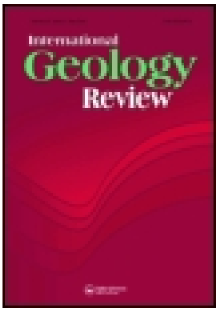

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Serpentinitic Mélanges Associated with HP and UHP Rocks in Central Asia

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Abstract

Serpentinitic mélanges containing eclogites, blueschists, and jadeitic rocks have been studied within the following foldbelts: Borus (West Sayan), Chagan-Uzun (Gorny Altai), Chara (East Kazakhstan), Kokchetav (North Kazakhstan), and Maksyutov (Southern Urals). The West Sayan (Borus belt) and Gorny Altai (Chagan-Uzun belt) are Caledonian foldbelts formed after collisions of paleo-seamounts with primitive island arcs, which resulted in the exhumation of eclogites and jadeitic rocks. The Chara belt of Hercynian age was formed during the Late Carboniferous–Permian collision of the Siberian and Kazakhstan continents and represents a strike-slip zone comprising serpentinitic mélanges and HP units of different ages. In Caledonian time, the mélanges represent an accretionary wedge at the margin of the Kazakhstan continent. The Kokchetav and Maksyutov foldbelts of, respectively, Caledonian and Hercynian ages resulted from collision of microcontinents with island arcs and formation of sheeted complexes incorporating large lenses of UHP-HP rocks and less serpentinitic mélanges.

Two types of serpentinitic mélange occur in all suture zones formed as a result of collision of island arcs with seamounts or other island arcs. Type I mélange contains HP rocks in antigorite or olivine-talc-antigorite schists associated with high-temperature mantle peridotites, which can be regarded as part of the hanging wall of a paleosubduction zone. Type II mélange is a part of an obducted oceanic crust and contains blocks and inclusions of LP and LT metamorphic rocks associated with island arc and/or seamount terranes. The suture zones formed by continent/island arc or microcontinent collision (the Kokchetav megamélange and the lower unit of the Maksyutov complex) comprise no large sheets of serpentinitic mélange, but only subordinate lenses of mélanges with HP rocks (the Maksyutov lower unit) or small and sporadic ultramafic lenses inside a tectonic mélange with a metasedimentary matrix.

Introduction

THE EURASIAN continent comprises several amalgamated cratons and microcontinents that collided mainly in Neoproterozoic and Paleozoic time. The largest suture zones in Central Asia such as the Southern Urals, Gorny Altai, West Sayan, Tuva (Russia), Kokchetav, and Chara (Kazakhstan) resulted from several collisional events that occurred during evolution of the Paleo-Asian Ocean. They incorporate associated serpentinitic mélanges, ophiolites, and HP and UHP units. Vendian–Cambrian (Kokchetav, Chagan-Uzun, Borus) and Devonian–Early Carboniferous (Chara, Maksyutov) complexes are well documented.

Figure 1 shows R. G. Coleman's scheme for suture zones incorporating HP-UHP units (Berzin et al., 1994; Dobretsov et al., 1995a). Serpentinitic mélanges contain eclogites, blueschists, and jadeitic rocks and belong to the following foldbelts (from east to west): Borus (West Sayan), Chagan-Uzun (Gorny Altai), Chara (East Kazakhstan), Kokchetav (North Kazakhstan), and Maksyutov (Southern Urals). Their locations are shown in the following tectonic maps corresponding to areas 1–5 in Figure 1.

R. G. Coleman visited the Chagan-Uzun, Chara, Kokchetav, and Maksyutov belts in 1993–1995. The Borus belt with jadeite-bearing serpentinitic mélange was described by N. L. Dobretsov in his Ph.D. thesis in 1962. Practically at the same time R. G. Coleman presented his Ph.D. thesis on the New Idria jadeite-bearing serpentinite, which he examined together with Dobretsov in 1979 (Coleman, 1961, 1977; Dobretsov, 1964).

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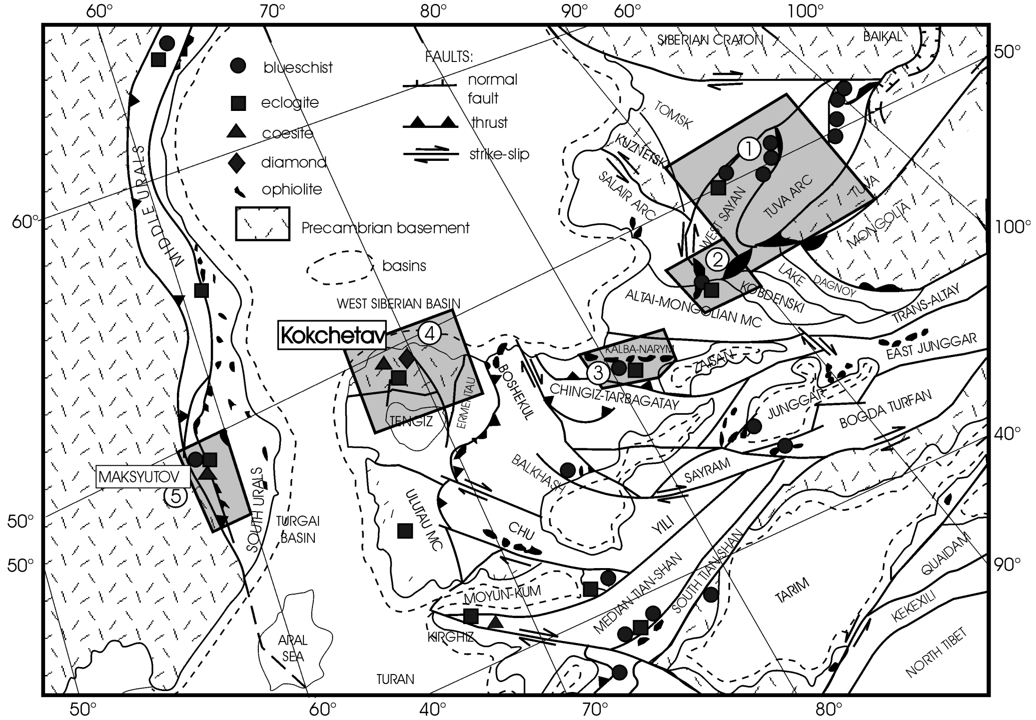

FIG. 1. Major tectonic features of Central Asia for the regions including UHP-HP complexes and serpentinitic mélanges (modified after Berzin et al., 1994): 1 = Borus (West Sayan); 2 = Chagan-Uzun (Gorny Altai); 3 = Chara (East Kazakhstan); 4 = Kokchetav (North Kazakhstan); 5 = Maksyutov (Southern Urals).

The West Sayan (Borus belt) and Gorny Altai (Chagan-Uzun belt) are Caledonian foldbelts formed after collisions of paleo-seamounts with primitive island arcs. These collisions resulted in the exhumation of HP rocks—eclogites and jadeitic rocks (Dobretsov and Tatarinov, 1983; Buslov et al., 2001, 2002).

The Chara belt of Hercynian age was formed during the Late Carboniferous–Permian collision of the Siberian and Kazakhstan continents and represents a strike-slip zone comprising serpentinitic mélanges and HP units of different ages. In Caledonian time, mélanges formed an accretionary wedge at the margin of the Kazakhstan continent (Buslov et al., 2001, 2002).

The Kokchetav and Maksyutov foldbelts of Caledonian and Hercynian ages, respectively, resulted from collision of microcontinents with island arcs and formation of sheeted complexes incorporating UHP-HP rocks and serpentinitic mélanges (Dobretsov et al., 1995a, 1995b, 1998). The Kokchetav belt in northern Kazakhstan occupies a key position in one of the largest suture zones within Eurasia (Sengör et al., 1993; Zonenshain et al., 1990; Berzin et al., 1994). The area is well known for the widespread occurrence of diamond- and coesite-bearing UHP metamorphic rocks (Sobolev and Shatsky, 1990; Shatsky et al., 1995). It is important that the Kokchetav belt is located very far from large continental blocks and is not related to a big collision, the mechanism usually used to explain the origin of UHP units (Ernst et al., 1995; Maruyama et al., 1996, 2000; Dobretsov et al., 1995a, 1995b, 1998; Dobretsov, 2000).

Our review shows that mélanges containing HP rocks result from oceanic island–island arc collision. The Borus, Chagan-Uzun, and Chara serpentinitic mélanges occur in association with oceanic island units. Foldbelts resulting from microcontinent–island arc collision contain much less serpentinite. This may be explained by the great thickness of microcontinent units, their granitic composition, and by much deeper subduction of rocks to depths exceeding 150 km. Oceanic islands involved in

TABLE 1. Belt and Isotopic Data of HP/UHP Rocks in Central Asia

Stages, Ma	Belts and isotopic data (rocks, methods)					
	Borus, West Sayan	Chagan-Uzun, Gorny Altai	Kokchetav	Uymon, Altai	Chara, East Kazakstan	Maksyutov, Southern Urals
640–620		Eclogite, Ar-Ar				
545–530	Blueschist, K-Ar	Eclogite, Ar-Ar, K-Ar	UHP-HP SHRIMP			
510–485					Eclogite K-Ar, Ar-Ar	
485–475		Ga-amphibolite, Ar-Ar, K-Ar		Blueschists, Ar-Ar, K-Ar		
450–400	Blueschist, K-Ar					
385–375						Eclogite Sm-Nd

subduction usually block subduction zones and prevent submergence of ophiolites to depths exceeding 60 km, i.e. within the stability field of serpentinite.

Table 1 shows geochronological data (Dobretsov and Tatarinov, 1983; Dobretsov et al., 1987, 1992, 1998, 2003; Claoué-Long et al., 1991; Dobretsov, 1991; Chi et al., 1993; Dobretsov and Kirdyashkin, 1994; Buslov and Watanabe, 1996; Shatsky et al., 1997; Kaneko et al., 2000; Maruyama and Parkinson, 2000; Buslov et al., 2001, 2002, 2003; Hacker et al., 2002; Katayama et al., 2002) on all the above belts and six stages of HP metamorphism, which took place within an interval between 640 and 375 Ma. A detailed interpretation of these stages will be given below.

