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Late Paleozoic-Early Mesozoic Geodynamics of Central Asia

M.M. Buslov[1], Y. Fujiwara[2], K. Iwata[2] and N.N. Semakov[1]

[1] *Institute of Geology, Russian Academy of Sciences, Siberian Branch, 630090, Koptyuga ave. 3, Novosibirsk, Russia, E-mail: misha@uiggm.nsc.ru*

[2] *Division of Earth and Planetary Sciences, Graduate School of Hokkaido University, 060-0810, Sapporo, Japan, E-mail: fujiwara@ep.sci.hokudai.ac.jp*

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Abstract

Correlation and synthesis of published and new structural, paleomagnetic and geochronological data from Central Asia show the important role of strike-slip faulting in their evolution. The pattern of major strike-slip faults outlines a terrane collage produced by a Late Devonian-Early Carboniferous collision of the Gondwana-derived Altai-Mongolia-Tuva composite microcontinent with Siberia, and a Late Carboniferous-Permian collision of East Europe and Kazakhstan, with Siberia. The accreted continental margins were cut by strike-slip faults and conjugate thrusts into numerous terranes, which mixed with one another and disturbed the previous structural and facies framework.

Those complex 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, East-European (Baltica) and Siberian continents. A system of sinistral strike-slip faults formed a mosaic-block structure of Central Asia along the margin of the Siberian continent as a result of the Late Carboniferous-Permian collision. This resulted in the formation of the Northern Eurasia continent. Early Mesozoic strike-slip faulting and conjugate thrusting resulted from the rotation of the Siberian and East European cratons.

Key words: geodynamics, geochronology, paleomagnetism, Altai-Sayan, Central Asia.

Introduction

This article reviews and integrates new results and previously published studies of the Late Paleozoic-Early geodynamics and tectonics of Central Asia. New structural, geochemical, geochronological, paleontological, and paleomagnetic evidence from East Kazakhstan, Altai-Sayan and Mongolia shows the important role of large-scale strike-slip motion in their evolution. Horizontal movements appear to have been multi-stage and more complex than previously believed. The mosaic structure of the Central Asia can be best explained by the plate tectonic concept of a collage of terranes.

Tectonic Setting and Geodynamics of Central Asia

In spite of many studies by different authors (Zonenshain et al., 1990; Berzin and Dobretsov, 1994; Berzin et al., 1994; Dobretsov et al., 1995; Mossakovsky et al., 1993; Didenko et al., 1994; Sengor et al., 1993) details of the geodynamic history of the Paleo-Asian Ocean have yet to be solved. The existence of microcontinents and terranes of Gondwana affinity in Central Asia is still under discussion, and detailed tectonic processes, namely age, kinematics and dynamics of fault zones have not yet been integrated.

The tectonic framework of Central Asia (Fig. 1) is made up of three main tectonic components, as outlined by Buslov et al. (2001, 2003):

(1) Precambrian microcontinents and terranes (Fig. 2), which are fragments of a Gondwana supercontinent (Mossakovskiy et al., 1993; Didenko et al., 1994; Pecherskiy and Didenko, 1995). In the Middle Paleozoic these fragments amalgamated and formed the Kazakhstan composite microcontinent, comprising the North Tien Shan, Ulutau, Kokchetav, Aktau-Mointin, Iliy and other Precambrian microcontinents, and the Altai-Mongolia-Tuva composite microcontinent, comprising the Altai-Mongolian terrane and the Tuva-Mongolian and Dzabkhan microcontinents. The amalgamation of the Precambrian microcontinents is recorded in collisional metamorphic and magmatic units dated as Ordovician-Early Devonian, as well as by the occurrence of nappe structures, olistostromes, and molasse.

(2) Terranes comprising fragments of Caledonian and Hercynian accretional-collisional belts, which were

detached from a parental block as a result of oblique subduction and collision of these terranes with the Siberian and East European continents.

(3) Strike-slip and oblique thrust faults that provide evidence of collisions of different ages. The periods of strongest deformation were in the Late Devonian, Early Carboniferous, Late-Carboniferous-Permian, Permian-Triassic and Triassic-Jurassic.

Late Paleozoic-Early Mesozoic Tectonics

New data on tectonics, paleomagnetism, geochronology, and paleogeography of the East Kazakhstan, Altai-Sayan and Mongolia call for some revision of previous ideas of their Devonian-Jurassic evolution. Our interpretation implies a key role for large-scale strike-slip faulting associated with multi-stage continental collision. Strike-slip faulting took place in the Late Devonian-Early Carboniferous during collision of the Altai-Mongolia-Tuva composite microcontinent with Siberia, and during the Late Carboniferous-Permian collision of East Europe and Kazakhstan with Siberia. As a result of these two collisions, the accreted continental margins were transected by strike-slip faults and conjugate thrusts into terranes which mixed with one another and disturbed the primary structural and facies framework associated with the evolution of the Paleo-Asian Ocean. Northward motion of East Europe and rotation of Siberia in Permian-Triassic and Jurassic time caused deformation within the continental areas of Altai-Sayan and East Kazakhstan.

A Late Devonian EW-striking suture zone comprising the Charysh-Terekta, Ulagan and Nortrh Sayan faults is an important boundary separating the Siberian continent from the Altai-Mongilia-Tuva composite microcontinent (Figs. 1,3). The Chara strike-slip zone of Late Carboniferous age is also an important structure separating the Kazakhstan and Siberian continents.

Altai-Sayan collision sutures: Gondwana-derived microcontinent, Siberia

Collision of the Altai-Mongolia-Tuva continent with the Siberian continent strongly influenced the evolution of the Altai-Sayan and East Kazakhstan regions. It occurred in two stages: oblique collision in the Late Devonian and frontal collision in the Early Carboniferous. The oblique collision produced the Late Devonian Charysh-Terekta and Ulagan suture zones (Fig. 1) composed of Precambrian-Eifelian rocks and exotic terranes (Zasur'ya, Charysh, and Uimon units) which are fragments of Late Cambrian-Early Ordovician oceanic crust, an Ordovician forearc basin, and a Middle Paleozoic subduction complex of high-pressure rocks first found in the Altai-Sayan area (Buslov, 1998; Buslov et al., 2001). The frontal collision produced the Late Devonian-Early Carboniferous Kurai and Teletsk-Bashkaus shear zones.

The units are separated by hundred meter-thick zones of sheared greenschists. Deformation and faulting in northwestern Gorny Altai can first be dated from the ages and distribution of plutonic rocks (Vladimirov et al., 1997). The Late Devonian (post-Emsian) imbricated structure associated with the right-lateral Charysh-Terekta strike-slip fault was intruded by the Late Devonian-Early Carboniferous Talitsa pluton and, together with the latter, is crosscut by Late Carboniferous-Early Permian left-lateral strike-slip faults of the North East and Bashkaus shear zones. The shear zones and the juxtaposed terranes are intruded by Late Permian-Early Triassic post-collisional plutons (230-255 Ma; Vladimirov et al., 1997). The sutures represent pre-Late Permian strike-slip faults (the Savvushki pluton and its satellite Volch'i Shkili pluton intrude the Rudny Altai terrane, the Sinyushin pluton cuts through the Altai-Salair terrane, and the Tigerets and Korovikha plutons cut the Altai-Mongolia terrane). This terrane collage was slightly reactivated in Triassic-Jurassic time, and strike-slip faults occasionally crosscut the Late Permian-Early Triassic intrusions.

The Charysh-Inya segment of the Charysh-Terekta zone is separated from the Anui-Chiya zone of the Salair-Altai terrane by the younger Bashchelak fault in the northeast, and grades southeastwards into the Terekta segment.

The Terekta segment in the central Gorny Altai (Fig. 4) is a Late Devonian imbricated structure cut by Late Devonian-Early Carboniferous strike-slip faults (Buslov, 1998; Buslov et al., 2000, 2001, 2003). Greenschist retrograde metamorphism associated with tectonic contacts and secondary schistosity give the impression of smooth transitions between the structural units of the segment. Greenschists are injected by island arc gabbro-diabases with 373±17 Ma K–Ar amphibole ages, which constrain the younger age limit of the structure. Its older age limit is indicated by the presence of the Eifelian rocks.

A section through the Terekta segment contains the following units (from northwest to southeast):

(1) Middle Paleozoic sandstones and shales are discordantly overlain by the Early-Middle Devonian Korgon volcaniclastics. Shales contain pollen of Middle Paleozoic plants. The sequence is flanked by green mylonite schists exposed in a 100–200 m wide strip that borders the Terekta Formation.

(2) Middle Paleozoic (?) Terekta Formation of metamorphosed volcanics and terrigenous carbonates of epidote-quartz-albite-chlorite and chlorite-albite-carbonate compositions, with interbeds and lenses of quartzite schist, marble, and metabasalt.

(3) Epidote-amphibolite and partly amphibolite facies

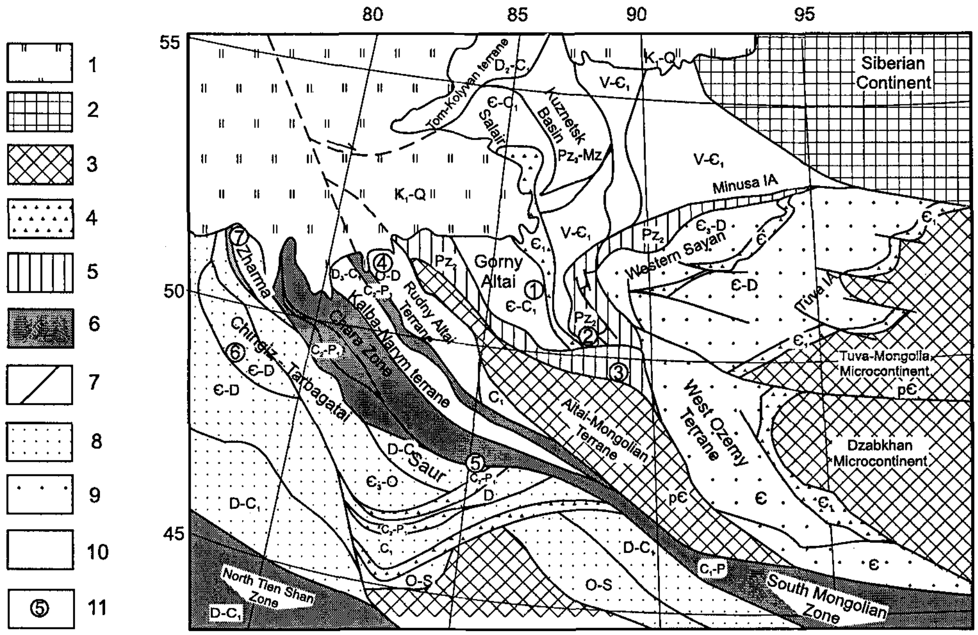

Fig. 1. Tectonic map of Central Asia (modified from Buslov, 1988).

rocks extend almost 100 km in a discontinuous strip. In the extreme east, the metamorphic rocks are known as the Turgunda complex. Biotite-amphibole schists have Early Silurian ages (415±3, 418±3, 418±2 Ma, Ar-Ar, amphibole) (Buslov, 1998; Buslov et al., 2001, 2003).

