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Late Paleozoic faults of the Altai region, Central Asia: tectonic pattern and model of formation

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Abstract

The present kinematic and dynamic analysis of large-scale strike-slip faults, which enabled the formation of a collage of Altai terranes as a result of two collisional events. The Late Devonian–Early Carboniferous collision of the Gondwana-derived Altai-Mongolian terrane and the Siberian continent resulted in the formation of the Charysh–Terekta system of dextral strike-slip faults and later the Kurai and Kuznetsk–Teletsk–Bashkauss sinistral strike-slip faults. The Late Carboniferous–Permian collision of the Siberian and Kazakhstan continents resulted in the formation of the Chara, Irtysh and North-East sinistral strike-slip zones. The age of deformation of both collisional events becomes younger toward the inner areas of the Siberian continent. In the same direction the amount of displacement of strike-slip faulting decreases from several thousand to several hundred kilometers. The width of the Late Paleozoic zone of deformation reaches 1500 km. These events deformed the accretion-collision continental margins and their primary paleogeographic pattern.

Keywords: Strike-slip fault; Collision; Altai-Mongolian terrane; Kazakhstan continent; Siberian continent

1. Introduction

In the past few decades the Central Asian foldbelt and, in particular, the Altai zones, have been regarded as a result of accretion-collisional processes (Zonenshain et al., 1990; Berzin and Dobretsov, 1994; Berzin et al., 1994; Mossakovsky et al., 1993; Didenko et al., 1994). The mosaic-block structure of Central Asia formed by (1) isometrically outlined microcontinents (Altai-Mongolian, Junggar, Sangilen, Central Mongolian, etc.) surrounded by island arcs and accretionary prisms and (2) transverse strike-slip faults resulting in the closure of the Paleo-Asian Ocean.

According to Sengör et al. (1993) a single Vendian–Paleozoic subduction zone with the Kipchak and Tuva-Mongolian island arcs existed between the Turkestan Ocean (almost identical to the Paleo-Asian Ocean) and the continents of Siberia and East Europe. In the Late Paleozoic rotation and migration of those continents strongly deformed the island arc, forming numerous oroclines. Strike-slip faults transected the island arc into many fragments. In the accretionary collage of Central Asia most important are Late Carboniferous dextral faults and Late Permian sinistral faults.

From published paleomagnetic and geochronological data we conclude that Late Paleozoic large-scale strike-slip faults formed the mosaic-block structure of the Altai (Buslov et al., 2001). The present paper proposes an interpretation of correlated structural elements of the Altai, and a new tectonic pattern and model of formation.

The Altai mountainous belt is situated in the territories of Russia, Kazakhstan, China and Mongolia. In geological literature the Russian part of the Altai is called the Gorny Altai, the Russia–Kazakhstan boundary area—Rudny Altai, the Kazakhstan part—the East-Kazakhstan area or Kalba area, the Chinese part—Chinese Altai, and the Mongolian part—Mongolian Altai. The Altai tectonic region is located between the Kazakhstan and Siberian continents and consists of accretion-collisional zones of different ages and Gondwana-derived terranes. The complicated structure and scenario of multi-stage evolution of the Altai implies the alternation of subduction-collision and collision.

A collage of terranes was formed by strike-slip deformation resulting from Late Devonian–Early Carboniferous collision of the Gondwana-derived

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Altai-Mongolian terrane and the Siberian continent and from Late Carboniferous–Permian collision of the Kazakhstan and Siberian continents. The collisional episodes and their related strike-slip faults and thrusts broke the accretion-collision margins of both continents into a plethora of tectono-stratigraphic units.

Thus, the most important final stages of the Paleo-Asian Ocean evolution were: (1) Late Devonian–Early Carboniferous oblique subduction of oceanic crust and collision of the Altai-Mongolian terrane and island arc, and (2) Late Carboniferous–Permian closure of the Irtysh-Zaysan branch of the Paleo-Asian Ocean, and collision of the Kazakhstan and Siberian continents.

2. Tectonic pattern of the Altai

We consider the tectonic structure of the Altai as a collage of terranes of different ages separated by numerous large-scale thrusts, strike-slip faults and nappes (Buslov, 1998). Fig. 1 shows the major structural units, which are a part of the Central Asian foldbelt, within the area in between the Kazakhstan and Siberian continents. The tectonic pattern of Altai includes three groups of structural and tectonic units: (1) the Gondwana-derived Altai-Mongolian terrane; (2) terranes of different ages—Kalba-Narym, Rudny Altai, Gorny Altai—composed of fragments of Caledonian and Hercynian accretion-collision zones. Accretionary prisms (wedges) consist of fragments of subducted terranes of oceanic lithosphere—ophiolites, seamounts and ocean islands—which had accreted to island arcs and/or active continental margins; (3) systems of strike-slip faults and thrusts of different ages—Chara, Irtysh, North-East, Charysh–Terekta, Kurai, Teletsk–Bashkauss—separating collisional terranes from the margins of collided continents. Strike-slip deformation commonly completes the formation of suture zones and/or they develop parallel to ophiolitic sutures within collided continents.

2.1. Late Carboniferous–Permian faults in the Altai: a result of the collision of the Kazakhstan and Siberian continents

Fig. 1 illustrates the Late Carboniferous–Permian faults of the Altai formed as a result of the collision between the Kazakhstan and Siberian continents, which took place after the closure of the Ural-Mongolian and Ob'-Zaysan branches of the Paleo-Asian Ocean. The Chara sinistral strike-slip fault is a main structure separating the continents, containing the Chara ophiolitic belt. Southwest of the fault are the Chingiz, Tarbagatai, Zharma and Saur terranes, which formed along the Kazakhstan continental margin. They are composed of the fragments of a Cambrian–Early Carboniferous island arc. Northeast of the Chara zone are terranes, which were displaced along the sinistral strike-slip faults and associated thrusts to the south from their initial position in the marginal zones of the Siberian continent (Buslov et al., 2001). Among these are the Kalba-Narym, Rudny Altai, Gorny Altai, Salair, and Tom'–Kolyvan' terranes. The Kalba-Narym and Rudny Altai terranes form an extensive

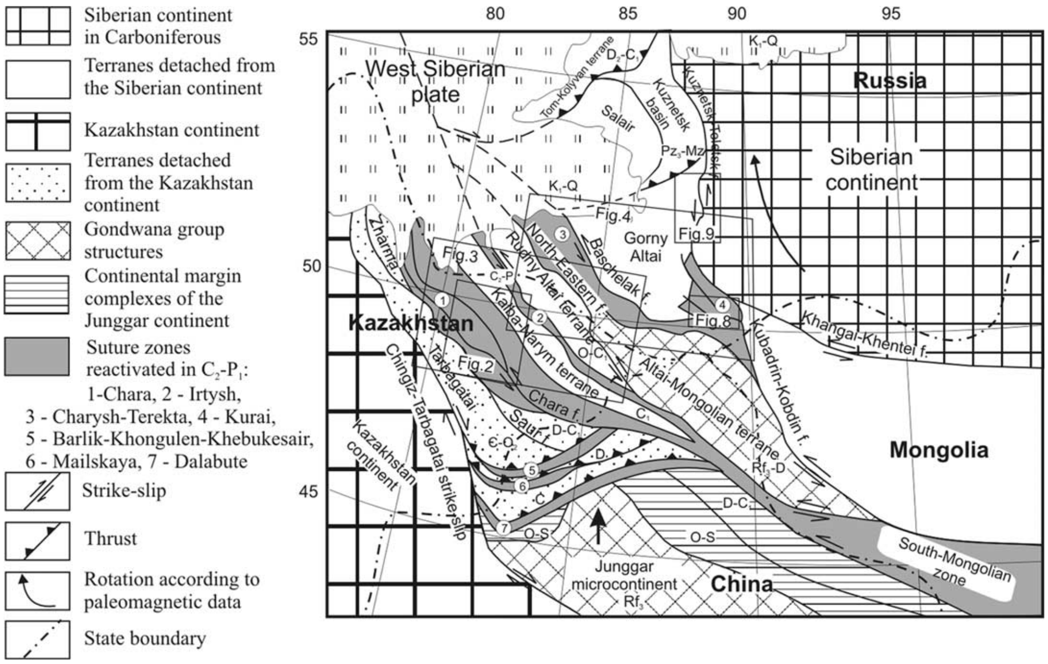

Fig. 1. The tectonic frame of the Altai as a result of the Late Carboniferous-Permian collision between the Siberian and Kazakhstan continents (by Buslov, 1998; Buslov et al., 2001).

NW-trending linear zone, which is traced by the important Irtysh and North-East shear zones, which accommodated the largest sinistral strike-slip displacements. To the east these displacements were less profound and they partly reactivated earlier fault zones in Kuznetsk Alatau, Gorny Altai, and Western Mongolia.

