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Accretionary prisms of the Sikhote-Alin Orogenic Belt: Composition, structure and significance for reconstruction of the geodynamic evolution of the eastern Asian margin

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ABSTRACT

We present overview for geological studies of the terranes of the Sikhote-Alin orogenic belt in the Russian Far East. The belt is formed by accretionary prisms with alternating tectonic packets of thrust-like slices which consist of complexly deformed marine (pelagic and hemipelagic deposits, as well as oceanic plateau and paleo-guyot fragments), marginal oceanic turbidites and chaotic (subduction mélange) formations. We reconstruct a stepwise history of accretion of paleo-oceanic crustal fragments of different ages, based on detailed lithological-biostratigraphic and structural analysis. We propose geodynamic model for evolution of the eastern margin of the paleo-Asian continent during the Mesozoic time by combining geological observations for the region with geological data for others terranes of the Sikhote-Alin Orogenic Belt. We recognize several principal Mesozoic geological processes that have led to formation of the continental crust at the eastern margin of Asia: (i) accretion of paleo-oceanic fragments to the continent margin during the subduction of the paleo-Pacific plate along the convergent margins, (ii) subsequent intense deformation of rocks of the accretionary prisms of the transform margin including folding and multiple thrusting which led to a multifold increase in thickness of sediments, (iii) formation of granitic–metamorphic complexes due to intrusion of the orogenic granites into the accretionary prisms.

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1. Introduction

The Sikhote-Alin Orogenic Belt, including part of the eastern margin of Asia, extends from the northern coast of the Sea of Japan to the southern coast of the Udsky Gulf of the Sea of Okhotsk (Fig. 1). Fragments of several ancient accretionary prism terranes are widely distributed within the orogenic belt, and they range in age from Jurassic to Early and Middle Cretaceous (Natal'in, 1993; Kemkin, 2006; Khanchuk, 2006; and others).

Accretionary prisms are intensely deformed and dislocated sedimentary complexes that form at the base of continental or island arc slopes at convergent plate boundaries during subduction of an oceanic lithosphere. Subduction of an oceanic plate under a continent or island arc is accompanied by intensive deformation of accreted sedimentary formations. At first, the upper part (trench-fill turbidites) of the sedimentary section is imbricated under the "bulldozer-like" scraping action in the frontal part of the slope basement (Fig. 2*A*). Imbrication is expressed as a series of tectonic slices of terrigenous composition. Next, a part of sedimentary section lying below the imbrication zone (pelagic and hemipelagic deposits) submerges into the subduction zone and buckles into small-amplitude and disharmonic, commonly overturned folds (effect of drag folding) in which the axial planes are inclined toward the trench. Buckling continues as long as the rock strength limit is exceeded and the rock fails by ruptures (faults). Later, along these faults, the deformed cover rocks of the oceanic plate are repeatedly underthrust and duplicated, forming an imbricate stack (Fig. 2*B*) (Seely et al., 1974; Kimura and Mukai, 1991; Kimura and Ludden, 1995; Kimura, 1997; Isozaki, 1997; Hashimoto and Kimura, 1999; and others). For this reason, accretionary prisms represent complicated tectono-sedimentary complexes (imbricate-underthrusted sedimentary packets) consisting of many repeated fault-bounded tectonic slices and blocks (Fig. 2*C*) composed of oceanic (pelagic and hemipelagic deposits and fragments of seamount and rises), marginal-oceanic (sand-shale beds), and chaotic (mélange and olistostromes) formations. The structure of ancient accretionary prisms is usually even more complex, due to the structural imprints of post-accretionary deformational events, which may result in the development of late thrust faults and/or strike-slip faults.

Being formed in zones of direct interaction of lithosphere plates, the accretionary prisms preserve information about the succession and character of the events that took place at the convergent boundaries along which they have been formed. The study of accretionary prism sedimentary formations is important for the several reasons, for example: understanding the geological structure and evolution of the regions composed of these formations; deciphering features of these complicated-structured sedimentary complexes; reconstructing the accretion succession of the paleooceanic fragments and history of the prism formation; revealing the specificity of the accretion process at different areas along the convergent boundary; correlating geological events in the zone of the lithosphere plate joint; and interpreting geodynamic evolution of the continental margins along which they developed.

Below, we present the results of a study of ancient accretionary prism fragments of the Sikhote-Alin-Orogenic Belt, the composition and structure of which record the geological history on the eastern margin of the paleo-Asian continent during the Mesozoic.

2. Methods of investigations

Our long-term study of the Sikhote-Alin accretionary prisms (more than 30 years) shows that they are characterized by complicated dislocation patterns and lithological monotony. For this reason it is difficult to decipher their structure and determine their primary stratigraphic succession. Reconstruction of the original details of the accreted oceanic plate cover requires understanding of the fragmentation process and their incorporation into the prism. The age of sedimentary rocks in different tectonic slices of the prism is useful for determination of the time of their formation and mutual correlation of the compositional varieties of tectono-stratigraphic slices within the prism (Kemkin, 2006, 2008; and others). Thus, biostratigraphic study of sections of strata within the prism is crucial to unraveling their stratigraphy. However, most of deposits constituting accretionary prisms lack macrofauna due to their unfavorable sedimentary environment. In this case, the most prospective group of fossils are the microfauna (conodonts, radiolarians, and foraminifers). Radiolarians offer advantages because they have no time limit, as do conodonts (only to the end of the Triassic), and no environmental limits, as do foraminifers (within the seamounts above the level of carbonate compensation). Radiolarians present in all bottom deposits, both in deep-sea (pelagic and hemipelagic) and relatively shallow (marginal-oceanic). For some rock types (chert and cherty-clayey), they are the sole group of organic remains.

The ages derived from radiolarian analysis provide the basis for differentiating the accretionary prisms into correlative tectono-stratigraphic units and also may be used to identify episodes of accretion of the oceanic plate cover fragments. This is possible because in spite of the predominance of tectonic contacts between various lithological groups of rocks composing accretionary prisms, within some individual tectonic slices, we can find continuous stratigraphic sections of considerable thickness that preserve the original (primary) sedimentary succession from pelagic to hemipelagic, or from hemipelagic to oceanic-margin depositional sequences. Studies of the microfaunal fossil assemblages present within such well-preserved sedimentary stratigraphic successions have allowed reconstruct important primary sections of accreted paleooceanic sedimentary deposits (e.g., Hori, 1992; Matsuoka et al., 1994; Kamata, 1996; Matsuoka, 1998; Kemkin and Kemkina, 1999; and others). Typically, undisturbed sedimentary successions comprise a lowermost unit dominated by pelagic cherts, which progressively grades upwards into hemipelagic chert- and clay-rich deposits, followed by an uppermost unit of terrigenous sedimentary rocks (e.g., turbidites). Such distinctive, tripartite sequences of sedimentary deposits are generally referred to as "Oceanic Plate Stratigraphy" sequences (e.g., Berger and Winterer, 1974; Matsuda and Isozaki, 1991; Wakita and Metcalfe, 2005; Safonova, 2009; and

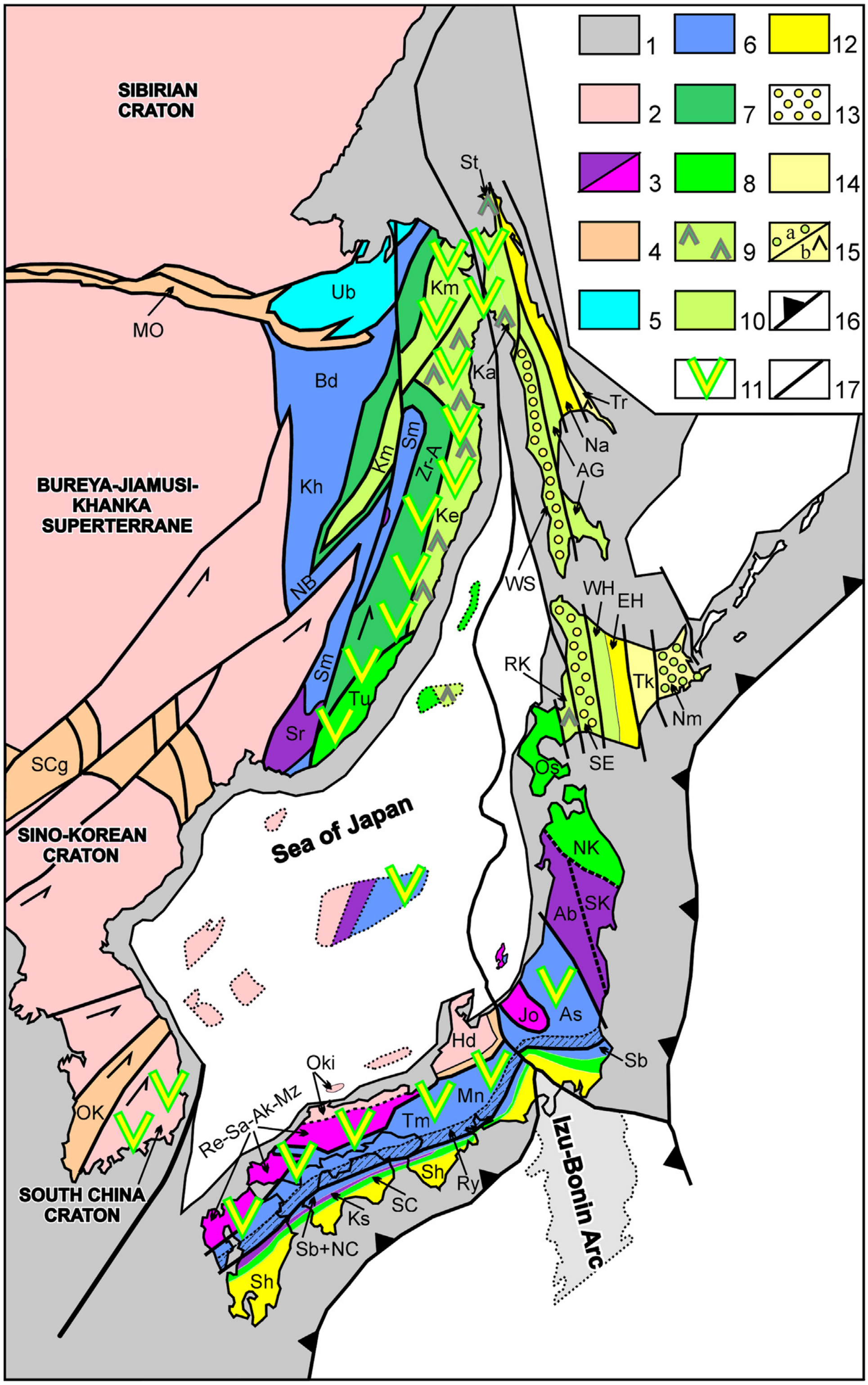

Fig. 1. Tectonic scheme of the Circum-Sea of Japan region (Tectonic division of the Sikhote-Alin Orogenic Belt according to Khanchuk, 2006, and the Japanese Islands according to Ichikawa et al., 1990 and Moreno et al., 2016).

