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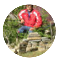

M.M. Buslov
Sobolev Institute of Geology and Mineralogy

Inna Safonova
Novosibirsk State University

Olga Obut
Russian Academy of Sciences

N. N. Semakov
Sobolev Institute of Geology and Mineralogy

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Evolution of the Paleo-Asian Ocean (Altai–Sayan Region, Central Asia) and collision of possible Gondwana-derived terranes with the southern marginal part of the Siberian continent

M.M. Buslov, I.Yu. Saphonova — *United Institute of Geology, Geophysics and Mineralogy, Russian Academy of Sciences, Siberian Branch, 630090, Koptyuga ave. 3, Novosibirsk, Russia*
T. Watanabe, O.T. Obut, Y. Fujiwara, K. Iwata — *Division of Earth and Planetary Sciences, Graduate School of Hokkaido University, 060-0810, Sapporo, Japan (e-mail: teruwata@ep.sci.hokudai.ac.jp)*
N.N. Semakov — *United Institute of Geology, Geophysics and Mineralogy, Russian Academy of Sciences, Siberian Branch, 630090, Koptyuga ave. 3, Novosibirsk, Russia*
Y. Sugai — *Division of Earth and Planetary Sciences, Graduate School of Hokkaido University, 060-0810, Sapporo, Japan*
L.V. Smirnova, A.Yu. Kazansky — *United Institute of Geology, Geophysics and Mineralogy, Russian Academy of Sciences, Siberian Branch, 630090, Koptyuga ave. 3, Novosibirsk, Russia*

ABSTRACT: The paper reviews and integrates new results on the evolution of the Paleo–Asian Ocean and its related geodynamics and geology of Altai–Sayan Region (ASR) in Central Asia. A revised terrane classification based on Vendian–Cambrian geodynamic units and evolution of terranes is described. Reactivated suture zones along the terrane boundaries are proposed. The obtained data suggest the important role of strike-slip deformations in the formation of mosaic-block structure of Central Asia. Those complicated and multi-stage deformations resulted from the Late Devonian–Early Carboniferous collision of Gondwana-derived terranes. The deformations reached their peak in the Late Carboniferous–Permian due to the collision of the Kazakhstan and Siberian continents. A system of sinistral strike-slip faults formed ASR along the margin of the Siberian continent as a result of the Late Carboniferous–Permian collision. The intrusion of granites occurred in East Kazakhstan and northwestern Gorny Altai in the Late Carboniferous and Permian. This resulted in the formation of the Northern Eurasia continent. Geodynamic evolution of the Paleo–Asian ocean and paleotectonics of ASR allow to recognize in the region the following five geodynamic stages: Vendian–Early Cambrian, Early Ordovician, Early–Middle Devonian, Late–Devonian–Early Carboniferous and Late Carboniferous–Early Permian times.

Key words: Gondwana-derived terranes, Paleo-Asian ocean, terranes, reactivated zones, collision, Altai–Sayan Region

1. INTRODUCTION AND THE TECTONIC SETTING IN THE ALTAI-SAYN REGION (ASR)

A concept of paleo-oceans based on plate tectonics in Central Asia was firstly introduced by Zonenshain (1972, 1973) as the Asian paleo-ocean from Late Precambrian to Paleozoic. He inferred a few sea-floor spreading centers and linear distribution of spreading isochrones judging from the biostratigraphical data and occurrences of ophiolites in Altai–Sayan or Altai–Sayan Region (ASR), situated in the territories of Russia, Kazakhstan, Mongolia and China, and surrounding regions. His assumption is presently not correct anymore, but the Central Asian Fold Belt has been successfully synthesized in terms of plate tectonics (Zonenshain et al., 1990). Zonenshain et al. (1990) used the terms of Paleo-Asian Ocean and Paleo–Asiatic Ocean for the same ocean. Almost simultaneously an international project entitled "Geodynamic evolution of the Paleo–Asian Ocean (or Paleoasian ocean)" launched in 1989 and lasted for 5 years (Coleman, 1994). Our Russian-Japanese joint research was commenced in 1992.

These joint studies and subsequent co-operative works have revealed that the fold belts of Central Asia were accretion and collision zones formed along the margin of the Siberian continent. They are composed of the fragments of oceanic crust, island arcs and microcontinents (Fig. 1). The geodynamics started with a breakup of Late Precambrian Pangea-like supercontinent (Zonenshain et al., 1990). Zonenshain et al. (1990) reconstructed the spreading axes that separated microcontinents from Gondwanaland in Vendian–Early Cambrian times. They assumed that the microcontinents originated from Gondwanaland, crossed the Paleo-Asian Ocean and collided with the Siberian and East European continents. Berzin and Dobretsov (1994) identified Gondwana-derived and Laurentia-derived microcontinents in the Central Asia foldbelt. Dobrestov et al. (1995) discussed and summarized the evolution of the Paleo–Asian Ocean, which opened by the breakup of Rodinia, followed

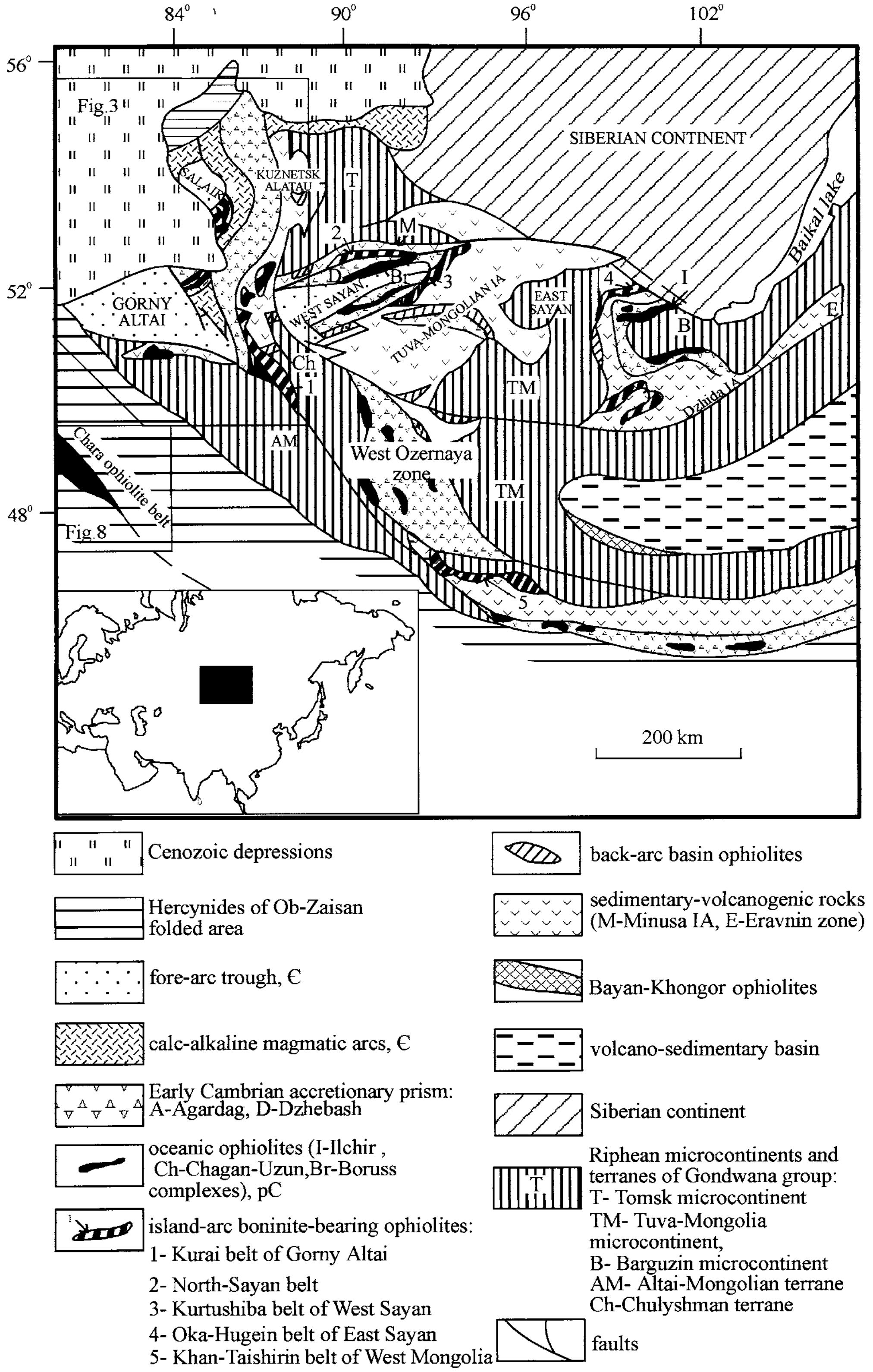

Fig. 1. Distribution of the Pre-Hercinian accretion-collision zones and microcontinents of the Gondwana and Eurasia groups in the Altai–Sayan Region in the southern side of the Siberian continent (Dobretsov et al., 1995). IA=Island Arc system (Tuva–Mongolian IA, Dzhida IA, Munisa IA).

by the breakup of Gondwanaland and accretion of fragmented Gondwana-derived terranes to the Siberian continent. The crustal evolution provides a prologue prior to the collision/accretion of Gondwana-derived terranes in Central Asia. They formed during a long period from the Vendian to the Early Carboniferous. Microcontinents of Tomsk, Tuva–Mongolia, and Barguzin, and terranes of Altai–Mongolian and Chulyshman have been proposed by Dobretsov et al.(1995). The distribution of microcontinents shows a mosaic pattern, and is separated by island arcs and accretionary zones (Fig. 1). The mosaic pattern resulted from the oblique subduction and its related large-scale horizontal displacements along the continental margin (Berzin and Dobretsov, 1994; Berzin et al., 1994; Dobretsov et al., 1995).

A similar idea was reported by Mossakovsky et al. (1993) and Didenko et al. (1994). They emphasized an important role of strike-slip faulting and showed a wide distribution of Gondwana-derived microcontinents and continents in the structure of the Central Asian fold belt. The Altai–Mongolian terrane, however, was regarded as Caledonian accretionary zone, same as Salair and Gorny Altai in their model (Fig. 2). Gordienko and Kuzmin (1999) emphasized the importance of similar tectonic analysis in the study of metallogeny.

According to another model by Sengör et al.(1993), a single Kipchak island arc existed in between the Turkestan Ocean (almost identical to our Paleo-Asian Ocean) and continents of Siberia and East Europe during the Vendian–Paleozoic. In the Late Paleozoic the rotation and migration of those continents deformed the island arc. The island arc was broken by strike-slip faults into many fragments. In the structure of Central Asia the most important are Late Carboniferous dextral faults and Late Permian sinistral faults. The model by Sengor et al. (1993) did not consider the role of Gondwana-derived microcontinents (terranes) in the formation of Central Asia structure and they did not discuss the origin of pre-Altaid continental crust and the tectonics forming their Vendian–Cambrian accretionary complexes which occur in ASR. Thus, the origin of Precambrian–Early Paleo-