2.1.1. Chara strike-slip zone

Three tectonic types of ophiolitic melange with different structure and age that formed in different geodynamic environments can be recognized in the Chara ophiolitic belt incorporated in the Chara strike-slip zone, which is up to 90 km wide (Fig. 2). Type I melange is an Early Paleozoic

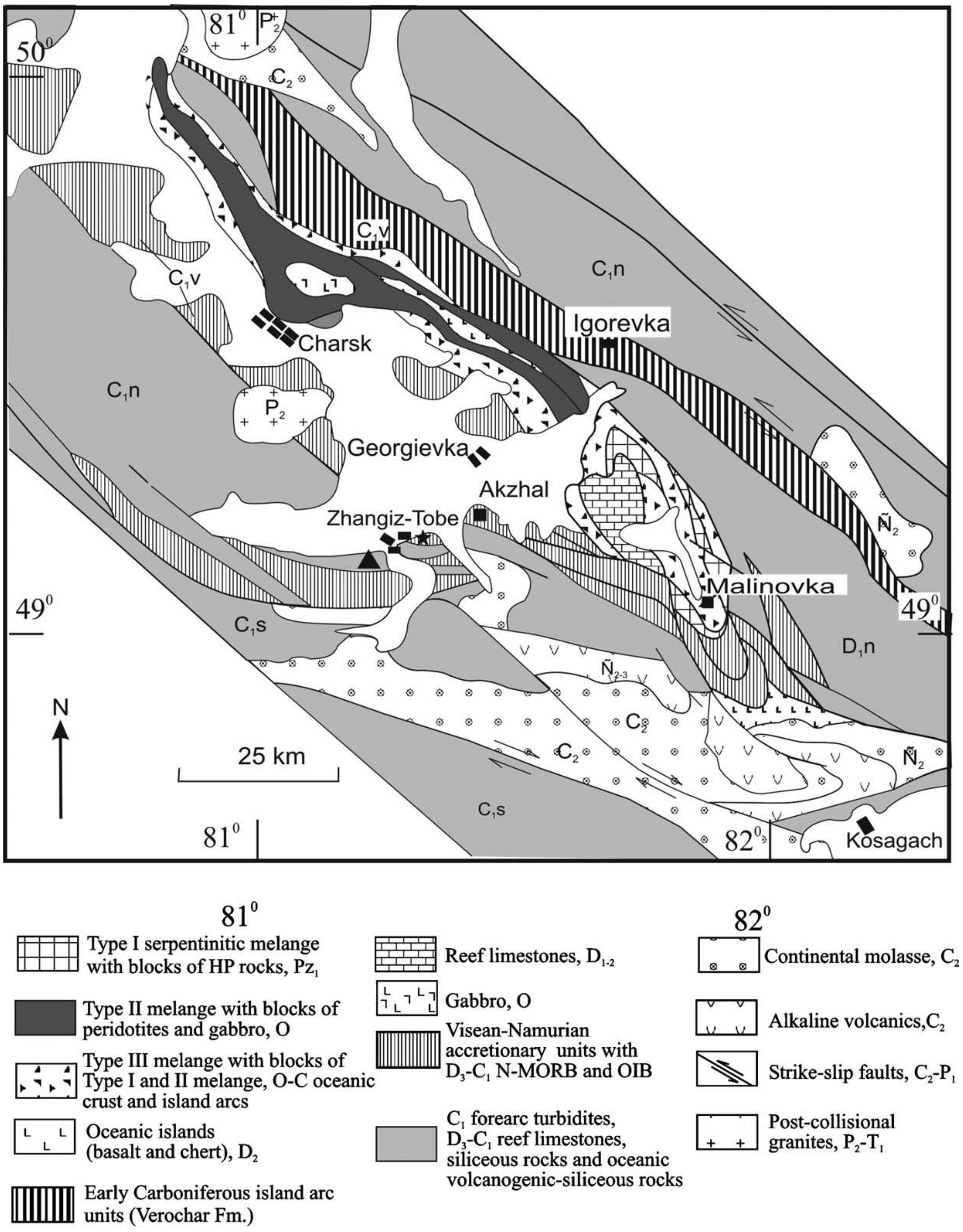

Fig. 2. The geological sketch of the Chara zone (modified from Abdulin and Patalakha (1981)).

subduction melange situated in the southeastern Chara zone, which contains blocks of high-pressure metamorphic rocks, gabbro and basaltic lavas in a matrix of serpentinite schists. K–Ar data on muscovite from garnet amphibolites and glaucophane schists show a short interval of exhumation ranging from 429 to 444 Ma (Late Ordovician–Early Silurian) (Buslov et al., 2001). The ages suggest that subduction occurred in Cambrian to Early Ordovician time. High-pressure rocks and ophiolites of similar age in southwestern Junggar of China (Tanbale blueschists) contain ophiolites of Late Cambrian to Early Ordovician age (Chi et al., 1993; Li, 1998; Xiao et al., 1994). The ophiolites are strongly deformed and consist of peridotite, gabbro, volcanic rocks, and serpentinite melange.

Type II Ordovician ophiolitic melange contains blocks and lenses of oceanic crust—serpentinized peridotite, gabbro, and amphibolite. Ophiolites with a similar composition occur in western Junggar. The Chara ophiolitic belt extends for a distance of more than 250 km along the Naila fault and consists of several ophiolitic bodies of Ordovician age: Barlik, Khongulenk, Khebukesair (Chi et al., 1993).

Type III Late Carboniferous to Early Permian melange separates tectonic thrust sheets, which outline the Chara ophiolite belt. The NW-oriented Type III mélange coincides with the strike of the Chara fault zone, and the blocks within the melange have a similar orientation.

In general, the Chara ophiolitic belt is surrounded by Devonian–Early Carboniferous sedimentary-volcanic rocks (Fig. 2), which we regard as fragments of Early Carboniferous system of accretionary prisms and fore-arc troughs. Like ophiolites, they are separated by strike-slip faults and consist of several units:

1. Namurian turbidites and blue tuffs (Kokpektin Formation) occur on both sides of the Chara ophiolites. The turbidites contain fine-clastic olistostromes and conglomerates composed of island arc pebbles.
2. Early Carboniferous island-arc pillow-lavas, andesitic and basaltic tuffs, reef limestones and siliceous rocks (Verochar Formation). These rocks constitute a tectonic zone northeast and southwest of the Chara ophiolitic belt and the Type III serpentinitic melange. Early Carboniferous radiolaria occur in siliceous rocks (Iwata et al., 1994, 1997a).
3. Visean-Namurian olistostromes containing Middle Devonian–Early Carboniferous oceanic crustal fragments (Ermolov et al., 1981) form a belt along the Chara zone.
4. Oceanic basalts and cherts (Karabaev and Terentjev Formations). Most outcrops of siliceous rocks contain Upper Devonian radiolaria (Iwata et al., 1997a).

Several Paleozoic island arcs, accretionary prisms and ophiolitic zones in the western Junggar were amalgamated in the Late Carboniferous (Chi et al., 1993). The correlation (ophiolite composition and age) between the West Junggar and Chara zones shows that they are fragments of the same Paleozoic accretion complex tectonized in Late Carboniferous time. They differ in their structural position. The Chara ophiolites and exotic island arcs occur as narrow sheets within the Late Carboniferous Chara strike-slip zone, whereas the West Junggar ophiolites together with thick sheets of island-arc and accretion complexes form a Late Carboniferous strike-slip-thrust system (Chi et al., 1993). Together the Chara strike-slip zone and the West Junggar imbricates form strike-slip duplexes at the edge of the Junggar microcontinent.

2.1.2. Irtysh strike-slip zone

The Irtysh strike-slip zone (Fig. 3) separates the Kalba-Narym and Rudny Altai terranes. The zone reaches 50 km in width near the Kurchum block and consists of many tectonic sheets of different composition separated by serpentinite melange, mylonites, blastomylonites and greenschists. In general the Irtysh sheeted structure comprises the rocks of the adjacent collided terranes: Kalba-Narym and Rudny Altai. The strike-slip zone generally consists of tectonic sheets of strongly metamorphosed rocks (granitic gneisses and schists) that have undergone partial blastomylonitization.

Melnikov et al. (1997, 1998) has shown that the Irtysh zone is dominated by variably scaled sinistral strike-slip faults of various scales. The structure of the zone is characterized by a NW–SE oriented, steeply dipping, ductile shear fabric with a regional, well-developed, weakly plunging mineral extension lineation. In all thin sections σ- and δ-shaped blasts and asymmetric shear banding indicate persistent and exclusive sinistral displacement. Ar/Ar data on mica (stepwise heating and laser ablation on muscovite/biotite) of shear fabrics, sampled in places 70–150 km from each other, show ages indistinguishable within the limits of error (281 ± 2.4, 283 ± 7, 283 ± 1.6, 282 ± 1.5, 279 ± 7, 280 ± 1.1 Ma) (Vladimirov et al., 1998). We consider that average 280 Ma age reflects the time of the sinistral strike-slip deformation. $^{40}Ar/^{39}Ar$ data on biotite, muscovite, hornblende and actinolite from blastomylonites and gneisses suggest two pulses of ductile sinistral deformation at 283–276 and 273–265 Ma (Travin et al., 2001).

2.1.3. North East strike-slip zone

The North East strike-slip zone (up to 10 km wide) separates the Rudny Altai terrane from the Gorny Altai and Altai-Mongolian terranes. This sinistral strike-slip fault zone consists of allochthonous blocks within greenschists. The Early Permian age of displacement along the fault is defined by the relationship between greenschists and granites (Vladimirov et al., 1997). Deformation affected Late Carboniferous granites of the Zmeinogorsk complex. The shear deformation zone was accompanied by intrusion of Late Permian–Triassic plutons (Savvushin, Tigerek),