1–present-day continental and island shelf; 2–ancient continental blocks: pre-Cambrian – Sino-Korean, South China, and Siberian cratons, Early Ordovician – Bureya–Jiamusy–Khanka superterrane, and fragments of ancient continental blocks: Hida (Hd) and Oki terranes, 3–pre-Jurassic terranes (mostly Early-Middle Palaeozoic): 3a – Renge-Sangun-Akiyoshi-Maizuru (Re-Sa-Ak-Mz) and Joetsu (Jo) terranes, 3b – Sergeevka (Sr), Khor, Southern Kitakami (SK), Abukuma (Ab), and Kurosegawa (Ks) terranes; 4–Permian–Triassic collision orogenic belts: Mongolo-Okhotsk (MO), Solonker-Chkhongien (SCg), Okcheon (OK); 5–Jurassic turbidite basin: Ul'ban (Ub) terranes); 6–Jurassic accretionary prism: Samarka (Sm), Nadanhada–Bikin (NB), Khabarovsk (Kh), Badzhal (Bd), Mino (Mn), Tamba (Tm), Ashio (As), Ryoke (Ry), Jurassic portion of the Sanbagawa (Sb), and Northern Chichibu (NC) terranes; 7–Early Cretaceous turbidite basin: Zhuravlevka–Amur (Zr-A) terrane; 8–Late Jurassic–Early Cretaceous (Neocomian) accretionary prism: Taukhe (Tu), Oshima (Os), Northern Kitakam (NK), Southern Chichibu (SC), and Ryukyu terranes; 9) – Hauterivian–Albian island arc: Kema (Ke), Kamyshov (Ka), Shmidt (St), Moneron, and Rebun-Kabato (RK) terranes; 10–Hauterivian–Albian accretionary prism: Kiselevka–Manoma (Km), Aniva–Gomon (AG), and Western Hidaka (WG) terranes); 11–Late Cretaceous volcanic arc (Eastern Sikhote-Alin volcanogenic belt); 12–Late Cretaceous accretionary prism: Nabil (Na), Eastern Hidaka others), and are considered to reflect a characteristic sequence of sedimentary processes that takes place globally on an ocean floor. The crust of the oceanic plate is overlain by layers that record progressive change in environments from pelagic to hemipelagic and then to marginal-oceanic conditions as it drifts from the place of origination (spreading zone) to the place of burial (subduction zone). Each distinctive lithological group of deposits in this succession possesses certain information (Kemkin, 2008; and others). For example, cherts record a history of pelagic sedimentation. In contrast, the hemipelagic formations, represented by siliceous mudstones and argillites, signal the approach of the oceanic plate to the convergent boundary. The terrigenous rocks (turbidites), which are accumulated in the trench, indicate the onset of submergence of this area of the oceanic plate into the subduction zone and, correspondingly, the subsequent accretion of its sedimentary cover fragments. Thus, if the age of these rocks is known in different tectonic slices of a prism, we can define the time of accretion of individual oceanic fragments and divide the prism into the tectono-stratigraphic units characterizing certain stages of its formation. Ultimately, with sufficient age estimates for various Oceanic Plate Stratigraphy sequences, mutual correlation and comparisons between individually classified tectono-stratigraphic units can be made, which in turn allows for the reconstruction of the complete stepwise history of accretion of different-aged fragments of oceanic crust. This reveals the overall structural framework of the accretionary prism as a whole.

Here, we present short generalized information about each of the Sikhote-Alin accretionary prism terranes.

3. Structure and composition of the Jurassic prism terranes

In the Sikhote-Alin Orogenic Belt, the Jurassic accretionary prism is represented by four fault-bounded terranes: Samarka, Nadanhada-Bikin, Khabarovsk, and Badzhal (Fig. 3) which are composed primarily of deformed Jurassic rocks and other units as old as the Middle Paleozoic.

3.1. Samarka terrane

The Samarka terrane extends as a ~100-km-wide band along the eastern edge of the Bureya-Jiamusi-Khanka superterrane northeastward of the southern coast of Primorye, east of the Amur and Ussuri Rivers downstream (Fig. 3). The terrane consists of repeated alternations of steeply dipping tectonic slices of different thickness that form something like a “many-layered cake”, including Mid- to Upper Jurassic sandstone and siltstone “alternating” with the slices containing Permian, Triassic, and Lower Jurassic bedded chert and siliceous mudstones, and chaotic formations of mélange containing blocks and clasts of Carboniferous–Permian carbonate rock, and basalt, gabbro, and ultramafic rocks (Figs. 4 and 5*a*). Near the contacts between slices, the rocks are strongly boudinaged and schistose. Within the slices, the rocks are crumpled into asymmetric, commonly overturned folds of various amplitude that trend northeast. The axial planes of the asymmetric folds exhibit southeast vergence and mirror of folding sloping dips to the northwest (Fig. 5*b*). This style of folding characterizes the uppermost structural levels of the terrane that are exposed in the west-northwest part of the terrane, and the lowermost ones in the east-southeast (Fig. 5*c*). The lithological composition of strata in the upper structural units of the Samarka terrane differs somewhat from that of

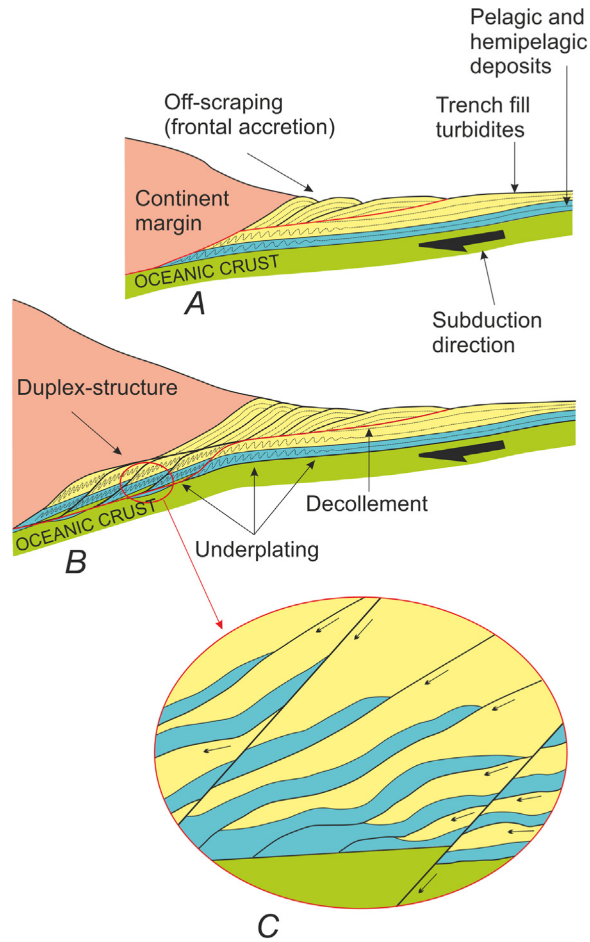

Fig. 2. Model of accretionary prism structure (modified after Isozaki, 1997; Hashimoto and Kimura, 1999; and others).
A – frontal accretion (imbrication of trench-fill turbidites); *B* – underplating and duplication of the cover rocks of the oceanic plate; *C* – imbricate-underthrusted structure of the accreted cover rocks of oceanic plate.

the lower and middle levels, and two subterranes – Eldovaka and Sebuchar – have been distinguished (Kemkin, 2008).

3.1.1. Eldovaka subterrane

The Eldovaka subterrane, which comprises the lower and middle structural units of the Samarka terrane, is composed of alternating Lower-Upper Jurassic sandstone-shale bodies, chaotic (mélange) deposits, and sections of Upper Permian, Triassic-Lower Jurassic, and Triassic–Middle Jurassic chert (Kemkin, 2006; Khanchuk, 2006; and others). Most structural slices comprise a single rock unit. However, isolated tectonic blocks may contain fragments of an almost complete section, including a lower part, composed of bedded chert, which is transitional through all

intermediate varieties to beds of sandstone and siltstone. In places at the base of the unit, tholeiitic basalt is overlain by chert along a sedimentary contact. Stratigraphic ages (Kemkin, 2006, 2008; and others) reveal four, coherent, more or less correlative, repeated stratigraphic sections that distinguish tectono-stratigraphic complexes in the Eldovaka subterrane: Katen, Breevka, Saratovka, and Amba-Matay.

(EH), and Shimanto (Sh) terranes); 13–Late Cretaceous fore-arc basin: Western Sakhalin (Ws) and Sorachi-Ezo (SE) terranes; 14, 15–subduction–accretionary complexes of the Paleo-Okhotsk subduction zone: 14–Late Cretaceous accretionary prism: Tokoro (Tk) terrane; 15a – Late Cretaceous fore-arc basin: Nemuro (Nm) terrane, 15b – Late Cretaceous island arc: Terpeniya (Tr) terrane; 16–present-day subduction zone; 17–faults.

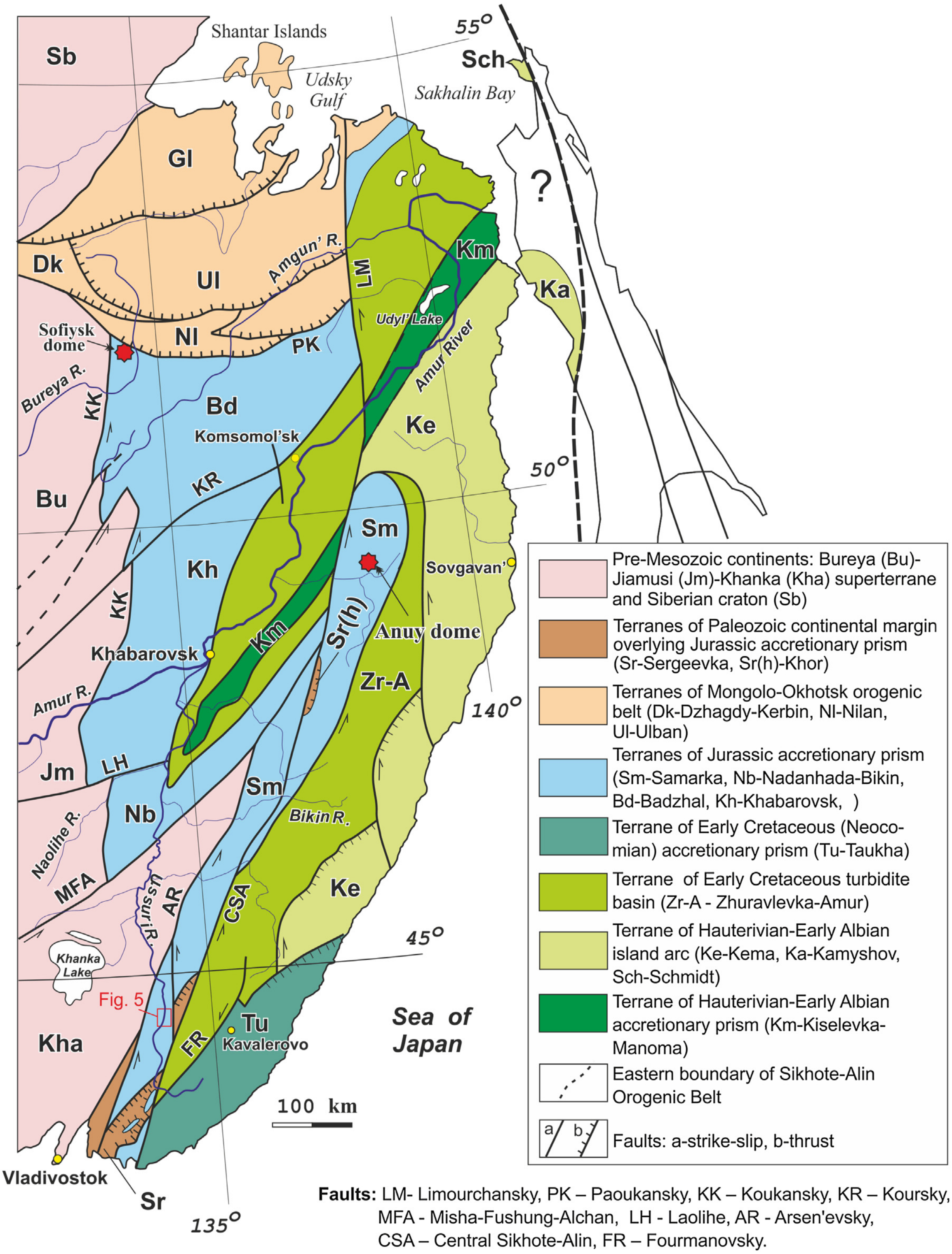

Fig. 3. Tectonic scheme of the Sikhote-Alin region and adjoining areas (modified after Khanchuk, 2006).

3.1.1.1. Katen complex. The Katen complex is in the easternmost part of the Samarka terrane (see 5 on Fig. 6) and constitutes its lowest structural level. The oldest units consist of chert and jasper (Fig. 7), for which ages fall in the interval from the Olenekian Stage of the Lower Triassic to the Bathonian Stage of the Middle Jurassic. The upper Norian part of the chert section consists in some exposures of distinctive chert and thin (1–3 to 7–10 cm) interbeds of gray pelitomorphic (micritic) limestone. Overlying strata include siliceous mudstones of Bathonian-Callovian age and Oxfordian-Kimmeridgian argillites transitional to Kimmeridgian-Tithonian siltstones alternating with sandstones.