Geologic Setting

The tectonic pattern of Central Asia (Fig. 1) consists of three main groups of structural elements. The first group includes Precambrian microcontinents and terranes (Fig. 2), which are fragments of the disaggregated Gondwana supercontinent (Mossakovskiy et al., 1993; Didenko et al., 1994; Buslov et al., 2000, 2001, 2003). During the Middle Paleozoic, the fragments amalgamated and formed the Kazakhstan composite microcontinent, comprising the North Tien Shan, Ulutau, Kokchetav, Aktau-Mointin, Ili, and other Precambrian microcontinents, and Altay-Mongolia-Tuva composite microcontinent, comprising the Altay-Mongolian terrane and Tuva-Mongolian and Dzabkhan microcontinents. 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 rocks. The second group includes terranes comprising the fragments of Caledonian and Hercynian accretional-collisional belts, which were detached from a parental block as a result of oblique subduction and collisions of these terranes with the Siberian and East European continents or related microcontinents. The third group includes strike-slip and oblique thrust fault zones reflecting collisions of different ages. The strongest tectonic deformations were recorded in Late Devonian, Early Carboniferous, Late Carboniferous–Permian, Late Permian–Triassic, and Triassic–Jurassic time (Buslov et al., 2000, 2001, 2003).

The Altay-Sayan and East Kazakhstan regions are located between the Kazakhstan and Siberian continents and consist of accretionary-collisional zones of different ages and Gondwana-derived terranes. The complicated structure and scenario of multi-stage evolution of Altay-Sayan and East

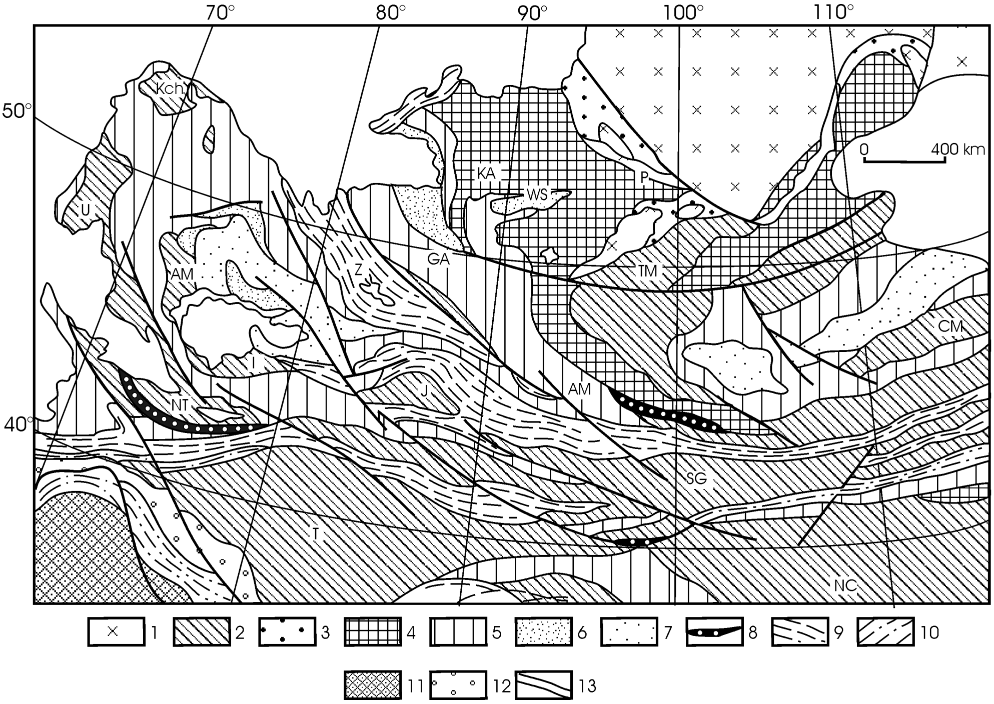

FIG. 2. Tectonic scheme of the Central Asian foldbelt (Mossakovskiy et al., 1993). Platforms and microcontinents: 1 = Siberian platform; 2 = Gondwana group (Platforms: T = Tarim, NC = North China; Microcontinents: Kch = Kokchetav, U = Ulutau, AM = Aktau-Mointin, I = Ili, NT = North Tian Shan, J = Junggar, TM = Tuva-Mongolian, CM = Central Mongolian, SG = South Gobi); Accretionary zones: 3 = Neoproterozoic; 4 = Salair (KA = Kuznetsk Alatau, WS = West Sayan); 5 = Caledonian (S = Salair, GA = Gorny Altai, AM = Altai-Mongolian); Sedimentary basins: 6 = Caledonian (Anui-Chuya); 7 = Early Hercynian; Collisional foldbelts: 8 = Caledonian; 9 = Early Hercynian (Z = Zaisan); 10 = Late Hercynian; 11 = Mesozoic; 12 = Pre-Kunlun trough; 13 = large faults.

Kazakhstan regions implies the alternation of subduction-collision and collision (Fig. 3).

The maximal opening of the Paleo-Asian Ocean was reached at 640–550 Ma (Dobretsov et al., 2003). At that time a long island arc composed of boninite-bearing volcanic rocks was formed. Primitive island arcs of that age have been reconstructed in Kazakhstan, Gorny Altay, West and East Sayan, and North Mongolia. The scale of boninitic island-arc magmatism of this stage was great and can be compared with the present-day situation in the western Pacific (Dobretsov et al., 1992; Watanabe et al., 1993; Berzin and Dobretsov, 1994; Buslov and Watanabe, 1996; Dobretsov et al., 1995a, 2003; Al'mukhamedov et al., 2001). The most widespread ophiolites are referred to this stage Kuznetsk-Altay, Borus, Kurtushibin belts in Altay-Sayan and the Lake Valley, Bayankhongor, and Khantaishirin belts, etc. Their U-Pb and Sm-Nd ages are within a short time interval at 568-593 Ma (Kroner et al., 2001; Windley et al., 2001; Khain et al., 2002; Dobretsov et al., 2003).

The Early Caledonian Altay-Sayan accretion-collision zones are composed of rock units that were formed within an island-arc system or were incorporated in it during subduction of the Paleo-Asian ocean crust under the Siberian continent. They are accretionary wedge, fore-arc trough, primitive and normal island arc and backarc basin units (Fig. 4). The accretionary wedges are characterized by sheeted structure and consist of ophiolites from the basement of an island-arc and rocks of a deformed oceanic crust (the Paleo-Asian oceanic plate). We propose a general scenario implying that oceanic islands submerged into the subduction zone together with the plate and, later, they were incorporated into an accretionary wedge. During subduction, the oceanic islands—the largest were up to 4

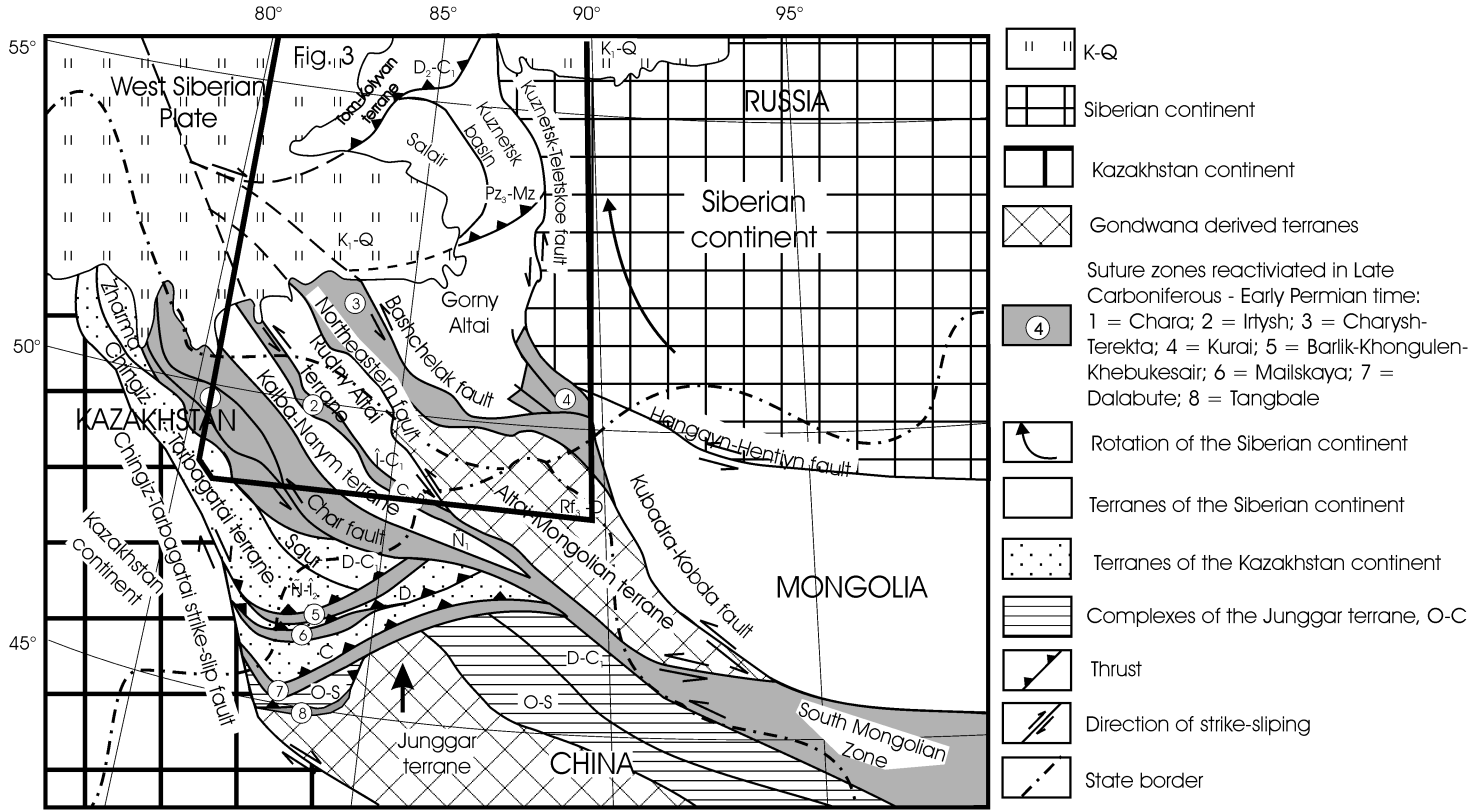

FIG. 3. Distribution of Late Carboniferous–Permian terranes resulted from the collision of the Siberian and Kazakhstan continents. The Ob'-Zaysan sea was situated between the Kazakhstan and Siberian continents and had a link with the South-Mongolian ocean. Continental margin units are divided into two groups—i.e., Siberian and Kazakhstan. Reactivated suture zone from the Chara ophiolite belt (No. 1) to the South Mongolian zone is the remnant of the ocean (Buslov et al., 2001, 2003).