(4) Metavolcanic Uimon Formation (455–400 Ma metamorphism, K–Ar), has the same composition as the Terekta Formation in part, but also has a protolith containing up to 40–60% metavolcanic schists, and is devoid of carbonate (marl) schists. Typical glauconitic schists are associated with metabasaltic lavas and their tuffs which often coexist with quartz schists containing piemontite or less often riebeckite. Schists experienced retrograde metamorphism of different degrees and are altered into porphyroblastic albite-chlorite (±phengite, quartz) schists.

(5) Strongly cleaved and sheared Devonian deposits. Fragments of rocks similar to the Eifelian Kholzun Formation of the Korgon zone are found in the less deformed northern part of the segment.

(6) Cambrian-Ordovician ophiolites are mainly composed of siliciclastics and ultramafics. The latter are almost everywhere altered to serpentinite schists that enclose oval blocks of massive serpentinite, or less often serpentinized dunite, pyroxenite, gabbro, and rodingite.

(7) Early-Middle Ordovician tuffaceous sediments and Late Cambrian-Early Ordovician slate (lower sub-formation of the Sugash Formation) and volcanic (upper sub-formation of the Sugash Formation) sequences. The tuff-sedimentary sequence is composed of alternating (often with rhythmic bedding) tuffaceous siltstones and clays, tuffaceous sandstones, slates, and shales. The Charysh Formation in northwestern Gorny Altai may be its equivalent. Slates contain deformed remnants of radiolaria and are generally equivalent to the Cambrian-Early Ordovician Zasur'ya slates.

(8) A volcanic basaltic andesite sequence of Cambrian (?) age consists of interlayered pyroxene and plagioclase porphyry, basic variolitic lavas, their tuffs and tuffites, diabase, diabase porphyry, and gabbro-diabase dikes and sills, less often sandstones (mainly graywake) and silty schists. The composition of the volcanic rocks corresponds to the island arc calc-alkalic series (Berzin and Kungurtsev, 1996).

The Kurai zone of thrusts and strike-slip faults (Figs. 4, 5) is located in the southwestern surroundings of the Altai-Mongolia terrane (Chulyshman zone) and separates it from the Gorny Altai terrane. The zone is imbricated and includes mylonites and mélange. In the axial part of the Kurai Ridge, it consists of the main body and imbricates (Berzin et al., 1994) and is composed of Early-Middle Devonian metamorphics of the Kurai complex, Silurian and Devonian sediments and Vendian-Early Cambrian volcaniclastics. Thrust surfaces are often marked by serpentinites existing in the form of lenses of schist tens of meters wide and mono- and polymictic mélange. The main body of the zone is made up of the Kurai complex of Early Devonian epidote-amphibolite-facies gneissic granites, migmatites, gneisses and schists of various compositions, amphibolites and pegmatites, with K–Ar and Ar–Ar amphibole ages within the range of 394-365 Ma (Early Devonian-Frasnian) (Buslov et al., 2001, 2003). The complex, up to several kilometers thick, is exposed over an area 70 km long and 10 km wide, and forms a large anticline with steeply dipping (70–90°) southwestern limb and a shallower dipping (40–80°) eastern limb.

In plan view the major folds are anticlines that vary in shape from isometric to elongate domes, strongly tightened, often inverted or tilted, separated by long and narrow synclines with sharp periclinal hinges. The lineation of the metamorphic rocks mostly dips SE at 4–7°, less often 15–20°, indicating NW thrusting of the Kurai complex. Blastomylonites in most cases are parallel to the lineation and make up zones often associated with crenulation cleavage.

The exposed basement of the Upper Il'dugem block (Fig. 5) is composed of high-grade gneisse, schist, quartzite, and amphibolite making in plan view an ellipse with a 3 km short axis and a 20 km long axis. We investigated the southeastern termination of the block where its rocks make up an antiform truncated in the south by the Triassic-Jurassic (?) Kubadra Fault. Near the latter, the metamorphic rocks experienced foliation and retrograde metamorphism. Several strips of greenschists occur parallel to the main fault line and almost everywhere are bordered by serpentinite schists and mélange. They are overlain by thick Vendian-Early Cambrian terrigenous carbonates intruded by massive gabbro-diorite-plagiogranites and their dykes. In its northwestern part, the wedge contains several more thrust sheets composed of volcaniclastics derived from the Uimen'-Lebed' primitive island arc and separated by serpentinites.

The Kurai thrusting must have occurred in Late Devonian-Early Carboniferous (Tournaisian) time because Devonian rocks are cut by Early Carboniferous strike-slip faults, abundant in the southern periphery. Near the Kubarda Fault the thrust sheet is imbricated with mylonitized cataclastic metamorphics of the Kurai complex and sheared Vendian-Middle Cambrian volcaniclastics locally separated by serpentinitic mélange. The rocks of the Kurai complex are strongly mylonitized, and mylonites and blastomylonites are often accompanied by biotite schists, with K–Ar and Ar–Ar ages on biotite within a narrow range of 333–323 Ma (Visean) (Buslov et al., 2001, 2003). Microstructures (biotite lineation) indicate right-lateral strike-slip faulting along Visean shear zones.

The Permian-Triassic NW Kubadra and Il'dugem faults that cut the Kurai zone dip steeply to the northeast and have brecciated, quartz-enriched, and chloritized mylonites along their fault surfaces. Mylonites, in the Kurai allochthon and in the autochthon, are bordered by 5–10 m- thick epidote-chlorite, muscovite-quartz-chlorite and quartz-chlorite-talc zones in which distinct slickensides and striation indicate a reverse geometry of faulting.

Therefore, the Kurai shear zone contains evidence of several deformation stages. The Late Devonian-Early Carboniferous frontal collision of the Altai-Mongolia terrane with Siberia is recorded in thrust sheets and imbricates of Devonian schists and gneisses of the Kurai

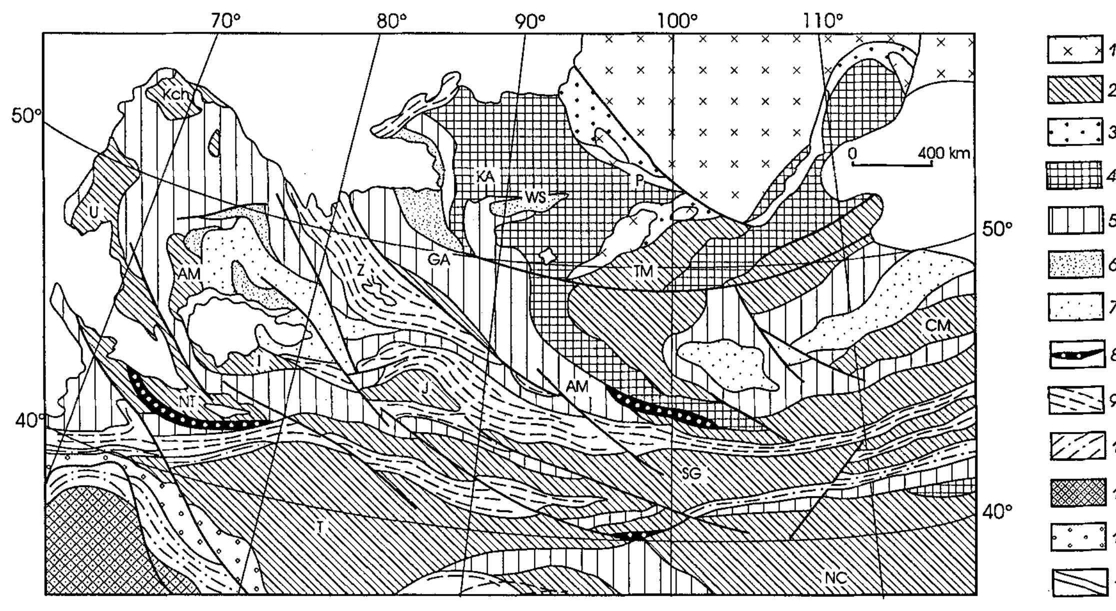

Fig. 2. Tectonic map of the Central Asian foldbelt (modified from Mossakovskiy et al., 1993). 1, 2–platforms and microcontinents: 1–Siberian platform, 2–Gondwana group (T–Tarim and NC– North China platforms, Kch–Kokchetav, U–Ulutau, AM–Aktau-Mointin, I–Iliy, NT–North Tian Shan, J–Junggar, TM–Tuva-Mongolian, CM–Central Mongolian, and SG–South Gobi microcontinents); 3-5–accretionary zones: 3–Late Riphean, 4–Salair (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–Zaysan), 10–Late Hercynian, 11–Mesozoic; 12–Predkunlun trough; 13–large faults.