3.1.1.2. Breevka complex. Structurally overlying Katen, the Breevka complex (see 4 on Fig. 6) is composed of (Fig. 8): (1) cherts, the age of which is between the Anisian Stage of the Middle Triassic and the Aalenian–Bajocian of the Middle Jurassic, (2) siliceous mudstones of

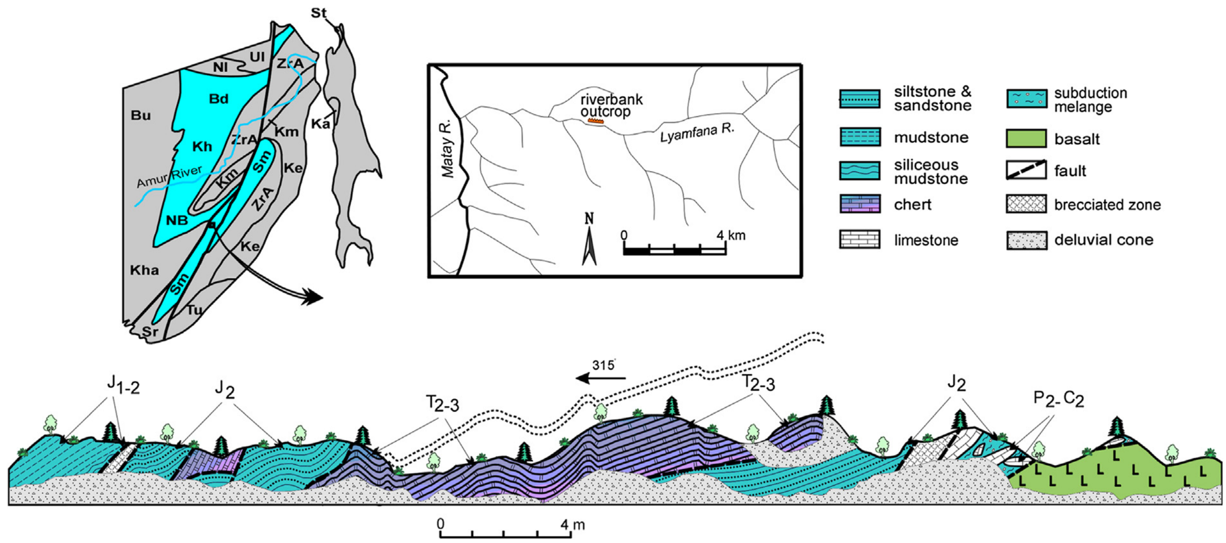

Fig. 4. Structure of the Samarka terrane in the Lyamfana River area (riverbank's outcrop).

Bajocian age, (3) Bajocian–Bathonian argillites and silty argillites, and (4) Callovian siltstones that is replaced upward by interbedded siltstones and sandstones. Above them, slices of chaotic units (mélange) crop out, composed of different-sized lumps, blocks, and fragments of cherts and sandstones within a matrix of siltstones and sandy siltstones.

3.1.1.3. Saratovka complex. The Saratovka complex occupies a much higher structural position than the Breevka complex (see 3 on Fig. 6). The complex consists of Upper Permian cherts at the base overlain by cherts with ages from the Anisian Stage of the Middle Triassic to the Pliensbachian–Toarcian of the Lower Jurassic. The contact with the Permian cherts is tectonic. The cherts are transitional into siliceous mudstones of Aalenian–early Bajocian age and upward into middle Bajocian–late Bathonian argillites and Bathonian–Callovian silty argillites and siltstones passing higher into turbidites.

3.1.1.4. Amba-Matay complex. The Amba-Matay complex (see 2 on Fig. 6) comprises the upper structural level of the Eldovaka subterrane (or upper part of the middle structural level of the Samarka terrane). The basement of the complex is composed of Lower to Upper Permian cherts and jasper (Fig. 9). Overlying cherts and jasper yield ages that fall between the Olenekian Stage of the Lower Triassic and the Pleinsbachian Stage of the Lower Jurassic. The cherts are transitional to siliceous mudstones of late Pleinsbachian–early Toarcian age, and upward to Toarcian–Aalenian argillites and silty argillites, and yet higher to Bajocian–Bathonian siltstones followed by interbedded siltstones and sandstones. Above lie chaotic formations containing siltstones with blocks and fragments of Carboniferous–Permian limestone and Permian and Triassic–Jurassic chert, sandstone, basalt, and gabbro. The composition and structure of the clastic part of the section and transitional layers of this complex are somewhat distinct in different areas. In particular, on the right (east) bank of the Matai River, among the siliceous mudstones, argillites, and siltstones, there are interbeds of hyaloclastite and basalt of variable thicknesses. The volcanic material indicates much effusive volcanic activity related to subduction.

3.1.2. *Sebuchar subterrane*

The Sebuchar subterrane is the upper structural level of the Samarka terrane (see 1 on Fig. 6) and comprises a tectonic stack of terrigenous (clastic) and chaotic formations and separated fragments of ophiolite. The Devonian–Permian ophiolite consists of: (1) gabbro and ultramafic rocks of middle Paleozoic age (Kalinovka complex); (2) basalt, commonly in association with overlying Carboniferous–Permian carbonate and chert rocks and Upper Permian black argillites (Sebuchar complex); and (3) Upper Permian greenish-gray and green sandstones and siltstones (Udeka complex).

3.1.2.1. Udeka complex. The Udeka complex is composed of 600–1000 m of Permian clastic strata that crop out as a narrow band along the east margin of the Kalinovka ophiolite. Sandstones are interbedded with thick (~20–30 m) intervals of siltstones and rare, thin interbeds of black silty argillites. The deposits of the Udeka complex tectonically overlap the Amba-Matay complex and, in turn, are tectonically overlain by the Kalinovka complex gabbro or by the volcanogenic-cherty formations of the Sebuchar complex. The age of the Udeka complex is defined by the Late Permian microfauna (Khanchuk, 2006). The Udeka complex occupies the lowermost structural position in the Sebuchar subterrane.

3.1.2.2. Kalinovka complex. The Kalinovka complex consists mainly of gabbro and ultramafic rocks represented by a series of rather spatially extensive slices as thick as 300–500 m that tectonically lie on the Udeka complex rocks or on the terrigenous (clastic)-mélange formations of the Eldovaka subterrane. Within the slices, comparatively complete sections of ophiolite are preserved. The lower part includes (Khanchuk, 2006; and others) serpentinized harzburgite and dunite and higher plagioclase dunite, wehrlite, clinopyroxenite, troctolite, and olivine gabbro-norite. The middle part is represented by two-pyroxene clinopyroxene, and amphibole gabbro. Geochemical and mineralogical data indicate that they were part of an oceanic plateau, the formation of which was related to the injection of a mantle plume (Khanchuk and Vysotskii, 2016; and others). The gabbroid age determined by K-Ar method is 410 ± 9 Ma and corresponds to the Early Devonian (Khanchuk, 2006; and others).

3.1.2.3. Sebuchar complex. The Sebuchar complex includes the basalt-sedimentary part of the ophiolite section. The complex is composed of a series of tectonic slices of basalt and associated sedimentary rocks. The base of the tectonic stack is, as a rule, composed of broken, strongly altered (spilitized) basalt that, in its

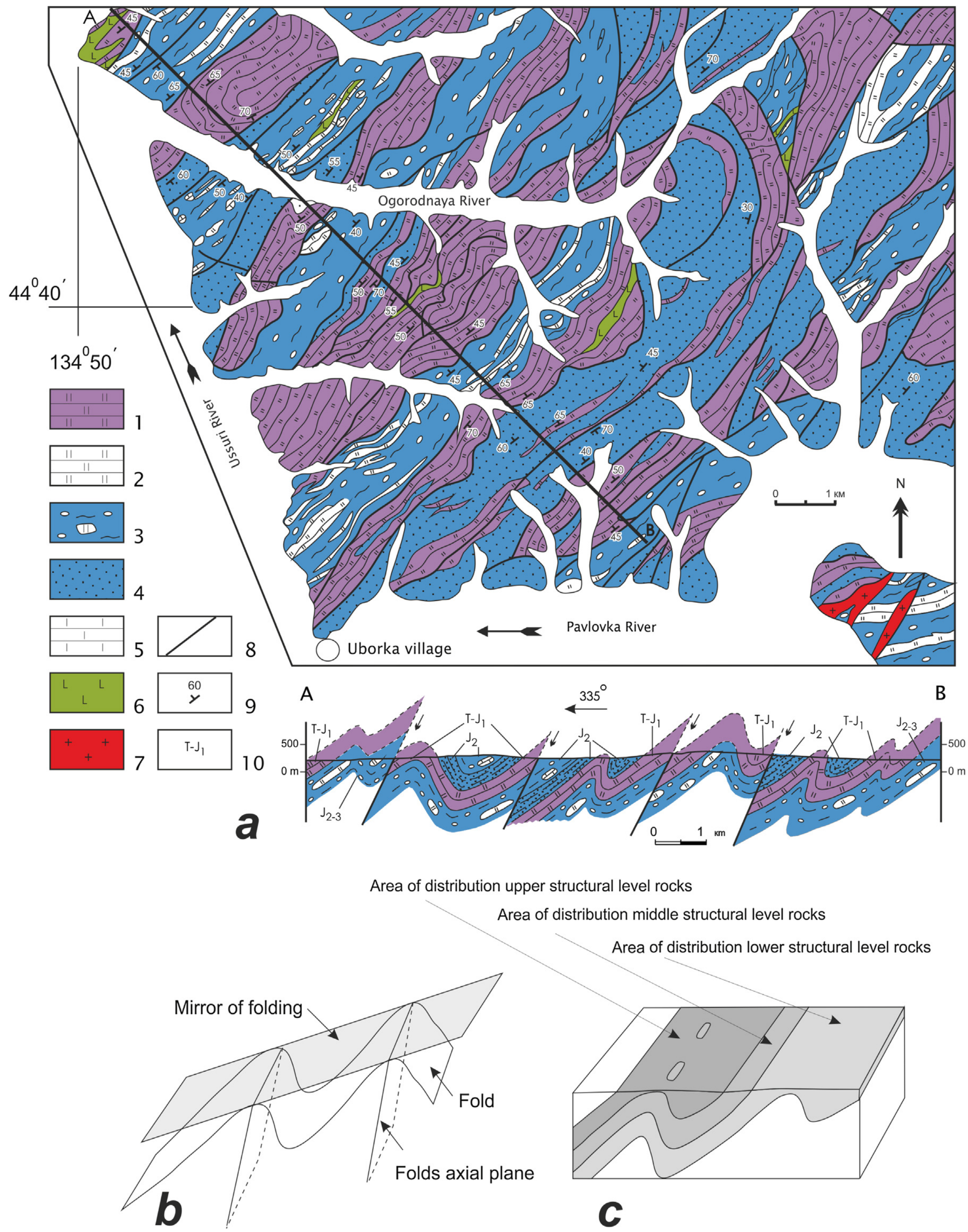

Fig. 5. Geological map of the Samarka terrane in the Uborka village area (a), style of folding (b) and distribution of structural levels (c).
1 – Permian, Triassic and Lower Jurassic cherts; 2 – Lumps and blocks of Permian, Triassic and Lower Jurassic cherts; 3, 4 – Middle-Upper Jurassic melange and turbidite formation; 5 – Lumps and blocks of Carboniferous – Permian limestones in subduction melange; 6 – Basalts; 7 – Late Cretaceous granites; 8 – Faults; 9 – Elements of rock occurrence; 10 – Age of deposits.

geochemical features, corresponds to oceanic tholeiite (Khanchuk, 2006; and others). This is overlapped by Carboniferous–Permian chert and limestone or by Permian argillite. Contacts of basalts with sedimentary rocks (if they were not disturbed by later tectonics) are depositional. In some slices, complicated facies relations are observed where basalts are overlapped by cherts, which, in their turn, are overlapped by argillites. Among the tectonic slices, some are composed of only basalt, or argillite, or chert. The terrigenous (clastic) rocks, interbedded with the fragments of the oceanic plateau, contain Early Jurassic radiolarians.

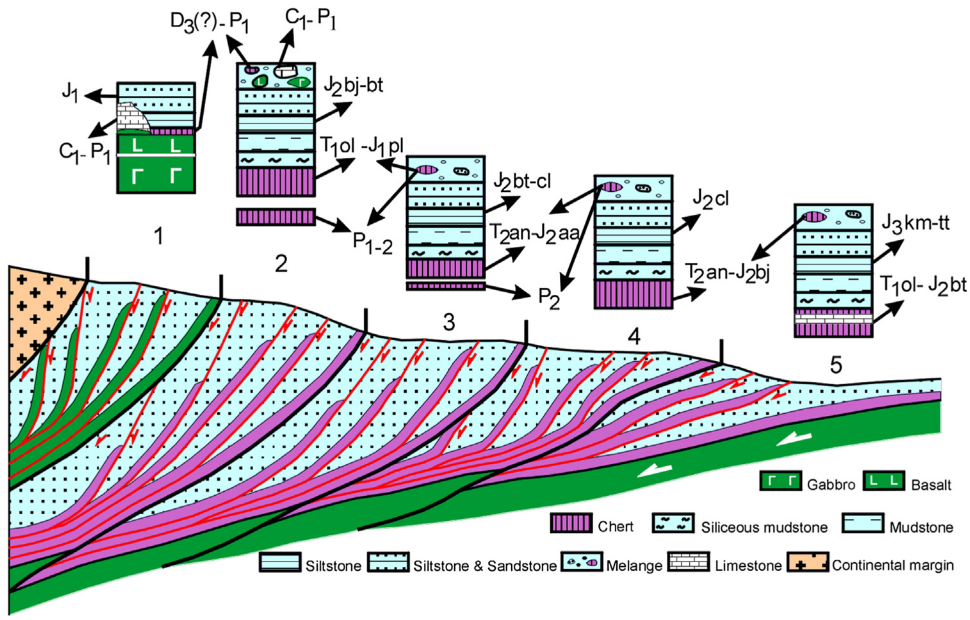

Fig. 6. Reconstructed structure of the Sikhote-Alin Jurassic prism (before orogenic deformations).