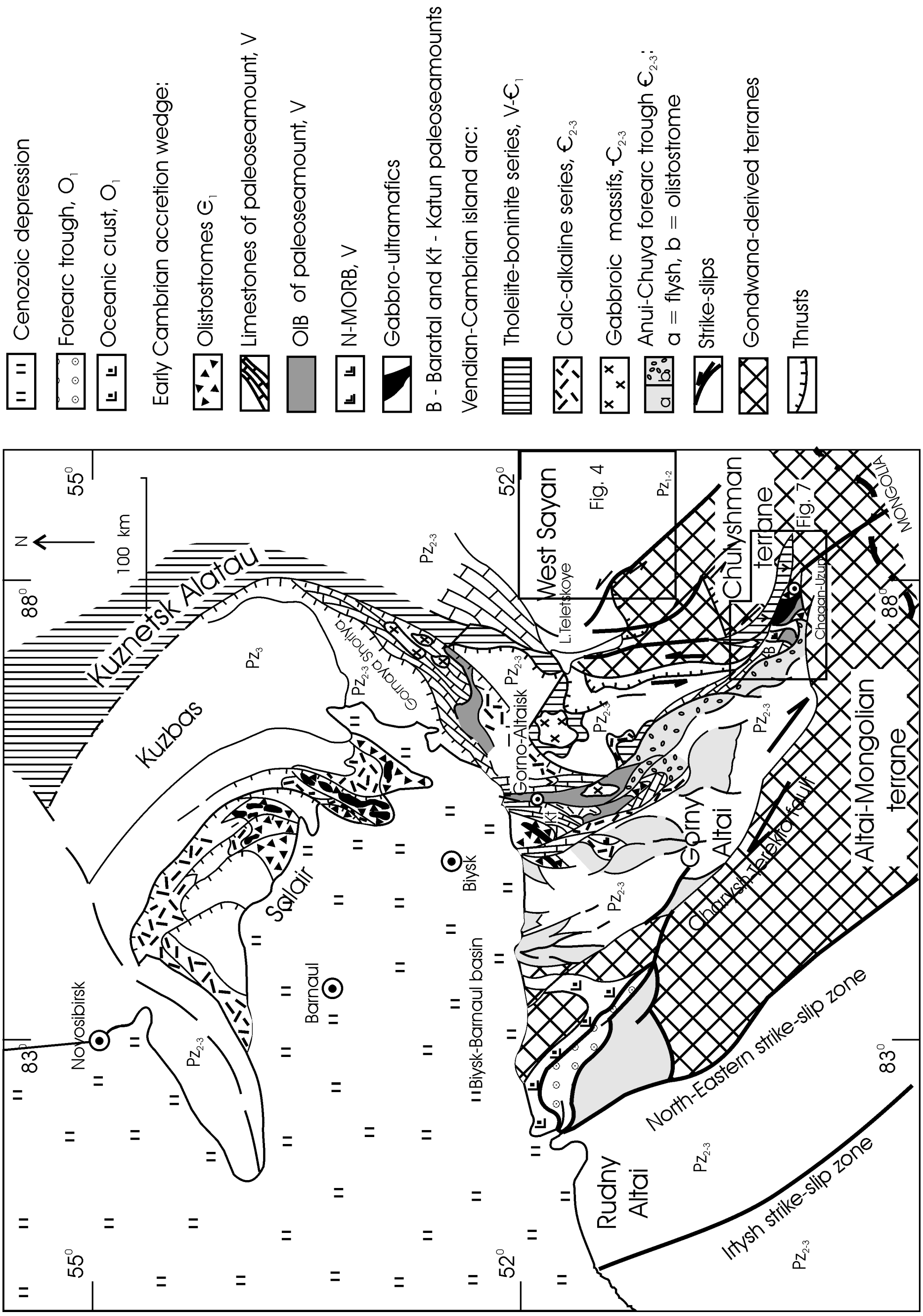

FIG. 4. Vendian–Cambrian island-arc units in Gorny Altai and Salair (Buslov et al., 2002).

km in height—collided with an island arc, resulting in reverse flow in the accretionary wedge and the related exhumation of high-pressure rocks (blueschists, eclogites, etc.). In response to the paleooceanic island/island arc collision, the subduction zone jumped oceanwards. Fragments of paleooceanic islands in accretionary wedges are, as a rule, cemented by olistostromes composed of dislocated island and island arc units. A new volcanic arc formed over the accretionary wedge. Forearc basins were filled with pelagic sediments and turbidites. The turbidites mainly consist of the fragments and debris of island-arc and accretionary units (Buslov et al., 1993, 2002; Buslov and Watanabe, 1996).

At 550–490 Ma, oceanic islands and Gondwana-derived microcontinents (Kokchetav, Tuva-Mongolian, Central Mongolian, and others) collided with a Cambrian–Early Ordovician island arc at the margin of the Siberian continent. As a result, the island-arc system was extensively modified. Collision occurred twice at 550–520 and 520–490, Ma during which many HP and UHP rocks were exhumed (Dobretsov, 1991; Dobretsov and Kirdyashkin, 1994; Buslov and Watanabe, 1996; Dobretsov et al., 1998). Some of the Late Cambrian–Early Ordovician island arcs are thought to inherit the Vendian–Early Cambrian island arcs (Salair, Gorny Altai, and Tuva).

The later formation of a tectonic collage and its related strike-slip deformation resulted from the Late Devonian–Early Carboniferous collision of the Gondwana-derived Tuva-Mongolian microcontinent with the Altai-Mongolian terrane and the Siberian continent, and from the 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.

The collision of the Altai-Mongolia terrane and Tuva-Mongolian microcontinent 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. Oblique collision produced the Late Devonian Charysh-Terekta and Ulagan suture zones (Fig. 3) composed of Precambrian-Eifelian rocks and exotic terranes, Ordovician forearc units, and a Middle Paleozoic HP subduction unit (Buslov et al., 2001, 2003). The frontal collision produced the Late Devonian–Early Carboniferous Kurai and Teletsk-Bashkaus shear zones.

The Chara shear zone separates the Siberian and Kazakhstan continents. The terranes located southwest of this zone (Tarbagatai, Zharma, and Saur) are aligned along the Kazakhstan continental margin and represent fragments of Cambrian–Ordovician and Devonian–Early Carboniferous island arcs, displaced along the Chingiz-Tarbagatai strike-slip fault to the south toward the Junggar microcontinent (Chi et al., 1993).

Serpentinitic Mélanges and HP Rocks of the Borus and Chagan-Uzun Belts

In this section we will consider the Borus belt in West Sayan (Fig. 5) and the Chagan-Uzun massif in Gorny Altai. These belts were described in detail in many papers (e.g. Dobretsov and Ponamareva, 1976; Dobretsov and Tatarinov, 1983; Dobretsov, 1985; Dobretsov et al., 1992, 1998; Buslov et al., 2003). The Borus and Chagan-Uzun belts comprise extended serpentinitic mélanges incorporating HP units. In Cambrian time, the Kurtushibin and Borus belts possibly constituted a single subduction zone, which was deformed in the Ordovician.

Borus belt

The Borus belt is a narrow synform up to 100 km long and 5–15 km wide (Fig. 5). The uppermost tectonic sheet comprises mantle peridotites and underlying mélange with inclusions of eclogite, jadeitic rock, jadeite-bearing albitite, and albite-mica schists. They possibly represent the hanging wall of a paleosubduction zone. Mantle peridotites consist of intercalated dunite, hartzburgite, and orthopyroxenite. Spinel lherzolite and hartzburgite are sparse. Serpentinitic mélange occurs as typical outcrops between the Yenisey and Kantegir rivers and 10 km west of Kantegir (Fig. 6). Rounded and lens-like inclusions 1 to 40 m long comprise eclogites (locally rimmed by jadeitic and jadeitic-diopside rocks), coarse-grained jadeitic rocks (with relict rims of diopside-jadeite), coarse-grained phengite rocks with a phengite-chlorite rim and various albitites (with aegirine-jadeite, amphibole, garnet, etc.), amphibolites, zoisite-hornblende rocks, and serpentinized peridotites. Figure 7 shows typical inclusions of such rocks (Dobretsov, 1964; Dobretsov and Tatarinov, 1983). The matrix consists of locally coarse-grained antigorite. Olivine-antigorite, talc-antigorite, talc-carbonate-antigorite schists, and other various inclusions are present in different parts of the mélange sheet. Inclusions of

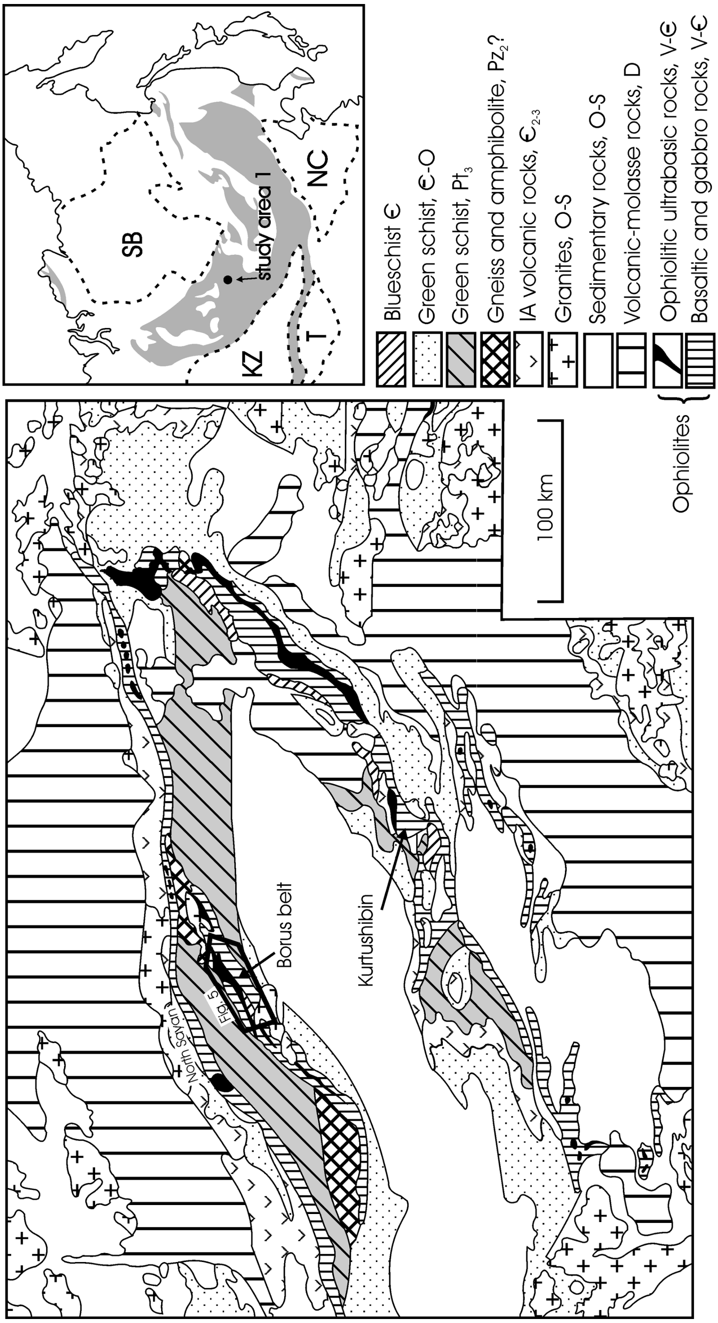

FIG. 5. Major tectonic features of the West Sayan, including HP complexes and serpentinitic mélanges (modified after Dobretsov and Tatarinov, 1983).

crossite-aegerine-jadeite-albite-quartz schists, jadeite-bearing albitite, partly albitized dikes of plagiogranite occur in the central part of the Borus Range in association with blueschist lenses (Fig. 6).