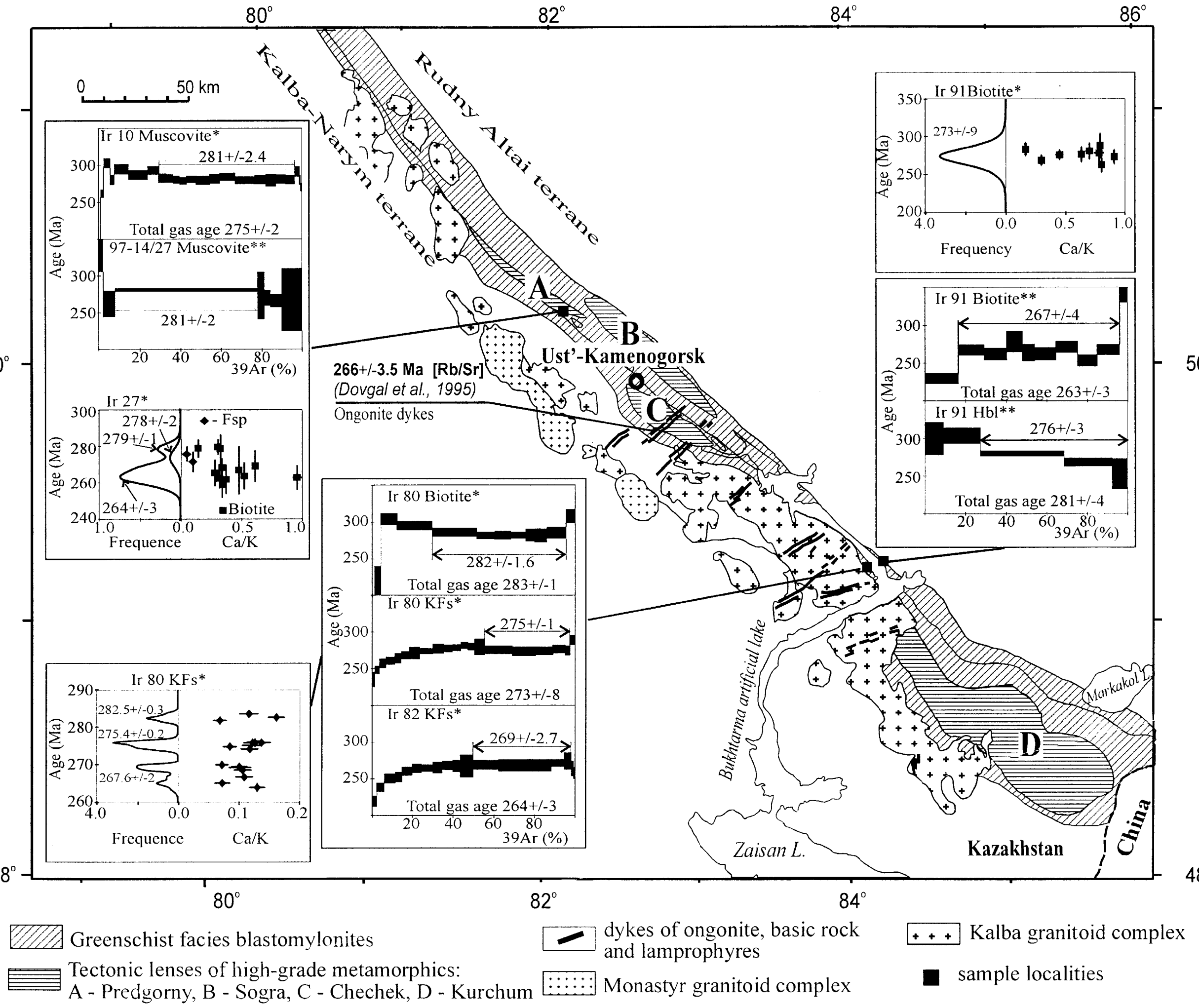

Fig. 3. A geological sketch of the Irtysh strike-slip zone: geochronological constraints (after Travin et al. (2001)).In the insets—the diagram ^{39}Ar-Age shows step heating results, the diagram Ca/K-Age shows laser ablation results with additional integral probability density (for 95% confidence probability interval). The dating was undertaken at the Free University of Brussels, Belgium(*) and the United Institute of Geology, Geophysics and Mineralogy of SB RAS, Novosibirsk, Russia (**).

the age of which defines an upper age limit of the sinistral movements.

2.2. Late Devonian–Early Carboniferous faults in the Altai: a result of the collision of the Altai-Mongolian terrane and the Siberian continent

The structure of the Altai was greatly affected by the collision of the Gondwana-derived Altai-Mongolian terrane and the Siberian continent. Two stages of collision resulted in the formation of the Charysh–Terekta and Teletsk–Bashkauss fault zones (Fig. 4). In the Middle Devonian–Early Carboniferous island-arc and oceanic crustal fragments collided with the Siberian continent and the dextral Teletsk-Bashkauu fault zone was formed. The collision was also accompanied by dextral displacement along the Charysh–Terekta fault and strike-slip faulting and thrusting in the Kurai zone.

2.2.1. Charysh–Terekta strike-slip zone

The Charysh–Terekta strike-slip zone consists of Upper Riphean–Eifelian rocks detached from the collided structures and exotic terranes, such as Zasura, Charysh and Uimon, which are fragments of Late Cambrian–Early Ordovician oceanic crust. These fragments were first discovered in the Gorny Altai, Ordovician fore-arc trough and Silurian–Early Devonian high-pressure rocks (Buslov, 1998; Buslov et al., 2000). Below, we provide a description of two sections of the Charysh–Terekta zone: Charysh-Inya and Terekta (Figs. 5 and 6).

In the Charysh-Inya section the zone of strike-slip faults is 120–130 km wide and consists of 5 deformed structural units [west to east: Inya, Kurya-Akimov, Charush, Zasura and Talitsk], which are the fragments detached from the collided terranes and oceanic crust (Fig. 5).

The base of *the Inya structural unit* consists of sand-shale deposits of the Suetka suite, which are similar to the Middle–Upper Cambrian flysch of the Kadrin suite of

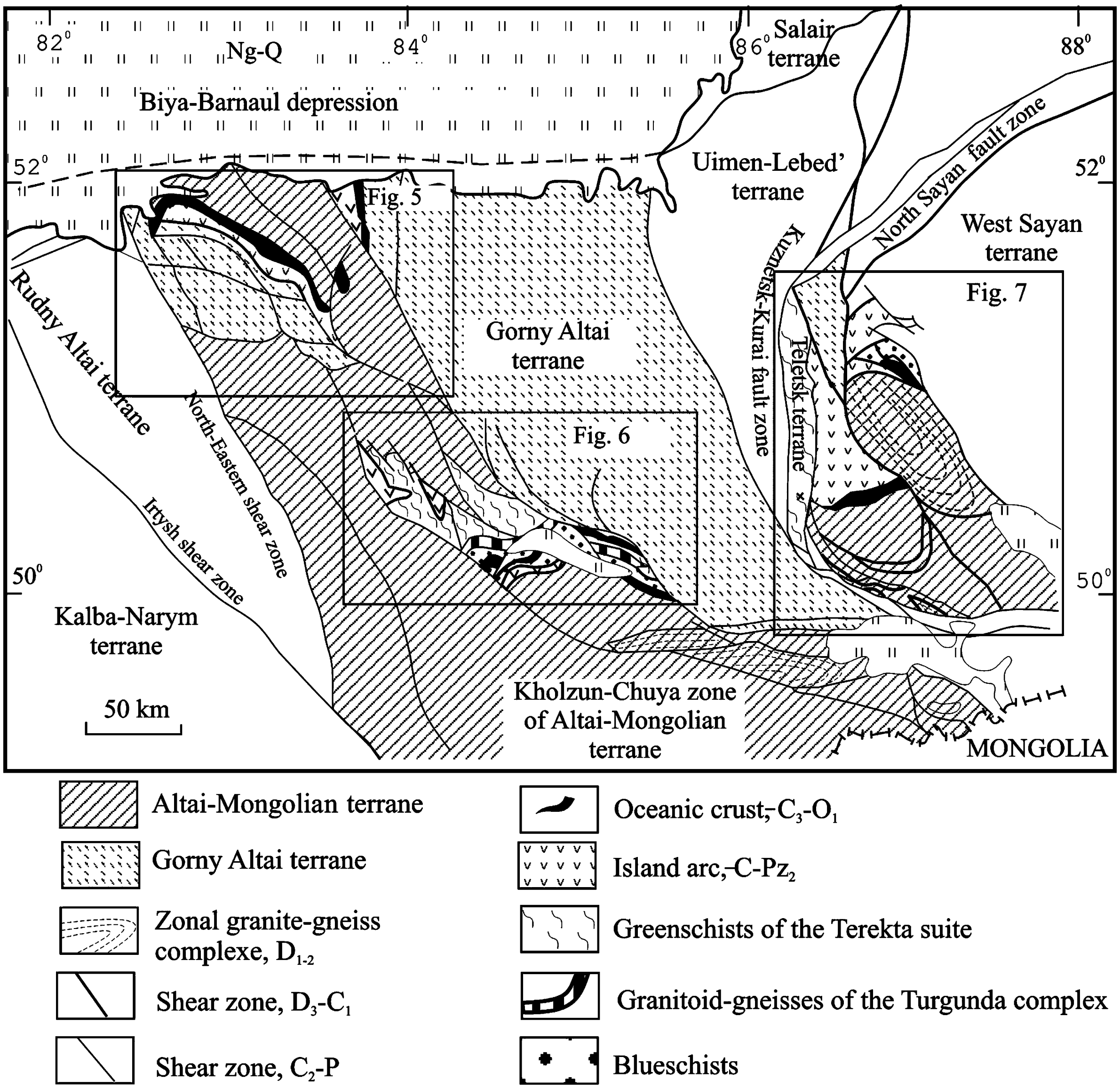

Fig. 4. The structural pattern of the Late Devonian—Early Carboniferous collisional stage between the Gondwana-derived Altai-Mongolian terrane and the Siberian continent.

the Anuy-Chuya fore-arc trough of the Gorny Altai terrane. The Suetka suite consists of feldspar-quartz sandstones and shales and polymictic terrigenous shales, sandstones, gritstone, and conglomerates. The composition of the clastic material (Volkov, 1966) shows that sand-shale fragments have been probably supplied by an island-arc, like the Gorny-Altai island-arc, from which the clastic material was delivered to the Anuy-Chuya fore-arc trough. Upsection, the Inya unit is composed of Ordovician–Silurian terrigenous-carbonate rocks, which are similar to the Anuy-Chuya zone units of the same age (Yolkin et al., 1994; Buslov et al., 2000), lithology, stratigraphy and fauna.

The Kurya-Akimov structural unit is composed of Early–Middle Devonian sedimentary-volcanogenic rocks of the Kukuy suite that consists of basic, intermediate and minor acidic volcanics, mottled tuffs, tuff-gritstones, sandstones and siltstones. Petrochemical data indicate the volcanics erupted in an active margin (Tikunov, 1995).