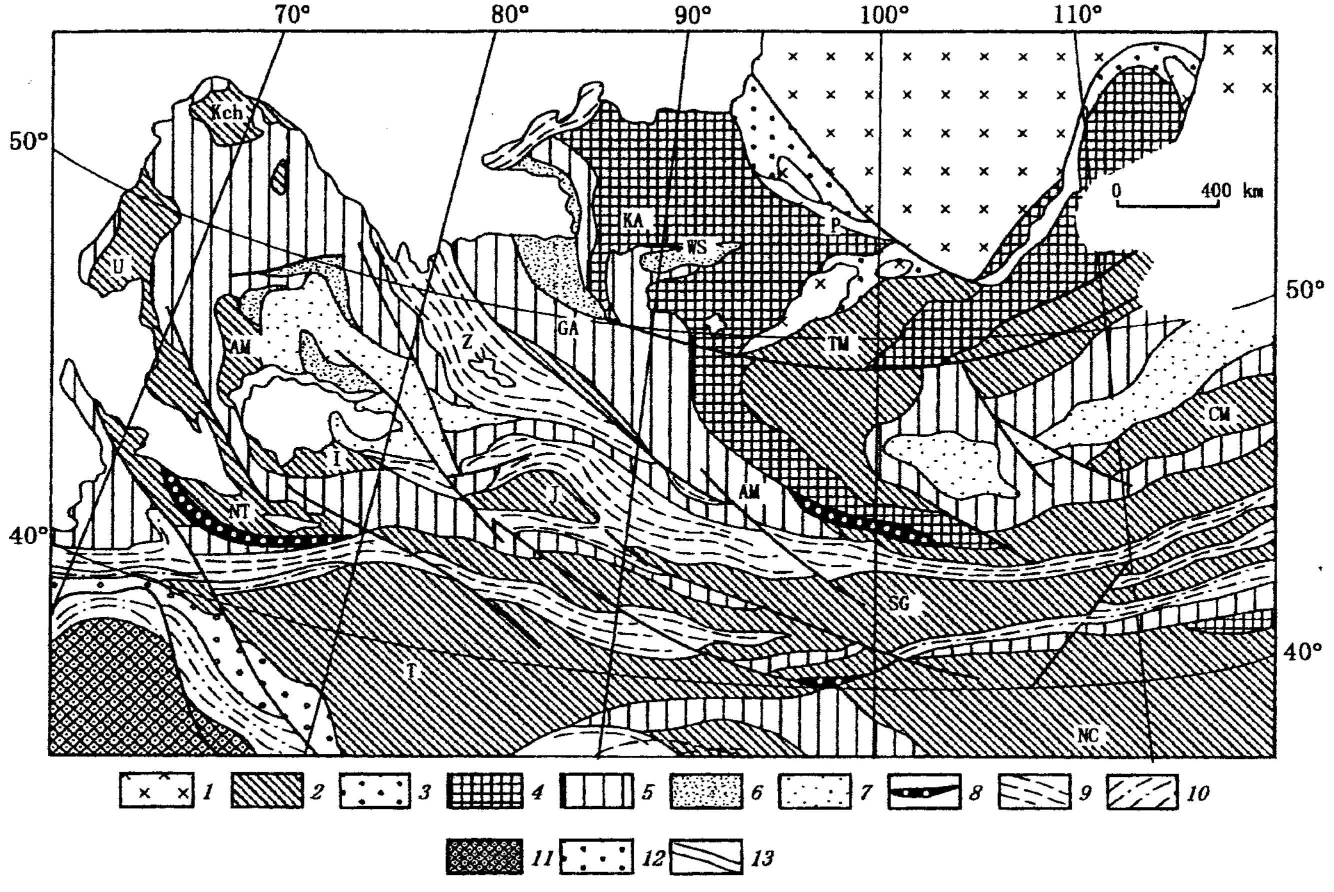

Fig. 2. The tectonic scheme of the Central Asian foldbelt (Mossakovsky et al., 1993). 1, 2=*platforms and microcontinents*: 1=Siberian platform, 2=Gondwana group (T=Tarim and NC=North China platforms, Kch=Kokchetav, U=Ulutau, AM=Aktau–Mointin, I=Iliy, NT=North Tian Shan, J=Junggar, TM=Tuva–Mongolian, CM=Central Mongolian, and SG=South Gobi microcontinents); 3–5= accretionary zones: 3=Late Riphean, 4=Early Caledonian (KA=Kuznetsk Alatau, WS=West Sayan), 5=Caledonian (S=Salair, GA= Gorny Altai, AM=Altai–Mongolian); 6, 7=sedimentary basins: 6=Caledonian (Anui–Chuya), 7=Early Hercynian; 8–11=collisional foldbelts: 8=Caledonian, 9=Early Hercynian (Z=Zaisan), 10=Late Hercynian, 11=Mesozoic; 12=Predkunlun trough; 13=large faults.

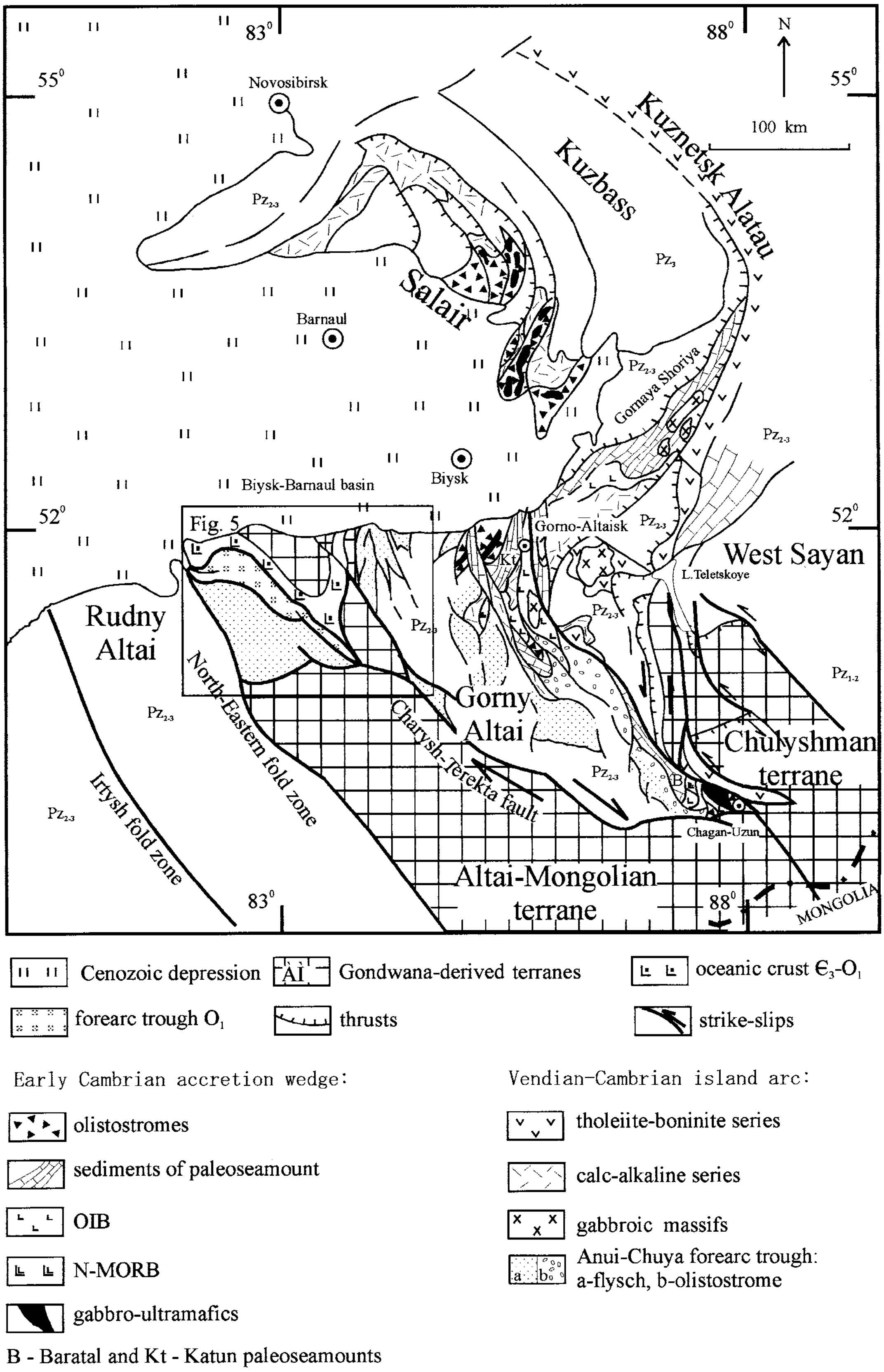

Fig. 3. Vendian–Cambrian island-arc units in Gorny Altai. Salair and Kuznetsk Alatau terranes. Note: the original units classification is different from Figs. 1 and 2.

zoic rocks in ASR, which we examine here, remains unsolved.

In spite of many studies by different authors, details of the geodynamic history of the Paleo-Asian Ocean have not been solved yet. Especially in ASR, the existence of the Altai–Mongolian microcontinent (terrane) of Gondwana group is still under discussion and detailed tectonic processes have not been integrated after Dobretsov et al. (1995). The fragments detached from Gondwanaland in Early Paleozoic have been postulated not only in Central Asia but also in the Middle East (Cocks, 2001 and the references). However, the breakup processes of Gondwana as well as those of Rodinia are still hypothetical. Based on our advanced terrane-analysis and more detailed reconstruction of paleogeography, we herein demonstrate that the hypothesis is mostly acceptable.

2. TERRANE CLASIFICATION AND ALTAI GEOLOGY

The Vendo–Cambrian island-arc system shown in Figure 1 is divided into several terranes by Late Paleozoic faults, which were, in turn, displaced and re-orientated relatively each other by large-scale faults. Now they are observed in Kuznetsk Alatau, Salair, Chulyshman, Gorny Altai, Altai–Mongolia, West Sayan and East Sayan in Russia as well as terranes in the Ozernaya and Khan–Taishirin zones in West Mongolia (Figs. 1 and 3). Hitherto, detailed geological and petrochemical studies in the Gorny Altai terrane and surrounding areas were given by Buslov et al. (1993) and geodynamic synthesis in Central Asia including the Gorny Altai terrane was discussed by Dobretsov et al. (1995). Afterward, a comprehensive and detailed geodynamic synthesis has not been presented, yet, although not a few data have been reported.

In this chapter, we compile the related data accumulated until now and integrate the geodynamic processes in the Gorny Altai region. We newly defined the terrane-boundaries as shown in Figures 3 and 4. The terranes are classified mainly based on Vendian–Cambrian geodynamic units of the Paleo-Asian Ocean bounded by large strike-slip faults (Fig. 3) and we use basically the new classification. However, as shown in Figure 4 we propose here to discriminate reactivated suture zones along the faults bounding terranes. They are composed of not only Vendian–Cambrian geodynamic units but also igneous, metamorphic and sedimentary rocks of Devonian and Carboniferous ages. Reactivated suture zones continuously distribute along major faults beyond the terrane boundaries. As shown in Figure 4, the Chara fold zone, Rudny Altai terrane and surrounding areas represent a Carboniferous–Permian junction structure of the Kazakhstan and Siberian continents. The northwestern part (Charysh and Inya areas) of the Gorny

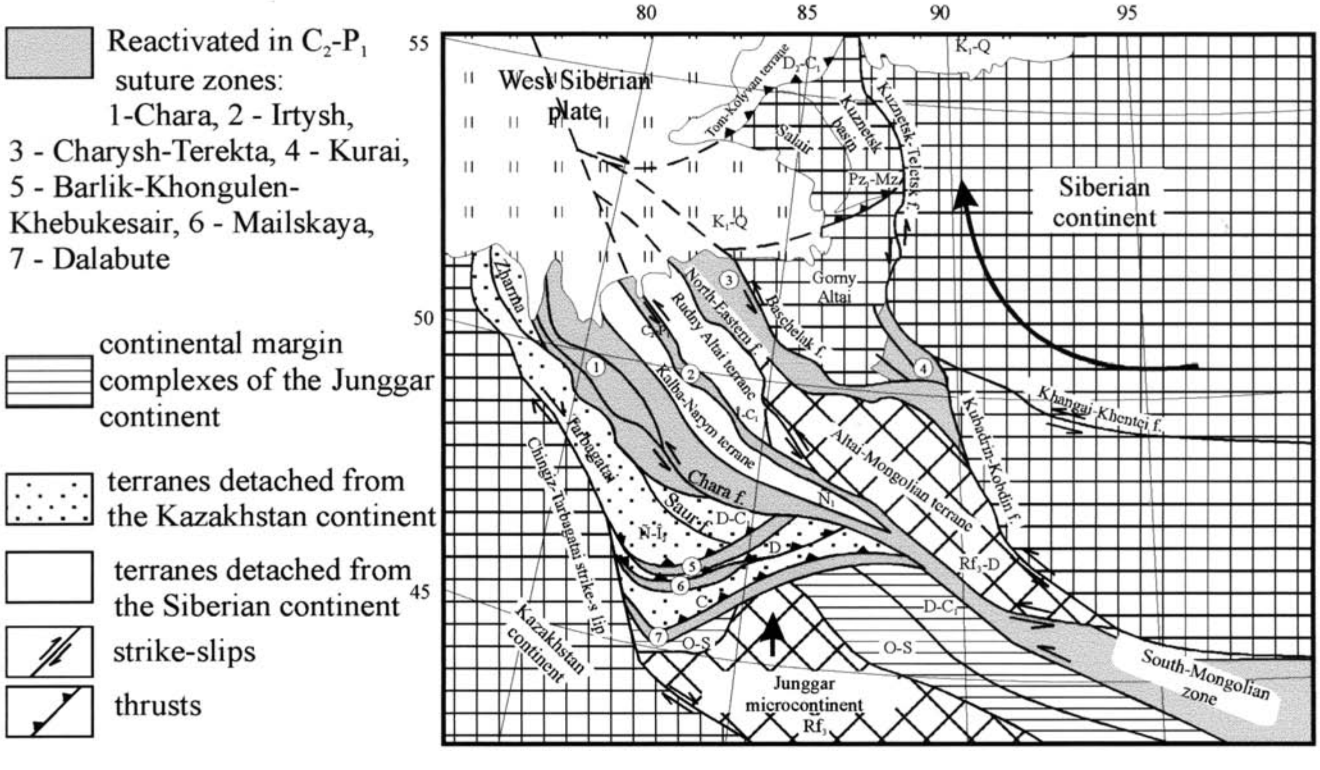

Fig. 4. Distribution of Late Carboniferous–Permian terranes resulted from the collision of the Siberian and Kazakhstan continents. The Ob'–Zaisan sea was situated between the Kazakhstan and Siberian continents and had a link with the South-Mongolian ocean. Continental margin units are divided into these groups, i.e., Siberian and Kazakhstan. Reactivated suture zone from the Chara ophiolite belt (No.1) to the South-Mongolan zone is the remnant of the ocean. Note: the original units classification is different from Figs. 1 and 2.