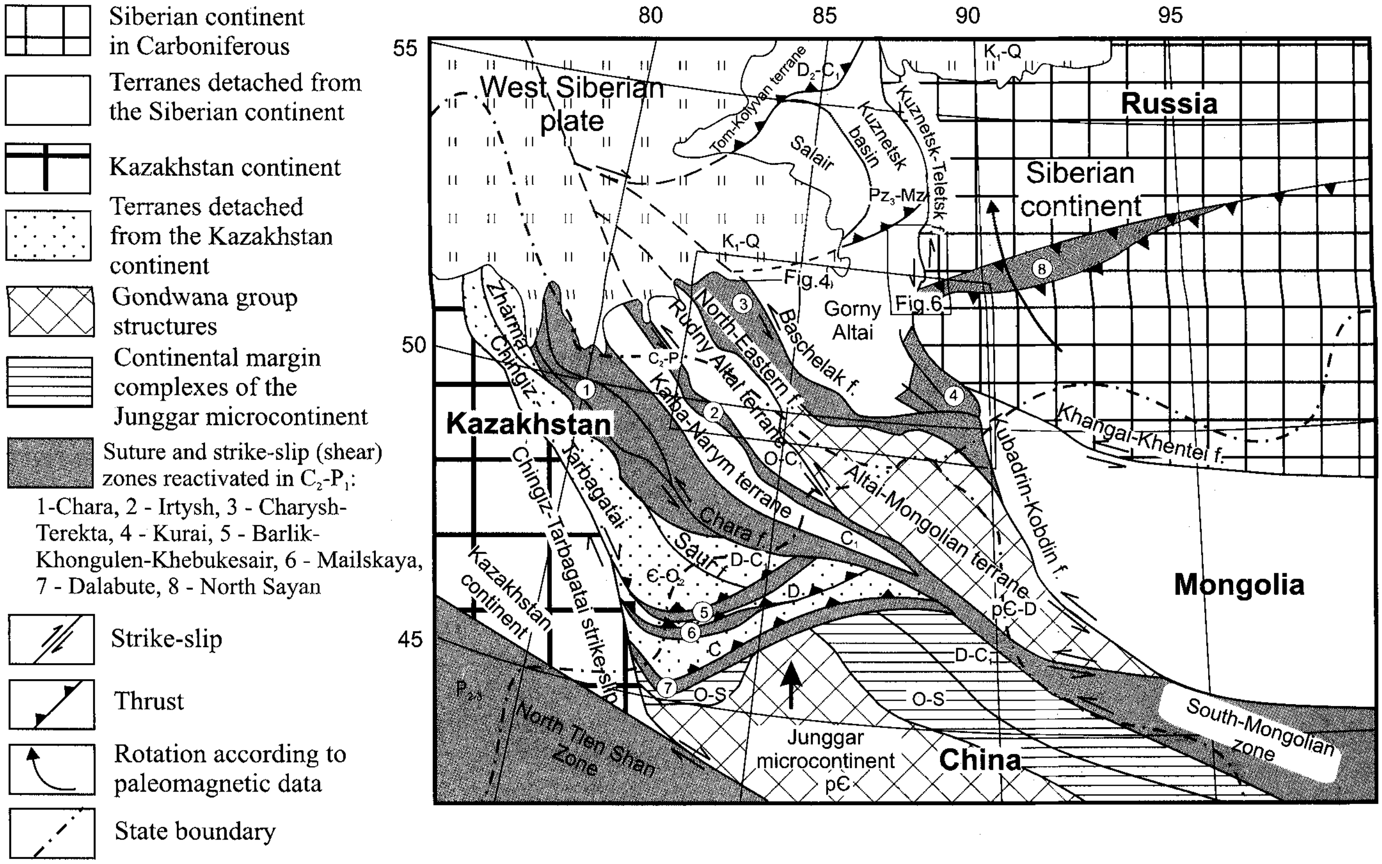

Fig. 3. Tectonic framework of terranes in the Altai-Sayan, East Kazakhstan and Western Junggar regions (modified from Buslov et al., 2003). 1–Siberian continent, 2–terranes rifted off Siberia, 3–Kazakhstan continent, 4–terranes rifted off Kazakhstan, 5–Gondwanian terranes, 6–continental-margin complexes of Junggaria terrane (microcontinent ?), 7–suture zones reactivated in Late Carboniferous-Early Permian (1–Chara, 2–Irtysh, 3–Charysh-Terekta, 4–Kurai, 5–Barleik-Honggulueleng-Hebukesair, 6–Mayila, 7–Dalabute, 8–Tangbale Ordovician ophiolites); 8 –strike-slip faults, 9–thrusts, 10–rotation, from paleomagnetic data, 11–political boundaries, 12–Cenozoic sediments.

complex, serpentinite schists and mélange, Silurian sediments and Devonian volcaniclastics, as well as in Early Paleozoic volcanics and sediments of the autochthonous Gorny Altai terrane. The Late Carboniferous (Visean) left-lateral strike-slip faults of the Kurai zone correlate well in age, geometry, and structural position with faults in eastern Gorny Altai, especially the well-documented Teletsk-Bashkaus shear zone.

Teletsk-Bashkaus shear zone

The eastern part of Gorny Altai (Fig. 5) includes three large terranes (Gorny Altai, Teletsk, and West Sayan) sutured by the Permian-Triassic Sayan and Early Carboniferous Teletsk-Bashkaus and Shapshal shear zones (Buslov and Sintubin, 1995; Sintubin et al., 1995; Smirnova et al., 2002). The Teletsk-Bashkaus Fault involves Early-Middle Devonian rocks, divides the Middle Paleozoic Ulagan-Erinat imbricated block into two segments, and displaces an Ordovician basin and ophiolite fragments by almost 80 km. Its Early Carboniferous age is constrianed by 343–309 Ma K–Ar and Ar–Ar mica and amphibole ages on metamorphic rocks (Buslov et al., 2001, 2003).

In the region of Lake Teletskoye the zone (Fig. 6) shows heterogeneous deformation and metamorphism. It includes two domains distinguished on the basis of metamorphic grade and orientation of main structures: the NW-striking greenschist Teletsk block (S, stereoplot I in Fig. 6) and the N–S striking epidote-amphibolite Chiri domain, located in the vicinity of Chiri Village (S, stereoplot II in Fig. 6) which has local HT metamorphism. Mineral lineation is distinctly horizontal, produced by extension, and marks left-lateral strike-slip faulting in the Teletsk block and is weak and parallel to schistosity in the West Sayan block, near Chiri Village (L, stereoplots in Fig. 6). Structure and metamorphism of rocks in the two segments reveal two tectonic and metamorphic stages in their evolution: (1) An Early-Middle Devonian stage that formed a fragment of zoned metamorphic complexes in the eastern part of Gorny Altai and (2) an Early Carboniferous stage of left-lateral strike-slip faulting along the greenschist Teletsk-Bashkaus shear zone.

According to our structural and geochronological data from the Teletsk region, the Early Carboniferous (Visean-Serpukhovian) and Permian-Triassic deformations were the most prominent (Figs. 5, 6). The earlier produced strike-slip and thrust faults observed on the margin of the Gorny Altai terrane and between the Teletsk and West Sayan terranes (Buslov and Sintubin, 1995; Sintubin et al., 1995; Smirnova et al., 2002). The fault trends correspond to a generally EW direction of compression (in the present frame of reference) and right-lateral strike-slip motion in the Teletsk-Bashkaus shear zone. The later deformation stage is most evident at the boundary of the Gorny-Altai and Teletsk-West Sayan terranes along a major shear zone associated with the Sayan Fault which truncates and deforms Early Carboniferous structures, and records a NS compression. The almost 90° swing in the direction of compression is evidence for dramatic restructuring of the Altai-Sayan region in Late Paleozoic time. This was a key episode in plate interaction associated with the Kazakhstan/Siberia collision and closure of the Paleo-Asian Ocean (Zonenshain et al., 1990).

Late Carboniferous-Permian faults: East Europe/Kazakhstan/Siberia collision

Deformation associated with the Late Carboniferous-Permian collision of East Europe, Kazakhstan, and Siberia was stronger than the earlier collision referred to above. It caused drastic change to the previous collisional pattern but remained relatively little affected by later activities.

Figures 1 and 3 outline the tectonic framework that resulted from this collision after closure of the Ural-Mongolia and South Mongolia arms of the Paleo-Asian Ocean. The pattern of strike-slip faulting in the orogenic belt formed in Kazakhstan was apparently controlled by a paleomagnetically-inferred counter-clockwise rotation of East Europe and a clockwise rotation of Siberia during and after the collision (Didenko et al., 1994; Pecherskiy and Didenko, 1995).

Siberia and Kazakhstan are separated by the Chara shear zone. Terranes southwest of this zone (Tarbagatai, Zharma, and Saur) aligned along the Kazakhstan continental margin represent fragments of Cambrian-Ordovician and Devonian-Early Carboniferous island arcs and are displaced along the Chingiz-Tarbagatai strike-slip fault to the south toward the Junggar microcontinent (Fig. 3) (Chi et al., 1993).

Terranes northeast of the Chara zone (Kalba-Narym, Rudny Altai, Gorny Altai, Salair, and Tom'-Kolyvan') are also offset along left-lateral strike-slip faults and conjugate thrusts to the south with respect to their original position on the continental margin of Siberia. The Kalba-Narym and Rudny Altai terranes make up a large NE-striking belt delineated by the Irtysh and North East zones of major regional strike-slip faults.

The Chara shear zone

The Chara shear zone (Figs. 1, 3), up to 80 km wide, is associated with the Chara ophiolite belt and includes three

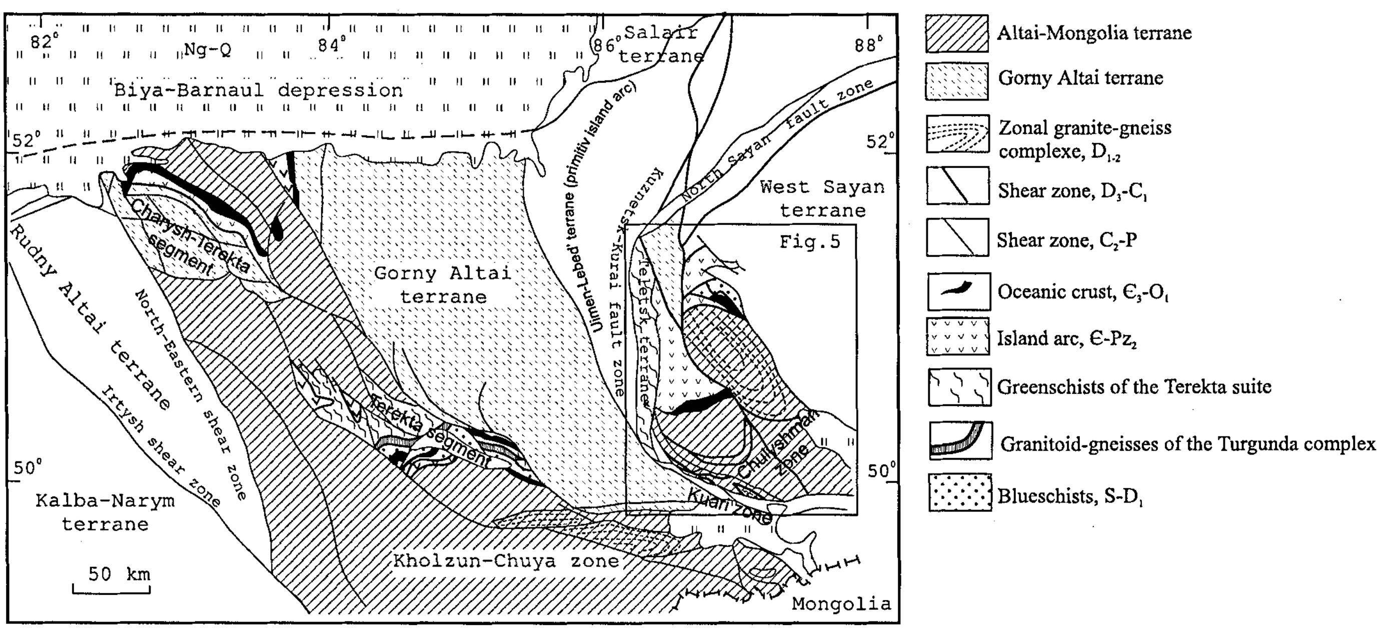

Fig. 4. Tectonic framework of the Late Devonian-Early Carboniferous transform junction of Altai-Mongolia terrane and Siberia. 1–Altai-Mongolia terrane, 2–Gorny Altai terrane, 3–Early Devonian zoned gneiss granite complex, 4–Late Devonian-Early Carboniferous strike-slip faults, 5–Late Carboniferous-Permian strike-slip faults, 6–Cambrian-Early Ordovician oceanic crust, 7–Cambrian-Middle Paleozoic island arc, 8–greenschists of Terekta Formation and Teletsk terrane, 9–gneiss granites of Turgunda complex, 10–blueschists.

main tectonic units that differ in structure, age, and geodynamic environment (Polyanskii et al.,1979; Dobretsov et al.,1979; Buslov et al., 2002).