The highest-temperature rocks are eclogites and coarse-grained jadeitites (sometimes with cancrinite) and diopside-jadeite (omphacitic) rocks with rare crystals of chrome-spinel and olivine. Chrome spinel is associated with a pyroxene with wide NaAl Na Cr isomorphic variation, up to 60% $NaCrSi_2O_6$) (Dobretsov and Tatarinov, 1983).

Middle tectonic sheets B1, B2, and C (Fig. 6) comprise fragments of ophiolites (serpentinites, serpentinitic mélange, metagabbro, N-MORB, metachert), seamounts (OIB-type metabasalts, carbonate, and carbonate-siliceous metatuffs, metagraywackes, black shales, and limestones). The serpentinitic mélange of the B-sheet contains metabasalts, metacherts, rodingite, actinolite, and nephritic rocks. The lower sheet consists of Late Precambrian epidote-chlorite and biotite-chlorite metamorphic schists, which differ from the Cambrian C-sheet rocks in structure, metamorphic assemblages, and composition. The latter are dominated by metagreywacke, metapelite, and marble. The B-sheet contains fragments of seamounts, and we suggest that exhumation of HP rocks resulted from seamount-island arc collision. A model for such collision and its related exhumation of HP rocks will be presented below.

The B-sheet is covered by deformed Late Cambrian rocks and intruded by Silurian–Early Devonian and Middle Devonian stocks and dikes (Fig. 6); therefore it was formed in Middle Cambrian time. The K-Ar ages of eclogites, garnet amphibolites, and associated mica schists range from 540 to 440 Ma (Table 1).

Chagan-Uzun belt

The Chagan-Uzun ultramafic belt is located in SE Gorny Altai (Figs. 1 and 4) and is structurally related with the Kurai accretionary wedge or belt (Fig. 8). This belt documents the collision of the Baratal paleooceanic island and the Uymon-Lebed' primitive island arc (Buslov et al., 1993, 2002; Watanabe et al., 1993). Oceanic island/island arc collision was responsible for the closing of the subduction zone and exhumation of deep-seated rocks—eclogites, blueschists, garnet amphibolites, and metaperidotites of the Chagan-Uzun belt.

The Kurai accretionary belt of Early Cambrian age consists of the sheets of the Baratal paleo-oceanic island, having variable composition and size, boninite-bearing island-arc units, and Chagan-Uzun ophiolites with serpentinitic mélange incorporating sheets and minor blocks of eclogite, garnet amphibolite, and barroisite-actinolite schists. The western part of the Kurai belt, south of the village of Kurai on the left bank of the Chuya, consists of metamorphic rocks, and polymictic and serpentinitic mélanges. The metavolcanic sequence contains two sheets of crystalline schists (garnet amphibolite and amphibolite), the thickness of which ranges from 50 to 250 m along strike. The amphibolites and garnet amphibolites possess chemical characteristics of N-MORB (Buslov et al., 1993, 2002; Ota et al., 2002). Type I polymictic mélange includes blocks up to several meters long of serpentinized pyroxene-olivine porphyrite, retrograded garnet amphibolite containing eclogite relicts, and amphibolite; the matrix consists of serpentinite schists and mylonites after metamorphic rocks and basalts. Type II serpentinitic mélange consists of foliated serpentinite incorporating blocks of massive serpentinite and light grey cryptocrystalline rodingite.

A 3 km thick sheeted-mélange zone in the eastern part of the Kurai belt near the village of Chagan-Uzun, on the left bank of the Chuya (Fig. 9), consists of ultramafic rocks of the Chagan-Uzun massif. The upper sheet is composed of massive ultramafic rocks: weakly serpentinized lherzolite and harzburgite (the upper half) and massive serpentinite (the lower half). The 1300°C temperature of lherzolite was estimated using the two-pyroxene thermometer (Dobretsov, 1984; Ota et al., 2002). The serpentinitic mélange is located in the base of massive ultamafics and contains lenses of metaolistostrome, limestone, basalt, silicite, amphibolite, garnet amphibolite, and eclogite (Buslov et al., 1993, 2002; Buslov and Watanabe, 1996).

The ophiolitic section consists of massive and foliated serpentinites, gabbro, gabbro-diabase, and diabase dikes (upper part) and metabasalts (lower part). A thick serpentinite mélange is present in the eastern part of the Chagan-Uzun massif, on the right bank of the Chuya (Fig. 9), and several-hundred-meter thick metamorphic sole of garnet-free amphibolite occurs at the contact between ultramafics and basalts.

The metamorphic rocks are of special interest. Eclogite and garnet amphibolite bodies are present in the mélange. The garnet amphibolite underwent greenschist-facies metamorphism developing along marginal parts of the sheets. A 4-5 m wide, 10 m

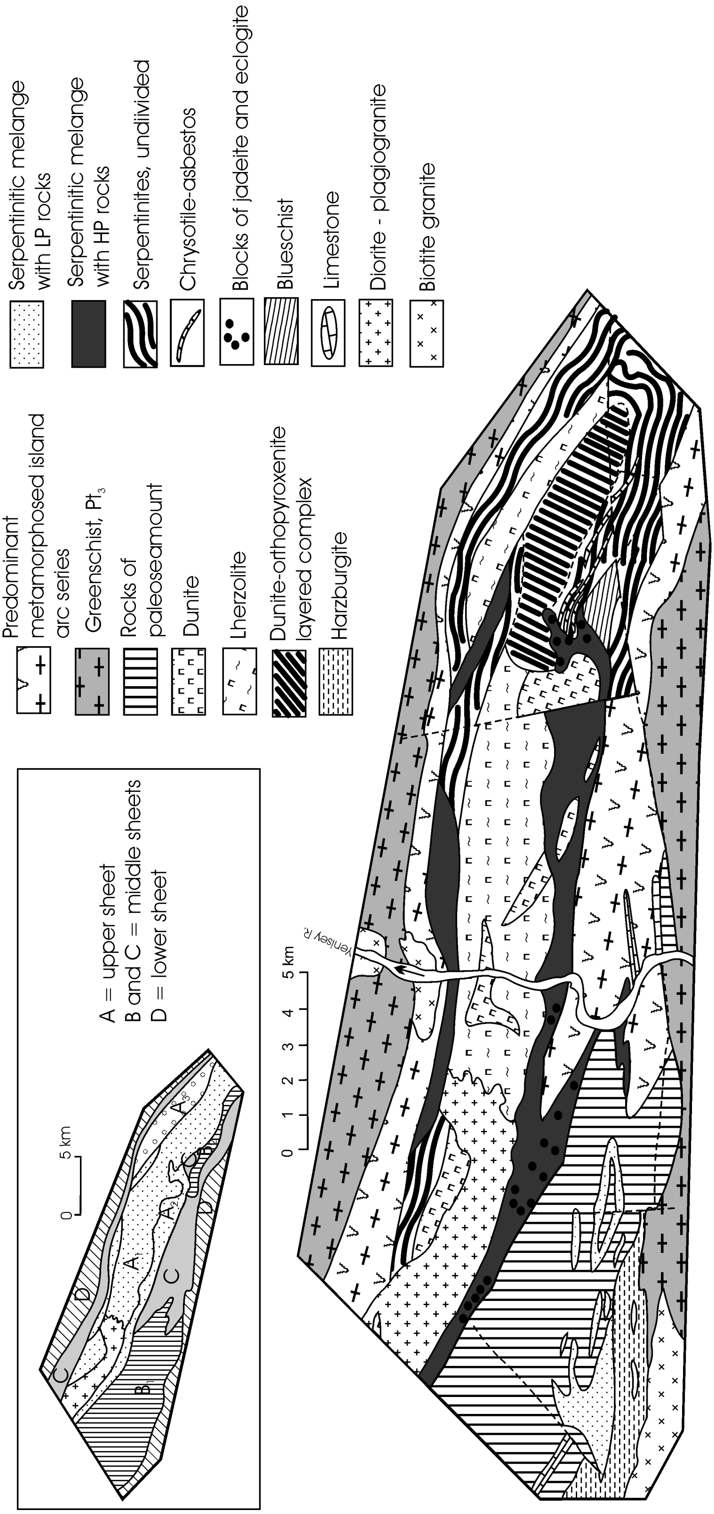

FIG. 6. Major tectonic features of the central part of the Borus belt (modified after Dobretsov and Tatarinov, 1983).