The Charysh tectonic sheet is composed of rhythmically bedded gray-green sandstones and siltstones interbedded with coarse-clastic rocks. The upper part of the section consists of rhythmically bedded mottled sandstones, siltstones, siliceous shales and cherts. The lower part was earlier attributed to the Suetka or undivided Suetka-Charysh suite, and the upper part to the Zasura suite. The sandstones and siltstones consist of fragments of feldspar and cherts. They include lenses and layers of gritstones and conglomerates with largely rounded fragments of cherts and porphyrites. The cherts and magmatic rocks are analogous to Late Cambrian–Early Ordovician rocks of the Zasura suite. Abundant

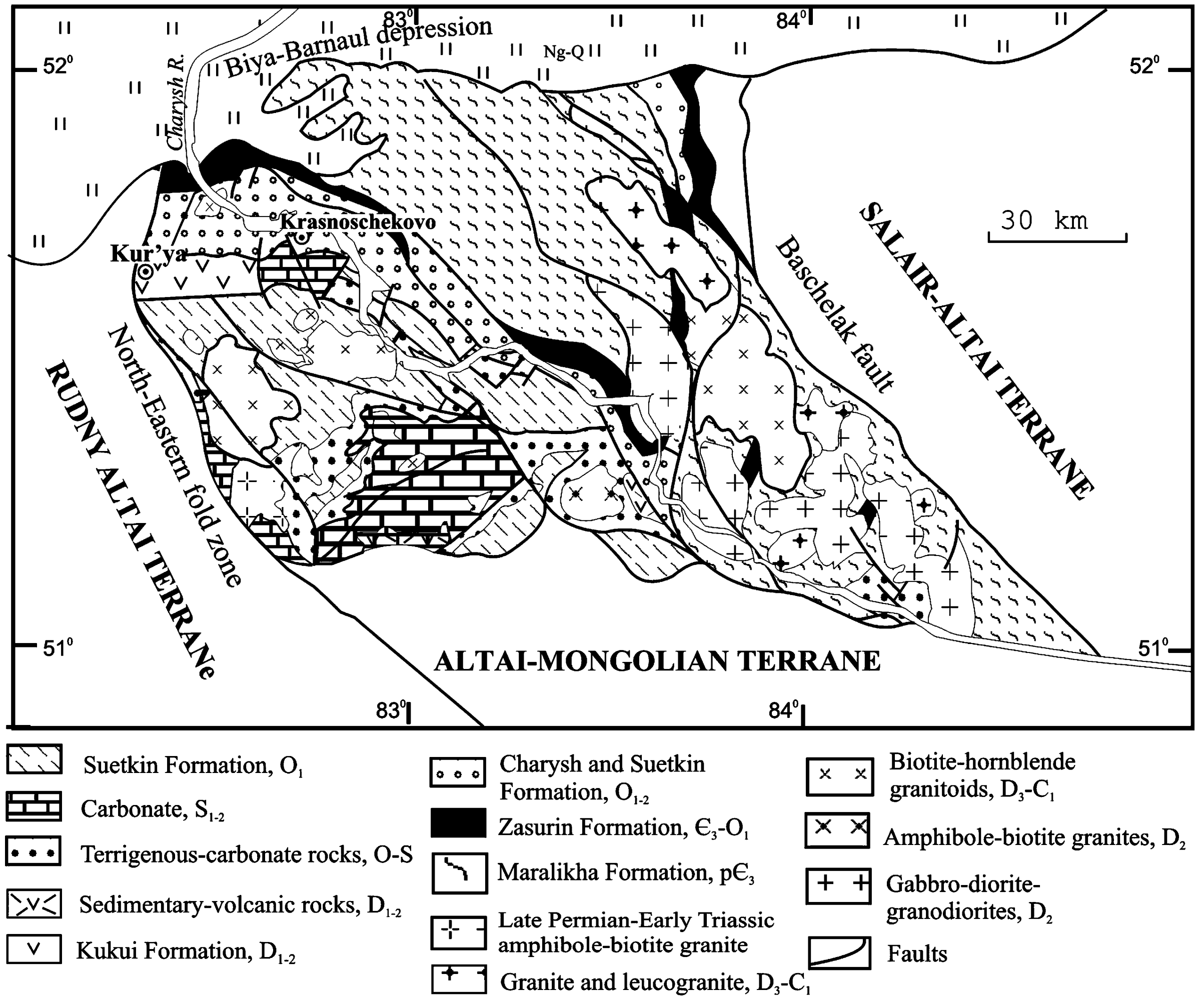

Fig. 5. Geology and structure of the Charysh–Terekta strike-slip zone—Charysh-Inya section in the north-western Gorny Altai terrane (modified from Iwata et al. (1994) and Vladimirov et al. (1997).

fragments of porphyrites, plagiogranites, granites, and diorites are compositionally similar to island-arc rocks. Because the conglomerates contain fragments of Late Cambrian–Early Ordovician rocks of the Zasura suite—the sequence is younger than Early Ordovician—the island arc should also be younger. According to data by K. Iwata, the siliceous-clay interbeds of the Charysh suite contain many varieties of Middle Ordovician *Conodonts*. Accordingly, these rocks represent an independent lithologic-stratigraphic unit which formed in a Middle–Upper Ordovician (?) fore-arc trough.

The Zasura structural unit consists of several lens-shaped tectonic sheets, which are composed of mottled sandstones, cherts, basaltic pillow-lavas, tuffs, sills and gabbro-diabase dikes. Layered siliceous rocks contain various *Conodonts* and *Radiolaria* indicating an Upper Cambrian–Early Ordovician age (late Tremadoc–early Arenig) (Iwata et al., 1997b). Poorly-rounded fragments of siliceous-argillaceous rocks and cherts, basalts, and tuffs of the Zasura suite occur in sandstone interbeds.

Geochemical data of Zasura basalts are similar to those of oceanic island and mid-oceanic ridge basalts (Buslov et al., 2000, 2001).

The Talitsk structural unit consists of clay and siliceous-clay shales, and sandstones. Different shales contain chlorite-quartz, sericite-chlorite-quartz, and sericite-chlorite. The sandstones consist of half-rounded fragments of quartz, feldspar, sphene, epidote, apatite as well as microquarztite, chert, and porphyrite in a quartzose, chlorite-quartz or sericite-chlorite-quartz matrix. Compositionally similar varieties comprise the Gornoaltaiskaya series (Volkov, 1966) of the Altai-Mongolian terrane.

Strongly foliated and crenulated greenschist-grade rocks and isoclinally folded and boudinaged layers mark the zones of shear deformation related to the Charysh–Terekta strike-slip fault.

Strike-slip deformation zones up to several kilometers wide occur close to the boundaries of the tectonic units. For example, a shear zone near Ust-Pustynka Village is over 3 km wide and is composed of schists after

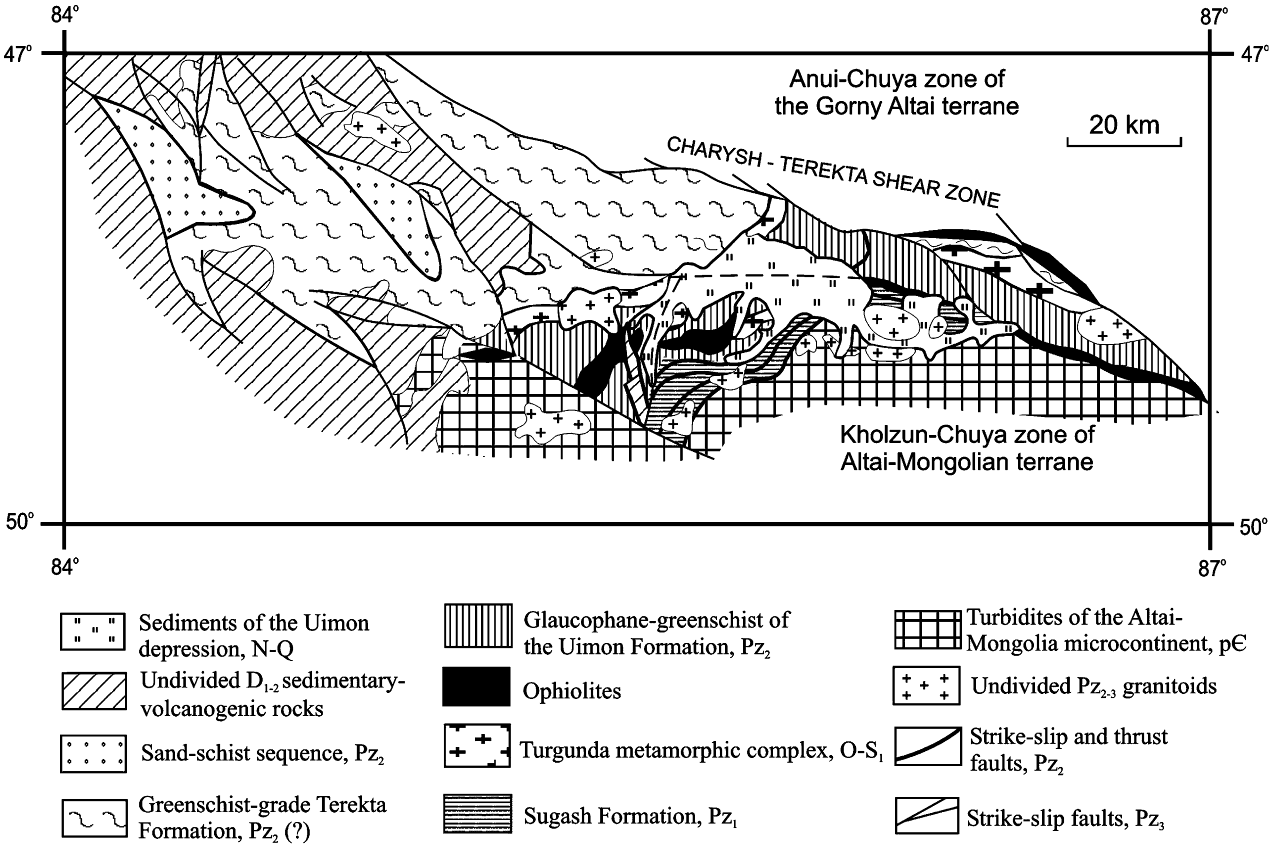

Fig. 6. Geology and structure of the Charysh–Terekta strike-slip zone—Terekta section in the central part of the Gorny Altai.

terrigenous rocks of the Suetka suite, volcanogenic-siliceous rocks of the Zasura suite and Ordovician–Silurian carbonates. The Suetka suite is dominated by greenschists. The Zasura suite consists of tectonic lenses of siliceous shales, cherts, basalts, and quartz-chlorite-sericite schists after sandstones and siltstones of the Suetka suite.

The Zasura and Talitsk tectonic units are everywhere bounded by a 2–3 m thick melange-greenschist zone, which includes lenses of Zasura magmatic rocks and cherts surrounded by greenschists formed after terrigenous rocks of the Maralikha and Charysh suites.