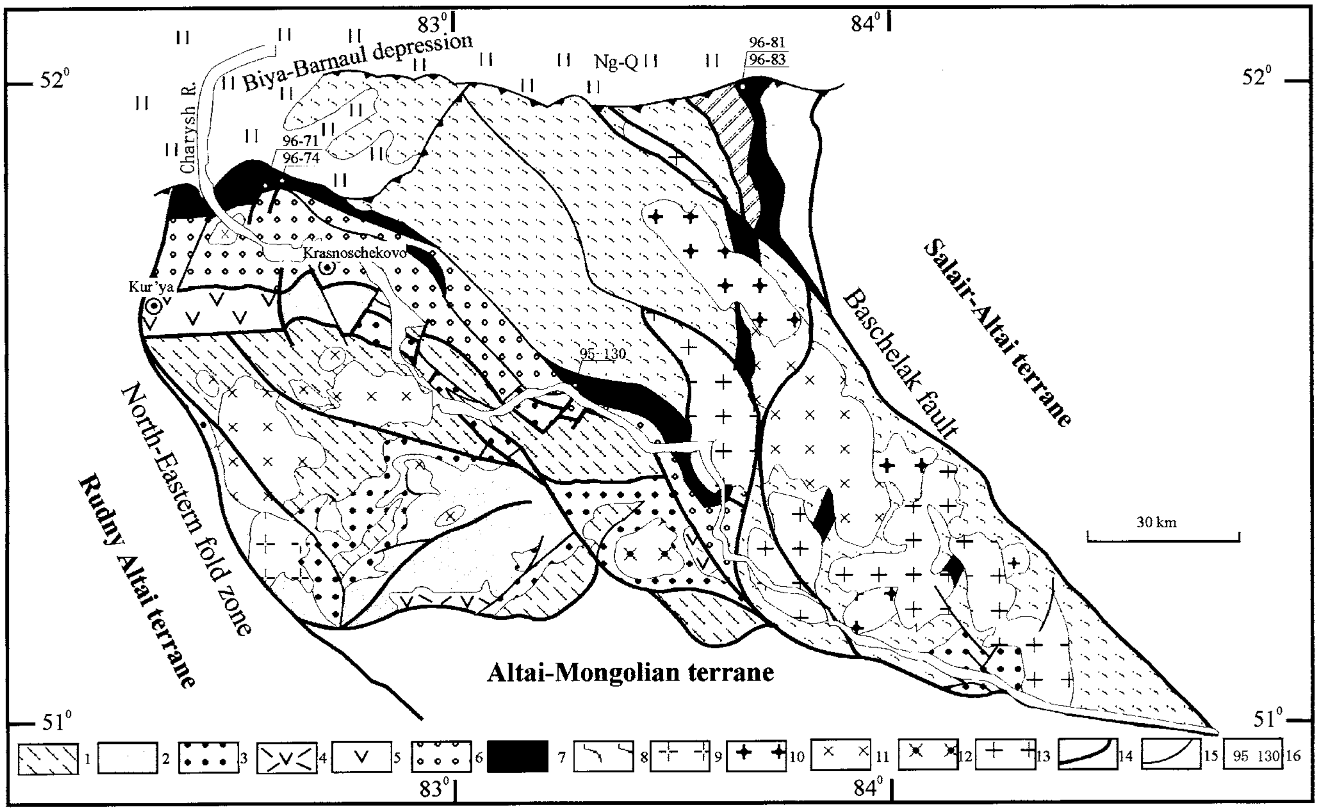

Fig. 5. Geology and structure of the Charysh–Inya and Talitza zones in the north-western Gorny Altai terrane (modified from Iwata et al. (1994) and Vladimirov et al. (1997). 1–8=structural units of the Charysh–Terekta folded zone: 1–4=Inya (1=Suetkin Formation, O_1, 2=carbonate and 3=terrigenous-carbonate rocks, O–S, 4=sedimentary-volcanic rocks, D_{1-2}), 5=Kur'ya–Akimov (Kukui Fm), 6=Charysh (Charysh and Suetkin Fm, O_{1-2}), 7=Zasurin (Zasurin Fm, C_3–O_1), 8=Talitza (Maralikha Fm, R_3), 9=amphibole–biotite gneiss, D_2, 10=granite and leucogranites, D_3–C_1, 11=biotite-hornblend granitoids, D_3–C_1, 12=amphibole-biotite granites, D_2, 13=gabbro–diorite–granodiorites, D_2, 14=tectonic faults, 15=stratigraphic boundaries, 16=sampling localities for geochemical, paleomagnetic and paleontological analyses.

Altai terrane (see Fig. 5) belongs to a reactivated suture zone which extend into the Altai–Mongolian terrane as shown in Figure 4. The Charysh and Inya areas of the Gorny Altai terrane (Fig. 5) display a Late Devonian–Early Carboniferous junction structure along the northeastern margin of the Altai–Mongolian terrane of the Gondwana group. Above-mentioned reactivated suture zones, thus, make definition/classification of Vendian–Cambrian terrane difficult. Since Vendian time, terranes, such as the Kuznetsk–Alatau, Salair, Chulyshman, and Gorny Altai terranes, had amalgamated with the Siberian continent and the Kazakhstan continent was formed by the Late Paleozoic. In the Middle Paleozoic the Salair–Altai terranes formed and the Gorny Altai terrane of the original concept did not exist. Devonian–Carboniferous igneous activity of terranes in ASR, thus, was the manifestation of an active continental margin.

2.1. Gorny Altai Terrane

The Gorny Altai terrane consists of a similar set of Vendian–Cambrian rocks as the Kuznetsk–Alatau and Salair terranes as shown in Fig. 3. However, as the Gorny Altai terrane contains a complete set of Vendian–Cambrian rocks, we describe only the Gorny Altai terrane, which is surrounded by the Chulyshman terrane on the east, Rudny Altai terrane on the west and Altai–Mongolian terrane on the south-west as shown in Fig. 3. Biostratigraphical study of stromatolites and microphillites indicating Vendian time and trilobites and archaeocyata of Cambrian time and structural study are enable to assume the ages of the volcanic units (Buslov et al., 1983). Petrochemical study by Buslov et al. (1993) deciphered the tectonic settings of volcanics. A number of Early Cambrian accretionary units including OIB and N-MORB and Vendian–Cambrian island arc units are recognized and contact each other in the Katun (nearby Gorno-Altaisk city) and Kurai zones (west of Chagan-Uzun Village) of the Gorny Altai terrane (Buslov et al., 1998a; Watanabe et al., 1993; Simonov et al., 1994; Buslov and Watanabe, 1996).

In Fig. 3 the outlines of the distribution of the following units are shown:

1) primitive Vendian–Cambrian island-arc with tholeiite-

boninite rock series;

2) Cambrian accretionary prism with OIB and MORB;

3) Early–Middle Cambrian normal island arc with calc-alkaline and shoshonitic rocks;

4) fore-arc trough consisting of Middle–Late Cambrian turbidites,

5) back-arc basin.

Study of the above-noted geodynamic units, which are best observed in the Katun (Cental Altai) and Kurai (East Altai) zones, made possible the reconstruction of paleogeodynamic processes (subduction and accretion), which seem to be similar to those in the western part of the Pacific active margin (Watanabe et al., 1993; Buslov and Watanabe, 1996).

We obtained several isotopic dates for blocks included in serpentinitic melange and metamorphic rocks of the Chagan–Uzun massif (Table 1, Fig. 3 shows the locality). The K–Ar phengite ages are 540±24 and 576±11 Ma (schists from serpentinitic melange). The K–Ar amphibole age of the garnet amphibolite (Chagan–Uzun massif) is 535±24 Ma and Ar–Ar amphibole ages from the eclogitic part are 636± 10 Ma and 627± Ma. The K–Ar amphibole age of island-arc ophiolites is 523±23 Ma. The Middle–Late Cambrian Anui–Chuya fore-arc trough was filled with clastic materials transported from Early–Middle Cambrian accretionary prisms and islandarcs (Buslov and Watanabe, 1996).

New data on the biostratigraphy of the Gorny Altai Series, which occurs in the southeastern part of the trough, have been obtained. The Chulektash Formation consisting of olistostrome–conglomerate rocks (or mélange with block-in matrix structure) is widely distributed in the junction area of the trough margin and Early Cambrian accretionary prism of the Kurai zone. The olistostrome and conglomerate bodies are present within a sandstone–shale sequence, which is similar to the Gorny Altai Series in the Anui–Chuya zone. The olistostrome is overlain by thick sandstone–shale flysch beds (multi-colored formation). This formation is composed of polymictic and quartz–feldspar sandstones with subordinate siliceous mudstones and carbonate–clay shales. Fossil sponge spicules–*Cjulanciella assymetrica* Fedorov, *Disparella* cf. *fusiformis* Fedorov–were obtained from the purple and/or red siliceous rocks of the Chulektash Formation and the multi-colored formation. The former species indicates Middle Cambrian age of host rocks, and the latter does Middle–Late Cambrian age (Buslov et al., 1998b). Biostartigraphic studies of the Gorny Altai Series in south–eastern part of the Gorny Altai terrane showed Middle Cambrian age of the olistostrome–conglomerate strata and Middle–Late Cambrian age of sandstone-shale strata. This allows to conclude that the marginal part of the Anui–Chuya fore-arc trough, consisting of Gorny Altai Series flysch sediments, is of Middle–Late Cambrian age.

Tremadocian folding, metamorphism and sedimentation break (Yolkin et al., 1994) and intrusion of granitoids (Vladimirov et al., 1997) occurred in the Late Cambrian–Early Ordovician which lead us to an episode of the Kuznetsk–Altai island-arc collision with the Siberian continent. U–Pb and Rb–Sr ages of the granite intrusions in Altai, Salair and Kuznetsk Alatau show that the peak of the folding and metamorphism was at about 490 Ma.

Our K–Ar ages of garnet amphibolites associated with diaphthorites after eclogites of the Chagan–Uzun massif are 473±13 and 487±22 Ma (Buslov and Watanabe, 1996), i.e., Ordovician (Table 1). This suggests the final stage of exhumation of eclogite with deformation and retrograde metamorphism.

Uplift ages of granite–gneiss rocks which are located to the northwestern side of the Chagan-Uzun serpentinite mélange (northwestern area of Kurai) is younger than the exhumation of high-pressure rocks. The K–Ar amphibole ages are 394±8, 374±8, and 365±12 Ma, Ar–Ar amphibole ages are 384±14 and 377±4 Ma, K–Ar biotite age is 374±5 Ma (Table 1). For South–Chuya granite-gneiss the Ar–Ar amphibole age is 407±4 Ma (Monie et al., 1998).

Thus, the Katun and Kurai areas, the eastern part of the terrane, preserve well the Early Paleozoic units but they were disturbed/dislocated by later tectonic events including magmatism and metamorphism.

2.2. Reactivated Suture Zone in the North–Western Gorny Altai terrane

The Charysh–Inya area is situated in north–western the Gorny Altai terrane (Fig. 3). A sheeted structure is situated between the Late Carboniferous–Permian North–Eastern and Baschelak sinistral strike-slip faults, close to Late Devonian–Early Carboniferous faults of the Charysh–Terekta fault zone (No.3 in Fig. 4). The sheeted Charysh-Inya zone extends over a distance of 120–130 km and consists of five deformed structural units (from west to east): Inya (1–4 in Fig. 5), Kur'ya–Akimov (5 in Fig. 5), Charysh (6 in Fig. 5), Zasurin (7 in Fig. 5), Talitsa (8 in Fig. 5). The strike-slip zone consists of compositionally variable Vendian–Eifelian blocks, which were detached from the Altai-Mongolian terrane and Siberian continent as shown in Fig. 4, and the Zasurin and Charysh structural units, which are the fragments of the newly discovered Late Cambrian–Early Ordovician oceanic crust and Ordovician fore-arc basin (Iwata et al., 1999; Buslov et al., 2000).