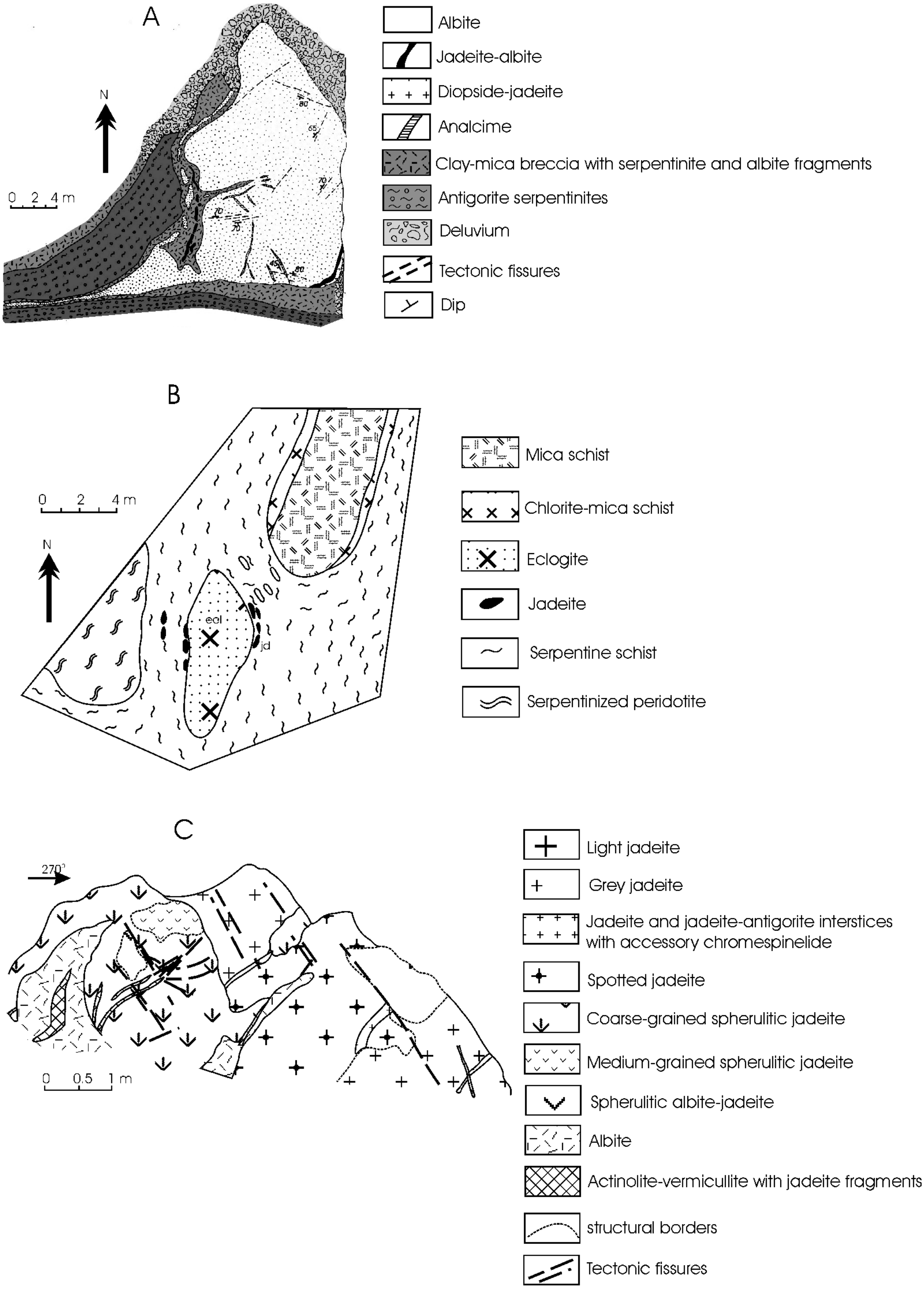

FIG. 7. Geology scheme of jadeite-albite body (A), eclogite-jadeite body (B), and jadeite body (C) (Dobretsov and Tatarinov, 1983) .

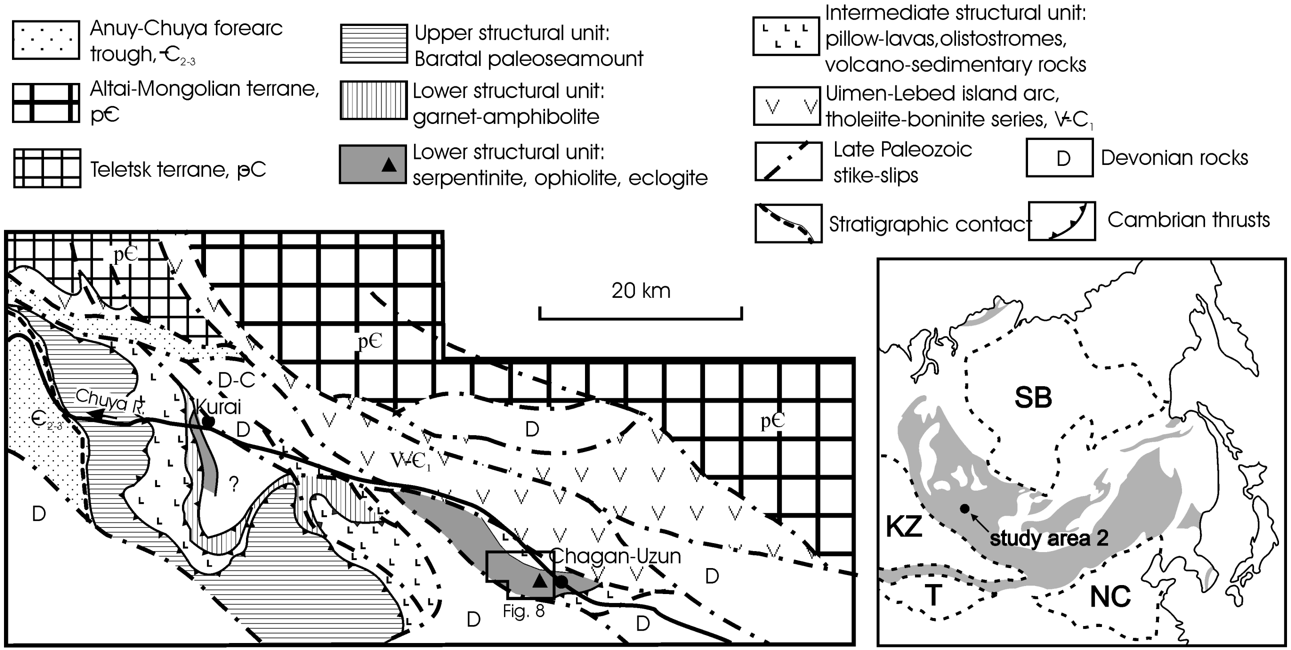

FIG. 8. Major tectonic features of Kurai zone, including HP complexes and serpentinitic mélanges, Gorny Altai (Buslov et al., 2002).

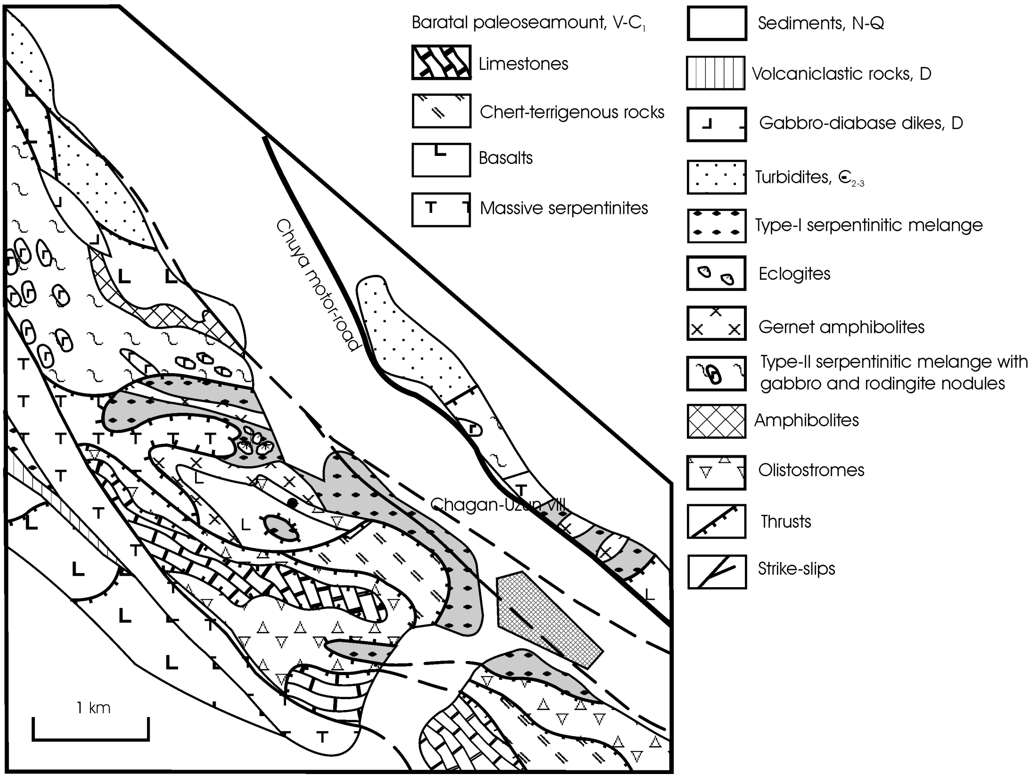

FIG. 9. Geological scheme of the Chagan-Uzun ophiolite belt.

long eclogite body contains garnet amphibolite composing its apical parts and narrow transverse zones up to several centimeters thick. Thus, we suggest that the garnet amphibolite resulted from back reaction of the eclogites (Buslov and Watanabe,1996; Buslov et al., 2002). The K-Ar amphibole ages of eclogites and their crossing garnet amphibolites are 535 and 487 Ma, respectively.

Up to 10 m long and 3–5 m thick greenschist lenses occur in the serpentinitic mélange and are oriented parallel to the general linearity. The greenschists possess clastic texture and could have resulted from metamorphism of olistostromes. Fragments are siliceous and carbonate rocks cemented by a chlorite-muscovite matrix. The K-Ar muscovite age is 540 Ma. The ages of 535 Ma (amphibole in eclogite) and 540 Ma (matrix) correspond to those of the Early Cambrian metamorphism of subducted accretionary rocks. Besides, they are close to the age of UHP metamorphism of subducted rocks of the Kokchetav massif in Kazakhstan (530–540 Ma) and other regions (Dobretsov et al., 1998; Table 1).

Clinopyroxene-free garnet amphibolite is texturally different from the above-described eclogitic garnet amphibole. The K-Ar amphibole age of garnet amphibolite is 473 Ma. The metamorphic sole at the base of the Chagan-Uzun ophiolites is composed of garnet-free amphibolites. Their K-Ar amphibole age is 523 Ma (Buslov and Watanabe, 1996; Buslov et al., 2002).

Several specimens of eclogitic and garnet amphibolite yielded older K-Ar ages, but the retrograde influence is obvious. Therefore, we obtained Ar-Ar geochronological data amphiboles, which are 627, 636, and 562 Ma. All three values indicate a low-temperature Ar loss and the plateau age is 635 Ma (Buslov et al., 2002; Ota et al., 2002). The latter value could reflect an older subduction stage, or is an error of the method. Formally, there are four groups of geochronological data (635, 535–540, 523, and 473–487 Ma; Table 1). The last three dates possibly correspond to subduction metamorphism, exhumation, and later deformation.

Boudinaged and deformed gabbro, gabbro-diabase, and diabase dikes cut the lower ophiolitic sheet and are compositionally close to the calc-alkaline island-arc series, which were estimated to be Early–Middle Cambrian (Buslov et al., 2002). P-T estimations for rock assemblages of the upper sheet, including eclogites, are 20 kbar and 660°C (Ota et al., 2002), i.e., they formed at a depth of 60 km, whereas metagabbro, rodingites, and garnet-free amphibolites of the lower sheet recrystallized at 2–3 kbar (6–8 km depth). We suggest that the upper sheet with eclogites is an assemblage of subducted rocks. The garnet-free amphibolites at the bottom of the lower sheet formed later, i.e., during the incorporation of hot ophiolites into the accretionary wedge or during their thrusting over oceanic floor basalts, as proposed for Oman ophiolites and other analogous cases (Nicolas, 1989).