The Talitsk structural unit consists of two large sheets separated by a zone of quartz-chlorite-sericite schists with strings of limestone lenses. The limestones contain deformed fossils—Early Devonian *Crinoidea* and corals (Gutak, 1997).

The age of deformation and faulting in the Charysh–Terekta zone (Fig. 5) can be estimated by studying relationships with dated intrusive bodies (Vladimirov et al., 1997). The sheeted Charysh–Terekta dextral strike-slip fault zone is intruded by Talitsk granites of latest Devonian–earliest Carboniferous age. Both the fault zone and granitic plutons are cut by the North-East and Bashchelak sinistral strike-slip faults of Middle Carboniferous–Early Permian age. Late Permian–Early Triassic magmatic bodies intrude the shear zones and their adjacent terranes, e.g. the Savvushin pluton and its satellite Volchji Shkili intrude the Rudny Altai terrane, the Sinyushin pluton—the Altai-Salair terrane, the Tigerets and Korovikhin plutons—the Altai-Mongolian terrane. In the Triassic–Jurassic the terrane structure was reactivated by strike-slip faults that locally cut Late Permian–Early Triassic plutons and other intrusions.

The Terekta section (Fig. 6) is located in central Gorny Altai. It is a Middle Devonian thrust sheet transected by Late Devonian–Early Carboniferous strike-slip faults (Buslov, 1992; 1998; Dobretsov et al., 1992). Greenschist retrogression within the tectonic contact zones and secondary foliation produce gradual transitions between the structural units.

A generalized section of the thrust structure consists of the following structural units (northwest to southeast) (Buslov, 1998):

1. A Middle Paleozoic sand-clay sequence unconformably overlain by Early–Middle Devonian volcanogenic-sedimentary rocks and bordered by the Terekta Formation with an intervening 100–200 m thick zone of greenschists.
2. Middle Paleozoic (?) metavolcanics and terrigenous rocks of the Terekta Formation as well interbeds and lenses of quartzite, marble, and metabasalt.
3. Strongly metamorphosed rocks, which are in the epidote-amphibolite and partly amphibolite facies of

metamorphism. They form a variably narrow zone, which extends for a distance of 100 km. In the easternmost part of the zone a sheet of strongly metamorphosed rocks, termed the Turgundin metamorphic complex, has Ar–Ar amphibole ages on biotite-amphibole rocks of 415–418 Ma (Early Silurian) (Buslov et al., 2001).

4. Volcanic and metamorphic rocks of the Uimon formation. The K–Ar and Ar–Ar mica and amphibole age of metamorphism is 455–400 Ma (Upper Ordovician–Early Devonian) (Buslov et al., 2001). Typical glaucophane-crossite schists occur within metabasalts (lavas and tuffs) associated with quartz schists containing piemontite, and riebeckite. Retrogression of the rocks has given rise to porphyroblastic albite-chlorite schists.
5. Devonian sediments show cleavage and shearing. In the northern part of the sheet, where the cleavage is less pronounced, fragments are preserved of a stratigraphic section comparable to that of the Early Devonian Kholzun Formation of the Korgon zone.
6. Cambrian–Ordovician (?) ophiolites are represented by siliceous-volcanogenic-sedimentary rocks and ultrabasics. The ultrabasic/basic rocks are transformed into serpentinite, pyroxenite, gabbro, and rhodingites.
7. Early–Middle Ordovician sedimentary-tuff and volcanogenic rocks of the Sugash Formation. The sedimentary-tuff sequence comprises mudstones, argillites, tuff-sandstones, and argillaceous cherts. Its analogue in the northwestern Altai is clearly the Charysh Formation. The volcanogenic sequence consists of interbedded diabase porphyrites, basaltic lavas, tuffs, diabase dikes and sills, gabbro-diabase, sandstones, and siltstones. The volcanic rocks have a calc-alkaline island-arc composition.
8. A Late Cambrian–Early Ordovician sequence consists of layered cherts containing deformed radiolaria analogous to the Zasura cherts of the same age.

2.2.2. Kurai strike-slip zone

The Kurai metamorphic strike-slip zone is located in eastern Gorny Altai (Fig. 7) and consists of tectonic sheets, imbricate structures, mylonites and melange zones (Buslov, 1992; 1998). In the axial part of the Kurai Range the zone contains a main body and sheeted zones (Fig. 8) separated by strike-slip faults and oblique thrusts. The metamorphic zone is composed of the Early–Middle Devonian metamorphic rocks of the Kurai complex, Silurian and Devonian sedimentary rocks and Vendian–Early Cambrian volcanogenic-sedimentary rocks. The fault planes are marked by serpentinites comprising linear schist bodies and monomictic and polymictic melange. The bodies are usually several tens of meters thick.

The main sheeted body is the Kurai zonal metamorphic complex, which is in the epidote-amphibolite facies. K–Ar and Ar–Ar amphibole and mica ages are within the 374–394 Ma interval (Buslov et al., 2001). The metamorphic sheet is several kilometers thick, 70 km long and 10 km wide. The complex is composed of granitic gneisses, migmatites, gneisses of different compositions, garnet-plagioclase-mica schists, amphibolites, and pegmatites.

The NW-striking schistosity dipping at 50–80° contains a mineral lineation, which dips 0–20° to the northwest. Kinematic indicators show sinistral movement along the mineral lineation.

In most cases, blastomylonites occur parallel to the schistosity. Their Ar–Ar and K–Ar muscovite age is 322–333 Ma, i.e. Early Carboniferous (Buslov et al., 2001). Several tectonic sheets occur along the southern frame of the Kurai complex, close to the young Kubadrin fault. There the Kurai metamorphic rocks and foliated Vendian–Middle Cambrian volcanogenic-sedimentary rocks, separated by serpentine zones, show cataclasis and mylonitization.

2.2.3. Teletsk–Bashkauss strik-slip zone

The Teletsk–Bashkauss strike-slip zone is up to 300 km long within the eastern Gorny Altai. In the north it changes to the Kuznetsk-Altai fault zone and in the south it extends to Mongolia. The strike-slip zone is several kilometers wide and it underwent two main times of formation: (1) Late Devonian–Early Carboniferous, (2) Late Permian–Triassic. The collision between the Gonwana-derived Altai-Mongolia terrane and the Siberian continent in Late Devonian to Early Carboniferous produced the Teletsk–Bashkauss shear zone. Left-lateral strike-slip along the Teletsk–Bashkauss fault, with an apparent displacement of about 80 km, split in two the Middle Paleozoic Ulagan–Erinat ophiolite suture (Fig. 7). The Late Permian–Triassic evolution of the North Sayan right-lateral strike-slip fault results from the collision between the Siberian and Kazakhstan continents (Buslov and Sintubin, 1995; Smirnova et al., 2002). The faulting occurred during east-west compression, and truncated and displaced the Late Devonian–Early Carboniferous structural pattern. The magnitude and direction of apparent displacement (30 km) is indicated by separation of Late Riphean greenschists and Middle Devonian granitoids into two blocks (Fig. 7).

The Teletsk–Bashkauss shear zone marks (Figs. 7 and 9) a Late Devonian–Early Carboniferous strike-slip fault along which Paleozoic rocks of the West Sayan block are in contact with Late Riphean complexes of the Teletsk block (Buslov and Sintubin, 1995; Sintubin et al., 1995). The zone is separated into two segments that differ in kinematics, structural and metamorphic history.

The northern segment (I in Fig. 9) is an NW–SE strike-slip zone with a nearly vertical foliation plane containing a well-developed, sub-horizontal mineral lineation that plunges shallowly southeastward. Different kinematic indicators (S–C relationships on both mesoscopic and microscopic scales, extensional shear bands C') show a left-lateral sense of movement along the lineation (Smirnova et al., 2002). The northern segment involves rocks of at least