3.2. *Nadanhada-Bikin terrane*

The Nadanhada-Bikin terrane underlies the basin of the Ussuri River downstream in the area from the Chernaya Rechka River mouth to the Naolihe River mouth (see Fig. 3). It extends along the northwest edge of the wedge-like protrusion of the Bureya-Jiamusi-Khanka superterrane as a northeast-striking band, ~60 km wide, for a distance of almost 350 km. Territorially, the terrane is divided into two parts: a southwest part (Nadanhada), situated in China, and a northeast part (Bikin), located at the meeting of Primorsky and Khabarovsky regions (Russia). The boundary between them goes along the Ussuri River valley, which also provides the boundary between Russia and China.

3.2.1. *Bikin part*

The northeastern (Bikin) part of the terrane is characterized by a complicated alternation of tectonic slices of chert and clastic rocks. Locally, mainly in the southeastern part of the district, interbeds of mafic volcanics and horizons of mélange crop out. The volcanogenic, cherty, and clastic rocks record asymmetric folds of various amplitude that strike northeast (in some areas submeridional). In the central and eastern parts the folds axial planes record northwest vergence, and the mirror of folding is inclined to the southeast. In the western part, conversely, the axial planes of folds have a southeast vergence, and the mirror of folding dips northwest. A total structural plan of the Bikin terrane part testifies that its central and northeast parts are composed of rocks of the lower structural level, and the southeast and west parts are composed of rocks of the upper level. The age of the transitional layers of the chert-terrigenous (clastic) sequences and features of the lithological compositions of the formations (Filippov and Kemkin, 2004; Kemkin and Filippov, 2011; Kemkin, 2012; and others) allow us to distinguish three tectonic-stratigraphic complexes, namely, Ulitka, Ussuri, and Khor within the Bikin part.

3.2.1.1. *Ulitka complex.* The Ulitka complex crops out in the central and northeast parts of the terrane and composes the lower structural level. It consists of bedded cherts, the age of which varies between the Anisian and Bathonian Stages (Fig. 10). The cherts give way to siliceous mudstones and argillites of Bathonian–Kimmeridgian ages, passing higher into Upper Jurassic–Lower Berriasian siltstones and alternation of sandstones and siltstones. In the lower, cherty part of the section of late Carnian–early Norian age, an interbed of pelitomorphic (micritic) limestone, ~40 m thick, crops out.

3.2.1.2. *Ussuri complex.* The Ussuri complex crops out in the western part of the study area on the Ussuri River east (right) bank and composes the middle structural level of the terrane. The complex consists of basal bedded chert beds that range from early Anisian through Early–Middle Jurassic ages. Upward in the section, a transition takes place to upper Bajocian siliceous mudstones and higher to Bathonian silty argillites, siltstones, and interbedded sandstones and siltstones.

3.2.1.3. *Khor complex.* The Khor complex is located in the south-southeast, eastern, and in part in the southwestern parts of the terrane and occupies its upper structural level. It is composed of Triassic (Anisian to Rhaetian Stages) and Lower Jurassic cherts, giving way to Pliensbachian siliceous mudstones. The Middle Jurassic section is composed of silty argillites and siltstones that coarsen up section into alternating beds of siltstones and sandstones. Among the terrigenous (clastic) rocks, there are repeated interlayers of mafic hyaloclastite, tuff, and flows of basalt and picrite-basalt. The interbeds are between 10 and 40 m thick, although some packets are as thick as 100 m. In addition, within the siltstone section, horizons of chaotic formations (mélange) containing blocks and fragments of Paleozoic limestones, basalts, sandstones and cherts are interspersed.

The lithologies and the ages of the rocks of the complexes of the Bikin part of the terrane, as well as their structural position, allow temporal correlation with the tectono-stratigraphic units of the Samarka terrane. The Ulitka complex is correlated with the Katen complex, the Ussuri complex is correlated with the Breevka complex, and the Khor complex is correlated with the Amba-Matay complex, which is characterized by mafic volcanic horizons interbedded among clastic beds and by the mélange with exotic (Paleozoic) fragments.

3.2.2. *Nadanhada part*

In the southwestern Nadanhada part of the terrane, the Nadanhada Ridge (or Wandashan Ridge, according to Sun et al., 2015)

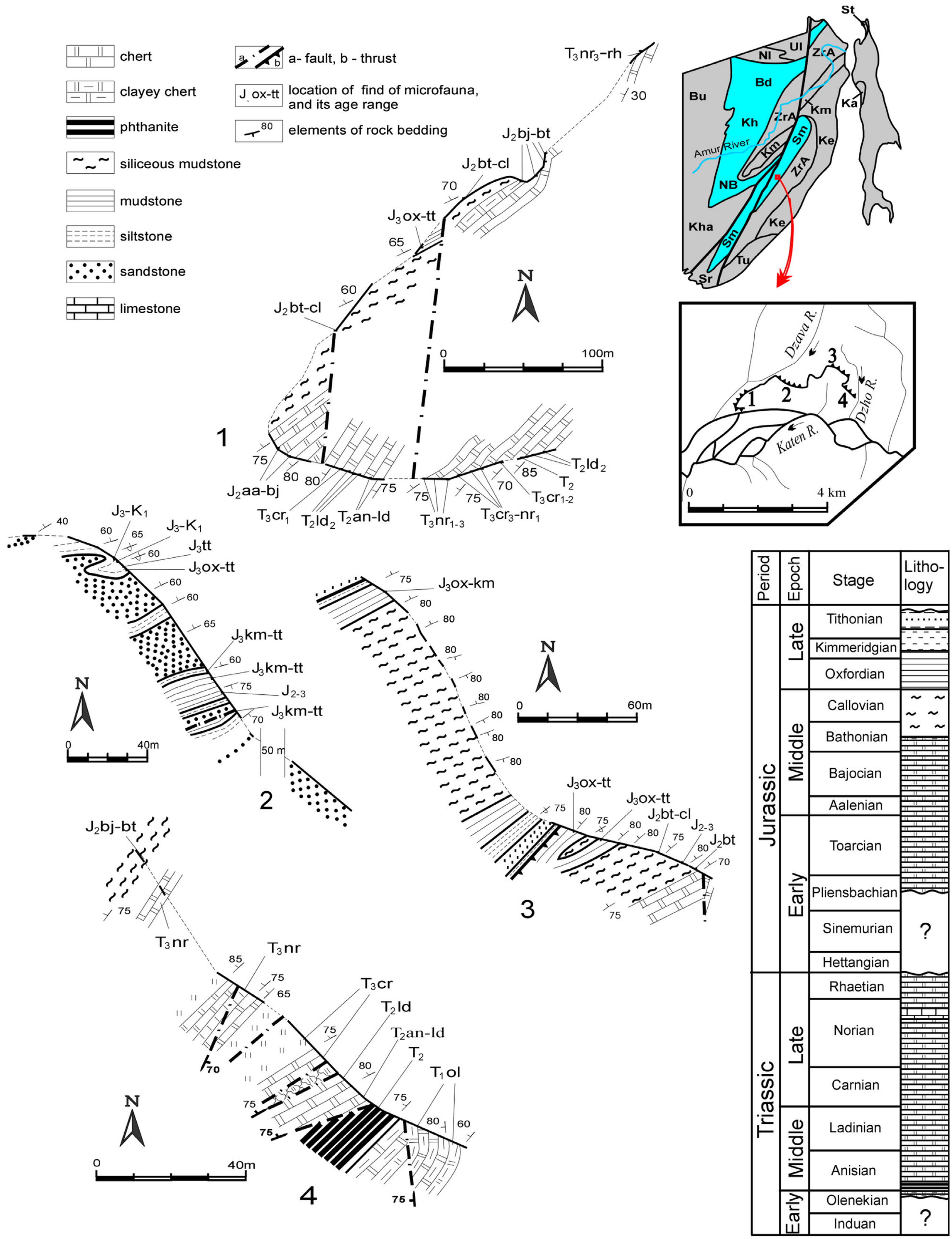

Fig. 7. Structure of chert-terrigenous formations in the Katen river area and reconstructed stratigraphic column (route map).

geological structure reveals a complicated stack of tectonic slices of sandstones, shales, cherts, and chaotic (mélange) formations (Fig. 11) that are crumpled into asymmetric overturned folds trending mostly northeast (Shao et al., 1992; Zhou et al., 2014; Sun et al., 2015; Wang et al., 2015). However, in the southwestern part of the district, the fold axes gradually assume a submeridional and then

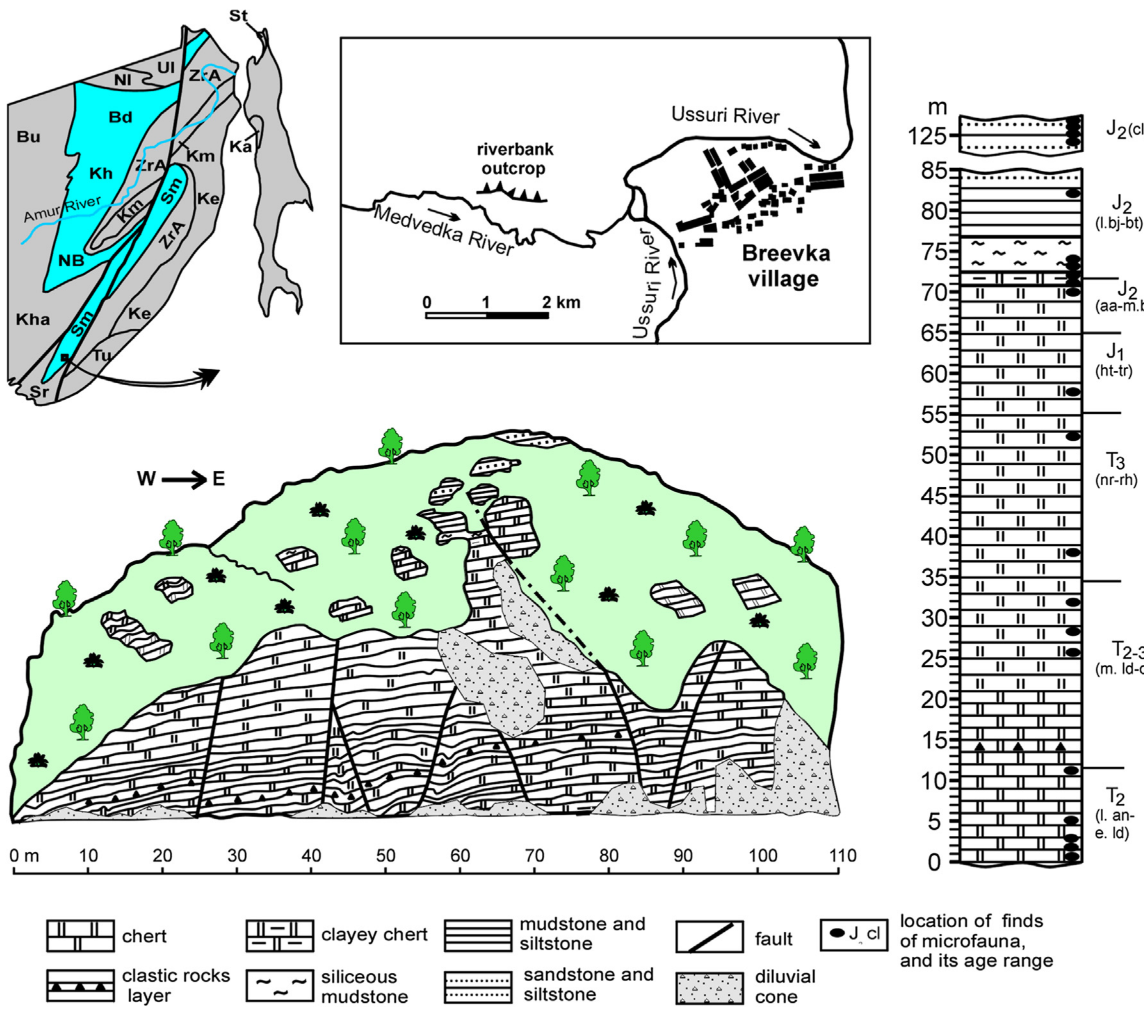

Fig. 8. Structure of chert-terrigenous formations in the Breevka village area (riverbank's outcrop).

northwest trend. The age of cherts within the slices falls between Middle Triassic and early Pliensbachian (Yang and Mizutani, 1991; Yang et al., 1993). In some slices, gradual transitions from cherts to terrigenous rocks take place, resulting in replacement of bedded cherts by siliceous mudstones, argillites, and then silty argillites and siltstones. Siliceous mudstones contain late Pliensbachian radiolarians, and argillites contain Aalenian radiolarians. In siltstones, Bathonian–Callovian radiolarians are present. Thus, the age of the transitional layers from cherts to terrigenous rocks falls within the late Pliensbachian period of Early Jurassic time. Rocks above the cherts and siltstones comprise a section of intercalated medium- to fine-grained sandstones and siltstones as well as chaotic formations characterized by different-sized blocks and fragments of Carboniferous–Permian limestones, basalts, Triassic cherts, gabbro, and serpentinized ultramafic rocks enclosed in a schistose silty argillite matrix. In the southwest tip of the district, mélange commonly contains rocks of the Paleozoic ophiolitic association known as the Dahechzhen complex (or Dongfanghong ophiolites, according to Sun et al., 2015), which form a stack of different-sized slices composed of serpentinite, gabbro, and basalt. In some units, limestones with Upper Carboniferous or Lower Permian fauna rest with depositional contact on basalt. The ultramafic and gabbroic part of the ophiolitic sheets is represented by the peridotite-gabbronorite rock association. The mineralogical-geochemical features of the Dahechzhen ophiolite are comparable to those of the Kalinovka complex (Khanchuk, 2006).