In the latest Early Cambrian, the Baratal oceanic island possibly blocked the subduction zone and collided with the Kurai fragment of the Uimen-Lebed primitive island arc. The collision resulted in the generation of reverse flow in the accretionary wedge and rapid exhumation of metamorphosed oceanic crust rocks—i.e., Chagan-Uzun ophiolites, eclogites and garnet amphibolites. Major- and trace-element chemistry of high-pressure metamorphic rocks is similar to MORB and OIB (Buslov et al., 1993, 2002).

Thus, the Chagan-Uzun belt in Gorny Altai consists of a succession of units similar to that exposed in the Borus belt: (1) mantle peridotites underlain by serpentinite mélange with eclogites; (2) ophiolites of normal oceanic crust (typically in an overturned position); (3) siliceous limestone and two types of paleoseamount basalts; (4) primitive island arc with boninitic dikes and brecciated pillow lavas. Unlike the Borus belt, which consists of strongly deformed and mixed rocks, the Chagan-Uzun belt contains well-preserved seamount fragments, such as the Baratal terrane, and primitive island-arc units (the Kurai belt) consisting of accretionary complex, dikes, and volcanic units.

We suggest that the uppermost unit of the Chagan-Uzun massif consists of mantle peridotites of the hanging wall of a paleosubduction zone. The evidence for this suggestion comes from the fresh appearance of rocks, high temperature estimates, and dunite-harzburgite and lherzolite composition of rocks. The two-pyroxene equilibrium temperature of the intercalated dunite-harzburgite and lherzolite is 1200–1300°C and the veins of gabbro-anorthosite rimmed by websterite containing plagioclase with melt inclusions formed at 900–1000°C (Bakumenko and Dobretsov, 1976).

Serpentinitic Mélanges and HP Rocks of the Chara and Maksyutov Belts

The Chara belt in East Kazakhstan and the Maksyutov belt in the Southern Urals belong to the Variscan stage of Paleo-Asian Ocean evolution, and they record younger collisional events.

Chara belt

The Chara belt extends over a distance of more than 200 km and consists of several allochthonous structural units, which correspond to accretionary units (including ophiolites, seamounts, and high-pressure rocks) of the surrounding terranes such as the west Junggar, the Zharma-Saur, and possibly the Rudny Altai terrane (Fig. 3). In the Chara belt (Fig. 10), three mélange units can be distinguished, which differ in structure, age, and geodynamics (Polyanskii et al., 1979; Ermolov et al., 1981; Dobretsov et al., 1992; Iwata et al., 1997; Buslov et al., 2001, 2003).

The Chara belt consists of an accretionary unit with Type I mélange (subduction-related) containing Early Paleozoic eclogites and blueschists, and a Silurian–Early Devonian seamount (OIB-type basalts and carbonate-siliceous rocks). The serpentinitic mélange consists of antigorite schists and 5–10 m inclusions of eclogites and garnet amphibolites and up to 1.5 km long blocks of metamorphic schists of variable composition characterized by lawsonite, glaucophane, epidote, etc. (Fig. 11).

These units include three groups of K-Ar ages: 510–480 Ma (amphibole and whole rocks from eclogite), 440–430 Ma (phengite), and 400–380 Ma (Dobretsov et al., 1992, Buslov et al., 2003). The geochronological data of 440-430 Ma in muscovite from eclogites, garnet amphibolites, and glaucophane schists show a short exhumation interval (Late Ordovician–Early Silurian). High-pressure rocks of similar age are known in the southwestern Junggar. The ages support an idea that the subduction may have occurred in Cambrian–Ordovician time (Dobretsov et al., 1992), which would be correlated to the Tanbale blueschists (western Mongolia, northern China) containing Late Cambrian–Early Ordovician ophiolites (Chi et al., 1993).

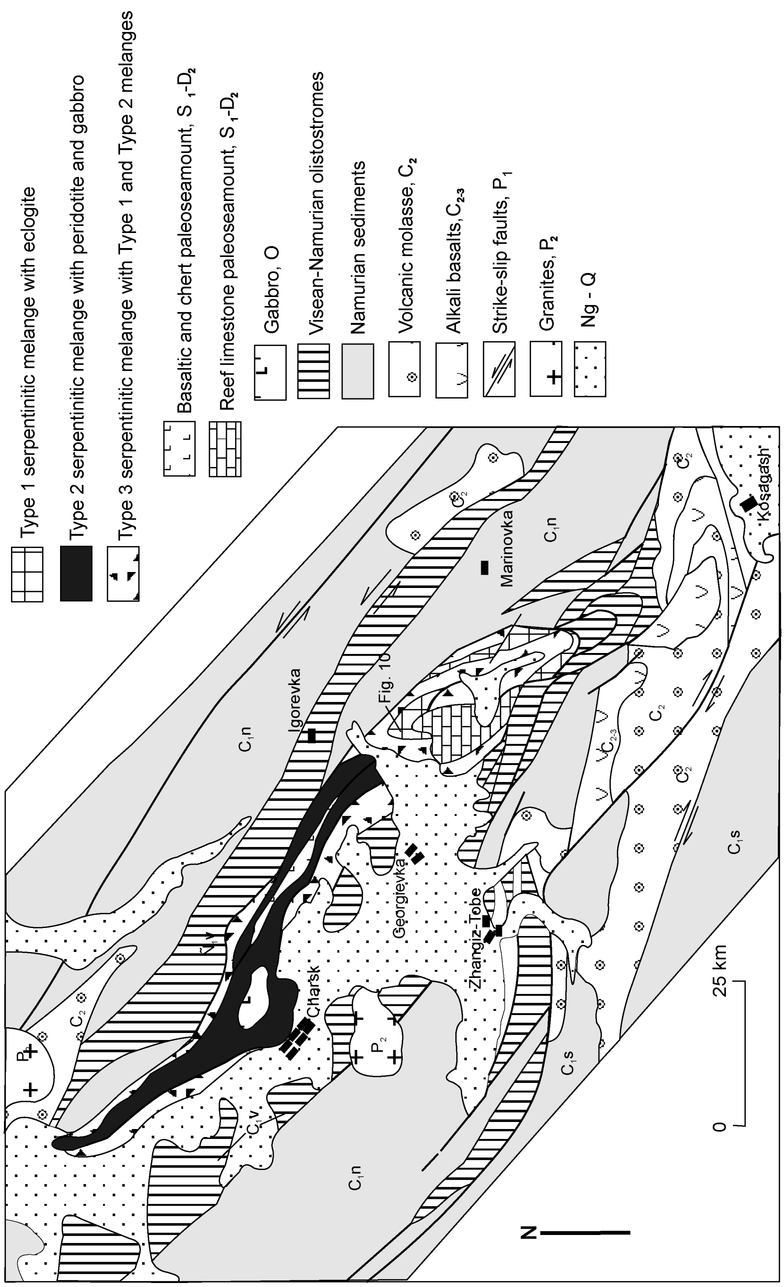

FIG. 10. Major tectonic features of the Chara belt, including HP complexes and serpentinitic mélanges (after Buslov et al., 2002).

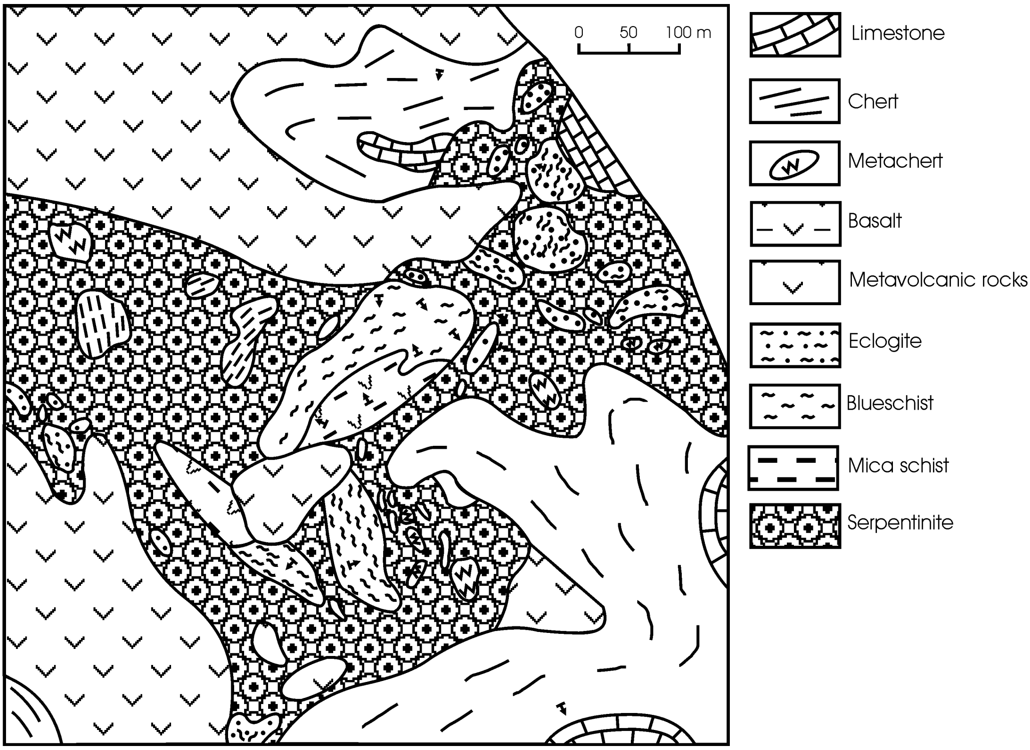

FIG. 11. Geological scheme of Type I serpentinitic mélange of the Chara belt.

Type II ophiolitic melange imbricated with blocks of Cambro-Ordovician oceanic crust of different sizes, composed of massive harzburgites, lherzolites, dunites and pyroxenites, gabbro, plagioclase amphibolites, and amphibole-plagioclase schists.

Type III polymictic mélange includes fragments of Types I and II mélange, Silurian–Carboniferous oceanic crust (peridotites, gabbro, ophiolites, pillow lava, and cherts, fragments of seamount units of Tournaisian–Visean age: brecciated limestones, calcareous cherts, chert, and OIB-type basalts). All those rocks are immersed in an olistostrome matrix containing Serpukhovian terrigenous rocks (Buslov et al., 2001, 2003).

The polyimictic mélange 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. Imbrications along the southwestern limits of the zone include fragments of the Early Carboniferous accretionary wedge of the Zharma-Saur island arc. Serpentinitic mélange in the interior of the Chara zone is chiefly oriented northwestward following the zone strike, as well as interthrust blocks of various compositions.

The Chara ophiolite belt occurs among Devonian–Early Carboniferous volcaniclastics (Fig. 10), 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 dikes. Younger Permian and Early Triassic faults occur locally. The Semeitau alkali basalts and intrusions were produced by Middle Permian–Early Triassic activity.