(1) Type I subduction mélange in the southeastern part of the zone, containing blocks of high-pressure metamorphics (garnet amphibolites, eclogites, glaucophane and garnet-glaucophane schists) (Dobretsov et al., 1979). K–Ar ages of muscovite in eclogites, garnet amphibolites, and glauconitic schists fall into a narrow range of 444 to 429 Ma (eight determinations, Table 1) and may correspond to the cooling/uplift of high-pressure rocks when they were brought to the surface (Late Ordovician-Early Silurian) (Buslov, 1998; Buslov et al., 2001). The subduction-related rocks are possibly as old as Cambrian-Early Ordovician

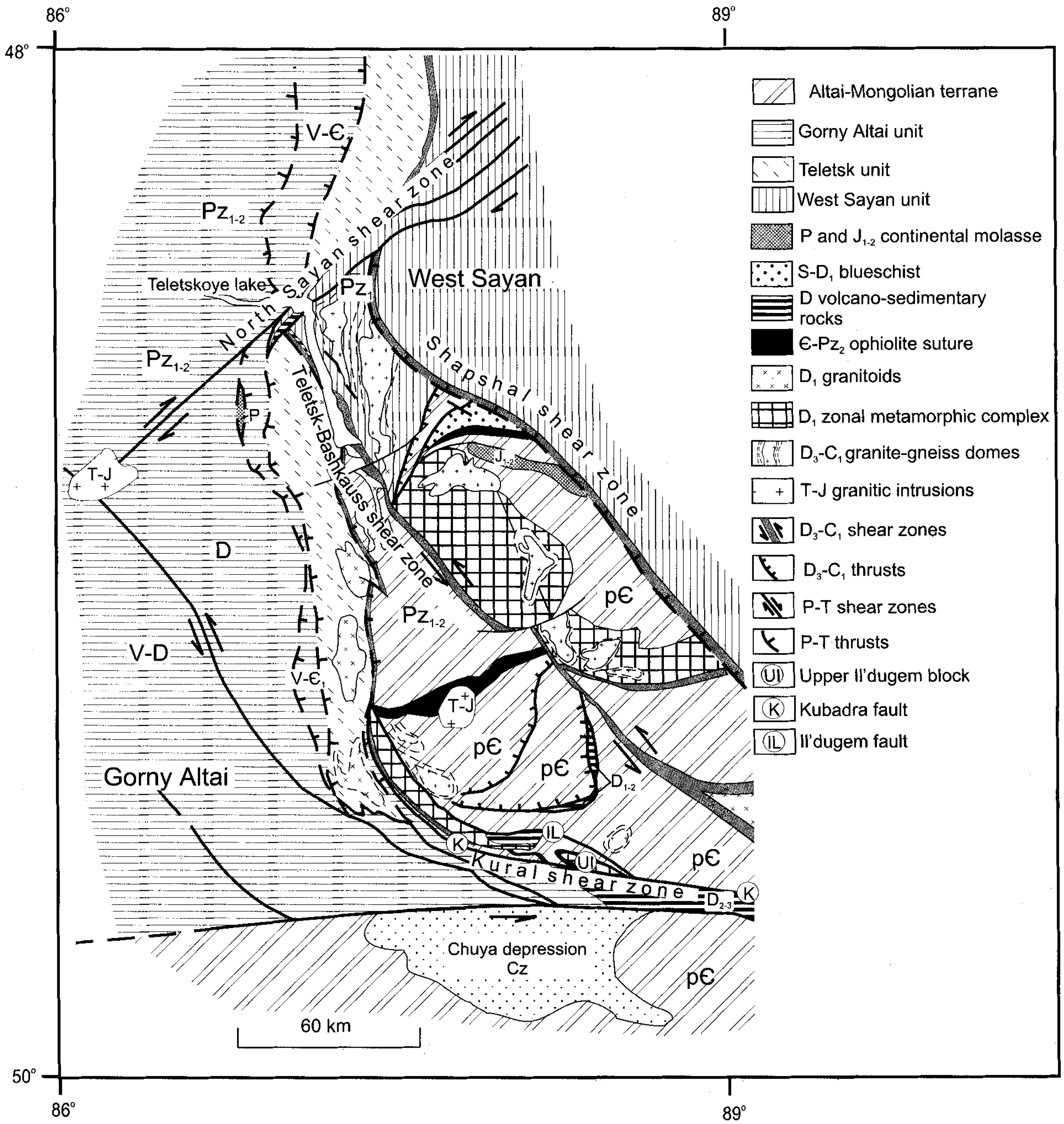

Fig. 5. Geological framework of eastern Gorny Altai (after Buslov et al., 2003). 1–Precambrian sands and schists of Altai-Mongolia terrane, 2–Paleozoic rocks of Gorny Altai terrane, undifferentiated, 3–Precambrian (?) greenschists of Teletsk terrane, 4–Cambrian-Ordovician (?) sands and schists of West Sayan terrane, 5–Permian coaliferous molasse, 6–S-D_1 blueschist, 7–Early-Middle Devonian volcaniclastics, 8–ophiolites, 9–Early Devonian granitoids, 10–Early Devonian zoned gneiss granite complexes, 11–Late Devonian-Early Carboniferous granite-gneisss domes, 12–T-J granitic intrusions, 13–Late Devonian-Early Carboniferous shear zones, 14–Late Devonian-Early Carboniferous thrusts, 15–Permian-Triassic shear zones, 16–P-T thrusts.

(Dobretsov and Ponomareva, 1969). North-west of the Junggar microcontinent, Tangbale blueschists also occur in association with Late Cambrian-Early Ordovician ophiolites (Chi et al., 1993; Xuchang Xiao et al., 1994).

(2) Type II ophiolitic mélange, imbricated with blocks of oceanic crust of different sizes, is composed of massive harzburgite, lherzolite, dunite and pyroxenite, gabbro, amphibolite, and amphibole-plagioclase schist.

Table 1. Paleomagnetic directions for Kazakhstan, Gorny Altai, South Mongolia and South Tien Shan Late Paleozoic terranes.

				Geographic coordinates			Stratigraphic coordinates			
No.	Object, Latitude and Longitude	Age	N	Dec	Inc	α_{95}	Dec	Inc	α_{95}	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
	Kurata Formation, Ursul River: lavas and sediments 51°20'N, 85°40'E	D_2gv_1	7	269	55	11	80	44	10	26
2	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
	Taldytyurgun Formation, Sukhoi Tydtugem River 50°11'N, 88°12'E	D_1em	4	44	59	89	88	45	8.9	27
	Altai-Mongolian terrane: island-arc formations									
3	Sebystai Formation, Kyzyl-Shin River: sandstones 49°58'N, 89°04'E	D_1em	18	104	31	-	225	3	8	1
	Sebystai Formation, Kyzyl-Shin River: sandstones 49°58'N, 89°04'E	D_1em	6	52	35	-	221	9	8.7	4
4	Ulandryk Formation, Chagan-Burgazy River: sandstones 49°50'N, 88°41'E	D_1em	6	346	10	30	338	–4	7	2
	Ulandryk Formation, Chagan-Burgazy River: sandstones 49°50'N, 88°41'E	D_1em	5	10	13	18	24	9	14	4
	Rudny ALtai terrane: island-arc formations									
5	Berezovo Formation, Zmeinogorsk: tuff-sandstones, 51°10'N, 82°13'E	D_1em	4	174	–41	59	99	–46	14	28
	Zavod Formation , Zmeinogorsk: tuff 51°10'N, 82°13'E	D_2gv	5	145	–67	73	244	37	13	21
	Zavod Formation , Zmeinogorsk: tuff 51°10'N, 82°13'E	D_2gv	6	48	–8	53	73	–36	22	20
6	Talovskaya and Shipunov Formations, respectively, Verkhneubinskoje and Shipunovskoje Villahes: marl and sandstone	D_2gv	38	205	–55	7.4	269	–51	4.5	32±4
	Zharma-Saur terrane: active margin formation									
7	Izhemenei Formation, Zaisan	D_2^2-D_3^1	47	311	–14	12	310	–47	9	28
	Kensai and Kaigenbulak Formations, Zaisan	$C_{2\text{-}3}$	66	340	–55	7	288	–54	4	35
	Chingiz-Tarbagatai terrane: island-arc units									
8	Kaidaul Formation: lava and tuffaceous sandstone	D_2gv-fr	40	254	–50	11.0	232	–41	6.4	
	Chadrin Formation: siltstone and sandstone	D_2gv-fr	18	216	–17	5.1	230	–31	8.9	21
	The mean terrane value		58	239	–41	9.4	231	–38	5.2	
	Central Kazakhstan volcanic belt									
9	EW-striking branch (Semibuzgin Formation): lava	$D_{1\text{-}2}$	53	291	–40.3	9.6	–5	315	8.7	
10	SW branch: lava	D_2	27	319	–52	12.1	2	284	14	
11	NE branch: lava	$D_{1\text{-}2}$	9	168	48	9.3	11	267	10	
	Belt mean value									22.5±1.5
	South Mongolia ophiolites									
12	Dzolen massif: sills	D_1	27	228.7	–48	7.2	208.5	–0.7	4.8	0.3
13	Turvan-Saikhan massif: sills	D_1	34	124.1	–81.6	9.6	180.2	–10.7	6.4	5.4
								Southern Urals		
14	Shildak massif: sheeted-dike complex	$D_{1\text{-}2}$	365	320	75	4.3	95	36	3.9	16
	Southern Tien Shan									
15	Kyrgyzstan and Khodzhagair allochthonous terranes: mean value	$D_{1\text{-}2}$	72	126	–13	30	137	–37	5	20.6

Note: the directions were obtained from the analysis of components (ZD) and by large-circle method (CG); N, number of samples measured; Dec and Inc declination and inclination (in degrees), respectively; a_{95}, the 96% significant level (Fischer, 1953); PL, paleopole latitude (°N). Objects data: 1-5 from Buslov et al. (2003); 6-8 – Burtman et al. (1998), 9-11 – Grishin et al. (1997), 12-15 – Kurenkov et al. (2002).