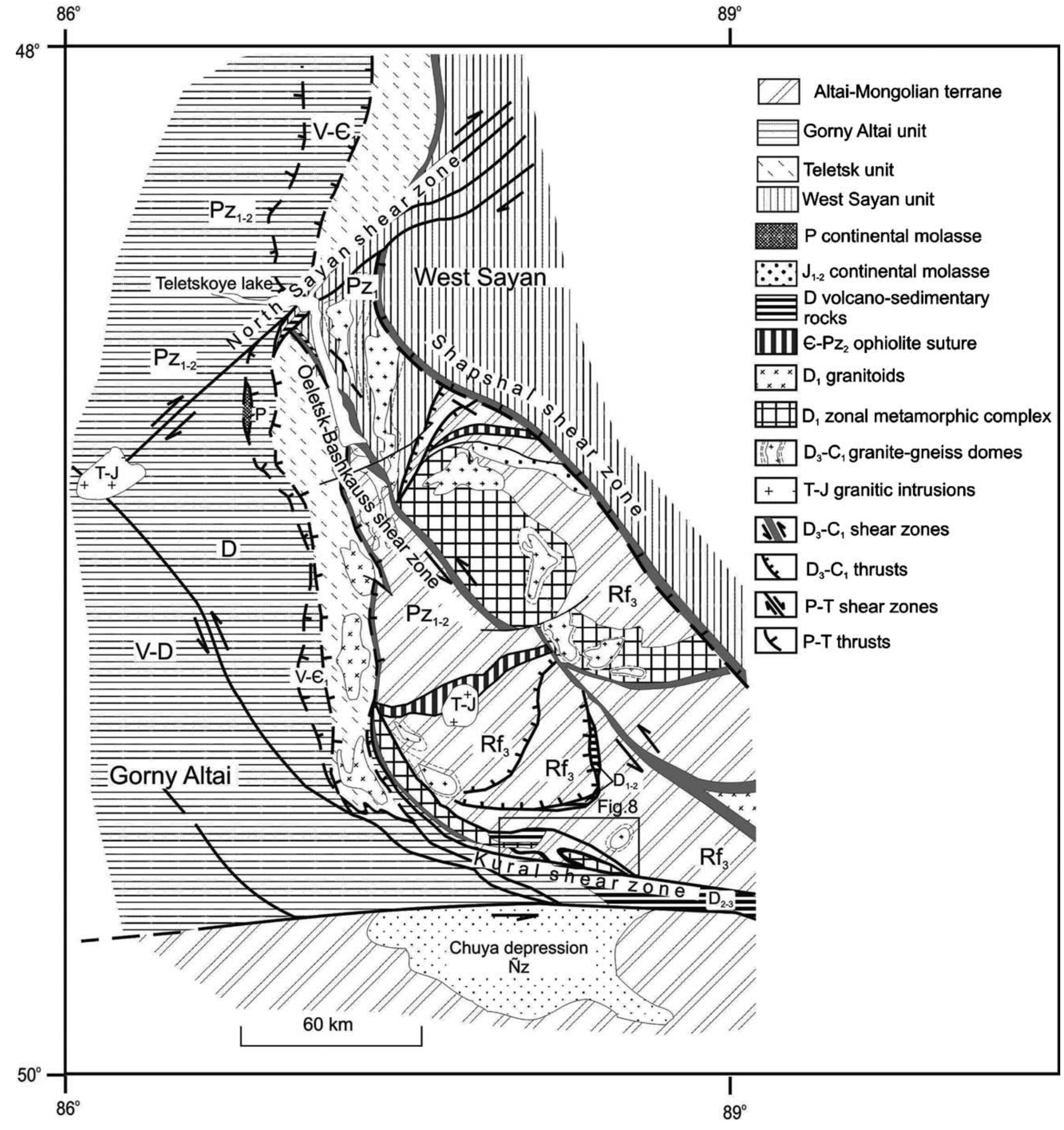

Fig. 7. Geological sketch of the eastern Gorny Altai.

two tectonic facies of different age: Early–Middle Devonian and Late Devonian–Early Carboniferous. Early–Middle Devonian granitoids of the Altyntauss massif and volcano-sedimentary rocks extend along the western side of Lake Teletskoye in a 3–4 km wide strip. They are granite or diabase blocks—topographically expressed as uplifts—surrounded by mylonites and blastomylonites of a granitoid and diabase composition. The Late Devonian–Early Carboniferous peripheral part of the shear zone is composed of greenschists enclosing mylonites. Unlike the northern segment, the southern one (II in Fig. 9) has a complex geometry. NS schistosity dips steeply. Weakly developed mineral lineation in fine-grained rocks plunges steeply or gently to the south. The segment separates granite gneiss domes and turbidites of the West Sayan block from an Early–Middle Devonian gabbro of the Altyntauss massif (southern Lake Teletskoye). The rocks of the Chiri segment (Smirnova, 2002) are migmatite gneiss, sheared two-mica granite, garnet-cordierite-biotite- and amphibole-biotite-quartz schist formed from Altyntauss gabbro-diabase. Locally actinolite and chlorite layers develop parallel to the regional foliation. Topographically

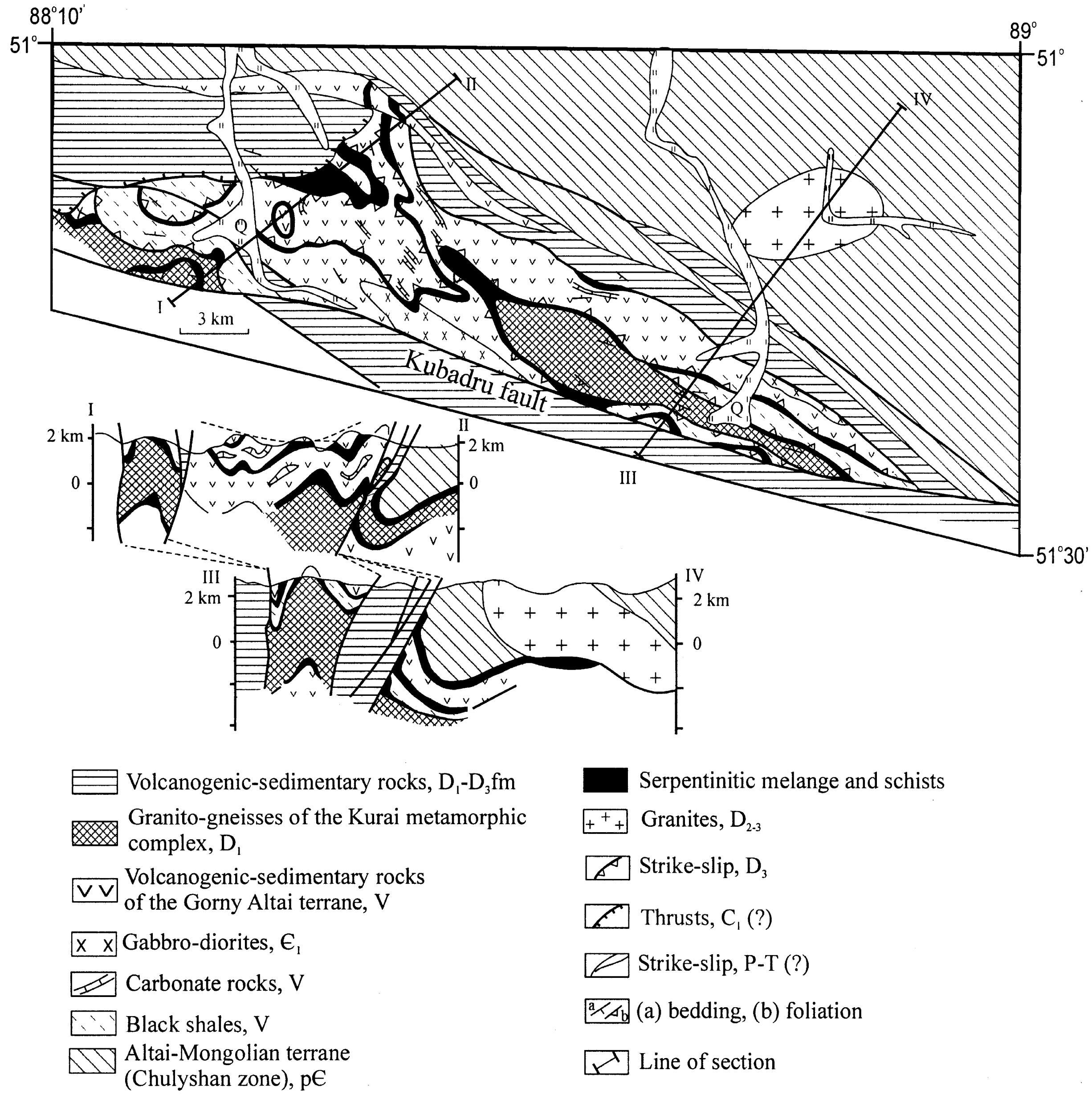

Fig. 8. Geological sketch of the Kurai strike-slip fault which destroyed the D_3 thrust structure at the base of the Altai-Mongolian terrane.

the Chiri segment represents the eastern listric master fault of southern Lake Teletskoye.

K–Ar and Ar–Ar data on biotite and muscovite from mylonites, mica schists and biotite-amphibole schists (Buslov et al., 2001) (Fig. 9) yield a Late Devonian–Early Carboniferous age for Teletsk–Bashkauss shear zone (367–318 Ma).

3. Description of terranes and paleomagnetic characteristics of the Devonian sections

The Altai-Mongolian terrane is composed of shelf and continental slope terrigenous rocks. At present, it is about 1000 km long and 250 km wide extending from the Russian Altai to the Mongolian and Chinese Altai. In Rudny and Gorny Altai it is bounded by the North-East and Charysh–Terekta strike-slip zones. The terrane is dominated by Vendian-Cambrian sandstones, siliceous shales, and phyllitic shales (Volkov, 1966; Dergunov, 1989). Dergunov, (1989) showed that upper flysch horizons contain sandstone, siltstone and sparse interbeds of acid tuffs and argillaceous cherts. The flysch is isoclinally folded and transgressively overlain by various Ordovician–Devonian units indicating a complex geodynamic evolution. In southern Gorny Altai Middle-Ordovician marine carbonate-terrigenous sediments overlap with a basal conglomerate deformed and metamorphosed basement rocks. The Emsian active margins (Korgon and Kholzun zones in Gorny Altai) (Tikunov, 1995; Gutak, 1997; Dergunov, 1989) are widely distributed