Western Junggar (Fig. 3) includes several Paleozoic island arcs, accretionary prisms, and ophiolite belts that were finally assembled in the latest Carboniferous (Chi et al., 1993). The ophiolites are fragments of Late Cambrian–Early Ordovician and Silurian–Early Devonian oceanic crust (Chi et al., 1993; Li, 1998). As in the Chara belt, they are strongly deformed peridotites, gabbroics, lavas, and serpentinitic melange. The geochemistry of lavas records environments of 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) are associated with roughly coeval glaucophane-crossite schists.

Correlation of geological data from the Western Junggaria, 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. This relationship is confirmed by similar ages and compositions of ophiolites in the Chara zone and Western Junggar (Fig. 3). However, in the present-day structural framework, slices of the 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).

The Maksyutov belt

The Maksyutov complex in the Southern Urals (Dobretsov et al., 1996; Echtler and Hetzel, 1997; Leech and Ernst,1998) is a N-S–trending belt 200 km long and 10–15 km wide. It consists of a lower unit of mica schists with blocks of eclogites, blueschists, and quartz-almandine-jadeite rocks (with relics of coesite) and an upper metamorphic unit. In the west, the Maksyutov complex tectonically overlies the Suvanjak greenschist terrane of Ordovician (?) age. In the east, it is juxtaposed against Silurian ophiolites covered by Lower Carboniferous rocks (Fig. 12).

The lower unit is dominated by garnet phengite-quartz metagreywackes, typically with chloromelanitic pyroxene and with inclusions of up to 20 m of coarse-grained rocks (enstatite ± Ol, Dy) rimmed by omphacite or garnet-talc-actinolite rocks; barroisite eclogite, bi-mineral and lawsonite eclogite; and almandine-quartz-jadeite rocks with relics of coesite in garnet porphyroblasts. The lower unit also contains phengite-rich rocks with microcline, crossite, quartz, sparse garnet (meta-arkose or gneissic blastomylonite) and Type I serpentinitic mélange (Antigan) (Fig. 12). It consists of antigorite schists with eclogites, metaperidotite, diopside-jadeite rocks, and garnet amphibolites. The eclogites have rediometric Sm-Nd ages of 385–375 Ma (Shatsky et al., 1997).

The upper unit consists of metabasalts with crossite-winchite and garnet, serpentinic mélange, black shales, metacherts, and sparse limestone lenses. The cherts and limestones contain Ordovician fossils. The Type II serpentinitic mélange contains rodingite with large crystals of lawsonite replaced by zoisite and mica, garnet and chlorite, as well as gabbro-amphibolite and metachert. The upper unit may be correlated with the Kraka ophiolites of Ordovician age and associated Ordovician sediments. The evidence for multi-stage evolution of the Maksyutov belt comes from strongly variable P-T estimations (Dobretsov et al., 1996; Ernst et al., 1995; Leech and Ernst, 1998).

Geological and isotopic data show at least two collisional stages in the Maksyutov complex. The first stage is recorded in Ordovician ophiolites that collided with the East European continent and were metamorphosed in Silurian time. Similar ages were fixed in other HP rock units in the Urals. During the second stage, the continent collided with Silurian ophiolites and a Devonian island at 370–380 and 360–350 Ma. Fragments of glaucophane and garnet occur in the Zilair flysch of Late Devonian–Early Carboniferous age and in Visean sedimentary rocks within the Main Uralian fault zone (see Fig. 12).

Serpentinitic Mélanges and UHP-HP Rocks of the Kokchetav Belt

Based on abundant geologic information, the Kokchetav region has been subdivided into five tectonic domains, which are shown in Figures 13 and 14. The first is a northern domain of Ordovician age, the second is the Kokchetav microcontinent domain, the third is a metamorphic megamélange domain incorporating UHP, HP, and MP rock units, the fourth is the White Lake domain, and the fifth is a granitic dome domain (with the LP Daulet belt) on the south.

The Kokchetav diamondiferous eclogite complex is most interesting and well-studied. It was described as a megamélange (Dobretsov et al., 1995b) and can be regarded as two tectonic domains: the Kumdy-Kol rhomb-shaped, diamond-bearing domain with a peak of metamorphism at 950°C and 45 kbar, and the Kulet coesite-bearing domain (Sobolev and Shatsky, 1990; Dobretsov et al., 1998; Okamoto et al., 2000). Isotopic data for the Kumdy-Kul domain indicate that the final stage

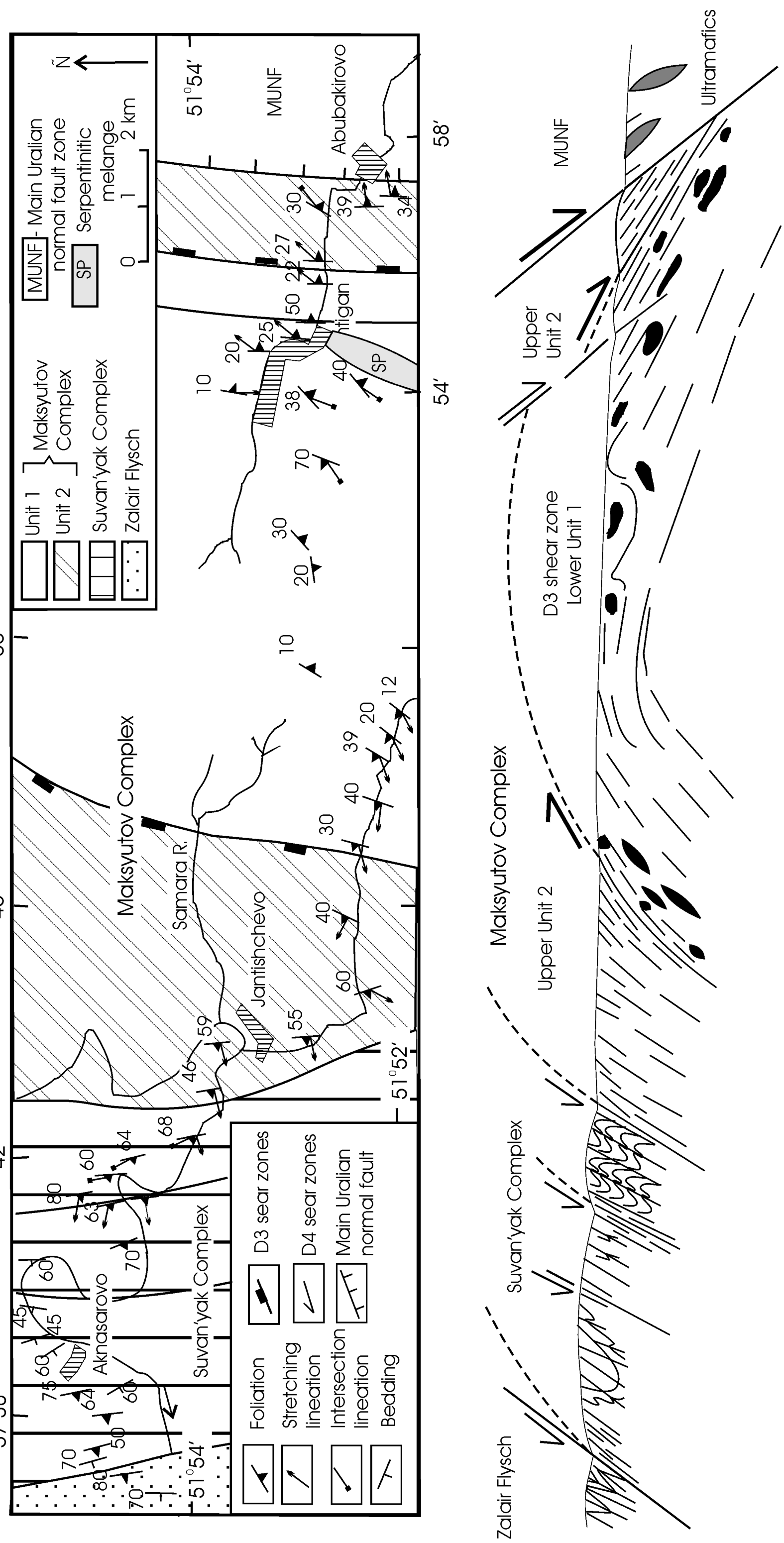

FIG. 12. Geologic map and E-W profile of the orogenic wedge at the latitude of the Maksyutov Complex (Echtler and Hetzel, 1997).

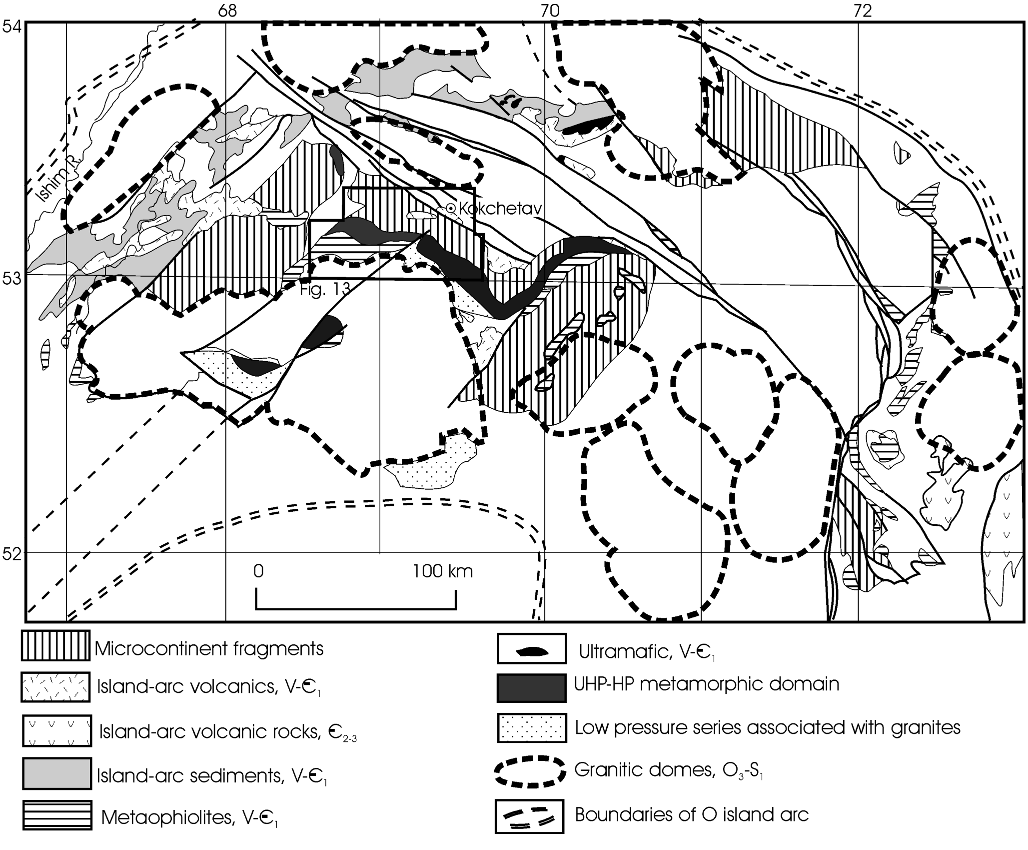

FIG. 13. Tectonic scheme of northern Kazakhstan (Dobretsov et al., 1998).

of subduction and the peak of UHP metamorphism took place at 540–528 Ma, and the early stage of exhumation at 528–524 Ma, which resulted in the crystallization of exhumed and melted rocks in the amphibolite facies of metamorphism at 520–515 Ma (Claoue-Long et al., 1991; Dobretsov at al., 1998; Kaneko et al., 2000; Maruyama and Parkinson, 2000; Katayama et al., 2002; Hacker et al., 2002). The Cambrian episode of UHP metamorphism is one of the most important phases of the evolution of geodynamic and metamorphic processes of the Earth's crust (Maruyama et al., 1996).