The lithological-structural data, the age of cherty- terrigenous rocks, and their close spatial occurrence with the chaotic formations and separated slices of the Paleozoic ophiolitic section suggest that the Nadanhada area is composed predominantly of tectonic-sedimentation packets of the upper part of the Jurassic accretionary prism. The fragments of the Dahechzhen ophiolite correlate with the Sebuchar subterrane of the Samarka terrane (Kalinovka and Sebuchar complexes), and the cherty-terrigenous sequence correlate with the upper structural unit of the Eldovaka subterrane (Amba-Matay complex).

3.3. Khabarovsk terrane

The Khabarovsk terrane crops out along the eastern margin of the north part of the Bureya-Jiamusi-Khanka superterrane, where it extends as a 100–130-km-wide band northeast of the Naolihe River valley (Laolihe fault) in the south to the Vandan River (Kursk fault) in the north (Fig. 3). Most of the Khabarovsk terrane is hidden under the alluvial deposits of the Amur River and its tributaries and, in part, deposits of the Ussuri River. Outcrops are restricted to the Amur River bank scarps (around Khabarovsk City and Voronezhskoe-2 Settlement), the Ussuri River (within the Khekhtsir reserve), on Dva Brata Mountain in the area of the Krasnaya Rechka railway station, and, in part, within the Vandan Ridge. The terrane structure in these districts is represented by repetitions of different-sized tectonic slices and blocks composed of cherts and siliceous-clayey rocks, metasandstones and

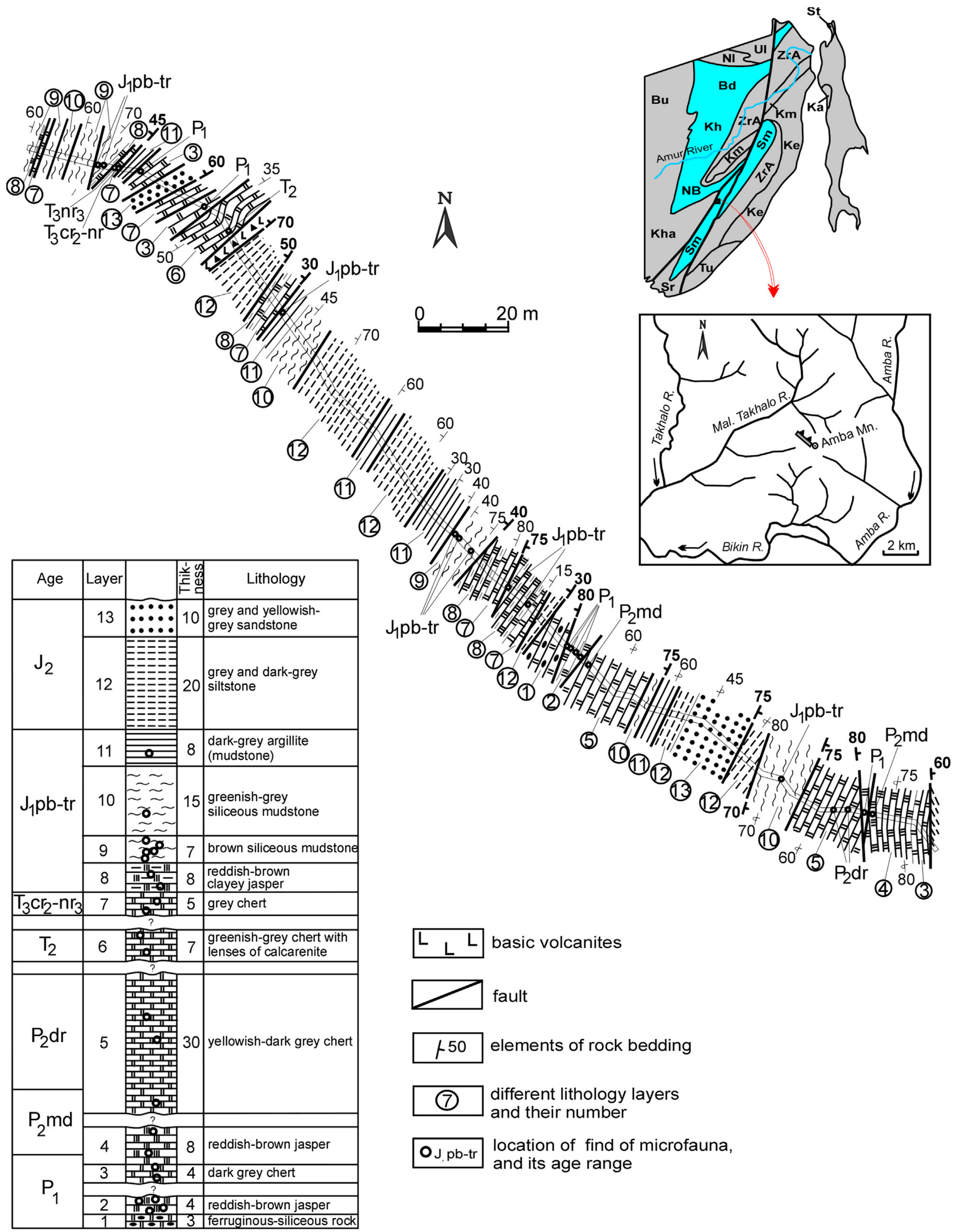

Fig. 9. Structure of chert-terrigenous formations in the Amba Mountain area and reconstructed stratigraphic column (route map).

metashales, sandstones, siltstones, volcanic layers, and chaotic (mélange) formations (Natal'in, 1993; Zyabrev et al., 1999; Zyabrev and Matsuoka, 1999; Ishida et al., 2002; and others). At present, in the terrane composition, two tectono-stratigraphic units are distinguished: Khabarovsk-Voronezh and Ussuri-Khekhtsir complexes (Kemkin et al., 2006).

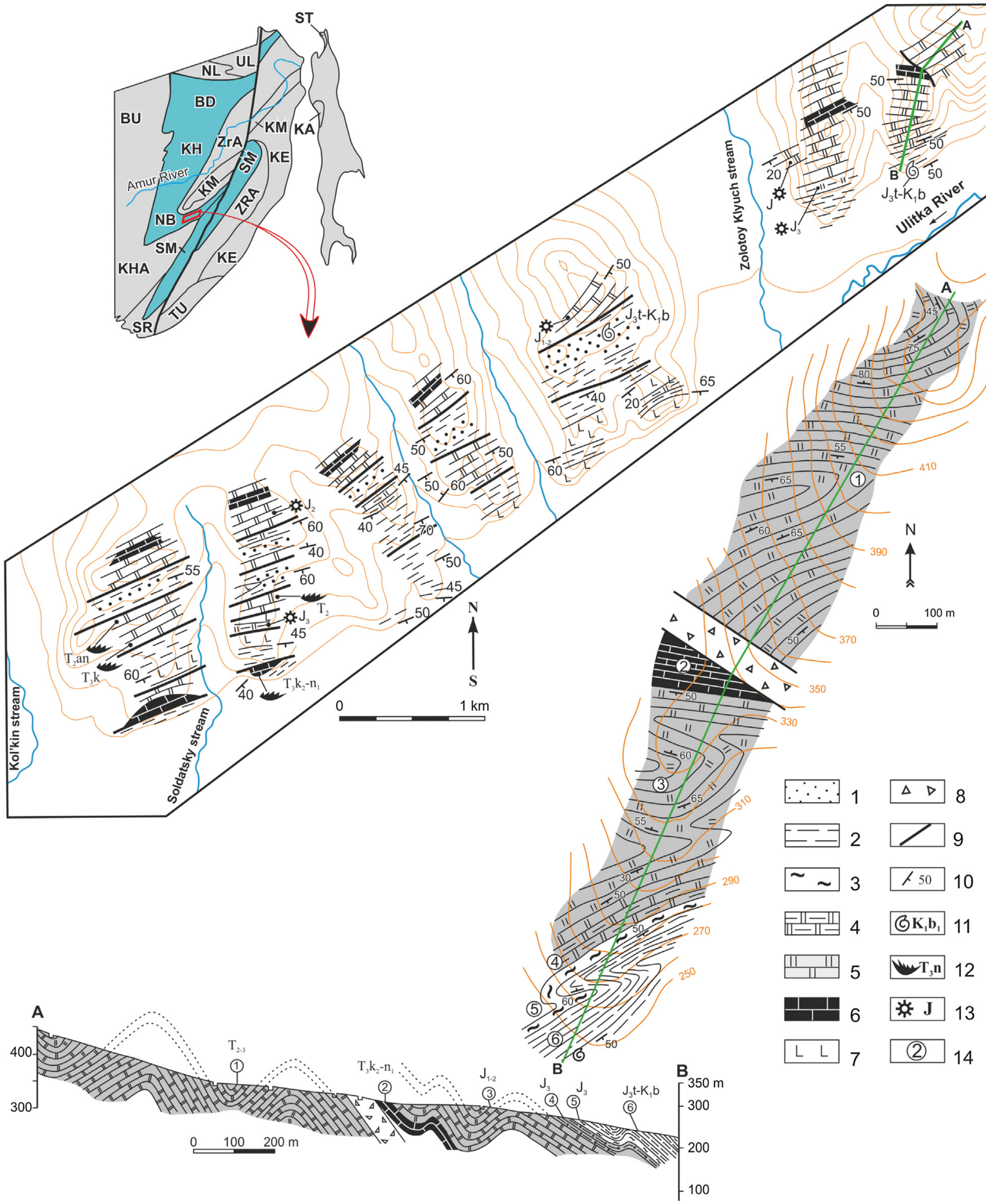

Fig. 10. Structure of the Nadanhada-Bikin terrane in the Ulitka River area (route map).

3.3.1. Khabarovsk-Voronezh complex

The Khabarovsk-Voronezh complex crops out in numerous bank scarps on the Amur River east bank in the vicinity of the Khabarovsk City and Voronezhskoe-2 Settlement. Its reconstructed section is as follows. A basal unit is composed of cherts and jaspers, the ages of which lie within the Olenekian Stage of the Lower Triassic to the Lower Jurassic. The chert beds are overlapped by Aalenian–Bajocian (Kojima et al., 1991; Wakita et al., 1992) siliceous mudstones, which changes upward to upper Bathonian–middle Callovian argillites and silty argillites. These are overlain by Oxfordian–Kimmeridgian (Ishida et al., 2002) siltstones with tuffaceous interlayers and Tithonian (Zyabrev and Matsuoka, 1999) siltstones with carbonate-manganese and clay-carbonate concretions. The section ends with interbedded thin sandstones and siltstones and horizons of mélange.