(3) Type III polymictic mélange includes fragments of Types I (subduction-related) and II (ophiolitic) mélange. It marks numerous young fault zones that bound the Chara ophiolite belt. Along the northeastern side of the Chara shear zone the mélange is imbricated with Early Carboniferous turbidites and olistostromes, Late Devonian-Early Carboniferous island arc rocks, and Devonian-Early Carboniferous limestones that fill the Kalba-Narym accretionary prism. Imbricates along the southwestern limits of the zone include fragments of an Early Carboniferous accretionary wedge of the Zharma-Saur island arc. Serpentinitic mélange in the interior Chara zone is most often oriented northwestward following the zonal strike, as well as interthrust blocks of various compositions.

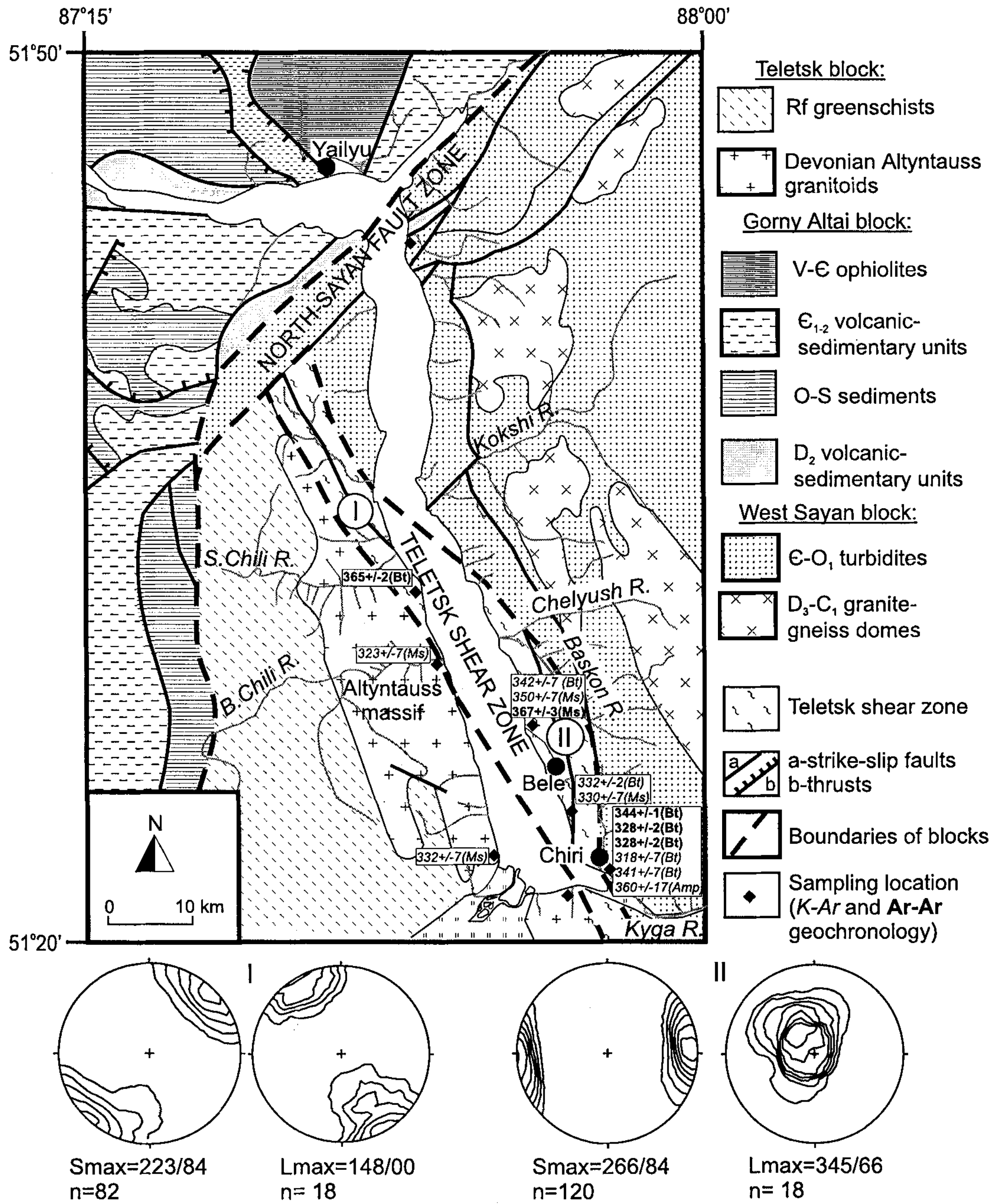

Fig. 6. Geological framework of the Teletsk region (after Smirnova et al., 2002). 1, 2–Teletsk terrane: 1–Riphean greenschists, 2–Devonian Altyntaus pluton; 3-6–Gorny Altai terrane: 3–Vendian-Cambrian ophiolites, 4–Early-Middle Cambrian volcaniclastics, 5–Ordovician-Silurian sediments, 6–Middle Devonian volcaniclastics; 7, 8–West Sayan terrane: 7–Cambrian-Early Ordovician turbidites, 8–Late Devonian-Early Carboniferous gneiss granite domes; 9–Teletsk shear zone; 10–strike-slip faults (a), thrusts (b); 11–other faults; 12–sampling sites for K-Ar and Ar-Ar dating. Schistosity (S) and lineation (L) stereoplots for Teletsk (I) and Chiri (II) domains of the Teletsk-Bashkaus shear zone are given at bottom.

The Chara ophiolite belt occurs among Devonian-Early Carboniferous volcaniclastics (Figs. 1, 3) which are most likely fragments of accretionary prisms separated from Kazakhstan and Siberia during the formation of the Chara shear zone. The mélange units are sealed by Late Carboniferous volcaniclastic wedges and dykes. Younger Permian and Early Triassic faults occur locally. The Semeitau alkali basalts and intrusions were produced by Middle Permian-Early Triassic activity (Ermolov et al., 1981; Iwata et al., 1994).

Western Junggar (Fig. 3) contains several Paleozoic island arcs, accretionary prisms, and ophiolite belts which were finally assembled in the latest Carboniferous (Chi et al., 1993). The ophiolites – Barli-Khongulen-Khebukesair, Mailskaya and Dalabute – are fragments of Late Cambrian-Early Ordovician and Silurian-Early Devonian oceanic crust (Chi et al., 1993; Li et al., 1998). As in the Chara belt, they are strongly deformed peridotites, gabbroics, lavas, and serpentinitic mélange. The geochemistry of the lavas suggests their derivation from primitive island arcs, mid-ocean ridges, and oceanic islands. The Late Cambrian-Early Ordovician (489–523 Ma) ophiolites of the Tangbale zone (Chi et al., 1993; Li et al., 1998) coexist with roughly coeval glaucophane-crossite schists (Xuchang Xiao et al., 1994).

Correlation of geological data from the Western Junggar, Tarbagatai, Zharma-Saur, and Chara zones indicates that they all belong to a single Paleozoic accretionary complex strongly deformed by Late Carboniferous-Early Permian and later strike-slip faulting, which is confirmed by similar ages and compositions of ophiolites in the Chara zone and Western Junggaria. However, in the present-day structural framework, slices of Chara ophiolites and the exotic island arc terranes occur along a suture, whereas the Western Junggar ophiolites, together with island arc and accretionary complexes are controlled by a regular pattern of Late Paleozoic strike-slip and conjugate thrust faults dipping to the north (Chi et al., 1993) (Figs. 1, 3).

The Irtysh shear zone

The Irtysh shear zone (Figs. 1, 3), 30–70 km wide, between the Kalba-Narym and Rudny Altai terranes, consists of imbricates of diverse compositions occasionally interthrust with serpentinitic mélange and schist, or with zones of mylonite, blastomylonite, and greenschist. The imbricated mélange contains rocks from the adjacent Kalba-Narym and Rudny Altai terranes.

The history of the Irtysh shear zone contains at least two stages: the first after intrusion of gabbro-diorites and prior to intrusion of the Kalba granites (Late Carboniferous-Early Permian), and a second that postdates the Kalba intrusion (Permian). The Kalba pluton can presumably be interpreted as a granite, coeval with the Irtysh strike-slip faults, which intruded the associated zone of extension and, locally, the shear zone axis. The age of the Kalba granites (270–290 Ma) and the linear geometry of intrusions branching northward at a high angle off the shear zone axis provide evidence for left-lateral movements in the Early Permian, which is confirmed by abundant structural criteria (Melnikov et al., 1997, 1998; Vladimirov et al., 1998). New step heating and laser ablation Ar–Ar age determinations (Vladimirov et al., 1998) of mica, amphibole, and K-feldspar from the blastomylonites and gneisses indicate two stages of left-lateral strike-slip faulting in the shear zone at 283–276 and 273–265 Ma (Ponomarchuk et al., 1994; Chikov and Zinoviev, 1996; Travin et al., 2001).

Therefore, the Irtysh zone shear zone acted as a left-lateral strike-slip fault in Late Carboniferous-Early Permian time. The movements continued until the latest Permian-Early Triassic after intrusion of the Kalba granites, and the zone then experienced a second period of movement in the Early Jurassic (Vladimirov et al., 1998).