The Zasurin unit (or sub-terrane) (7 in Fig. 5) is composed of several tectonic lenses consisting of multicolored sandstones, gray, green, violet and dark-red siliceous rocks, pillow-lavas with variolitic or aphyric texture, plagioclase and pyroxene–plagioclase basalts and their volcanoclastics, and gabbro and gabbro–diabase sills and dikes. Dark-red, rarely green stratified cherts contain various Late Cambrian–Early Ordovician (Late Tremadoc–Early Arenig) conodonts and radiolarians (Iwata et al., 1997).

Geochemical investigation of the Zasurin volcanics (Figs.

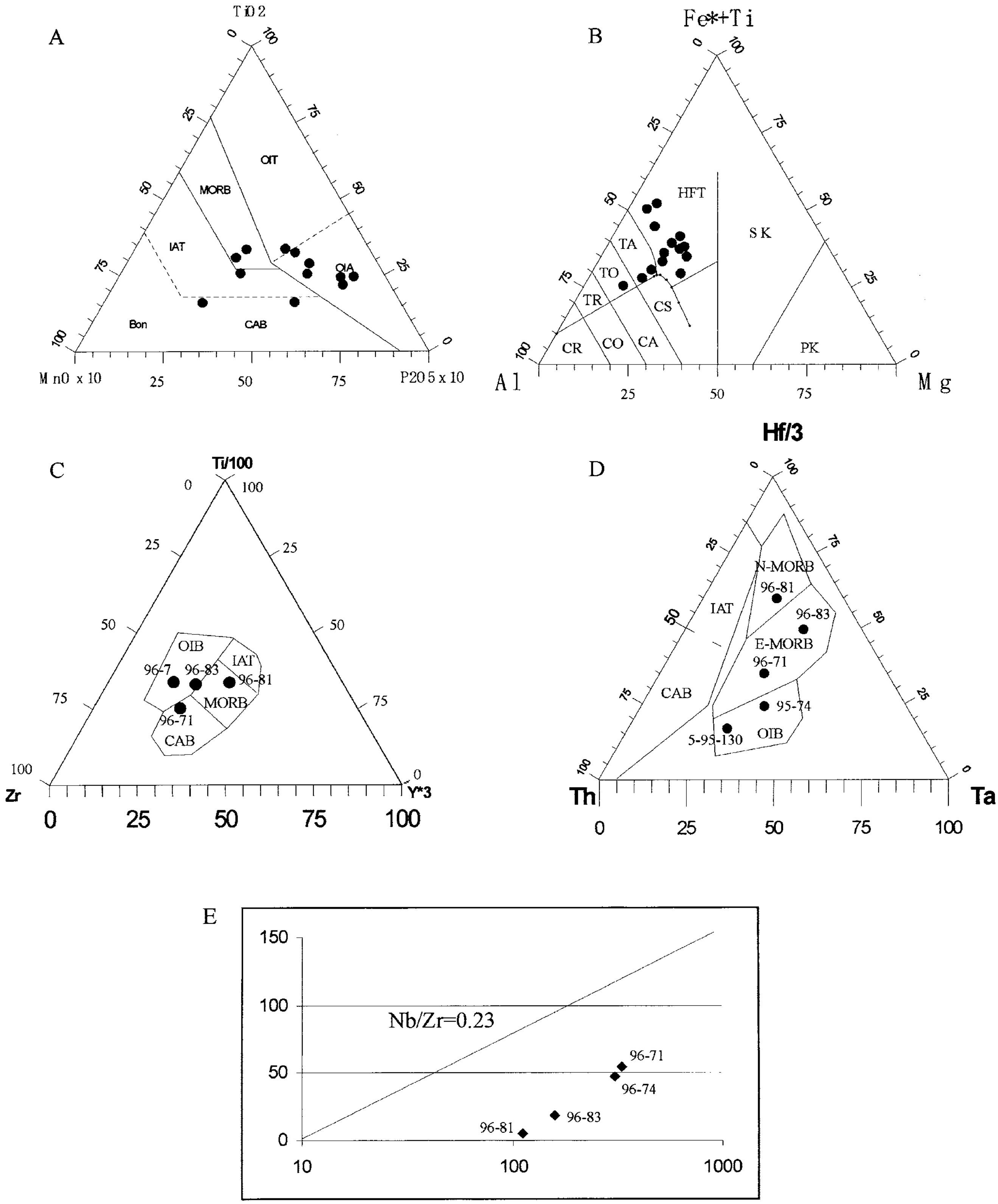

Fig. 6. Major and trace element concentrations in the Zasurin basaltoids: Al_2O_3–FeO+TiO_2–MgO classification diagram; discrimination diagrams: MnO–TiO_2–P_2O_5, Th–Hf–Ta, Zr–Ti–Y; Nb/Zr plot (definition of the fields see in Fig. 9).

6 and 7) showed that they possess characteristics of OIB (basalts–B-95-130, glassy fragments–96-71, gabbro–96-74) and MORB (basalt–96-81, gabbro–diabase B 96-83). According to the concentration of major elements (Fig. 6) the vol-

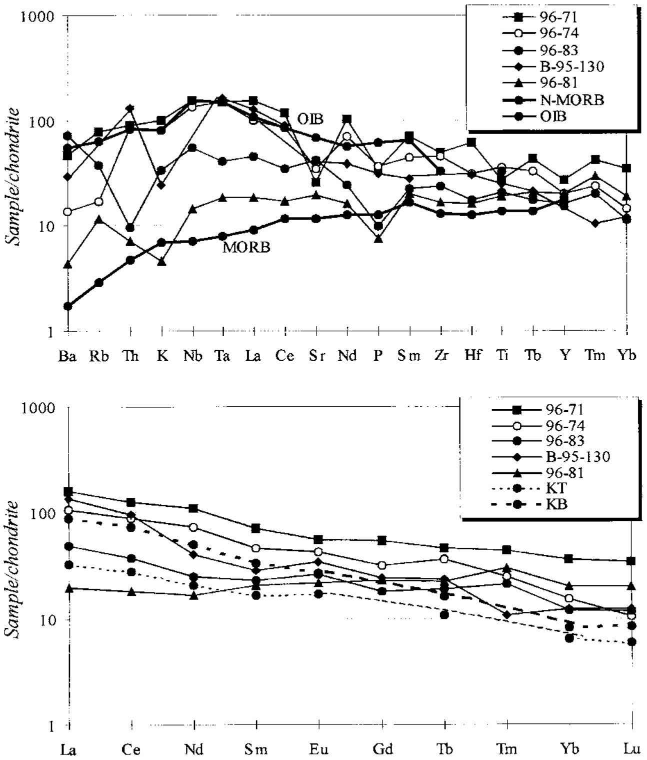

Fig. 7. (**A**) Trace element concentrations in the Zasurin rocks normalized to the composition of chondritic meteorites. The normalizing values and average N-type MORB and OIB concentrations are taken from Rollinson (1993). (**B**) Rare earth element abundances in the Zasurin rocks normalized to chondritic meteorite values. KB=plagioclase basanite; KT=Khaula tholeiitic basalt, Hawaiian ocean islands system (Clague and Frey, 1982; Garcia et al., 1986).

canics under investigation are mostly tholeiites (Al_2O_3–FeO +TiO_2–MgO triangle). In the MnO–TiO_2–P_2O_5 discrimination diagram by Mullen (1983) the compositional points concentrate in three fields: MORB, oceanic island tholeiite and oceanic island alkaline basalt. Concentrations of minor elements, incompatible elements and REE in the Zasurin volcanics indicate that they are intermediate between MORB and OIB. Figure 6 shows the diagram of Th–Hf/3–Ta (Wood, 1980) where sample 96-81 falls in N-MORB field and samples 96-71 and 96-83–in the field of within-plate tholeiites and E-MORB. Samples 96-74 and B-95-130 fall into the field between within-plate tholeiites and within-plate alkali basalts. Trace element concentrations normalized to the composition of the primordial mantle and chondritic meteorites are shown in Figure 7. The plots were compared with the average N-type MORB and OIB curves (Rollinson, 1993). Figure 7 shows that the average MORB curve is close to those of 96-81, and 96-83, 96-71 and 96-74 curves to the average OIB curve. Comparison of REE patterns of the Zasurin volcanic rocks and Honolulu and Kuala basalts, Hawaiian islands, (Clague and Frey, 1982; Garcia et al., 1986) demonstrate that the former with OIB characteristics are very close to Hawaiian basalts in LREE content. Therefore, based on geochemistry two types of basalt can be recognized: close to MORB (type I) and close to OIB (type II). This fact suggests the presence of an open ocean between the Altai-Mongolian terrane and the Siberian continent in the Late Cambrian–Early Ordovician.

From Ordovician till Silurian no igneous activity was recorded and terrigenous-carbonate rocks of passive margin type developed. In the Devonian the igneous activity of probably an island-arc system (we call the Chingiz–Baschelak system) occurred (Nos.4, 10 and so on in Fig. 5).

2.3. Altai–Mongolian Terrane

The Altai–Mongolian terrane is composed of shelf and continental slope terrigenous rocks. We compile herein the result on this terrane. Judging from palinspastic reconstruction of Rodinia supercontinent by Li (1998), it is speculated that the basement of the terrane detached from the North China block (Gondwana Group in a broad sense) of Rodinia in the Late Riphean. More evidences concerning the Gondwana group were reported in Berzin et al. (1994) and Berzin and Dobretsov (1993). In present, the terrane (Fig. 4) is about 1000 km long and 250 km wide extending into the areas of southern Gorny Altai (northern part of the terrane), Rudny Altai (northwestern part of the terrane), West Mongolia (eastern part of the terrane) and Chinese Altai (southeastern part of the terrane). In the Rudny and Gorny Altai areas it is bounded by the North–Eastern and parallel running strike-slip faults. The terrane is dominated by Vendian–Cambrian rhythmically–layered quartz–feldspar and polymictic sandstones, siliceous shales, and slates. In the Gorny Altai and Western Mongolian areas these sequences are considered a 6 km thick Middle Cambrian–Early Ordovician flysch-like sequence (Volkov, 1966; Volokovich and Leontjev, 1964; Dergunov, 1989). Dergunov et al.(1980) showed that the upper flysch horizons contain violet and red sediments and sparse interbeds of acid tuffs and clay-siliceous sediments. The flysch varieties are isoclinally folded and transgressively overlain by various Ordovician–Devonian units indicating a complex geodynamic evolution of the Altai–Mongolian terrane. In the southern Gorny Altai area, the Middle–Ordovician gray marine sediments (Kabin and Biryuksa suites) overlap deformed and metamorphosed basement rocks through basal conglomerates. Upper Ordovician–Lower Silurian gray marine sediments are found in the Gorny Altai and Western Mongolia areas (Volokovich and Leontjev, 1964; Dergunov et al., 1980). The Emsian active margin units (Korgon and Kholzun zones in Gorny Altai) (Tikunov, 1995; Gutak, 1997; Dergunov et al., 1980) are widely distributed in the Western Mongolia area (Dergunov et al., 1980). The Emsian units transgressively overlap the Vendian–Early Cambrian and Ordovician-Silurian rocks of the Altai–Mongolian terrane.

The Altai–Mongolian terrane is intruded by Late Devonian–Early Carboniferous granitoids (Vladimirov et al., 1997) and gabbro-diabase dikes and silles (Yolkin et al., 1994). They seem to mark the extension in reactivated suture zones related to strike-slip deformations, which occurred along the boundary between the Altai–Mongolian terrane and Siberian continent.

2.4. Chara Ophiolitic Belt: A Reactivated Suture Zone along the Margin of the Kazakhstan Continent

Fig. 4 shows the structural pattern of Central Asia, which was formed in Late Carboniferous–Permian time. Salair–Altai terrane in Figure 4 is a new name after amalgamation of the Salair and Gorny Altai terranes, but it is substantially equivalent to the Gorny Altai terrane in Figure 5. The Chara ophiolitic belt (No.1 in Fig. 4, also see Fig. 1) is a main collisional zone located along the northeastern margin of the Kazakhstan continent in the Middle–Late Paleozoic.

The Chara ophiolitic belt (Fig. 8) was studied in 1993, 1995 and 1997. It consists of several allochthonous structural units, which correspond to accretionary units (including ophiolites and high-pressure rocks) of the surrounding terrane such as the west Junggar, the Zharma–Saur and, possibly, the Rudny Altai terrane (see Fig. 4). In the Chara belt, the three melange units, which are different in structure, age and geodynamics, can be distinguished (Abdulin and Patalakha, 1981; Dobretsov et al., 1992; Iwata et al., 1996):

The Type I mélange, Early Paleozoic subduction melange, (legend 1 in Fig. 8), situated in the southeastern Chara zone. Blocks of high-pressure metamorphic rocks are characteristic of this melange. The high-pressure metamorphic rocks are meta-gabbro, meta-diabase, meta-basalt, meta-volcaniclastics (hyaloclastite), meta-graywackes, metamorphosed deep-water siliceous sediments, eclogites, amphibolites and glaucophane schists (Dobretsov et al., 1992). New geochronological data (Table 1, 8 measurements) were obtained by the K–Ar method in muscovite from eclogites, garnet amphibolites and glaucophane schists, showing a short interval of exhumation ranging from 429 to 444 Ma (Late Ordovician–Early Silurian). High-pressure rocks of the similar age are known in the southwestern Junggar. The ages support an idea that the subduction may have occurred in Cambrian–Early Ordovician time (Dobretsov et al., 1992) which would be correlated to the Tanbale blueschists (West Mongolia, N. China) containing ophiolites of Late Cambrian–Early Ordovician (Chi et al., 1993; Xiao et al., 1994).

