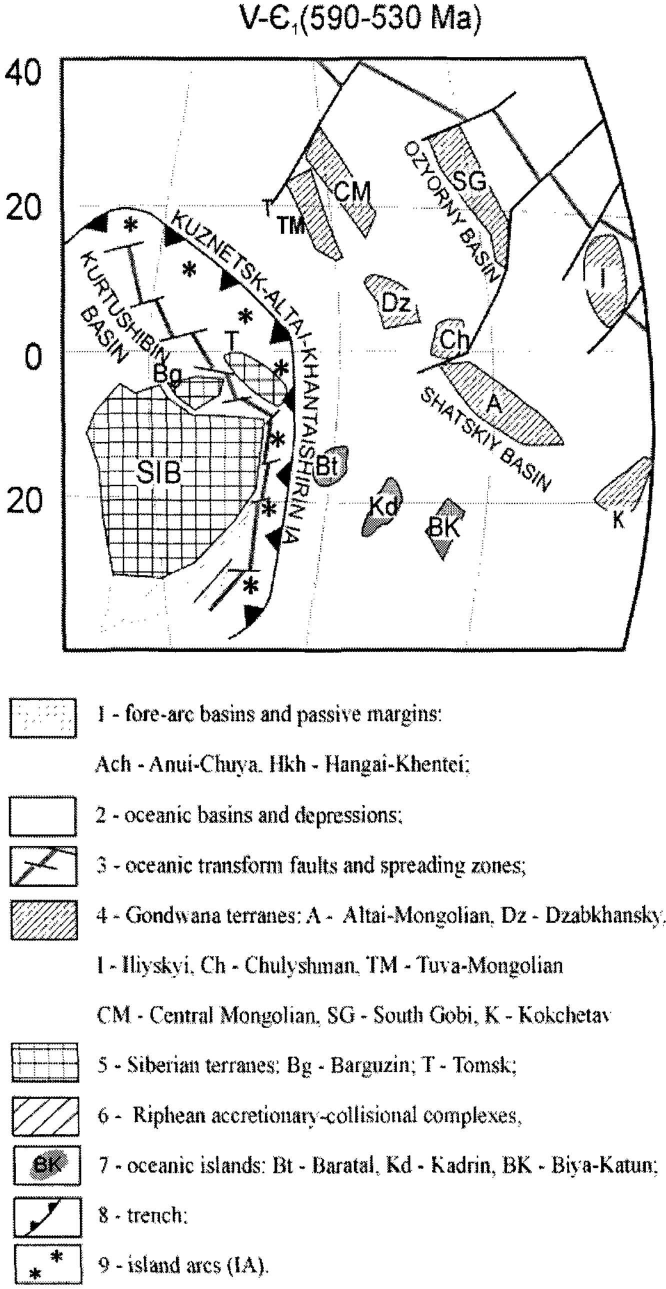

Fig. 10. Vendian-Ordovician paleo-late reconstructions of the Paleo-Asian Ocean (compiled by geological data with paleomagnetic constraints (Zonenshain et al., 1990; Didenko et al., 1994; Didenko, 1997; Kazansky et al., 1998; Metelkin, 1998; Gordienko and Mikhaltsov, 2001).

The Kokchetav diamondiferous eclogite complex is most interesting and well-studied. It was described as a megamélange (Dobretsov et al., 1995b) and can be regarded as two tectonic domains: the Kumdy-Kul rhomb-shaped diamond-bearing domain with the peak of metamorphism at 950°C and 45 kbar and the Kulet coesite-bearing domain (Dobretsov et al., 1998; Theunissen et al., 2000). Isotopic data for the Kumdy-Kul domain indicate that the final stage of subduction and the peak of UHP-metamorphism took place at 540–528 Ma, the early stage of exhumation at 528–524 Ma, which resulted in the crystallization of exhumed and melted rocks in the amphibolite facies of metamorphism at 520–515 Ma (Theunissen et al., 2000; Dobretsov and Shatsky, 2002). The Cambrian episode of UHP metamorphism is one of the most important phases of the evolution of geodynamic and metamorphic process of the Earth crust.

The late Cambrian–early Ordovician collision resulted in granulite facies metamorphism, such as in Olchon and Tuva (Salnikova et al., 2001), and intrusion of granites, which are widely distributed in Tuva and Altai-Sayan (Vladimirov et al., 1996, 2000).

The collision structurally re-arranged the Paleo-Asian Ocean and formed several smaller oceans, such as Junggar-Ob', Kazakhstan, and Uralian. Evolution of these oceans in connection with a general history of the Paleothetis will be discussed elsewhere.