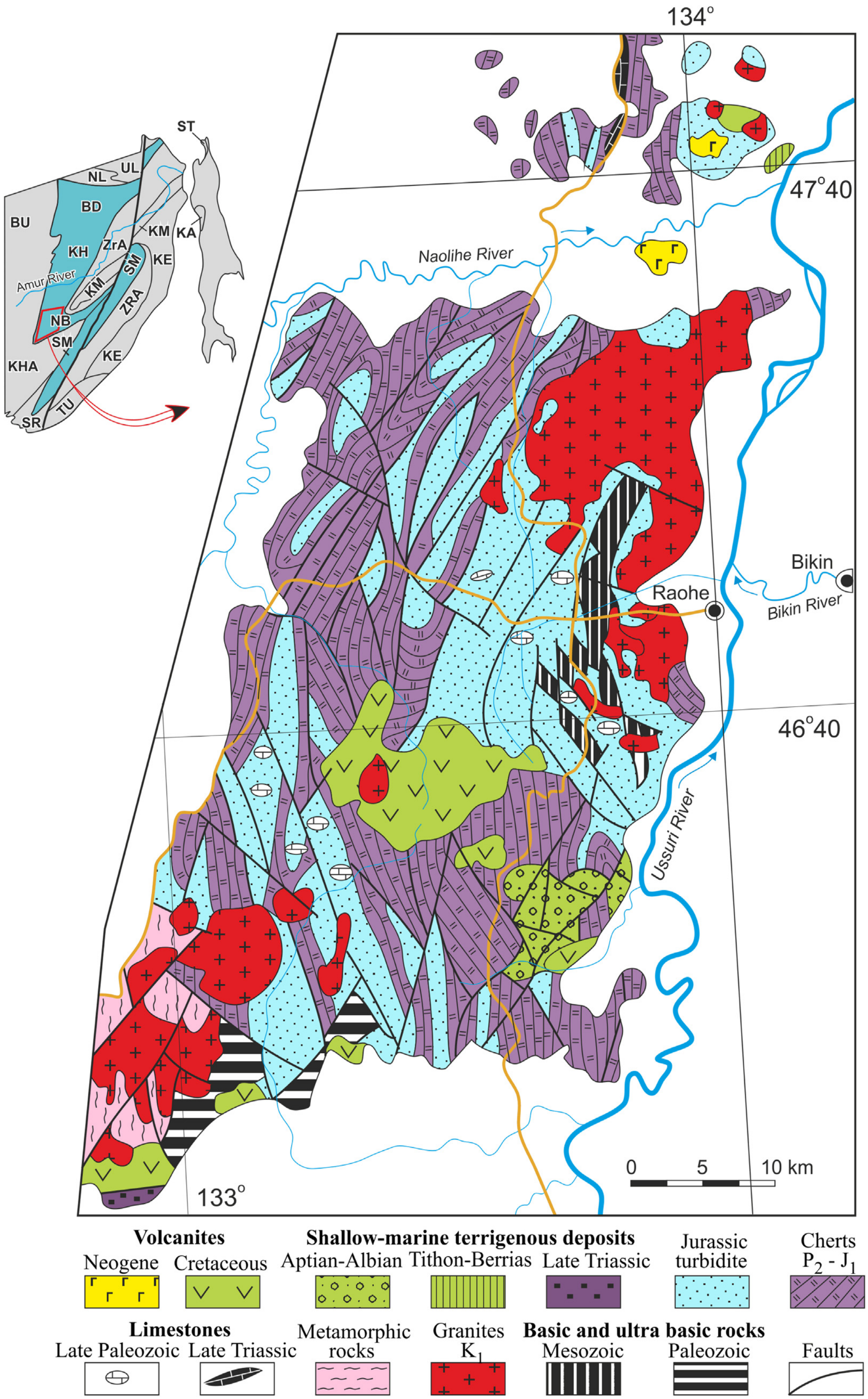

Fig. 11. Geological map of the Nadanhada-Alin area (modified after Shao et al., 1992; Sun et al., 2015; and others).

3.3.2. *Ussuri-Khekhtsir complex*

The Ussuri-Khekhtsir complex is studied on the east (right) bank of the Ussuri River mouth and western spurs of the Bol'shoy Khekhtsir Ridge. The lowest part consists of bedded cherts, the lower age boundary of which has not been defined due to the strong recrystallization of the rocks; the upper boundary corresponds to the Aalenian–early Bajocian (Kemkin et al., 2006). Overlying upper Bajocian clayey chert follows, which is transitional into siliceous mudstones by late Bajocian–early Bathonian time. The highest units are lower Bathonian argillites and dark-gray siltstones, passing into the alternating siltstones and sandstones.

Similarities in lithological and age data indicate that the units of the Khabarovsk terrane are correlative with isolated structural units of the Samarka terrane. The Khabarovsk-Voronezh complex corresponds to the Saratovka complex, and the Ussuri-Khekhtsir corresponds to the Breevka complex. It should be also noted that on the northern spurs of Bol'shoy Khekhtsir Ridge (on Dva Brata Mountain), Triassic bedded cherts crop out (Klets, 1995), which at the Carnian–Norian level contain interlayers of pelitomorphic limestone. A correlative chert-carbonate section was mapped (Wang et al., 1986) on the north bank of the Naolihe River mouth, the southmost part of the Khabarovsk terrane within China. The chert-carbonate part of the chert-clastic sequences of the Jurassic prism is known only from the lower structural units of the Samarka and Nadanhada-Bikin terranes (Katen and Ulitka complexes). These data suggest that in the Khabarovsk terrane composition, a further, minor tectonostratigraphic unit must be distinguished (Krasnorechensk complex).

3.4. Badzhal terrane

The Badzhal terrane is located northward of the Khabarovsky terrane (Fig. 3), and at the present time, it has not been studied in the same detail as other fragments of the Jurassic accretionary prism. It is best known in the eastern part, corresponding to the lower structural level, within which two tectonostratigraphic complexes are distinguished, Silinka and Gorin (Kemkin, 2006).

3.4.1. Silinka complex

The Silinka complex is studied on the north bank of the Silinka River in the area northwest of Komsomolsk-on-Amur City. It is composed of Middle Triassic through Middle Jurassic gray bedded cherts with thin (2–4 cm) and medium beds (4–7 cm). The gray cherts commonly has yellowish or brownish tint, whereas clayey chert is greenish–dark-gray. Above, they are transitional into greenish-gray siliceous mudstones of Kimmeridgian–Tithonian age followed by upper Tithonian black siltstones, and interbedded siltstone and dark-gray sandstone.

3.4.2. Gorin complex

The Gorin complex is also composed of cherts that are gradually replaced upward by clastic rocks (Fig. 12). According to the microfauna data, the age of the cherts is middle Anisian through Early Jurassic (Toarcian inclusive). Higher siliceous mudstones contain Bathonian–early Kimmeridgian radiolarians, and overlying clastic rocks contain middle Kimmeridgian to early Tithonian radiolarians.

In the southwestern part of the terrane, thrust slices of basalt were mapped, along with associated Carboniferous–Permian limestone strata and the Permian cherts. These data suggest that the Badzhal terrane structure is correlative to the Samarka terrane.

4. Structure and composition of the late Jurassic-early Cretaceous prism terranes

In the Sikhote–Alin orogenic belt, a Late Jurassic–Early Cretaceous accretionary prism is represented by the Taukha terrane, which is located in the southern part of Sikhote–Alin Ridge, in the Far East of Russia (Fig. 3). The Taukha terrane is distributed as a strip about 60 km in width that extends NE–SW along the northwestern coast of the Sea of Japan from the mouth of the Kievka River up to the mouth of the Dzhigitovka River. The terrane consists of repeated alternation of steeply dipping tectonic slices composed of the oceanic (fragments of paleoguyots and abyssal plain sediments), marginal-oceanic (sandstone-siltstone beds), and chaotic (subduction mélange) formations (Figs. 13 and 14) that formed as a result of consecutive accretions of Paleo-Pacific formations onto the eastern Paleo-Asian continental margin (e.g., Khanchuk, 2006; Kemkin, 2006; and others). The rocks forming the Taukha terrane are crumpled into asymmetric folds of variable amplitude that are often overturned and trend to the northeast. The axial planes of the folds exhibit northwest vergence and the mirror of folding is sloping dip to the southeast. This style of folding has exposed the lower structural units of the terrane to the northwest and the upper structural units to the southeast.

According to available data (e.g., Kemkin and Kemkina, 2000; Kemkin, 2006; and others), the terrane consists of three successive tectonostratigraphic units that are similar in lithology and structure, but differ in ages of the rocks. Each unit is made up of marine deposits (mainly cherts and lesser amounts of limestones) in the lower part, and these gradually change upwards in the section to terrigenous rocks that originated on an oceanic margin. In the upper part, terrigenous rocks give way to subduction-related mélange formations that are chaotic deposits composed of variably sized and aged blocks and fragments set in a siltstone matrix (Fig. 13). The lithologies and ages of these blocks and fragments indicate they were derived directly from the overlying tectonostratigraphic unit.

4.1. Erdagou complex

The lower unit (Erdagou complex, see 3 on Figs. 15 and 16) contains a sequence of Upper Jurassic to Lower Cretaceous (Lower Berriasian) bedded cherts and clayey cherts that are underlain by Middle Jurassic (Callovian) basalts (Erdagou suite) and overlain by Upper Berriasian–Upper Valanginian siltstone and sandstone deposits (Silinka suite) (Kemkin and Kemkina, 2000; Kemkin, 2006). The bedded cherts together with the basalts are about 150 m thick, whereas the terrigenous rocks have been estimated to be 2500 m thick. However, the real thickness is much less than this, because the turbidite part has been repeated tectonically several times. The cherts give way gradually to the overlying conformable terrigenous rocks through a transitional pack of Berriasian siliceous mudstones and mudstones. Valanginian–Hauterinian mélange formations also conformably overlie the turbidites (Kemkin et al., 1997). Blocks and fragments in this mélange consist of Middle to Upper Triassic limestones, high-Ti alkaline basalts, Triassic and Jurassic cherts, and Middle to Upper Triassic and Lower Cretaceous terrigenous rocks. The ages and lithologies of these blocks (excluding the Triassic terrigenous rocks) indicate that they were derived from the overlying Gorbousha complex. The lumps and blocks of Triassic shallow-marine terrigenous rock contain a macrofauna (including *Monotis*), and they were most likely derived from the continental margin under which the Taukha prism was formed. The mélange formations range from 100 to 200 to 400 m in thickness in different areas.

4.2. Gorbousha complex

The middle unit (Gorbousha complex) consists of Middle to Upper Triassic limestones (Tetyukha suite) with high-Ti alkaline basalts at the base (400–500 m thick) that are interpreted as fragments of paleoguyots (Khanchuk, 2006), and four repeating chert-terrigenous sequences (Gorbousha suite, see 2 on Fig. 15 and Fig. 17). Lower Triassic to Upper Jurassic bedded cherts and clayey cherts (about 100 m thick) give way gradually to upper Tithonian– Berriasian siltstones and sandstones, and then to a Berriasian–Valanginian mélange (Kemkin and Kemkina, 1999; Kemkin et al., 1999). Blocks and fragments in this mélange con-