The North-East shear zone

The North-East shear zone, a few kilometers wide, between the Altai-Mongolia and Rudny Altai terranes (Figs. 1, 3) (Distanov, 1962), was produced by left-lateral strike-slip faulting and consists of allochthonous and autochthonous blocks surrounded by greenschists. Faulting took place in the Early Permian, as inferred from the relationships of the substratum with mylonites and granitoids affecting Ordovician-Carboniferous volcaniclastics and Late Carboniferous granitoids of the Zmeinogorsk complex. The shear zone is sealed with the Late Permian-Triassic Savvushki and Tigerek plutons (Vladimirov et al., 1997), whose ages constrain the younger limit of left-lateral strike-slip displacement of the Rudny Altai terrane relative to the adjacent structures.

Thus, the Chara, Irtysh, and North East shear zones all formed in the Late Paleozoic but had different prehistories and histories.

Terrane characteristics

Geology

The Altai-Mongolia terrane is about 1000 km long, 500 km wide, and lies in the territories of southern Gorny and Rudny Altai, where it is bounded by the North East and Charysh-Terekta strike-slip faults, and by western Mongolia and the Chinese Altai (Figs. 1, 3). Most of the terrane is composed of rhythmically bedded Precambrian quartz-feldspar or less often polymictic sandstones, and Middle Cambrian-Early Ordovician (?) slates, and phyllitic shales (Gorny Altai flysch up to 6 km thick in Gorny Altai and Western Mongolia (Volkov, 1966; Dergunov, 1981)).

The terrane contains Late Precambrian-Devonian polymetamorphic gneiss-granite complexes (e.g., Kurai, Chulyshman, South Chuya) within the limits of the Gorny Altai Group. High- and medium-pressure amphibolite- and epidote-amphibolite-facies metapelites in the South Chuya complex are compositionally similar to the surrounding sands and schists. Their major- and minor-element compositions suggest that they may be derived from a mature island arc. Rocks of the South Chuya complex and the Gorny Altai Group have the oldest Nd model ages in the region of ~1.5–1.3 Ga, indicating a mid-Proterozoic provenance (Kruk et al., 2002).

The sand-schist sequences are isoclinally folded and transgressively overlain by various Ordovician-Devonian complexes which represent an intricate geodynamic evolution of the Altai-Mongolia terrane. These complexes are: (1) Middle Ordovician gray marine sediments (Biryuksa Formation and its equivalents) in southern Gorny Altai rest upon basal conglomerates and a folded and metamorphosed basement; (2) Late Ordovician island arc volcaniclastics and intrusives in the Chinese and Mongolian Altai (Volkov, 1966; Dergunov, 1981), and (3) Late Ordovician-Early Silurian gray marine sediments in Gorny Altai and Western Mongolia (Volkov, 1966; Dergunov, 1981). The Vendian-Early Cambrian and Ordovician-Silurian sequences are transgressively overlain by Emsian island arcs known in the Korgon and Khalzun zones of Gorny Altai (Kruk et al., 2002; Dergunov and Luvsandanzan, 1984) and in Western Mongolia.

Following the Eifelian-Early Givetian hiatus (Dergunov and Luvsandanzan, 1984), together with Late Devonian-Early Carboniferous granitoids (Vladimirov et al., 1997), Upper Givetian dark-colored fine-grained deposits may mark extensional zones related to deformation along the transform boundary between the Altai-Mongolia terrane and the Salair-Altai zone of the Siberian craton.

The Gorny Altai terrane (Fig. 4) is made up of an intricate assemblage of tectonic units formed near the continental margin of Siberia (Buslov et al., 1993; Yolkin et al., 1994; Watanabe et al., 1993; Buslov and Watanabe, 1996) and includes Late Vendian-Cambrian island arcs overlain by Ordovician-Early Devonian carbonates deposited on a passive-margin shelf (Yolkin et al., 1994). In the Emsian-Early Givetian, the region became an active continental margin. Late Devonian-Early Carboniferous dark-colored fine-grained shallow-marine deposits within the terrane (Cheremshanka Formation and its equivalents) most likely formed in a rift environment associated with strike-slip faulting along the continental margin of Siberia, and with intrusion of gabbro diabase dykes and sills in long, wide belts in central Gorny Altai (Yolkin et al., 1994).

The Kalba-Narym terrane (Figs. 1, 3) is bounded by the Chara and Irtysh shear zones and is composed of Late Devonian-Early Carboniferous deposits of the Takyr Formation intruded by the Early Permian Kalba granitoids which also heal the western boundary of the terrane.

The Takyr Formation, with a total thickness about 1500 m, consists of black shales and siltstones with fine oligomictic sandstone fragments increasing up the section. The geodynamic environment of this formation remains contentious. According to Rotarash and Gredyushko (1974), it was deposited in a deep-water trench on oceanic crust and belongs to a subduction complex (buried Benioff zone), and was later incorporated in the Irtysh shear zone and the chaotic olistostrome complex bordering it to the southwest. In our view, it more likely formed on a passive continental margin, and its equivalents are found in the Tom'-Kolyvan' and Salair zones (Figs. 1, 3).

The Rudny Altai terrane (Figs. 1, 3) at the base of the section is mainly composed of Ordovician-Silurian (?)-Early Devonian volcaniclastic complexes derived from oceanic crust (Gritsyuk et al., 1995). The rocks have greenschist metamorphic facies assemblages and fall into three compositional groups. The oldest basaltic metamorphic schists are overlain by facies-variable ortho- and para-schists passing up into metamorphosed sandstones and shales (Korbalikha Formation) whose Early Devonian (Lochkovian-Pragian) age is constrained by phytoplankton and spores (Gritsyuk et al., 1995). The Ordovician-Silurian (?) oceanic crust is overlain conformably, without visible gap, by Early Emsian calcareous-argillaceous and polymictic sandstones possibly deposited in a deep-water trench.

The stratigraphically higher section of the terrane contains thick Devonian-Carboniferous sequences. The Emsian-Early Givetian strata are composed of forearc-basin terrigenous rocks and reef limestones intercalated with tuff and polymictic sandstones, with red, lilac, gray, black, and green chert clasts and volcanic rocks of different compositions which are unknown at the base of the Devonian section; judging by their compositions, they may be derived from an Early Devonian island arc and its basement. With their Emsian faunal assemblages and facies (Yolkin et al., 1994), the deposits of the Rudny Altai terrane are similar to those in the Salair region. The Late Givetian-Late Devonian deposition of volcanoplutonic island arcs in Rudny Altai was paralleled by the formation of forearc basins in Salair and Gorny Altai (Yolkin et al., 1994).

The Chingiz-Tarbagatai terrane comprises Cambrian-Devonian volcanogenic-sedimentary rocks. The Devonian beds are discordant to Silurian rocks and consist of a thick sequence of tuff-sandstone, tuff-mudstone and andesitic lava (Kaidaul Formation). The Kaidaul Formation yields Devonian flora and is concordantly overlain by Givetian-Franian sedimentary-carbonate sedimentary rocks (Mossakovskiy et al., 1993; Burtman et al., 1998).

Paleomagnetic data

Paleomagnetic data (Table 1) indicate that the Emsian volcaniclastics of the Altai-Mongolia terrane formed near the equator at 1–4° N, whereas the coeval sandstones and tuffs of the Taldy-Kurgan and Aksai Formations of Gorny Altai that belong to the active continental margin of Siberia formed at paleolatitudes between 27 and 30° N. The Early Givetian lavas, tuffs and sediments of the Kurata Formation were deposited on the active continental margin at 23–26°N. Paleomagnetic data from a Devonian section near Zmeinogorsk in the Rudny Altai terrane give paleolatitudes of 28±11°N for Emsian sandstones and siltstones of the Berezy Formation and 20±12°N for Givetian tuffs of the Zavod Formation. The Middle-Late Devonian Rudny Altai active continental margin had an NE strike, which agrees with that obtained by Gritsyuk et al. (1995) who estimated the paleolatitude to be at 32±4°N.

In the west, the Rudny Altai terrane is separated by the Irtysh shear zone from the Kalba-Narym and West Kalba terranes that involve Late Devonian-Early Carboniferous forearc basins and accretionary prisms (Yolkin et al., 1994). The rocks of the Rudny Altai, Kalba-Narym, and West Kalba terranes are fragments of a single Salair-Altai island arc which were offset for hundreds of kilometers along strike-slip faults as a result of the Late Carboniferous-Permian collision of Kazakhstan with Siberia. The terranes associated with the Salair-Altai island arc are separated from the coeval Devonian-Early Carboniferous island arcs of the Chingiz-Tarbagatai zone of Kazakhstan by the Chara ophiolite suture. The Middle-Late Devonian Chingiz-Tarbagatai island arc had an EW strike and originated at 21±4°N. It coincided with the Rudny Altai island arc along the paleomeridian over a distance of 600–1000 km (Burtman et al., 1998). Therefore, the total amount of left-lateral horizontal motion along the Chara and Irtysh strike-slip faults may reach 650 to 1650 km. Late Silurian-Early Devonian rocks in Central Kazakhstan form a belt consisting of three branches which have EW-, SW- and NE-strikes. The rocks overlap the Caledonian folded basement of the Kazakhstan composite continent. The paleomagnetic data of Grishin et al. (1997) show that the volcanic belt of the Kazakhstan continent was located at 5–10°N in the Silurian and at 21–24°N in the ealiest Middle Devonian. In the Early-Middle Devonian, the belt had a N–S strike in northern and northeastern Kazakhstan and a W–E strike in the southwest, in the ancient frame of reference. The inferred paleomagnetic position of the Early Devonian Altai-Mongolia terrane at 2000–3000 km distance from the Siberian continental margin agrees well with its Late-Devonian-Early Carboniferous history.

Magneto-tectonic investigations (Didenko, 1992; Kurenkov et al., 2002) showed that the Early Devonian ophiolites of Southern Mongolia (Dzilen and Gurvan-Saihan massifs) were formed not far from the equator. Didenko (1992) suggested that the South Gobi microcontinent bounding the South Mongolian Ocean from the south was located at 24°N in the Late Silurian-Early Devonian and at 5°N in the Early Carboniferous, i.e., it migrated a distance equivalent to 20° during the Devonian. In the present-day structural framework it is located south of the ophiolites, suggesting rotation of the Altai-Mongolia-Tuva plate through 180° (Fig. 8). Such a rotation may explain the above-mentioned northward migration of the southwestern part of the plate comprising Emsian island-arcs of the Altai-Mongolian terrane. The Early-Middle Devonian ophiolites of the South Urals (South Mugodzhar massif) were formed at 16°N, whereas the Uralian part of the East European continent was located at 13°N. Didenko (1992) believes that the South Mogodzhar ophiolites were formed near the northern margin (in present coordinates – near the eastern margin) of the East European continent.