Volcanic-siliceous rocks yield radiolarians and conodonts of Middle Devonian–Early Carboniferous age. Silurian, Lower Devonian and Givetian carbonates occur closely to Early Paleozoic high-pressure rocks of the Chara belt (Iwata et al., 1994; Iwata et al., 1996, 1999). The volcanics possess chemical characteristics of MORB and within-plate basalt (Fig. 9). In the MnO–TiO_2–P_2O_5 diagram (Mullen, 1983)

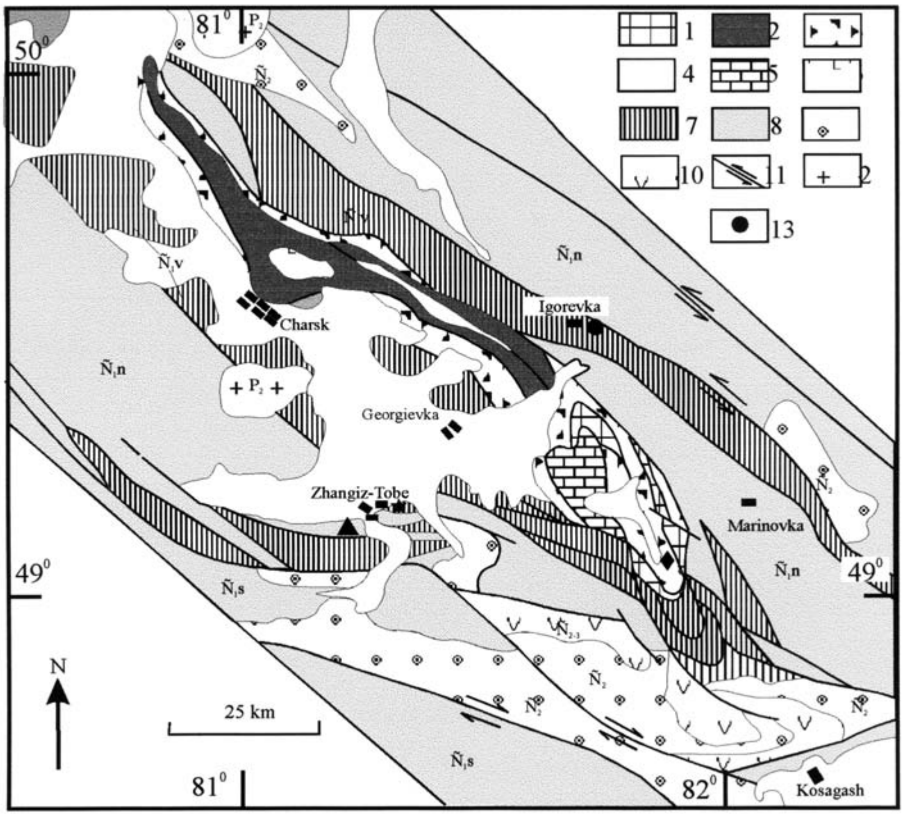

Fig. 8. The geological scheme of the Chara zone (modified from Abdulin and Patalakha, 1981). 1–6=oceanic crust units, 1=Early Paleozoic Type I serpentinitic melange with blocks of high-pressure rocks, 2=Ordovician Type II melange with blocks of weakly altered peridotites and gabbro, 3=Type III melange with blocks of Type I and II melange, Ordovician-Carboniferous oceanic crust and island arcs of the Kazakhstan and Siberian continents; 4–6=large fragments of oceanic crust: 4=Middle Devonian oceanic islands (basalt and chert), 5=Early–Middle Devonian seamounts (reef limestones), 6=Ordovician gabbro, 7=Visean–Namurian accretionary units with Middle Devonian–Early Carboniferous N-MORB and OIB, 8=Early Carboniferous fore-arc turbidites, Late Devonian–Early Carboniferous reef limestones, siliceous rocks and oceanic volcanogenic-siliceous rocks, 9–10=collisional units, 9=Late Carboniferous continental molasse, 10=Late Carboniferous alkaline volcanics, 11=Late Carboniferous–Early Permian strike-slip faults, 12=Late Permian–Early Triassic post-collisional granites.

Table 1. Geochronological data from Gorny Altai and Kazakhstan.

No.	Structural and geographical position of samples	Latitude and longitude of sampling localities	Lithology, sample number	Analyzed mineral	K content, %	K-Ar age, Ma	Ar-Ar age, Ma
Kurai metamorphic complex, southeastern Gorny Altai							
1	Kurai granite-gneiss complex, the Kuektanar upstreams	50°11′N 88°90′E	Crystalline schist 95-7-1	Amph			384±14 isochron
2	-- // -- the Kuektanar upstreams	50°11′N 88°90′E	Crystalline schist 95-7-2	Amph			377±4,5 isochron
3	Block in mylonite from a shear zone, the Kurai upstreams	50°20′N 87°59′E	Amphibolite 92-27802	Amph	0.92±0.02	394±8	
4	Block in mylonite from a shear zone, the Kurai upstreams	50°20′N 87°59′E	Amphibolite 92-72802	Amph	0.77±0.02	374±8	
5	-- // --	50°20′N 87°59′E	Gneiss 92-72909	Bi	6.54±0.02	374±5	
6	-- // --	50°20′N 87°59′E	Amphibolite 92-72901	Amph	0.17±0.01	365±12	
7	Matrix from a shear zone	50°20′N 87°59′E	Mica schist 92-81112	Bi	5.77±0.12	327±7	
8	-- // --	50°20′N 87°59′E	Mica schist 92-81112	Bi			333±6 isochron
9	-- // --	50°20′N 87°59′E	Mica schist 92-B	Bi	4.30±0.09	322±7	
Tokpak massif, southeastern Gorny Altai							
10	The southern Tokpak massif, the Maly Kodru upstreams	50°12′N 88°55′E	Granite 8983	Bi	6.22±0.12	353±7	
11	-- // --	-- // --	Granite 8984	Bi	6.20±0.11	354±6	
Teletsk-Bashkaus fault zone							
12	Local marginal foliation zones, the Bol. Chili right bank	51°27′N 87°42′E	Mylonitized granite 35	Bi			366±2
13	-- // --	-- // --	-- // -- 99-1	Mu			365±15 isochron
14	-- // --	-- // --	-- // -- 99-2	Mu			370±6
15	-- // --	-- // --	-- // -- 94-100	Mu	6.48±0.13	323±7	
16	The Chulashman mouth left bank	51°22′N 87°44′E	-- // -- 94-90	Mu	5.04±0.1	331±7	
17	Axial part of the zone, Kamelik cape	51°26′N 87°48′E	Biotite schist 94-98	Bi	5.75±0.12	343±7	
18	--//--	--//--	Migmatite 94-99	Mu	6.94±0.14	350±7	
19	Axial part of the zone, 4 km south of Bele Vil.	51°23′N 87°48′E	Mylonitized gabbro 24.3	Bi	5.17±0.103	332±7	
20	-- // --	-- // --	-- // --	Mu	3.88±0.078	331±7	
21	-- // --	-- // --	-- // --	Amph	0.441±0.022	390±20	
22	-- // --	-- // --	-- // -- 24.1	Bi			332±2

Table 1. (continued)

No.	Structural and geographical position of samples	Latitude and longitude of sampling localities	Lithology, sample number	Analyzed mineral	K content, %	K-Ar age, Ma	Ar-Ar age, Ma
Teletsk-Bashkaus fault zone							
23	Southern extremity of the Teletskoye Lake	51°21′N 87°48′E	Gabbro-amphibolite	Amph	0.18	352±16	
24	The Chiri series, Chiri Vil.	51°22′N 87°49′E	Biotite schist 94-82	Bi	6.03±0.121	318±7	
25	-- // --	-- // --	Biotite schist 94-83	Bi	6.00±0.12	341±7	
26	-- // --	-- // --	Amphibole schist 28-27	Amph			260±8
27	-- // --	-- // --	Blastomylonite 94-84	Amph	0.42±0.021	360±17	
28	-- // --	-- // --	Crystalline schist after gabbro 26-32	Amph			375±5
29	The Kokshi series: the Chishte mouth	51°44′N 87°40′E	Biotite schist 94-114	Bi	5.09±0.102	349±7	
30	matrix, the Chulyshman midstreams	50°56′N 88°11′E	Mica schist 95-76-1	Bi			312±1
31	-- // --	-- // --	Mica schist 95-76-2	Bi			309±3
Actinolite-barroisite schists, the Teletsk zone, Gorny Altai							
32	Shear zone around the Biya source	51°45′N 87°09′E	Metaschist B 970	Amph	0.17±0.05	383±17	
Metamorphic rocks of the Chagan-Uzun ophiolitic massif, Gorny Altai							
33	Blocks in serpentinitic melange	50°07′N 88°20′E	Eclogite 965A	Amph	0.23±0.01	535±24	
34	-- // --	-- // --	Eclogite 95-124-3	Amph			636±10
35	-- // --	-- // --	-- // --	Amph			627±5
36	-- // --	-- // --	Garnet amphibolite 92-1-25	Amph	0.24±0.01	487±22	
37	-- // --	-- // --	-- // --	Amph	0.28±0.08	473±13	
38	Metamorphic sole of ophiolites	50°08′N 81°20′E	Amphibolite 94-127	-- // --	0.16±0.01	523±23	
39	Blocks in serpentinitic melange	50°07′N 88°20′E	Greenschist 93062213	Chl	0.32±0.02	540±24	
40	-- // --	-- // --	-- // --	Mu	2.67±0.01	567±11	
The Chara zone, East Kazakhstan							
41	Blocks in serpentinitic melange, Baturinka Vil.	49°24′N 81°54′E	Garnet amphibolite 930627, 93062906	Mu	8.6±0.17	431±6	
42					6.47±0.17	429±6	
43					8.50±0.17	437±6	
44					8.47±0.17	432±6	
45	-- // --	-- // --	Blueschist 930627	Mu	7.79±0.16	440±5	
46					8.36±0.17	444±7	
47	-- // --				8.58±0.17	445±7	

Note: Amph=Amphibole, Bi=Biotite, Mu=Muscovite.

The dates 3-7, 9-11, 15-21, 23-25, 27, 29, 32-33, 36-47 have been obtained in Okayama University, Japan, by Buslov M.M., Watanabe T. and Itaya T. the dates 1-2, 8, 12-14, 22, 28, 30, 31, 34, 35 have been obtained in the UIGGM SB RAS by Travin, A.V.; the date 26 has been obtained in Brussels University by B. Dehandschutter.