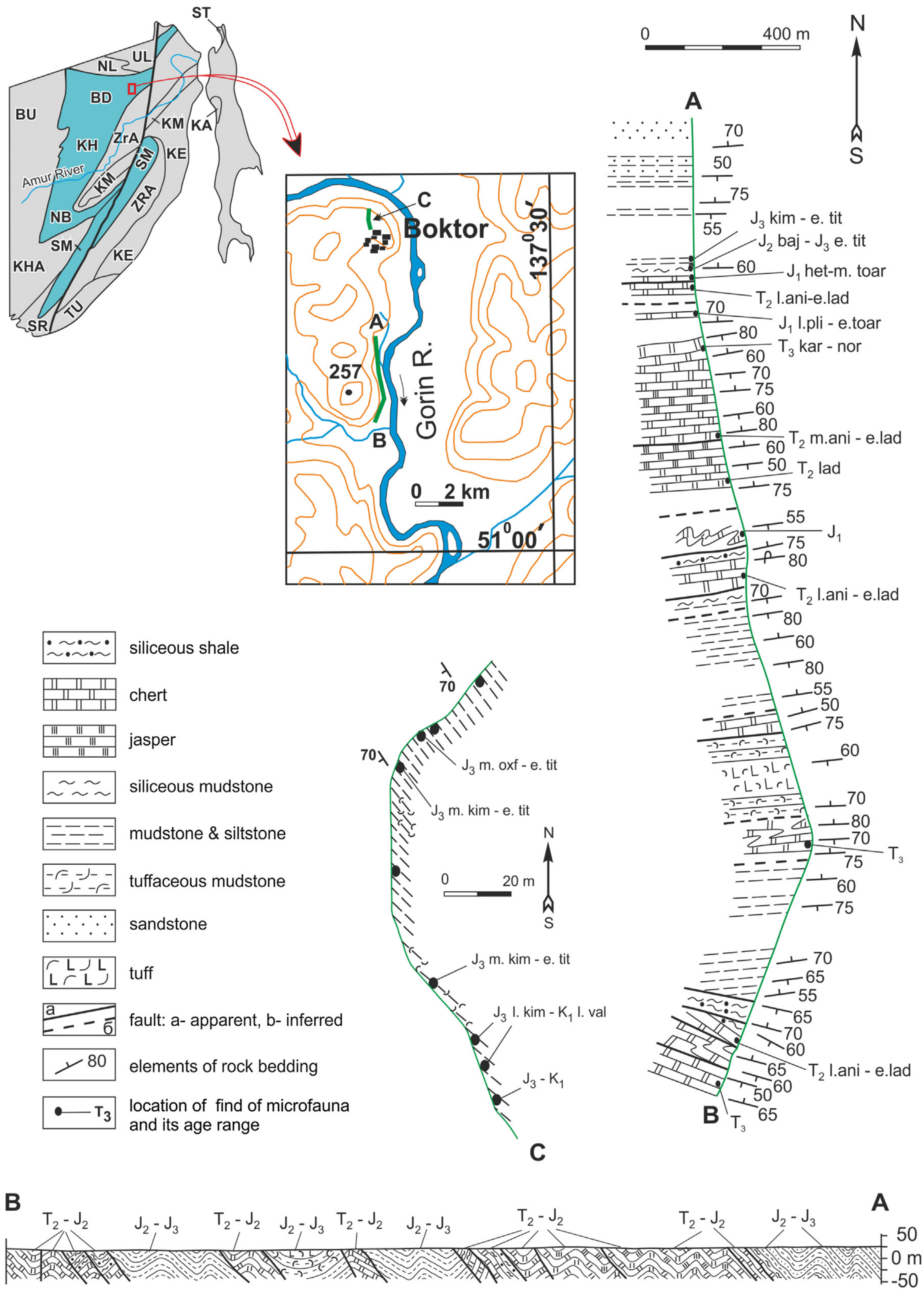

Fig. 12. Structure of the Badzhal terrane in the Gorin River area (route map).

sist of Devonian, Carboniferous, and Lower Permian limestones and basalts, Carboniferous, Permian, Triassic, and Middle Jurassic cherts, and Upper Jurassic terrigenous rocks (sandstones and siltstones). In different slices the terrigenous rocks vary in thickness from 350 to 700 m. The thickness of the mélange formation is equivalent to the Erdagou complex.

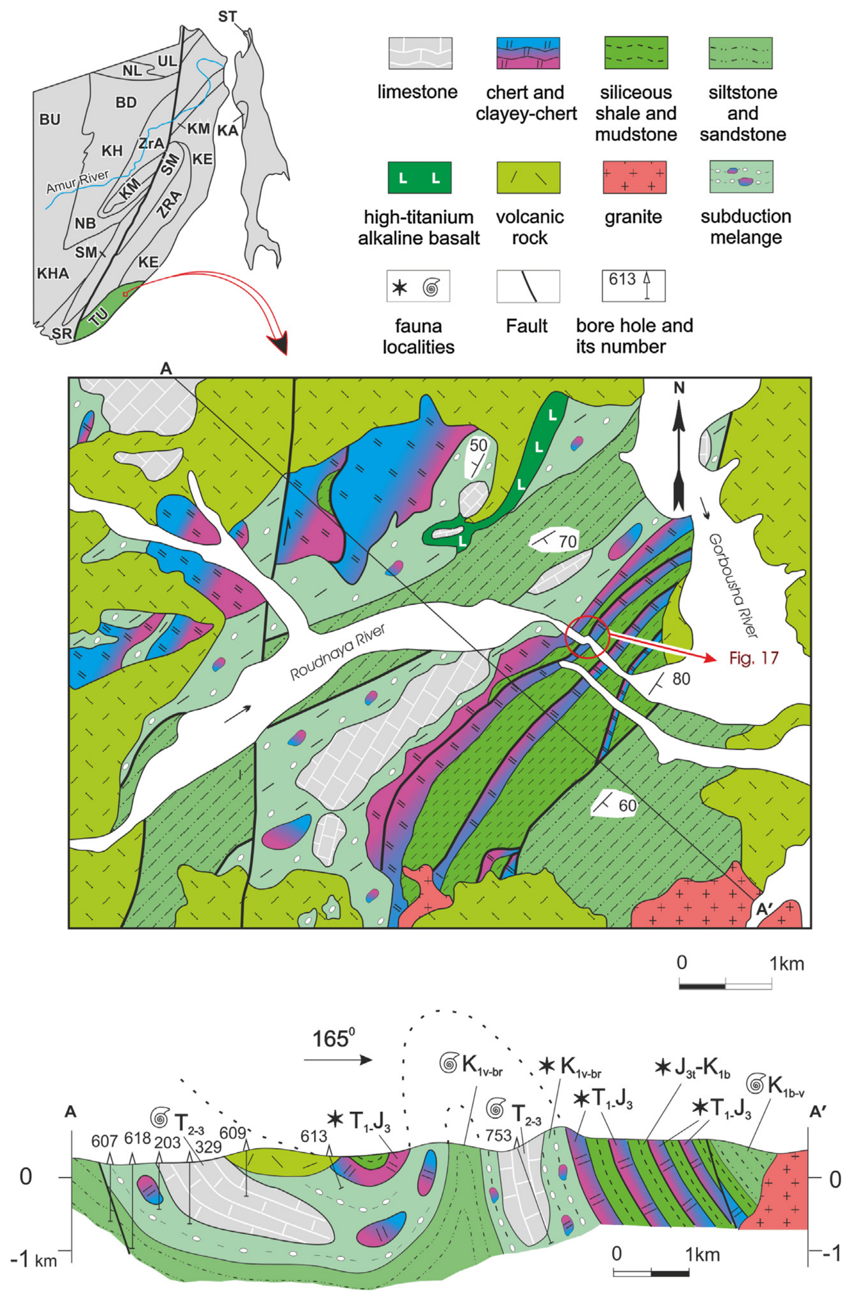

Fig. 13. Structure of the Taukha terrane in the Dal'negorsk Town area (after Khanchuk, 2006).

4.3. Skalistorechenka complex

The upper unit (Skalistorechenka complex) is composed of Upper Devonian to Lower Permian limestones (Skalistorechenka suite), associated with high-Ti alkaline basalts (about 400 m thick, and which are also interpreted as fragments of paleoguyots; Khanchuk, 2006), together with Carboniferous to Middle Jurassic cherts that are overlapped by Upper Jurassic siltstone and sandstone deposits (Pantovyi Creek suite) (Kemkin and Kemkina, 2000; Kemkin, 2006). The thicknesses of the bedded cherts and clastic deposits are unknown due to the fragmentary nature of the outcrops.

5. Structure and composition of the early Cretaceous prism terranes

The Early Cretaceous accretionary prism in the Sikhote–Alin structure is represented by the Kiselevka–Manoma terrane (after Natal'in, 1993) or the Nizhneamursk terrane (according to Khanchuk, 1994). The terrane is

found on both banks of the lower reaches of the Amur River, and it extends as a strip 5–20 km wide that stretches in a northeast direction from the mouth of the Ussuri River to the coast of Sakhalin Bay (Fig. 3). Cenozoic and Late Cretaceous volcanic rocks overlie the Kiselevka–Manoma terrane, and the rocks underneath crop out as isolated erosional "windows". There are three such blocks: the northeastern or Kiselevka block (located on the

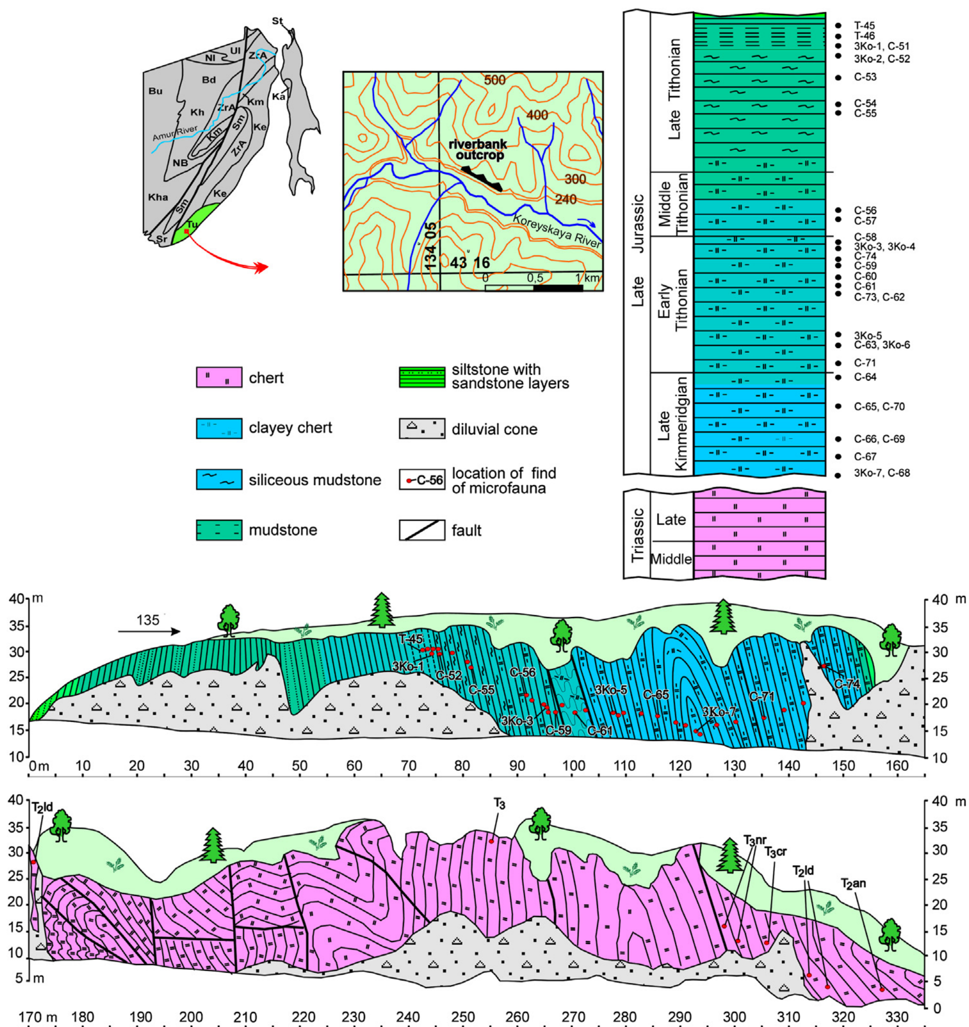

Fig. 14. Structure of the Taukha terrane in the Koreyskaya River area (riverbank's outcrop).

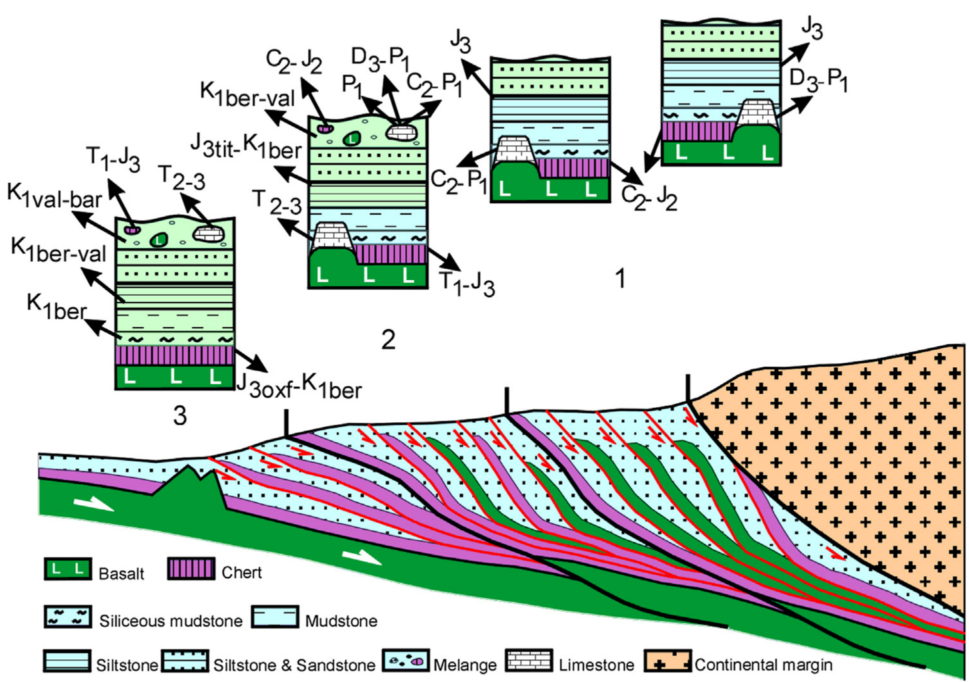

Fig. 15. Reconstructed structure of the Sikhote-Alin Late Jurassic – Early Cretaceous prism (before orogenic deformations).