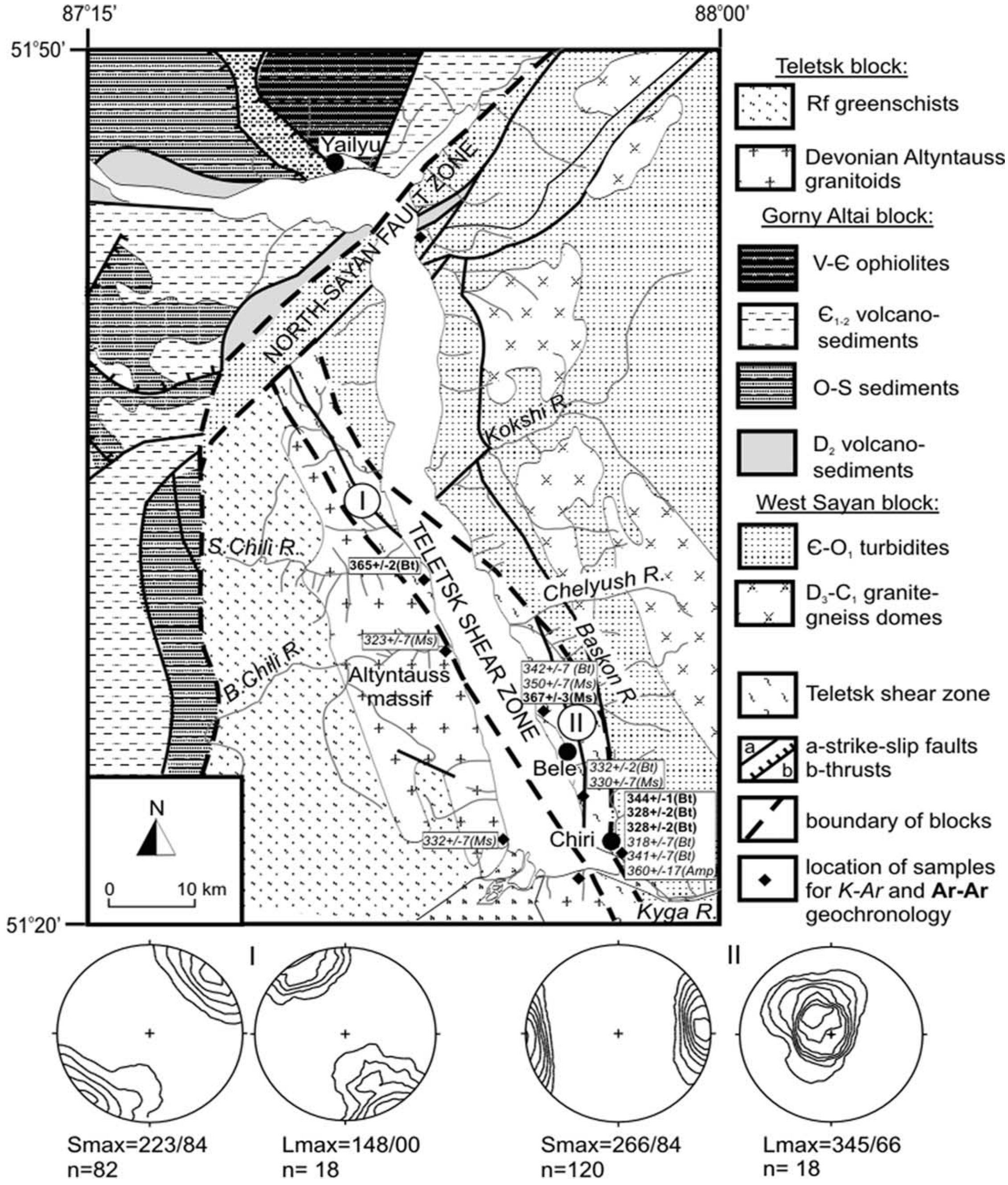

Fig. 9. Geological sketch of the Teletsk–Bashkauss strike-slip zone.

in Western Mongolia. The Emsian units transgressively overlap 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), which mark extension of zones related to strike-slip deformation, which occurred along the terrane/ Siberian continent collisional boundary.

Paleomagetic data (Buslov et al., 2000; 2001), obtained in the laboratories of UIGGM, Hokkaido University and the Institute of Earth Physics RAS, indicate that Emsian rocks of the Altai-Mongolian terrane (Sebystai and Ulandryk suites) formed near the equator at 1–4° N.

The Kalba-Narym terrane is located between the Chara and Irtysh strike-slip fault zones and is composed of Late Devonian–Early Carboniferous sedimentary rocks of the Takyr Formation intruded by Early Permian granitoids of the Kalba complex. The Takyr Formation consists of black shales and siltstones with thin interbeds of fine-grained polymictic sandstones, which gradually increase in thickness up the section giving a total thickness of over 1500 m. Buslov et al. (1993) and Berzin et al. (1994) suggested that the Takyr Formation is a passive margin and its analogues occur in the Tom'-Kolyvan zone and Salair (Fig. 1).

The Gorno-Altai terrane consists of several tectonic units formed near the Siberian continental margin (Yolkin et al., 1994; Buslov et al., 1993; Tikunov, 1995; Simonov et al., 1994; Buslov and Watanabe, 1996; Kazansky et al., 1998). We recognize a Late Vendian–Cambrian island-arc, which consists of Late Vendian primitive island arc varieties, a Late Vendian–Early Cambrian accretionary wedge, Cambrian normal island-arc varieties and their related fore-arc and back-arc basin rocks. Late Vendian–Cambrian island-arc margin units are overlain by Ordovician–Early Devonian passive margin terrigenous-carbonate sediments (Yolkin et al., 1994). The tectonic regime changed in the Emsian–Early Givetian resulting in the formation of an active margin. Gabbro-diabase dikes and sills (Yolkin et al., 1994) and granites (Vladimirov et al., 1997) are widely distributed within the terrane. They may have formed in extensional environment related to strike-slip faulting of the Siberian continental margin.

Active margin units of Emsian (Taldytyurgun sandstones and tuffs) and Early Givetian (Kuratin lavas, tuffs and sediments) age formed in 27–30° and 23–26° N, respectively (Buslov et al., 2000; 2001).

The Rudno-Altai terrane is composed of sedimentary-volcanogenic units which have a base of Ordovician–Silurian (?) oceanic crust (Gutak, 1997; Gritsuk et al., 1995). The rocks have greenschist facies assemblages and represent two composition groups. The first is a metaschist overlain by ortho- and paraschists. The oceanic crust is conformably overlain by a weakly metamorphosed deep trench (Gritsuk et al., 1995), sandstones and schists (Korbalikhin suite), dated as Early Devonian by the occurrence of phytoplankton and spores (Lochkovian-Pragian stage) (Gutak, 1997).

Upsection there is a thick Devonian–Carboniferous unit containing Emsian–Givetian terrigenous rocks and limestones that probably accumulated on the slope of a fore-arc trough. They contain interbeds of tuff, polymictic sandstone and conglomerate. Clastic material is represented by cherts and volcanics of variable composition, which are unknown at the base of the Devonian section in Rudny Altai. Emsian fauna and lithological composition (Yolkin et al., 1994), indicate the deposits of the Rudno-Altai terrane are close to those of Salair. In the Late Givetian–Late Devonian volcanic and plutonic island-arc rocks formed in Rudny Altai and back-arc basin rocks in Salair and Gorny Altai (Yolkin et al., 1994).

The paleomagnetic data (Buslov et al., 2000; 2001) on the Devonian section near Zmeinogorsk town show that Emsian sandstones and siltstones of the Beryozovskaya suite formed at 28° N and Givetian tuffs of the Zavodskaya suite at 20° N. Our data agree with those of Burtman et al. (1998) that show that the Rudno-Altai active margin had a NE strike in the Middle-Late Devonian and was located at 32 ± 4° N.

4. Discussion

The data summarized above indicate Late Paleozoic large-scale strike-slip displacements, which were responsible for the formation of the present mosaic-block orogenic structure in the Altai-Sayan and East Kazakhstan. Rocks of the Late Cambrian–Early Ordovician oceanic crust and Ordovician fore-arc are possibly fragments of an accretionary wedge formed at the margin of the Altai-Mongolian terrane. 'Oblique' collision of the Altai-Mongolian terrane and the Siberian continent, and subsequent collision of the Kazakhstan and Siberian continents resulted in the deformation of the accretionary wedge. The latter was split into several tectonic sheets and then broken by transverse strike-slip faults.

The Irtysh shear zone separates the Rudno-Altai terrane from the Kalba-Narym and West-Kalba terranes that are mainly composed of a Late Devonian–Early Carboniferous fore-arc and accretionary wedge (Yolkin et al., 1994; Rotarash et al., 1982). The Rudno-Altai, Kalba-Narym and West-Kalba terranes are fragments of a single active margin of the Siberian continent. They were offset many hundreds of kilometers relative to each other along strike-slip faults 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 on the Irtysh shear zone (Sengör et al., 1993). In turn, the Chara ophiolitic suture separates the above-mentioned terranes from the Devonian–Early Carboniferous rocks of the Chingiz-Tarbagatai terrane belonging to the Kazakhstan continent. Paleomagnetic data show that the Middle–Late Devonian volcanic-sedimentary rocks of the latter terrane formed at 21° N. Thus, the Chingiz-Tarbagatai and Rudno-Altai island arcs traveled around 650–1650 km before they collided (Burtman et al., 1998). This value defines a total rate of sinistral strike-slip displacement along the Chara and Irtysh zones.

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 a NS strike in the ancient system of coordinates, and the southeastern segment—a EW strike. According to our data the Emsian volcanic belt of the Altai-Mongolian terrane formed at 21–24° N and had an almost NS strike.

The paleomagnetic and structural data enable us to make the following conclusion about the scale and direction of strike-slip displacements resulted from the Altai-Mongolian terrane/Siberian continent collision (Franian–Early Carboniferous) and then from the Kazakhstan continent/Siberian continent collision (Middle Carboniferous–Permian). Paleomagnetic and geochronological data show that the Emsian rocks of the Altai-Mongolian terrane migrated over a distance of more then 2000 km before they were accreted to the Gorno-Altai terrane. In the Emsian, the Salair-Altai active margin of the Siberian continent had a EW strike and bounded the latter to the south, at 23–30° N. In the Emsian-Givetian volcanic-sedimentary rocks of the Rudny Altai (21–28° N) were located near the Salair-Altai zone (23–30° northern paleolatitude), probably comprising together an EW-striking volcanic belt. In the Devonian-Carboniferous the Siberian continent and the Devonian active margin rotated clockwise with a speed up to 2° per 1 Ma (Pechersky and Didenko, 1995). In the Eifelian, the Altai-Mongolian terrane drifted northwards, starting from 1–4° N, as did the Paleoasian ocean lithosphere, which simultaneously migrated in the same direction and subducted beneath the Siberian continent.

At the end of the Middle Devonian the Altai-Mongolian terrane drift closer to the Siberian continent, and its active margin had a NE strike and was located at 32–30° N (like the Rudno-Altai zone) (Burtman et al., 1998). The collision between the Altai-Mongolian terrane and Siberian continent resulted in the formation of dextral strike-slip zones: the Charysh–Terekta, Kuznetsk-Kurai and Teletsk fault zones. The above geological and geochronological data show that the strongest strike-slip deformations in the Charysh–Terekta fault zone occurred in the Late Devonian. In the Teletsk fault zone, strike-slip displacements are recorded by shear zones consisting of Early Carboniferous rocks (Buslov and Sintubin, 1995). Thus, strike-slip deformation in the Devonian–Early Carboniferous separated the marginal part of the Siberian continent into several terranes.

Paleomagnetic, compositional and structural data on the Charysh–Terekta strike-slip zone indicate a complex interaction of the Altai-Mongolian terrane with the Siberian continent. After the terrane collided with the continent in the Late Devonian, it continued slipping along the continental margin before it met the Rudno-Altai island arc. That movement agrees well with a general migration of the Paleoasian oceanic lithosphere and Kazakhstan continent westwards, towards the East European continent (ancient coordinates) (Pechersky and Didenko, 1995). The later collision of the Kazakhstan and Siberian continents complicated the pre-existing structure. Such a mechanism helps us explain the 2000 km gap between the paleolatitudes of the Emsian rocks of the Anui-Chuya zone in Gorny Altai and those of the Altai-Mongolian terrane.