The Kokchetav UHP belt resulted from the collision of a Precambrian microcontinent and a Vendian–Early Cambrian island arc and then with an Ordovician island arc. The complicated structure of this belt may be interpreted as megamélange (Dobretsov et al., 1995b, 1998). This megamélange includes the Kulet-type tectonic mélange, the matrix of which consists of multiply sheared mica schists and blocks of kyanite-garnet-phengite schists with coesite relics in garnet, as well as pods of eclogite, barroisite-garnet amphibolite, sheared granitic gneisses, and ultramafic lenses.

Ultramafic lenses up to 1–1.5 km long occur in different parts of the tectonic mélange and comprise antigorite, olivine-antigorite, anthophyllite-antigorite, talc-antophyllite, pyrope-talc ± anthophyllite, and spinel-garnet-olivine ± antigorite rocks. Exotic Ti-clinohumite-pyrope-olivine rocks are present within a large eclogite body in the Kumdy-Kol diamond-bearing metamorphic block (Fig. 15).

The absence of serpentinitic mélange in the Kokchetav belt can be explained by two factors. First, subduction mainly involved microcontinental rocks, not ophiolites. Second, the depth of UHP and

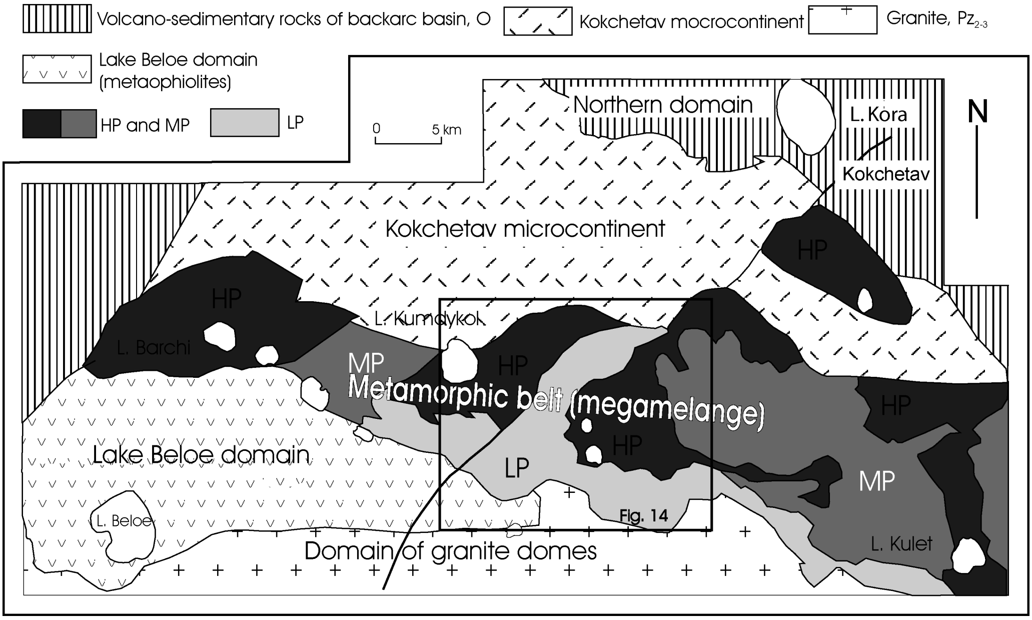

FIG. 14. Tectonic scheme of the Kokchetav belt (after Dobretsov et al., 1998).

HP metamorphism exceeded 150 km, i.e., outside the field of serpentine stability.

Conclusions

The West Sayan (Borus belt) and Gorny Altai (Chagan-Usun belt) are Caledonian foldbelts formed after collisions of paleo-seamounts with primitive island arcs that resulted in the exhumation of HP rocks—eclogites and jadeitic rocks. The jadeitic rocks of the Borus belt resulted from Na-rich high-pressure metasomatism that produced various Na-Al-Cr-rich pyroxenes. The Chara belt of Hercynian age was formed during the Late Carboniferous–Permian collision of the Siberian and Kazakhstan continents, and represents a strike-slip zone comprising serpentinitic mélanges and HP units of different ages. In Caledonian time, the mélanges formed an accretionary wedge at the margin of the Kazakhstan continent. The Kokchetav and Maksyutov foldbelts of Caledonian and Hercynian ages, respectively, resulted from collision of microcontinents with island arcs, and formation of sheeted complexes incorporating large lenses of UHP-HP rocks and serpentinitic mélanges. Foldbelts that resulted from microcontinent–island arc collision contain much smaller amounts of serpentinite. Oceanic islands involved in subduction usually block subduction zones and prevent submergence of oceanic island units to depths greater than 60 km—i.e., the subducted complex remains within the stability field of serpentinite.

Two types of serpentinitic mélange typify all suture zones formed as a result of collision of island arcs with seamounts or other island arcs. Type I mélange contains HP or UHP rocks in antigorite or olivine-talc-antigorite schists associated with high-temperature mantle peridotites, which can be regarded a part of the hanging wall of a paleosubduction zone. Type II mélange is a part of an obducted oceanic crust and contains blocks and inclusions of LP and LT metamorphic rocks associated with island arc and/or seamount terranes. The suture zones that originated from island arc or continent/microntinent collision (the Kokchetav megamélange and the lower unit of the Maksyutov complex) lack large sheets of serpentinitic mélange. Instead, they contain only subordinate lenses of mélanges with HP rocks (the Maksyutov lower unit) or small and sporadic ultramafic lenses inside a tectonic mélange with a metasedimentary matrix.

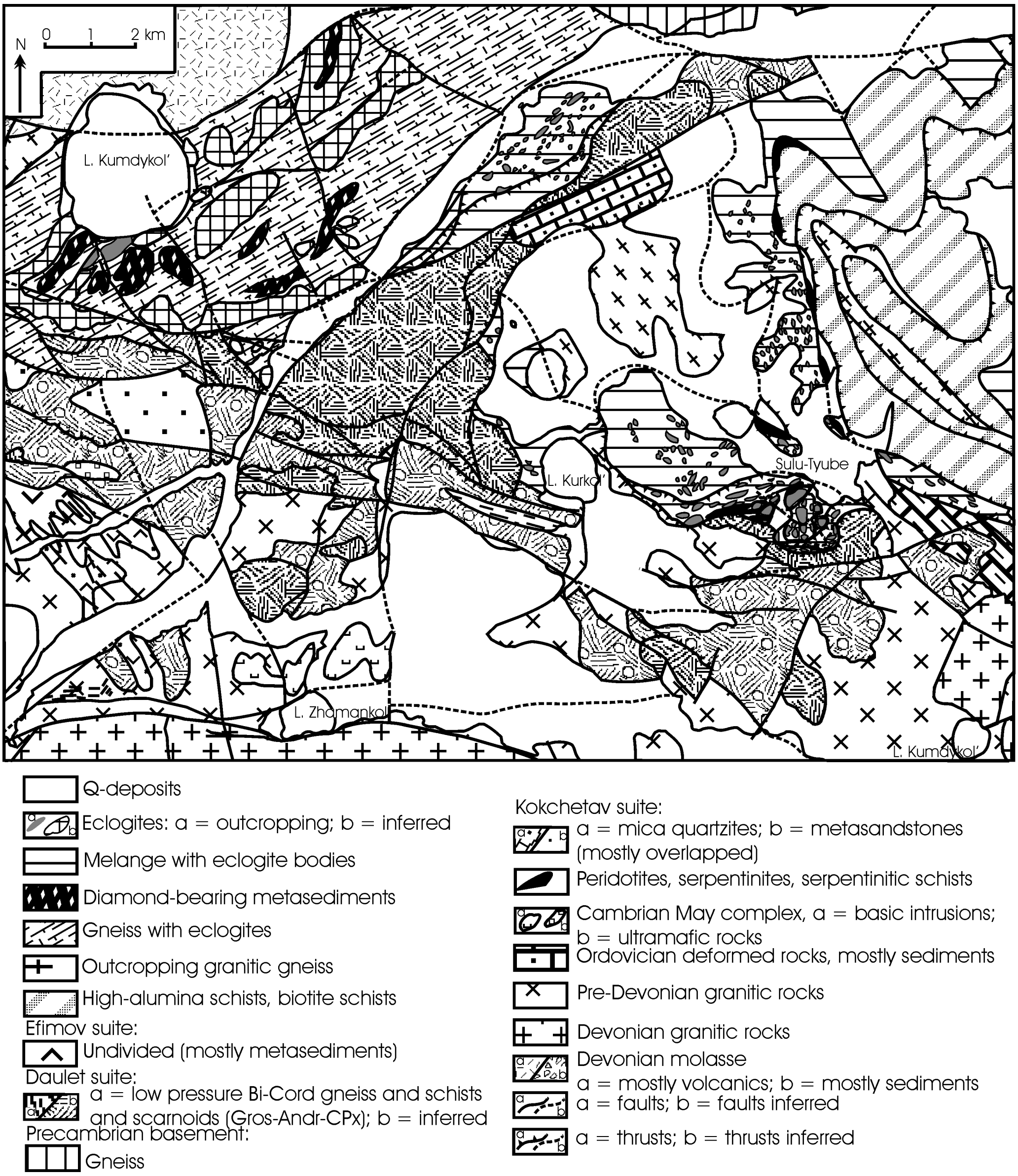

FIG. 15. Geological scheme of the megamélange zone in the central part of the Kokchetav belt (modified after Dobretsov et al., 1998).

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