Discussion and Conclusions

The paper reviews and integrates recent geological and geochronological data from Siberia showing two tendencies:

1. Rb-Sr ages for phlogopite-bearing lherzolite (1130±119 Ma) and lamproite (1268±12 Ma) of the Tumanshet and Urik grabens are interpreted to represent the first stage of activity of the Pacific superplume (Maruyama, 1994), which possibly later led to the breakup of Rodinia (Gladkochub et al., 2000). The oldest ophiolites of the Paleo-Asian Ocean are possibly the Dunzhugur ophiolites with plagiogranites having a U–Pb age of 1020 Ma (Khain et al., 2002). They may record initial stages of the breakup of Rodinia and the opening of the Paleo-Asian Ocean.

2. We believe that the many Sm–Nd and zircon ages for dyke series and ophiolites (700–750 Ma) can be referred to the first stage of the opening of the Paleo-Pacific Ocean.

Thus, two stages of the Rodinia breakup can be suggested: (1) the first stage at 970–850 Ma resulted in the opening of the Paleo-Asian Ocean; (2) the second stage at 750–700 Ma resulted in the opening of the Paleo-Pacific.

The breakup of Rodinia, which resulted in the opening of the Paleo-Asian Ocean, is dated by (a) the dyke series in Transbaikalia (Nersin Complex, 860–886 Ma, Ar–Ar) and in the Aldan shield (950 Ma, Sm–Nd); (b) the plagiogranites of the Sunuekit massif (880 Ma, Rb–Sr) and the oldest enderbites of the Sludinsk Lake area (the U–Pb age of zircon – 905–860 Ma) (Makrygina et al., 1993; Tsygankov et al., 1998); (c) the oldest passive margin sediments of the Patoma or Baikal series (850–900 Ma) (Khomentovsky and Nagovitsyn, 1998).

The initial subduction started at 850–700 Ma and is dated by the Sm–Nd age of the island-arc volcanic rocks of the Namakan block (the Kolyana island arc in northern Transbaikalia, 840–850 Ma), U–Pb zircon age of trondjemite (790±5 Ma) (Rytsk et al., 2001), Rb–Sr age of suprasubdution gabbro (774, 735, and 733 Ma), Sm–Nd and Rb–Sr ages of the Sarkhoy island arc series (745–729 Ma) (Izokh et al., 1998), U-Pb zircon age of the Porozhny subvolcanic porphyry granites of the Yenisei uplift (700–710 Ma) (Vernikovsky et al., 2001).

In the period from 660 to 620 Ma the collision of initial island arcs and continents/microcontinents took place. This stage is marked by the Sm–Nd ages of Muya eclogites (650 Ma, northern Transbaikalia) (Dobretsov et al., 1995a), migmatites and amphibolites of the Njurundukan belt (635–623 and 590–570 Ma) (Konnikov et al., 1994; Neimark et al., 1995), metamorphic units of the Near-Yenisei belt (640–620 Ma) (Vernikovsky et al., 1994a), and orogenic molasse (640–620 Ma).

The maximal opening of the Paleo-Asian Ocean was reached at 640–550 Ma. At that time a long island arc composed of boninite volcanic rocks was formed. Primitive island arcs of that age have been reconstructed in Kazakhstan, Gorny Altai, West and East Sayan, and North Mongolia. The scale of boninitic island-arc magmatism of this stage was great and can be compared with the present-day situation in the western Pacific (Dobretsov et al., 1992b; Berzin and Dobretsov, 1994; Al'mukhamedov et al., 2001). According to the paleomagnetic data (Metelkin, 1998) those island arcs – Kurtushibin, West Sayan, Gorny Altay, Bayangol, Egyingol, etc. – were located around the Siberian continent, between the 12°N and 10°S latitudes. The most widespread ophiolites are referred to this stage – Altay, Borus, Kurtushibin, Tuva, Mongolia, Lake Valley, Bayankhongor, Khantaishirin and others. Their U–Pb and Sm–Nd ages are within a short time interval – 568–593 Ma (Khain et al., 2001).

At 550–490 Ma oceanic islands and Gondwana-derived microcontinents (Kokchetav, Tuva-Mongolian, Central Mongolian and others) collided with the Cambrian-early Ordovician island arc of the Siberian continent. As a result, the island-arc system was extensively modified. Collision occurred twice at 550–520 and 520–490 Ma during which many HP and UHP rocks formed (Dobretsov and Kirdyashkin, 1994, Buslov and Watanabe, 1996). Some of the late Cambrian-early Ordovician island arcs are thought to inherit the Vendian-early Cambrian island arcs (Salair, Gorny Altai, and Tuva). But most island arcs in Mongolia-Okhotsk region and Kazakhstan seem to be newly formed and independent. That time, the new oceans – the Junggar, Kazakhstan and Uralian – with an Ordovician island arc were formed.

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