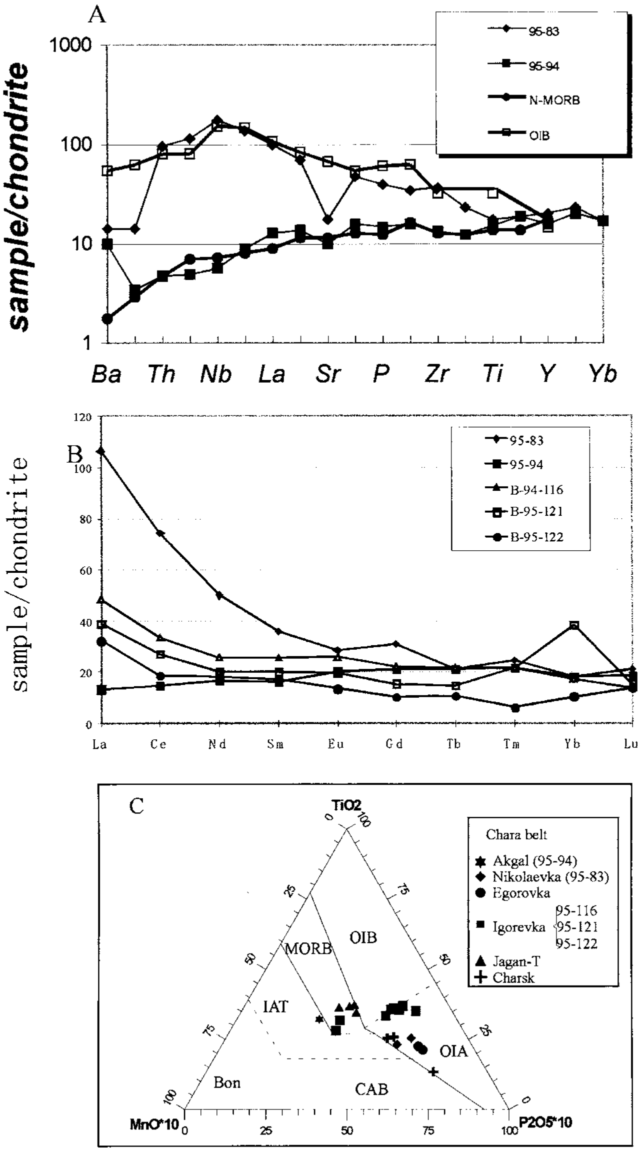

Fig. 9. (**A**) Trace element concentrations in the Chara rocks normalized to the composition of the primordial mantle. The normalizing values and average N-type MORB and OIB concentrations are taken from Rollinson (1993). (**B**) Rare earth element abundances in the Zasurin rocks normalized to chondritic meteorite values. (**C**) The $MnO-TiO_2-P_2O_5$, discrimination diagram for the Chara rocks. The fields are MORB; OIT=ocean-island/seamount tholeiite; OIA=ocean-island/seamount alkali basalt; CAB=island-arc calc-alkaline basalt; IAT=island-arc tholeiite; Bon=boninite. Sampling points see in Fig. 8.

the compositional points are in the MORB, oceanic island tholeiite (OIT) and oceanic island alkaline (OIA) basalt fields. The multi-element spider diagram and REE patterns show that they are close to N-MORB and OIB. The formation of the Type I mélange, thus, ranges probably from the Cambrian–Early Ordovician to the Early Carboniferous.

The Type II mélange, Ordovician ophiolitic melange, (legend 2 in Fig. 8), contains blocks of oceanic crust–basaltic lavas and layers of siliceous mudstone and chert with radiolarians of the Middle Devonian–Early Carboniferous age (Iwata et al., 1996). The lavas are high-Al and high-Ti alkali plagiobasalts of tholeiitic low-Ti basaltic series (Polyansky et al., 1979), which formed at mid-oceanic ridges. Compositionally, similar ophiolites are found in west Junggar. The Chara ophiolitic belt extends over a distance of more than 250 km along a fault called Naila and consists of several ophiolitic bodies of Ordovician age: Barlik, Khongulenk, and Khebukesair (5 in Fig. 4) (Chi et al., 1993).

The Type III mélange, Late Carboniferous–Early Permian, (legend 3 in Fig. 8), separates tectonic sheets, which were brought to the fault zone from the margins of Siberian and Kazakhstan continents. They are traced into younger fault zones and dominate in the region, outlining the Chara ophiolite belt of tectonic sheets and blocks. The Type III mélange usually has a NW orientation and coincides with the strike of the Chara fault zone. The blocks inside the melange are also oriented in the same direction. The blocks are variable in composition and include the rocks from the subduction and ophiolite tectonic units.

2.5. Rudny Altai Terrane

Structure and paleomagnetic characteristics of the Rudny Altai terrane (Fig. 4) were under investigation. The Rudny Altai terrane is situated between the Irtysh and North–Eastern fault zones (Figs. 3 and 4). A Silurian (?)–Early Devonian oceanic crust was found at the base of the section (Gritsuk et al., 1995; Gutak, 1997). The rocks were metamorphosed under the greenschist facies conditions and compositionally can be divided into three types with descending order.

1) The oldest are mafic schists, which are overlain by the metamorphic schists formed after magmatic and sedimentary rocks. Those schists are in turn overlain by metamorphosed sandstones and mudstones (Korbalikha Formation) dated as Early Devonian (Lokhovian and Pragian) by phytoplankton and pollen remains (Gutak, 1997).

2) The Middle Paleozoic oceanic crust is overlain by Early Emsian carbonate-clay and polymictic sandstones that are regarded as fore-arc trough sediments (Gritsuk et al., 1995).

3) The youngest sediments overlying the Rudny Altai terrane are of Devonian–Carboniferous age. The Emsian–Early Givetian part of the section is composed of terrigenous rocks and reef limestones that were accumulated near an island-arc and contain the beds of tuff and polymictic intraformational sandstone and conglomerate.

Rudny Altai terrane sediments are very similar to those from the Salair terrane in the Emsian faunal composition (Yolkin et al., 1994).

2.6. Kalba–Narym and Tarbagatai Terranes

In the east, the Irtysh shear zone (No. 2 in Fig. 4) separates the Rudny Altai terrane from the Kalba–Narym terrane and adjacent terranes,which is composed mainly of Late Devonian–Early Carboniferous fore-arc trough and accretionary wedge units (Yolkin et al., 1994; Rotarash et al., 1982). The Kalba–Narym terrane is similar in lithology to the Rudny Altai terrane. Both terranes are assumed to be the fragments of a single active margin of the Siberian continent in the Late Paleozoic. They were offset many hundreds kilometers relative to each other along strike-slip faults probably due to the Middle Carboniferous–Permian collision of the Kazakhstan and Siberian continents. The thickness of metamorphic units indicates a 1000 m strike-slip offset for the Irtysh shear zone (Sengor et al., 1994). In turn, the Chara ophiolitic suture separates the above noted terranes from the Devonian–Early Carboniferous rocks of the Tarbagatai terrane along the Chingiz–Tarbagatai strike-slip fault (see Fig. 4) belonging to the Kazakhstan continent.

3. GEODYNAMIC EVOLUTION OF THE PALEO-ASIAN OCEAN AND PALEOTECTONICS OF ALTAI-SAYAN REGION

New data and past publications show that the present mosaic-block structure of Central Asia resulted from several accretion and collision stages. This region is special for the occurrence of large-scale strike-slip faults (up to several thousand kilometers) caused by subduction and collision of seamounts and island-arcs. The results of our recent investigations and already published papers on the paleogeography of the Paleo-Asian Ocean (Zonenshain et al., 1990; Berzin et al., 1994; Buslov and Kazansky, 1996; Mossakovsky et al., 1993; Sengor et al., 1993; Didenko, 1997; Didenko et al., 1994; Pechersky et al., 1994; Scotese and McKerrow, 1990; Khramov and Pechersky, 1984; McKerrow et al., 1992; Buslov et al., 2000) allowed us to advance a new tectonic model for the Vendian–Paleozoic geodynamic evolution of ASR. Five geodynamic stages can be recognized as described later (**3.2.**).

Table 2. Paleomagnetic directions of East Kazakhstan and Gorny Altai Paleozoic terranes.

No.	Object Latitude and longitude	Age	N	Dc	Ic	α95	Da	Ia	α95	PL
	Gorny Altai terrane: active margin formations									
1	Kurata Formation, Kislaya River: lavas, tuffs, sediments, 51°20′N, 85°40′E	D_2gv_1	9	205	69	12	82	41	8	23 N Lt
2	Kurata Formation, Ursul River: lavas and sediments 51°20′N, 85°40′E	D_2gv_1	7	269	55	11	80	44	10	26 N Lt
3	Taldytyurgun Formation, Sukhoi Tydtugem River: red-coloured sandstones and tuff-sandstones 50°11′N, 88°12′E	D_1em	4	61	42	15	86	49	10	30 N Lt
4	Taldytyurgun Formation, Sukhoi Tydtugem River 50°11′N, 88°12′E	D_1em	4	44	59	89	88	45	8.9	27 N Lt
	Altai-Mongolian terrane: island-arc formations									
5	Sebystai Formation, Kyzyl-Shin River: sandstones 49°58′N, 89°04′E	D_1em	18	104	31	-	225	3	8	1 N Lt
6	Sebystai Formation, Kyzyl-Shin River: sandstones 49°58′N, 89°04′E	D_1em	6	52	35	-	221	9	8.7	4 N Lt
7	Ulandryk Formation, Chagan-Burgazy River: sandstones 49°50′N, 88°41′E	D_1em	6	346	10	30	338	-4	7	2 N Lt
8	Ulandryk Formation, Chagan-Burgazy River: sandstones 49°50′N, 88°41′E E	D_1em	5	10	13	18	24	9	14	4 N Lt
	Rudny Altai terrane: island-arc formations									
9	Zavod Formation , Zmeinogorsk: tuff 51°10′N, 82°13′E	D_2gv	5	145	-67	73	244	37	13	21 N Lt
10	Zavod Formation , Zmeinogorsk: tuff 51°10′N, 82°13′E	D_2gv	6	48	-8	53	73	-36	22	20 N Lt
11	Berezovo Formation, Zmeinogorsk: tuff-sandstones, 51°10′N, 82°13′E	D_1em	4	174	-41	59	99	-46	14	28 N Lt
12	Keisa and Kaigenbulak Formations, Zaisan	C_{2-3}	66	340	-55	7	288	-54	4	35 N Lt
	Zharma-Saur terrane: active margin formation									
13	Izhmenei Formation, Zaisan	D_2^2-D_3^1	47	311	-14	12	310	-47	9	28 N Lt
	Gorny Atai teranw : Charysh-Terekta scaly structure									
14	Ophiolites (Zasurin Formation)	Є$_3$-O$_1$	6	153	-14	64	173	7	20	4 N Lt
15	Turbidites of the fore-arc trough (Suetkin Formation), Ust'-Chagyrka Village: sandstones	Є$_2^2$ - Є$_3$	6	60	60	8	42	42	11	24 N Lt

Note: paleomagnetic directions were defined as a result of component analysis (ZD) and by large-circle method (CG); N=number of samples; D=inclination; I=dip; c=in modern coordinates, a=in ancient coordinates; α95=confidence angle (Fischer statistics); PL=paleo-latitude. Object No. 1-5 from Buslov and Kazansky (1996); 6-11, 14, 15=new data got by Fujiwara , Hokkaido University, Japan; 12-13=data by Didenko et al. (1994), Didenko (1997).

3.1. Paleomagnetic Study

Here we compile our results (Tables 2 and 3) and previous plaeomagonetic studies from Vendian to Early Carnobiferous. The data hold a key for undestanding lateral movements of terranes in ASR. Tectonic interpretation will be followed in the next section (**3.2.**).

3.1.1. Vendian–Early Cambrian

Correlation of paleomagnetic and geological data on the terrane of the Caledonian accretion–collisional structure (Kazansky et al., 1998) has been carried out. Vendian–Early Cambrian seamounts, Late Riphean (?)–Early Cambrian oceanic ophiolites occurring in the Early Cambrian accretionary prism, and the formations of the Vendian primitive island arc and Cambrian back-arc basin in the Gorny Altai terrane have been studied. Three heterochronous magnetization components were recognized in the course of laboratory investigations: *A*–prefolding (close to initial magnetization), *B*–cofolding (related to the earliest folding stage), and *C*–postfolding. Comparison of the paleomagnetic poles calculated in these directions with the trajectory of the apparent wandering of the paleomagnetic pole of the Siberian continent, along with the geodynamic and structural peculiarities of the region under consideration and new geochronological data, suggests that component *A* (Early Cambrian) corresponds to the period when the Biya–Katun and Baratal seamounts (see Buslov et al.,1993) collided with the Uimen–Lebed' primitive island arc of the Kurai belt (see Fig. 1 and Buslov et al., 1993); component *B* (Late Cambrian–Early Ordovician) is a metachronous magnetization; component *C* resulted from large-scale strike-slip faulting and thrusting in the region in the end of the Paleozoic. Since the beginning of the Cambrian, the studied fragments of the Gorny Altai terrane were the elements of the Kuznetsk–Altai island-arc system located within 12–36°S (Table 2) and outlining the northeastern (in the ancient coordinates) margin of the Siberian continent. By the beginning of the Ordovician, the island-arc system had the same latitude with the Siberian continent (component B in Table 1), i.e amalgamation with the continent. At that time the system moved northward to 7–18°S. Rotation of the system was discussed in comparison of the results on the Siberian continental margin and the terrane was turned 30–40° counterclockwise (Kazansky et a., 1998).

3.1.2. Late Cambrian–Early Ordovician

Our paleomagnetic data on the Late Cambrian–Early Ordovician oceanic lavas of the Zasurin Formation (Table 3, Charysh–Terekta structure), northwestern Gorny Altai, show that they formed at 4±10°N. The Middle–Upper Cambrian turbidites of the Suetkin Formation (Inya tectonic zone), the northwestern Gorny Altai terrane, formed at 24 ±9°N (Table 3, Charysh-Terekta structure). The data indi-

Table 3. Paleomagnetic data from the Vendian–Cambrian Complexes of Gorny Altai.