Ophiolites of the southern Tien Shan were located at 19–22°N in Silurian-Devonian time and at 28–32°N in the Middle Devonian, suggesting that the Turkestan Ocean was located in the tropics of the northern hemisphere and was oriented in a meridional direction (Burtman et al., 1998; Kurenkov et al., 2002) (Fig. 7, Table 1).

Geodynamic Evolution of the Paleo-Asian Ocean and Continental Growth of Central Asia

The results of our investigations integrated with those from published papers on the paleogeography of the Paleo-Asian Ocean geodynamics and tectonics of Central Asia (e.g., Zonenshain et al., 1990; McKerrow et al., 1992; Mossakovsky et al., 1993; Sengor et al., 1993; Berzin et al., 1994; Didenko et al., 1994; Pecherskiy and Didenko, 1995; Buslov and Kazanskiy, 1996; Didenko, 1997; Buslov et al., 2000, 2001, 2003; Puchkov, 2000; Kurenkov et al., 2002) enable us to propose a new tectonic model for the Late Paleozoic-Early Mezosoic geodynamic evolution of Central Asia. New data and past publications show that the present mosaic-block structure of Central Asia resulted from several accretion and collision stages. In this region, prominent large-scale strike-slip faults up to several thousand kilometers long were the results of subduction and collision. Four geodynamic stages can be recognized (Fig. 7).

Early-Middle Devonian

In the Early Devonian the Paleo-Asian Ocean was split into several basins. The Ob'-Zaysan Ocean (basin) was situated between the Kazakhstan and Siberian continents and had a link with the South-Mongolian ocean (Fig. 8). The Uralian Ocean bounded the East-European continent in the northwest. The Turkestan Ocean merged with the Uralian Ocean in the north. The paleomagnetic data of Didenko et al. (1994) and Kurenkov et al. (2002) showed that at that time the Paleo-Asian Ocean was situated near the equator and had an EW-strike. The Turkestan Ocean had a NS-strike and was situated between Katazia (comprising the Tarim, Afghan-Tajik and Kyzyl-Kumy Gondwana-derived microcontinents) and the Kazakhstan continent. During Early-Middle Devonian time the oceanic lithosphere of the western Paleo-Asian Ocean (the Zaysan Ocean) was subducted beneath the Siberian and

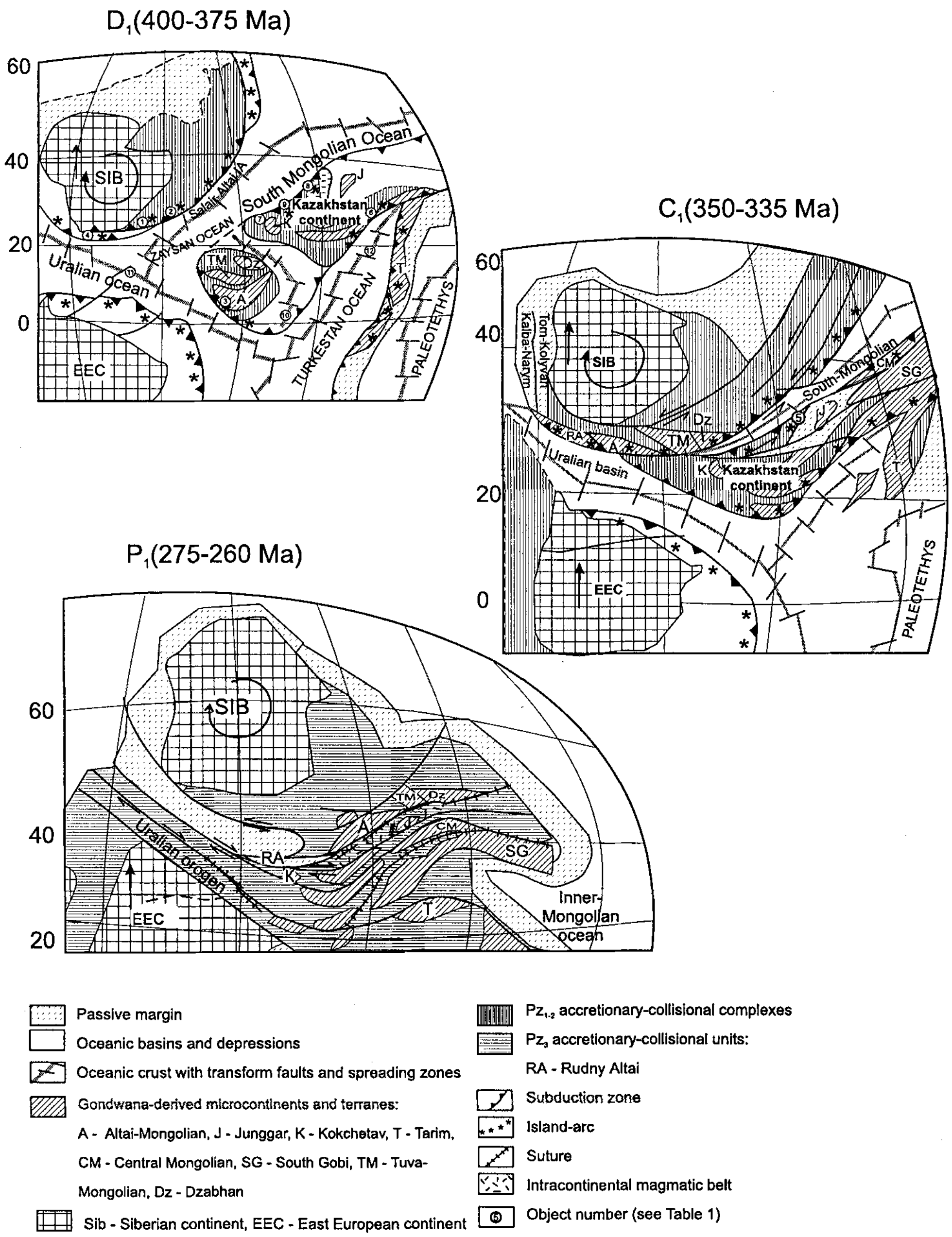

Fig. 7. Late Paleozoic geodynamic reconstructions of the Paleo-Asian Ocean (modified from Buslov et al., 2003). 1–forearc basin and passive margin, 2–oceanic basins, 3–oceanic crust with transform faults and spreading zones, 4–Gondwanian microcontinents and terranes (A–Altai-Mongolia, Jg–Junggaria, K–Kokchetav, T–Tarim, CM–Central Mongolia, SG–South Gobi, 5–SIB–continent of Siberia, EEP–East Europe Platform, 6–Early Paleozoic accretionary complex, 7–Late Paleozoic accretionary complex (RA–Rudny Altai), 8–subduction zone, 9–island arc, 10–sutures, 11–continental magmatic belt.

Kazakhstan continents and the Altai-Mongolia-Tuva microcontinent. A broad volcanic-plutonic belt (Salair-Altai) formed at the southeastern margin of the Siberian continent, and the Zharma-Saur island-arc formed at the northwestern margin of the Kazakhstan continent. The Altai-Mongolia-Tuva microcontinent and Kazakhstan continent were situated far from the Siberian and East European continents – probably, at the eastern margin of the Paleo-Asian Ocean. The Altai-Mongolia-Tuva microcontinent moved northward, starting at 1–4°N, towards the Siberian continent. In the Early Devonian (Emsian-Early Givetian) the Gorny Altai active margin was situated at the southeastern border of the Siberian continent (25±10°N). The Emsian volcanic-arc formed over the Altai-Mongolia-Tuva microcontinent terrane and was located near the equator, around 1°–4°N. The Siberian continent then rotated clockwise (Pecherskiy and Didenko, 1995). In Givetian time, the EW-trending Siberian continental margin was located at 20°N. The Berezovo Formation of Emsian age (Rudny Altai) – fore-arc trough of the Salair-Altai active margin (27°–30°N) – moved in the same direction along the Siberian continent. 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-Mongolia-Tuva microcontinent migrated to the same latitudes and collided with the Altai-Sayan zone of the Siberian continent. The subsequent subduction of the Ob'-Zaysan oceanic crust resulted in oblique collision of the Gondwana-derived terranes along the Siberian continental margin, formation of the Charysh Terekta zone, and faulting and thrusting in the Altai-Sayan region.

Late Devonian-Early Carboniferous

In the Middle-Late Devonian, the Kazakhstan plate together with the Altai-Mongolia-Tuva microcontinent moved westward and rotated clockwise. This movement resulted in attachment (and further collision) of the Altai-Mongolia-Tuva microcontinent and part of 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.

In the Late Devonian, the Altai-Mongolia-Tuva microcontinent approached the Siberian continent, and its Devonian active margin was located near 20°N (paleolatitude of the Rudny Altai Givetian tuffs). The meridional drift velocity is estimated to be about 20–25 cm per year (up to 2,000 km total displacement). 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; Smirnova et al., 2002; Buslov et al., 2002, 2003). In the Early-Middle Devonian the Siberian continent moved northward to 20° and rotated clockwise 10–15°. Dextral strike-slip faulting took place along the margin of the Siberian continent, thus provoking the detachment of the terranes.

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 $C_{2\text{-}3}$) and collided with the Siberian continent, which continued its clockwise rotation (Pecherskiy and Didenko, 1995). The Rudny Altai and Zharma-Saur island-arcs formed in the Late Devonian.

The Ob'-Zaysan Ocean crust continued to subduct beneath the Siberian and Kazakhstan continents in the Early Carboniferous (Iwata et al., 1997). The Altai-Mongolia-Tuva microcontinent accreted to the Rudny Altai back-arc area, and northward compression of this continent formed the Kuznetsk-Kurai and other dextral strike-slip faults at the margin of the Siberian continent. Oceanic basins of Paleo-Tethys-II (e.g., Inner Mongolian Ocean) were formed coevally with the closure of Paleo-Tethys-I oceans (Uralian, Ob'-Zaysan and South Mongolian Oceans).

The Early Carboniferous saw closure of the Ural-Mongolian and Ob'-Zaysan Ocean, branches of the Paleo-Asian Ocean. The Baltica, Kazakhstan and Siberian Continents amalgamated to form a large landmass (the North Eurasia continent).