5. Late Paleozoic evolution of the Paleoasian ocean: paleoreconstructions

Based on our own and published paleomagnetic and structural data (Yolkin et al., 1994; Rotarash et al., 1982; Buslov and Kazansky, 1996; Burtman et al., 1998; Sengör et al., 1993; Grishin et al., 1997; Pechersky and Didenko, 1995; Buslov and Sintubin, 1995; Didenko, 1997; Didenko et al., 1994; Pechersky et al., 1994) we suggest the following paleoreconstructions for the Emsian–Early Givetian and Early Carboniferous stages of the Paleoasian ocean evolution (Fig. 10).

The Emsian-Givetian stage. The Gorno-Altai and Rudno-Altai volcanic belts were located in a band at the 21–30° N, close to the southern and southeastern margins of the Siberian continent. The Altai-Mongolian terrane was located near the equator at 1–4° northern paleolatitudes. At the end of the Middle Devonian the Altai-Mongolian terrane came closer to 21–30° N and collided with the Siberian continent. Due to the subduction of the Ob-Zaisan oceanic crust, the terrane started slipping along the EW-striking margin of the Siberian continent. This resulted in the formation of the sheeted suture structure of the Charysh–Terekta zone.

The Early–Middle Carboniferous stage. In the Early Carboniferous the Altai-Mongolian terrane was driven between the Gorno-Altai and Rudno-Altai zones. The Kazakhstan continent bounded by an active margin migrated northeastward (28° N in the D_2^2–D_3^1 and 35°N in the C_{2-3}) (Buslov et al., 2000; 2001) before it collided with the Siberian continent rotating clockwise. In the Middle Carboniferous the Ob-Zaisan basin closed and the collision of continents started.

The Permian stage. The collision of continents resulted in the formation of the sinistral strike-slip faults in the Altai (Chara, Irtysh and North–Eastern faults) and in reactivation of the Charysh–Terekta, Kuznetsk-Kurai and other faults. The rate of displacement along the strike-slip faults is estimated to be many hundred kilometers. The collision was followed by the deposition of Late Carboniferous molasse and extrusion of andesitic-dacitic, trachyandesitic and trachydacitic lavas (Berzin et al., 1994; Ermolov et al., 1981; Rotarash and Gredyushko, 1974).

6. Conclusions

The tectonic pattern of the Altai includes three groups of structural-tectonic units: (1) the Gondwana-derived Altai-Mongolian terrane; (2) terranes of different age—Kalba-Narym, Rudny Altai, Gorny Altai, which are composed of the fragments of Caledonian and Hercynian accretion-collision zones. Accretionary prisms (wedges) contain subducted fragments of oceanic lithosphere—ophiolites, seamounts and ocean islands—which had accreted to island arcs and/or active continental margins. (3) Systems of strike-slip faults and thrusts of different age—Chara, Irtysh, North-East, Charysh–Terekta, Kurai, Teletsk–Bashkauss, which separate collisional terranes from the margins of collided continents. The strike-slip zones commonly completed the formation of the suture zones and/or they developed parallel to ophiolitic sutures within collided continents.

Our kinematic and dynamic characterization of the large-scale strike-slip faults in the Altai enable us to make the following conclusion. The collage of Altai terranes formed as a result of two collisional events. The Late Devonian–Early Carboniferous collision between

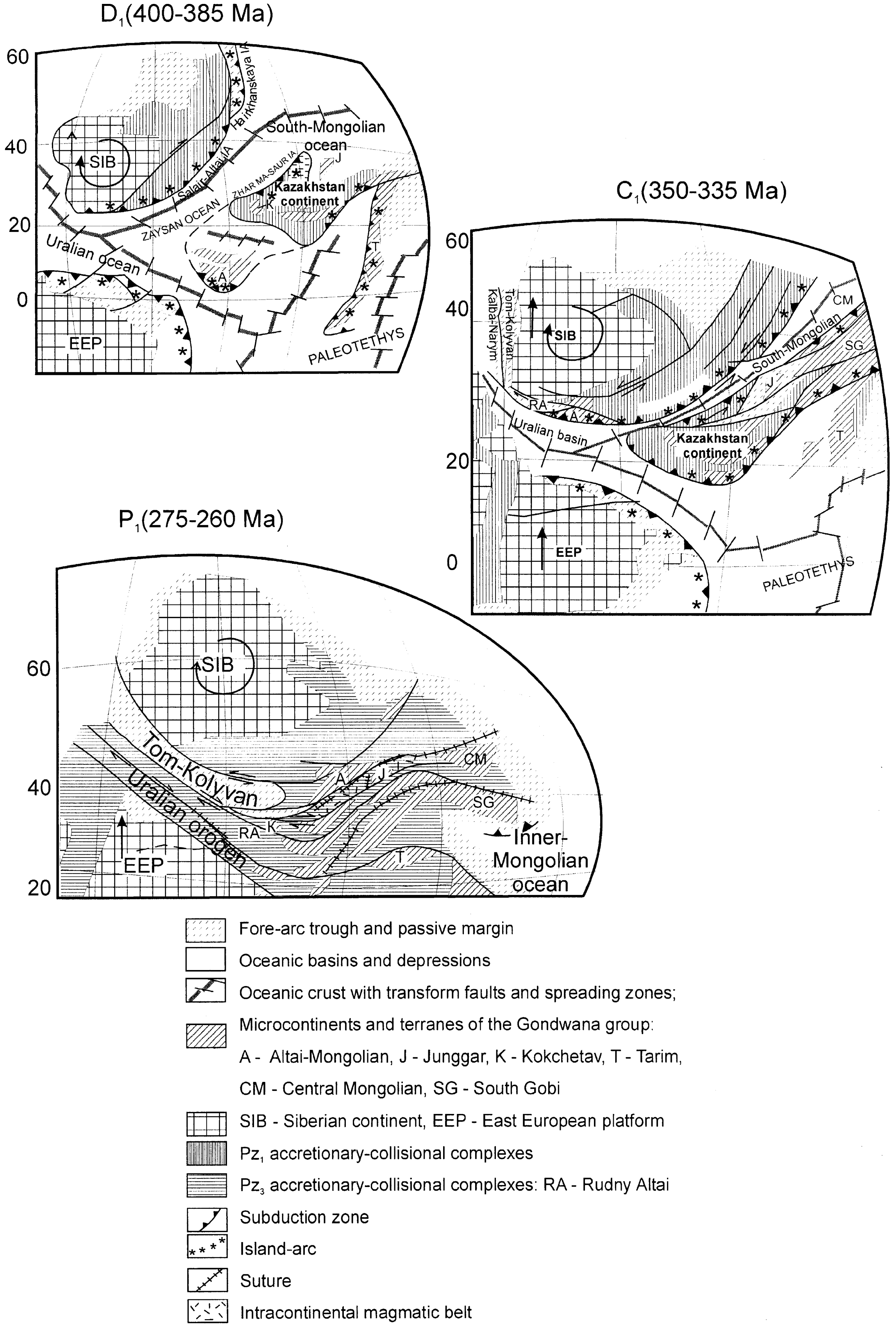

Fig. 10. Late Paleozoic geodynamic reconstruction of the Paleo-Asian Ocean [compiled from geological relations, paleomagnetic data and reconstructions of Zonenshain et al. (1990), Didenko et al. (1994) and Didenko (1997)].

the Gondwana-derived Altai-Mongolian terrane and the Siberian continent resulted in the formation of the Charysh–Terekta system of dextral strike-slip faults and later the Kurai and Kuznetsk–Teletsk–Bashkauss systems of sinistral strike-slip faults. The Late Carboniferous–Permian collision of the Siberian and Kazakhstan continents resulted in the formation of the Chara, Irtysh and North-East sinistral strike-slip zones. The age of deformation of both collisional events become younger toward the inner areas of the Siberian continent. In the same direction the amount of strike-slip faulting decreased from several thousands to several hundreds of kilometers. The width of the Late Paleozoic zone of deformation reached 1500 km. The deformations disrupted the accretion-collision continental margins and their primary paleogeographic pattern.

Our own and published paleomagnetic and structural data allowed us to suggest the following paleoreconstructions for the Paleoasian ocean evolution. In the Emsian-Govetian the Gorno-Altai and Rudno-Altai volcanic belts were located in a band at 21–30°N, close to the southern and southeastern margins of the Siberian continent. The Altai-Mongolian terrane was located near the equator at 1–4°N. At the end of the Middle Devonian the Altai-Mongolian terrane came closer to 21–30°N and collided with the Siberian continent. In the Early Carboniferous the Altai-Mongolian terrane was driven between the Gorno-Altai and Rudno-Altai zones. The Kazakhstan continent migrated northeastward (28°N in the D_2^2–D_3^1 and 35°N in the C_{2-3}) before it collided with the Siberian continent. In the Early Carboniferous the Ob'-Zaisan basin closed and the collision of continents started. In the Permian the collision of continents resulted in the formation of sinistral strike-slip faults, molasse and lavas in the Altai.

The presently popular concept by (Sengör et al., 1993) considers Altaides a single geodynamic system of the Urals and Central Asia. Based on our results and conclusions we believe that it is too oversimplified. The conception ignores the autonomous formation of accretionary-collisional and folded areas in the Urals, Kazakhstan, and Altai-Sayan. Only since the Early Carboniferous, after the closing of the Paleoasian ocean, the above-noted folded areas had a common history during the formation of Pangea. At the same time Sengör and co-authors suggested a nice idea about the Late Paleozoic oroclinal folding and strike-slip deformation of Kazakhstan structures squeezed between the Siberian and East European cratons (Sengör et al., 1993). Special attention should be paid to the ideas about the role of Gondwana-derived microcontinents and terranes in the formation of Central Asia structural pattern (Zonenshain et al., 1990; Berzin and Dobretsov, 1994; Berzin et al., 1994; Mossakovsky et al., 1993; Didenko et al., 1994).

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