No.	Objects Latitude and longitude	Age	Component	N	Method	Dg	Tg	α95 g	Kg	Ds	Is	α95s	Ks	R,%	PL
1	Early Ordovician molassa 52°04′N, 87°06′E	O_1	B	7	GC	136	-49	6.3	23	157	-20	6.3	23	0	10 S Lt
2	Anui-Chuya fore-arc trough: conglomerate pebbles 50°14′N, 87°43′E	Є_3	B	7	ZD	117	-75	10.1	27	142	-23	10.1	27	70	12 S Lt
3	Biya-Katun paleoseamount: pillow-lavas 52°06′N, 85°54′E	Є_1^1	A	8	ZD	207	-76	7.3	46	112	-29	7.3	46	25	21S Lt
4	Marginal sea spreading complex: sills 51°48′N, 87°10′E	Є_1	A	17	ZD	35	-77	9.9	12	101	-37	9.9	12	75	21 S Lt
5	-- // -- 51°48′N, 87°10′E	Є_1	B	12	ZD	167	-55	6.5	39	144	-14	6/5	39	85	7 S Lt
6	Primitive island-arc: JV - complex of dikes and sills 50°14′N, 88°35′E	V-Є_1	A	9	ZD	79	46	4.8	96	80	-29	4.8	96	10	15 S Lt
7	-- // -- 50°14′N, 88°35′E	V-Є_1	B	6	ZD	136	20	11.2	26	138	-33	11.2	26	50	18 S Lt
8	dikes and sediments, 50°14′N, 88°35′E	V-Є_1	A	7	GC	136	-48	4.3	15	65	-55	4.3	15	20	36 S Lt
9	"dike in dike" complex, 50°14′N, 88°35′E	V-Є_1	B	7	ZD	153	-24	15.5	12	148	-29	15.5	12	50	15 S Lt
10	Ophiolites, V: pillow-lavas 50°15′N, 87°53′E	V	A	9	ZD	47	67	11,2	23,5	117	-41	11,2	23,5	85	23 S Lt
11	Baratal paleoseamount : pillow-lavas 50°15′N, 87°53′E	V	A	3	GC	83	-40	7,7	109	108	-30	7,7	109	100	16 S Lt

Note: N=number of samples; method=method of ChRM determination (ZD=component analysis, GC=large-circles method); D=inclination, I=dir, α95=confidence angle, K=clustering: g=in the modern, s=in the ancient coordinates; R(%)=percentage of samples with reverse polarity, PL=paleo-latitude; component B=Early Ordovician remagnetization (No. 1-11 from Kazansky et al., 1998).

cate a rapid and northward accretion of the oceanic crust.

3.1.3. Early–Middle Devonian

Paleomagnetic study for Devonian rocks (Emsian and Givetian) were carried out from four different terranes: the Gorny Altai, Altai–Mongolian, Rudny Altai and Zharma–Saur terranes (northeastern side of the Tarbagatai terrane, marginal part of the Kazakhstan continent) (Table 3).

The Gorny Altai: Taldytyurgun sandstones and tuffs (Emsian time) and Kuratin lavas, tuffs and sediments (Early Givetian time) lithologically indicate Siberian continent active margin units and the paleolatitudes of the Emsian and Early Givetian units are 27–30° and 23–26°N, correspondingly. As shown in Table 3, the Gorny Altai active margin was situated at the southeastern border of the Siberian continent (25±10°N).

The Rudny Altai: According to paleomagnetic data on the Devonian stratotype section near Zmeinogorsk (Table 3), Emsian sandstones and mudstones of the Berezov Formation formed near 28°N, and Givetian tuffs of Zavod Formation at 20–21°N. The Rudny Altai active margin extends northeastwards. In the Middle–Late Devonian the Rudny Altai active margin was situated at 32°N (Burtman et al., 1998).

Tarbagatai terrane: Paleomagnetic studies of the Early-Middle Devonian volcanic-sedimentary belt in Central Kazakhstan showed that it formed at 21–24°N (Grishin et al., 1997). The northern and northeastern segments of the belt had NS strike in the ancient system of coordinates, and the southeastern segment–EW strike, suggesting a sinistral drag from the northeast.

The Altai–Mongolian terrane: The Emsian volcanic-arc formed over the terrane basement and was located near the equator, around 1–4°N.

Siberian continent: In Emsian time, the Siberian continent rotated clockwise (Pechersky et al., 1994). In Givetian time the EW–trending Siberian continental margin was located at 20°N. The Berezovo Formation (Rudny Altai) of Emsian age, fore-arc trough of the Salair–Altai active margin, at 27–30°N. The Rudny Altai terrane is assumed to move along the Siberian continent.

3.1.4. Late Devonian–Carboniferous

In the Late Devonian, the terranes approached the Siberian continent and the paleolatitude of the Rudny Altai terrane, Givetian tuffs indicates that Devonian active margin was located near 20°N. The Tarbagatai terrane (or Chingiz–Tarbagatai terrane) and Rudny Altai active margin terrane are assumed to have traveled around 650–1650 km before they met (Burtman et al., 1998).

As in the Early Devonian the Altai–Mongolian terrane was located near equator (1–4°N), The difference of paleolatitude between the Alltai–Mongolian and Kazakhstan continents defines a total rate of sinistral strike-slip displacement along the Chara and Irtysh zones (see Fig. 4). The drift velocity during Devonian (the range is from the end of D_1 to the beginning of D_3: approximately 10 my) is estimated to be about 20–25 cm per year (about a 2,000 km total displacement).

In the Late Devonian (Fransian) the Rudny–Altai island-arc active margin was located at about 20–21°N extending along the E–W trending margin of the Siberian continent. In the Late Devonian–Early Carboniferous time, the Kazakhstan continent together with the Zharma–Saur active margin (see Fig. 4) moved northeastward (28°N for D_2–D_3 and 35° N for $C_{2\text{–}3}$) and collided with the Siberian continent, which continued its clockwise rotation (Pechersky and Didenko, 1995).

3.2. Evolution of Paleo-Asian Ocean

In the Vendian the Paleo-Asian Ocean, which was opened by the breakup of Rodinia or successive tectonic movement, was situated between the Siberian and East Gondwana continents and was about 3000–4000 km across. Based on the above-described terranes in ASR, the following evolutionary processes can be envisaged. This comprehensive tectonic evolution is synthesized from the voluminous data published in Russian literature, however, it contains speculative ideas due to the lack of precise chronological and structural data. Even so, we herein present a hypothetical tectonic evolution (Fig. 10).

3.2.1. Vendian–Lower Cambrian: age of arc-trench system

In the Vendian–Early Cambrian the East Gondwana broke. Microcontinents and terranes (e.g., the Altai–Mongolian and Chulyshman terranes) were probably detached from East Gondwana and moved westwards, i.e. towards the central part of the ocean. Sediments probably accumulated in the East Gondwana marginal trough. At that time the Kuznetsk–Altai–Khantayshir island-arc system formed along the western and northern margins of the Siberian continent and the Tuva–Mongolian and Barguzin microcontinents were detached from the Siberian continent and several marginal seas formed (Simonov et al., 1994; Dobretsov et al., 1995; Kazansky et al., 1998). The Kuznetsk–Altai–Khantayshir primitive island-arc system with boninite-bearing ophiolites formed at the margin of the Siberian continent. Assumed hot spots within the Paleo–Asian Ocean were responsible for the formation of oceanic seamounts, such as Biya–Katun and Baratal described by Buslov et al. (1993) (see Fig. 3 for their locations; Kt and B). Seamounts or oceanic islands approached the subduction zone and collided with the island-arc in the Early Cambrian. This led to the closure of the subduction zone and induction of reverse flows in the accretionary wedge. Exhumation of metaperidotites and serpentinitic melange of the Chagan–Uzun Massif occurred along the island-arc slope. This resulted in the exhumation of high-pressure rocks to the surface and the jumping of the subduction zone. A nor-

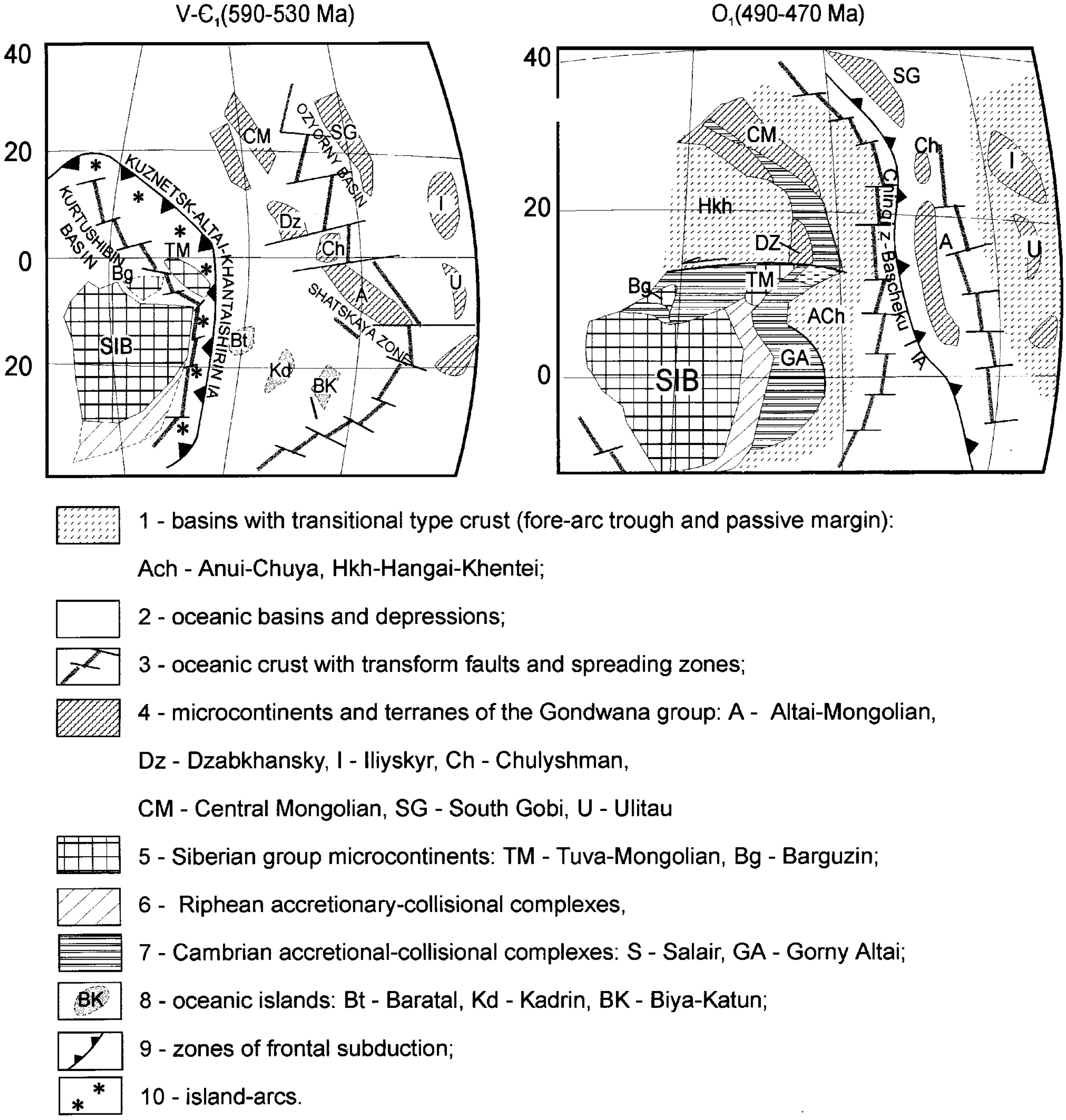

Fig. 10. Vendian–Cambrian geodynamic reconstruction of the Paleo-Asian Ocean (compiled geological, paleomagnetic data and Zonenshain's reconstruction (Zonenshain et al., 1990; Didenko et al., 1994; Didenko, 1997). 1=basins with the transitional type crust (fore-arc trough and passive margin): Ach=Anui–Chuya, Hkh=Hangai–Khentei; 2=oceanic basins and depressions: D=Dzhida and others; 3=oceanic crust with transform faults and spreading zones; 4=orogenic volcanic-plutonic complexes; 5=ophiolitic sutures; 6=microcontinents and terranes of the Gondwana group: A=Altai–Mongolian, Dz=Dzabkhansky, IJ=Iliysk–Junggar, K=Kokchetav, KIK=Kulundin–Kokchetav, SD=Syrdarja, T=Tarim, Ch=Chulyshman, CM=Central Mongolian, SG=South Gobi, U=Ulitau, HB=Hingan–Bureya; 7=Lawrasia group microcontinents: TM=Tuva–Mongolian, Bg=Barguzin; 8=Riphean accretionary-collisional complexes, 9=Cambrian accretional-collisional complexes: S=Salair, GA=Gorny Altai; 10=Middle Paleozoic accretion-collision belts; 11=residual and superimposed troughs: HKh=Hangai–Khentei, MT=Minusa–Tuva; 12=oceanic islands: Bt=Baratal, Kd=Kadrin, BK=Biya–Katun; 13=the zones of frontal (a) and oblique (b) subduction; 14=primitive island-arcs.

mal island-arc system formed during Middle–Late Cambrian time over the primitive island-arc system (Watanabe et al., 1993; Buslov et al., 1998b; Buslov and Watanabe, 1996) (Fig. 10; Table 3).