Late Carboniferous-Early Permian

According to paleomagnetic data (Didenko et al., 1994; Pecherskiy and Didenko, 1995) the East European (Baltica) continent rotated counterclockwise, and the Siberian Continent rotated clockwise. In the Late Carboniferous the Ob'–Zaysan Ocean closed due to the collision of the Baltica, Kazakhstan and Siberian continents. Paleo-Tethys-I closed due to the collision of North Eurasia and the Tarim and Afghan-Tajik microcontinents. The collision of the Baltica and Siberian continents created a prototype of the North Eurasia continent, resulting in the formation of 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 Irtysh and North-East shear zones. The largest sinistral strike-slip faulting occurred along those zones (Fig. 6). They were responsible for reactivation 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. In these areas thrust faults bound the Tom'-Kolyvan' terrane and Salair mountains from the SE, and are associated with conjugate faults, such as Baschelak, Kubadra-Kobda and others, which reactivated the older Late Devonian-Early Carboniferous strike-slip faults.

The amount 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 (Zonenshain et al., 1990), respectively. The amount 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 amount of horizontal displacement between the Irtysh and Kuznetsk-Teletskoye-Khangai-Khentei fault zones can be estimated as 200–1,000 km, the greatest displacement being in the Chara zone.

The Late Carboniferous-Permian evolution of East Kazakhstan and Altai-Sayan regions is exemplified by diversity and lateral variability of facies and depositional environments. Five main facies of Late Carboniferous-Permian continental deposition (including formation of Kuznetsk, Gorlovka, Karaganda, and Kendyrlyk coal basins) have been demarcated along the junction between the Siberian and Kazakhstan continents (Irtysh River basin) on the basis of faunal and floral evidence (Betekhtina, 1966, 1983, 1985) (Fig. 8): (1) alluvial-deltaic coastal plain, (2) repeatedly flooded alluvial-deltaic coastal plain, (3) brackish-water gulfs and lagoons, (4) alluvial-deltaic basinal plain, (5) repeatedly flooded alluvial-deltaic basinal plain (Betekhtina, 1966).

Cordaitean flora typical of mid-latitude wet temperate climate, showing affinity with the Tunguska paleofloristic province (often called Angara flora), were found in the Kuznetsk and Gorlovka coal basins (Betekhtina, 1966, 1983, 1985) but have not been identified in the Karaganda coal basin within the Kazakhstan continent, where the flora is of Westphalian affinity corresponding to a wet tropical or subtropical climate (Betekhtina, 1966).

Fauna assemblages in Late Paleozoic coal deposits are mostly non-marine bivalves, with rheofiles (freshwater inhabitants) and organisms of brackish water basins that remain connected with seas (Betekhtina, 1983). The flora of the Kuznetsk and Gorlovka basins, as well as of the southern Siberian platform, coexists with a particular assemblage of non-marine bivalves referred to as "M fauna" (Betekhtina, 1983, 1985). No elements of this fauna are found in the Carboniferous and Early Permian Karaganda and Kendyrlyk basins, where non-marine bivalves are of a specific (Zaysan) geographic type (Betekhtina, 1985) evolved in environments of large intracontinental lakes and seas (Betekhtina, 1983, 1985).

In the latest Early Permian, elements of M fauna spread southward into Southern Kazakhstan and northwestward into the Pechora coal basin of East Europe (Betekhtina, 1985).

Therefore, the Carboniferous-Permian continental margin of Siberia (territory of present-day Kuznetsk and Gorlovka basins) had a temperate climate, and the Karaganda basin of Kazakhstan and the Pechora basin in East Europe was situated in the tropics. The position of the Pechora basin north of the other basins in the present-day framework can be explained by northward displacement of East Europe with respect to Kazakhstan and Siberia in post-Permian time.

Judging by the present position of continents and coal basins, East Europe may have moved 5000 km northward since the Late Carboniferous (after closure of the Mongolian branch of the Paleo-Asian Ocean), while Siberia rotated clockwise and remained at the same latitude (Didenko et al., 1994). This interaction of large continental blocks must have been responsible for large-scale right-lateral strike-slip faulting along the margins of East Europe and Siberia (Buslov et al., 2003).

Triassic-Jurassic

According to paleomagnetic data (Didenko et al., 1994; Pecherskiy and Didenko, 1995), the East European continent had reached its present position by the earliest Jurassic and was finally welded with the Siberia-Kazakhstan continent. Therefore, strike-slip faulting in the composite continent continued until the Early Jurassic. Ubiquitous Early Jurassic coal-bearing molasse in the Kazakhstan and Altai-Sayan regions marks the final evolutionary stage of the Central Asian orogen and Eurasia.

Triassic-Jurassic deformation mostly acted upon continental margins. Specifically, the Troitsk system of large strike-slip faults formed along the eastern continental margin of East Europe (McKerrow et al., 1992). These and other large strike-slip faults in the Urals (Puchkov, 2000) originated in the Late Permian-Early Triassic and remained active until Early Jurassic. Large strike-slip and thrust fault systems in the Altai-Sayan region in the southwestern periphery of Siberia are clearly expressed in the Tom'-Kolyvan' zone and Salair. Seismic and deep drilling data reveal thrusting of the Tom'-Kolyvan' zone and Salair onto the Kuznetsk basin (thrusts and thrusts with a strike-slip component) (Zonenshain et al., 1990; Savel'eva et al., 1998). Triassic-Jurassic structures are less pronounced in Gorny Altai, but may be poorly studied due to the scarcity of deposits of this age. However, new fission-track data (De Grave and Van den Haute, 2002)

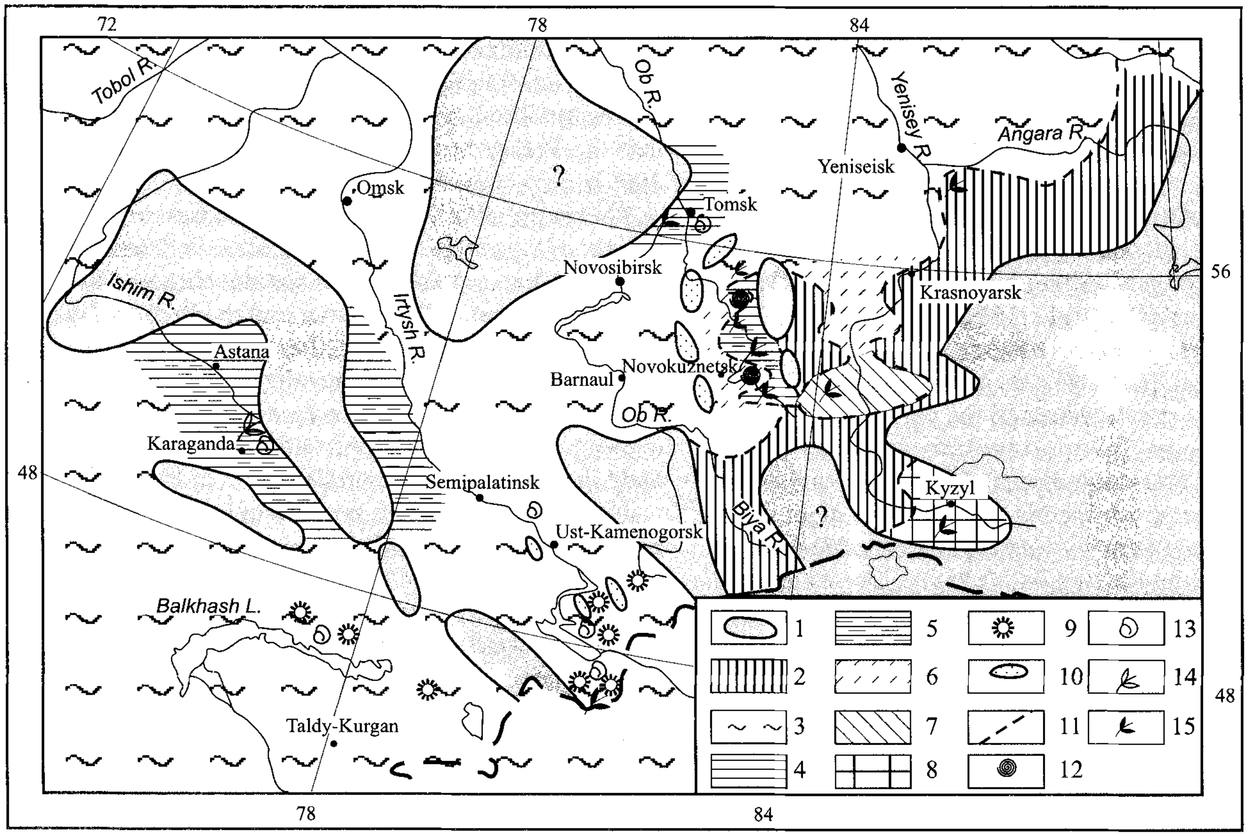

Fig. 8. Paleogeographic reconstructions of South Siberia and Kazakhstan, after Betekhtina (1983). 1–land, environments not specified, 2–plain land, weak denudation and slow deposition, 3–sea, environments not specified, 4–alluvial-deltaic coastal plain, 5–repeatedly flooded areas, 6–brackish-water gulfs and lagoons, 7–alluvial-deltaic basinal plain, 8–gray coal-bearing continental alluvial-lacustrine deposits, 9–regions of long-lasting volcanic activity, 10–temporally flooded islands and rises, 11–hypothetical facies boundaries, 12–suppressed marine fauna, 13–normal marine fauna, 14–flora of Westphalian biogeographic province, 15–flora of Tunguska (Angara) biogeographic province.

indicate a large-scale orogeny in Triassic-Jurassic time, when over 3 km of the crustal section was eroded. This correlates well with molasse deposition of this age. The widespread occurrence of Late Triassic-Early Jurassic rare-metal granites in Gorny Altai (De Grave and Van den Haute, 2002) may also be evidence for collisional environments. Late Permian-Middle Triassic rare-metal granites recently identified in Gorny Altai were interpreted to have formed during postcollisional compression (Vladimirov et al., 1996, 2001). Activity of the western Altai-Sayan region in Triassic-Jurassic time is indicated by strike-slip and thrust faults in the Salair and Tom'-Kolyvan' zones and granite magmatism and orogeny in Gorny Altai.

Summary

This article reviews and integrates new results on the evolution of the Paleo-Asian Ocean and its related Late Paleozoic-Early Mesozoic geodynamics and tectonics in Central Asia. Our data confirm the important role of strike-slip deformation in the formation of the mosaic-block structure of Central Asia.

The complicated and multi-stage deformations resulted from the Late Devonian-Early Carboniferous collision of Gondwana-derived terranes. The periods of deformation 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 a mosaic-blocky structure of Central Asia along the margin of the Siberian continent as a result of the Late Carboniferous-Permian collision. This resulted in the formation of the Northern Eurasia continent. Early Mesozoic strike-slip faulting and conjugate thrusting resulted from the rotation of the Siberian and East European cratons.

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