3.2.2. Early Ordovician: a collision stage

In the Late Cambrian–Early Ordovician time the Kuznetsk–Altai–Khantaishirin island-arc system and microcontinents of the Laurentia Group collided with the Siberian continent. The marginal seas closed and the Early Caledonian accretionary-collisional belt formed. Before that time, all those units moved northward, and consequently the Kuznetsk–Altai island-arc changed its location from 36°S to 7–18°S, and rotated counterclockwise by 30–40° (Kazansky et al., 1998). In a period from the Early Ordovician to the Early Devonian the subduction of the Paleo-Asian ocean beneath the Siberian continent attenuated and vanished. An extended carbonate-terrigenous shelf formed along the passive margin of the continent, whose remnants are well preserved in Gorny Altai (Yolkin et al., 1994). The subduction appeared and continued in the eastern side of a mid-oceanic ridge in the Paleo-Asian (Fig. 10). The sheets of the Late Cambrian–Early Ordovician oceanic crust and Early Ordovician fore-arc trough in Gorny Altai are probably fragments of the ocean, which separated terranes and microcontinents of the Gondwana Group and the Siberian continent. Collision of the Altai–Mongolian terrane with the Siberian continental margin (Gorny Altai) caused the deformations of island-arc units, which split into tectonic sheets at the frontal part of the island-arc.

3.2.3. Early–Middle Devonian: formation of reactivated suture zones

In NW Gorny Altai an island-arc system (Chingiz–Baschelak system) has supposedly formed in the Ordovician–Silurian(Fig. 10). During Devonian time, fragments of the Ordovician–Silurian island-arc together with the Altai–Mongolian terrane were attached to the Siberian continent. This was accompanied by dextral displacements along the Charysh–Terekta fault zone (see Fig. 3), which led to the deformation of island-arc rocks and formation of a sheeted structure in the frontal part of the Altai–Mongolian terrane. In the Early Devonian the Paleo–Asian Ocean was split into several basins. The Ob'–Zaisan Ocean (basin) was situated between the Kazakhstan and Siberian continents and had a link with the South–Mongolian ocean. The Uralian Ocean bounded the East-European continent from the northwest. During Early–Middle Devonian time the oceanic lithosphere of the western Paleo-Asian Ocean (the Zaisan Ocean) subducted beneath the Siberian and Kazakhstan continents. A wide volcano–plutonic belt (Salair–Altai) formed at the southeastern margin of the Siberian continent. The Zharma-Saur island-arc formed at the northwestern margin of the Kazakhstan continent (see Fig. 4 for the location). The Altai–Mongolian and Chulyshman terranes were presumably situated far from the Siberian and Kazakhstan continents–at the southeastern margin of the Uralian Ocean. In the Early Devonian the Altai–Mongolian and Chulyshman terranes collided and a single Altai–Mongolian–Chulyshman terrane was formed. This was accompanied by the formation of the Kurai, Chulyshman and South-Chuya granite–gneiss complexes (see Table 1 for ages). In the Late Devonian, collision of terranes and marginal-continent units induced dextral strike-slip faulting (Charysh–Terekta, Kuznetsk–Kurai and other faults), which was responsible for the formation of Late Devonian–Early Carboniferous shear zones (Buslov and Sintubin, 1995; new data). The dextral strike-slip faulting took place along the margin of the Siberian continent, thus provoking the detachment of the terranes.

In the Late Devonian (Frasnian) the Rudny–Altai island-arc active margin was located at about 20–21°N extending along the EW-trending margin of the Siberian continent. In the latest Devonian the Altai–Mongolian terrane migrated to the same latitudes and collided with the Altai–Sayan zone of the Siberian continent. The subsequent subduction of the Ob'–Zaisan oceanic crust resulted in an oblique collision of Gondwana-derived terranes along the Siberian continental margin, formation of the Charysh–Terekta zone, and faulting and thrusting in the Altai–Sayan region. In the Middle–Late Devonian the Kazakhstan plate together with Altai–Mongol–Chulyshman terrane moved westward and rotated clockwise. This movement resulted in the attachment (and further collision) of the Altai–Mongolian terrane and partly the Chingiz–Baschekul island-arc to the Siberian continent. In the latest Devonian the Altai–Mongolian terrane started sliding along the convergent margin of the Siberian continent and split into several blocks (Altai–Mongolian, Talitsa, Chulyshman).

The main event of the second stage was the sinistral faulting, which occurred along the North–Eastern shear zone and the Baschelak fault (see Fig. 3). This fault initially was responsible for the formation of the geological structures, which were broken later, and in ASR as a result, the Rudny Altai terrane was attached to the Salair, Gorny Altai and Altai–Mongolian terranes.

3.2.4. Late Devonian–Early Carboniferous: successive collision and lateral displacement

In Late Devonian–Early Carboniferous time, the Kazakhstan continent together with the Zharma–Saur active margin moved northeastward (28°N for D_2–D_3 and 35° N for C_{2-3}) and collided with the Siberian continent, which continued its clockwise rotation (Pechersky and Didenko, 1995). The Rudny Altai and Zharma–Saur island-arcs formed in the Late Devonian.

In the Early Carboniferous the Ob'–Zaisan Ocean crust subducted beneath the Siberian and Kazakhstan continents (Iwata et al., 1997). In the Late Carboniferous the Ob'–Zaisan Ocean closed due to the collision of the Baltica, Kazakhstan and Siberian continents. In Early Carboniferous time, the Altai–Mongolian terrane accreted to the Rudny Altai back-arc area, and northward compression of the Chulyshman terrane formed the Kuznetsk–

Kurai and other dextral strike-slip faults at the margin of the Siberian continent. In Rudny Altai, volcano-plutonic island-arc units formed in the Late Devonian and Early Carboniferous.

3.2.5. After Late Carboniferous: closure of the Paleo-Asian Ocean

In the Late Carboniferous–Permian the Ural–Mongolian and Ob–Zaisan Ocean branches of the Paleo-Asian Ocean closed. The Baltica, Kazakhstan and Siberian Continents amalgamated to form a large landmass. According to paleomagnetic data (Didenko et al., 1994; Pechersky and Didenko, 1995) the East European (Baltica) continent rotated counterclockwise, and the Siberian Continent rotated clockwise. This collision created a prototype of the northern Eurasia continent resulted in the formation of ASR and the Chara, West Junggar and Chingiz–Tarbagatai fault zones in Kazakhstan. The Kalba–Narym and Rudny Altai terranes form a NS-trending linear zone, which is well traced into the Kurchum–Irtysh and North–East shear zones. The largest sinistral strike-slip faulting events occurred along those zones (Fig. 4). They were responsible for the re-activation of older faults in Kuznetsk Alatau, Gorny Altai, and western Mongolia (Buslov and Sintubin, 1995; Buslov, 1998). The greatest displacements occurred along the Kuznetsk–Teletskoye-Khangai–Khentei sinistral marginal strike-slip faults. The adjacent structures of Salair, Gorny Altai and West Mongolia are located between the main fault system and the marginal ones.

The rate of horizontal displacement along the Irtysh and Kuznetsk fault zones was estimated to be about 1,000 km (Sengor et al., 1993; Burtman et al., 1998) and 120 km, respectively (Zonenshain et al., 1990). The rate of sinistral displacement along the Teletsk–Khangai–Khentei fault was estimated to be 200 km judging from the displacement of the carbonate cover of the amalgamated Tuva–Mongolian and Dzabkhan microcontinents and their adjacent Cambrian suture zone. According to the above mentioned data the rate of horizontal displacement between the Irtysh and Kuznetsk –Teletskoye–Khangai–Khentei fault zones can be estimated as 200–1,000 km; the greatest ones being expected in the Chara zone.

Most investigators (e.g., Ermolov et al., 1981; Rotarash and Gredyushko, 1974) consider the Chara belt an ophiolitic suture of the Ob–Zaisan oceanic basin. We believe that it is a main strike-slip zone between the Late Paleozoic Kazakhstan and Siberian continents composed of accretionary terranes of different ages.

Judging from the paleomagnetic results and types of igneous activity and related basin structure, the collision of the Kazakhstan and Siberian continents occurred during the closing of the Paleo-Asian Ocean (Middle Carboniferous). The mosaic of terranes, which was formed due to the Middle Carboniferous–Permian collision of the Siberian and Kazakhstan continents, is shown in Figures 3 and 4.

The intrusion of granites occurred in East Kazakhstan and NW Gorny Altai in the Late Carboniferous and Permian. This resulted in the formation of the continental crust of the Northern Eurasia continent. The post-orogenic mollasse sediments were transported from hilly areas and filled intermontane and lowland basins (Berzin et al., 1994; Iwata et al., 1999). Late Permian–Early Triassic granitoids intruding those three terranes provide a good evidence for large-scale displacements in the region. Triassic–Jurassic deformations of the third stage had less influence on the Late Paleozoic geological structure of Rudny Altai and Gorny Altai and resulted in low-amplitude strike-slip faults breaking the Late Permian–Early Triassic granitic bodies.

4. SUMMARY

The collaborative studies showed that many tectonostratigraphic units of the Altai–Sayan region were reoriented relatively to their primary position most probably due to Late Paleozoic large-scale faults. Those strike-slip faults separate the amalgamated terranes, which cannot be regarded as fragments of marginal-continental paleotectonic zones with primary (direct) paleogeographic zonations. The paper deals with two subjects: 1) terrane classification and 2) speculative tectonic evolution in ASR.

1) In this paper we proposed newly defined terrane classification in ASR. The Gorny Altai and Altai–Mongolian terranes and the Chara ophiolite belt in the Kazakhstan continent, and the Rudny Altai, Kalba–Narym and Tarbagatai terranes are introduced. Description of the Gorny Altai terrane is presented in detail. The terrane preserves the best components of the Vendian-Cambrian arc trench system. The terrane was reactivated in the Devonian and Carboniferous along the western and south-eastern boundaries of the terrane. A detailed geological map of the reactivated suture zone (Fig. 5) is presented. Another reactivation zone of the Chara ohiolite belt is introduced.

2) The above classification, new chronological (isotope and biostratigraphical) data, and paleomagnetic data allowed a new interpretation of the geodynamic evolution and tectonics of Central Asia. Based on these data, mosaic structure of the terranes attributes to large lateral displacements due to the essential collision among arcs, seamounts, microcontinents and the Siberian and Kazakhstan continents. Some of paleomagnetic data from neighboring terranes indicate a large-scale displacement along the shear zones, but our structural research has not been completed yet. In this paper we show a hypothetical idea on the lateral displacement under discussion. Thus, our interpretation on the tectonic evolution in ASR is rather speculative, but it would be worth to regard as a working hypothesis.

A Summarized Story is Following

The research activities of our team made possible the interpretation of the evolution of the Paleo-Asian ocean. The data on stratigraphy and composition of Paleozoic tectonic units–oceanic island units, ophiolites, olistostromes (or mélange), and high-pressure metamorphics–have been interpreted. The collision of terranes was responsible for the generation of reverse flows in accretionary prisms during the subduction, and exhumation of high-pressure rocks to the surface. The closure of the Paleo-Asian Ocean (the Ob'–Zaisan Ocean) occurred later than that it was reported before, namely, at the Early Carboniferous-Middle Carboniferous boundary. Paleo-ocean-island terranes are found within ophiolitic belts. Microcontinents and terranes were attached to the Siberian continent and successively deformed its margin during the subduction of the oceanic lithosphere. The obtained data suggest the important role of strike-slip deformations in the formation of mosaic-block structure of Central Asia. Those complicated and multi-stage deformations resulted from the Late Devonian–Early Carboniferous collision of Gondwana group terranes. The deformations reached their peak in the Late Carboniferous–Permian due to the collision of the Kazakhstan, East-European (Baltica) and Siberian continents. A system of sinistral strike-slip faults formed at the margin of the Siberian continent and ASR as a result of the Late Carboniferous–Permian collision. The Altai–Mongolian terrane, which once was a part of the Gondwana Group in Rodinia, had its leading role in the formation of the Late Devonian–Early Carboniferous strike-slip faults in ASR. Their structural position shows that the Junggar, Tarbagatai, Zharma–Saur and Chara zones are fragments of a unique Paleozoic accretionary complex, which was strongly deformed by Late Carboniferous–Early Permian sinistral strike-slip faults.

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