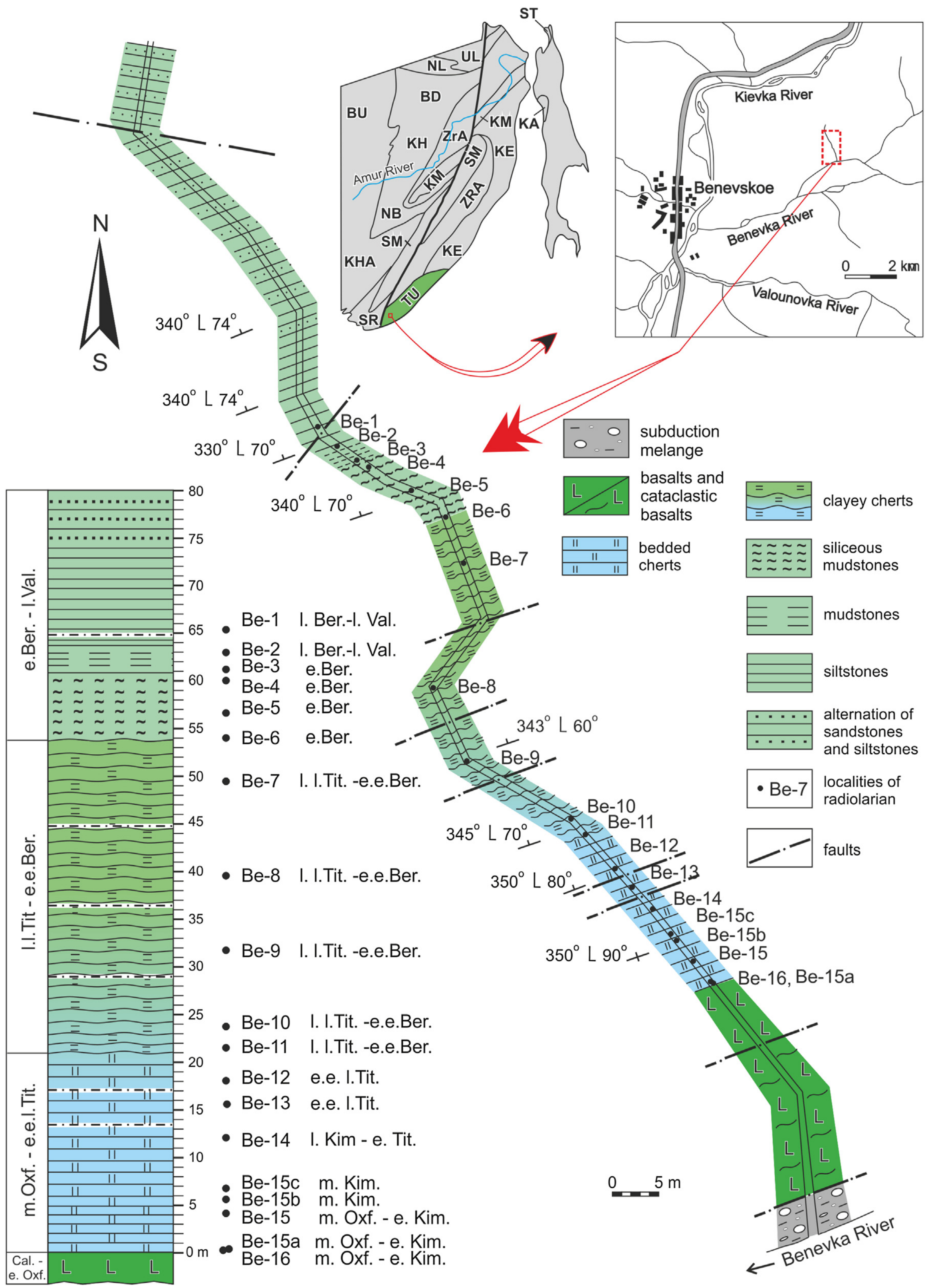

Fig. 16. Structure of the Taukha terrane in the Benevka River area (route map).

left (north) bank of the Amur River from Kiselevka village to Udyl Lake), the central or Manoma block (on the right (south) bank of the Amur River at the downstream basin of the Manoma and Anuy rivers), and the southwestern or Vyazma block (on the right (east) bank of the mouth of the Ussuri River). The Kiselevka–Manoma terrane represents a package of tectonic slices that are composed mainly of Jurassic to Early Cretaceous bedded cherts that alternate with high-Ti alkaline basalts and some associated Jurassic limestones. In individual tectonic slices, gradual transitions can be observed from cherts to siliceous mudstones, and then to siltstones

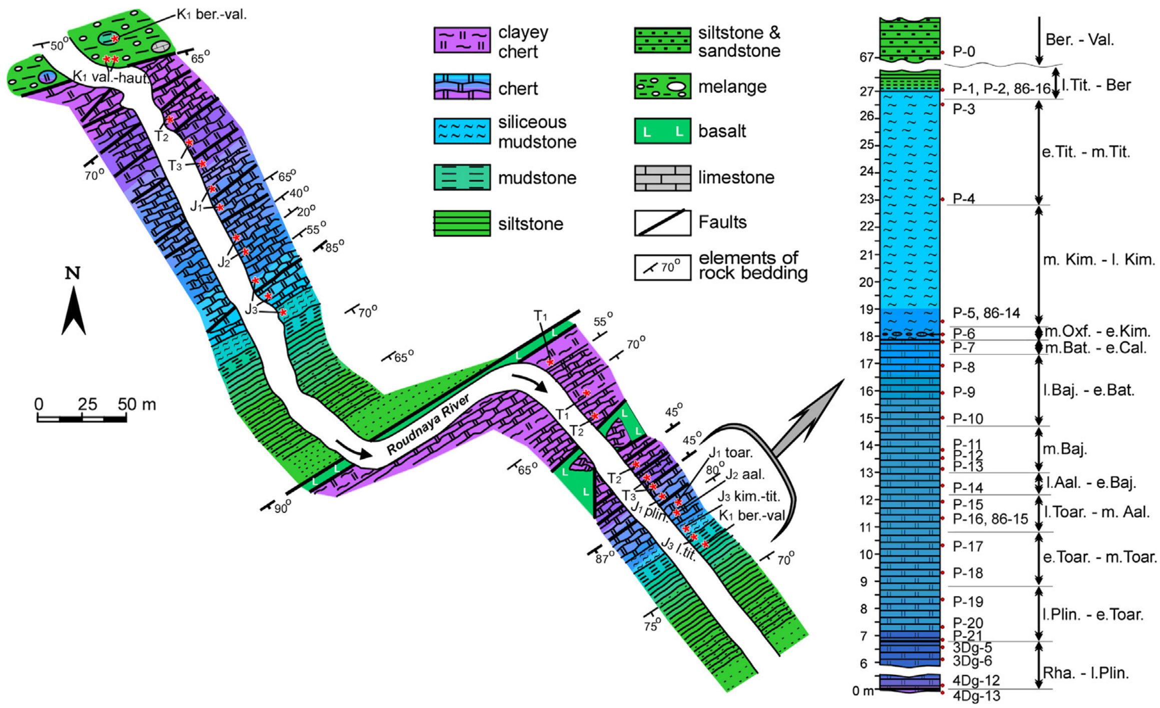

Fig. 17. Structure of the Gorbousha complex in the Dal'negorsk Town (riverbank's outcrops). See location on Fig. 12.

and turbidites (Markevich et al., 1997; Filippov, 2001; Filippov and Kemkin, 2009; Zyabrev and Anoikin, 2013). The ages of the cherts in such slices range from Early Jurassic to middle Barremian (e.g., near Kiselevka village and in the Manoma River basin) or from Jurassic to Valanginian (at Udyl Lake, and on the right bank of the mouth of the Ussuri River), whereas the siliceous mudstones are Barremian–Aptian or Hauterivian–Barremian in age, respectively. Clastic rocks (siltstones and the matrix of mélanges) in the respective areas are either Albian or Barremian–Aptian in age. These data allow us to recognize at least two tectonostratigraphic units within the Kiselevka–Manoma terrane, reflecting the evolutionary development of this Early Cretaceous accretionary prism.

It should be noted that terrigenous (clastic) rocks of the Kiselevka–Manoma terrane (i.e., siltstones, sandstones, and mélange) in all three blocks (Kiselevka, Manoma, as well as Vyazma) are represented by greywackes that lack any arkosic component (Markevich et al., 1997; Filippov, 2001; Filippov and Kemkin, 2009). This indicates that the paleo-oceanic formations of the Kiselevka–Manoma terrane were not subducted under the Paleo-Asian continent, but under an island arc located to the east of the continent, with the intervening ocean acting as a barrier to arkosic detritus. The products of volcanic activity in this arc are found among the upper horizons of chert and siliceous mudstone in the form of interbeds of tuff and other layers (Filippov, 2001; Filippov and Kemkin, 2009). This arc is called the Kema–Rebun–Kabato island arc, and the frontal and axial parts are now located on Hokkaido island (Rebun–Kabato belt), Sakhalin island (Schmidt terrane), and Moneron island. The back-arc portion (Kema terrane) was accreted onto the Sikhote–Alin structure and Sakhalin (the Kamyshovy terrane) (Ichikawa et al., 1990; Khanchuk, 2006; and others).

It should also be noted that fragments of the axial part of this island arc are sporadically found as tectonic slices that alternate with slices of chert-terrigenous rocks of the Kiselevka–Manoma terrane at the Udyl Lake (Nechaev et al., 1996; Markevich et al., 1997). These fragments consist of sand-sized, crystal, and vitric basic tuff that is interbedded with volcaniclastic turbidites, tuffaceous sandstones and mudstones, basalts, and rare tuffaceous siliceous shales.

6. Discussion

The above descriptions of the terranes of the accretionary prisms of the Sikhote-Alin Orogenic Belt reveal that their structure is represented by multiple tectonic packets of thrust-like slices consisting of complicatedly-deformed marine (pelagic and hemipelagic deposits, also oceanic plateau and paleoguyot fragments), marginal-oceanic turbidites and chaotic (subduction mélange) formations (Table 1). This complex structure makes it difficult to decipher the primary stratigraphic succession of deposits composing this region and thus the overall geology.

However, detailed lithological-biostratigraphic and structural investigations have allowed us to reveal the primary stratigraphic succession of the rocks composing the tectonic slices. Firstly, there are pelagic-hemipelagic- terrigenous deposits; this succession, as mentioned above, is called the Oceanic Plate Stratigraphy Sequence. Data on the rock ages in the different tectonic slices of the Sikhote-Alin accretionary prisms show that these prisms contain fragments of several different-aged initial sequences of the Oceanic Plate Stratigraphy Sequences. For example, in the Samarka terrane of the Jurassic accretionary prism, five such different-aged initial Oceanic Plate Stratigraphy Sequences were established – the Sebuchar, Amba-Matay, Saratovka, Breevka, and Katen tectono-stratigraphic complexes, and in the Taukha terrane three such initial sequences were recognized – the Skalistorechenka, Gorbousha, and Erdagou tectono-stratigraphic complexes.

Also revealed is that the age of the rocks composing the tectono-stratigraphic complexes of the Sikhote-Alin accretionary prisms progressively rejuvenates from the upper structural level of the prisms to the lower one. For example, in the tectono-stratigraphic complexes of the Eldovaka subterrane of the Samarka terrane, the age of the transitional layers (siliceous mudstones, which record the approach of ocean floor to a continental margin) was determined as late Pliensbachian–early Toarcian,

Table 1
Main characteristics of accretionary complexes of the Sikhote-Alin Orogenic Belt and adjacent areas.

Accretionary complex	Geographic location	Marginal-oceanic formations and their age	Oceanic formations and their age
Fragments of the Jurassic prism: Samarka, Nadanhada-Bikin, Khabarovsk, Badzhal terranes Tamba, Mino, Ashio, Rioke terranes Northern Chichibu, Sanbagawa terranes	Sikhote-Alin Ridge, Russia Far East Inner Zone of the Japanese Islands Outer Zone of the Japanese Islands	Early to Late Jurassic mudstones, siltstones and sandstones	Fragments of the Middle Paleozoic and Middle-Late Jurassic ophiolites of an oceanic plateau (ultramafic, gabbro and basalt rocks), Early-Carboniferous to Early Permian and Late Triassic limestones, Permian and Early Triassic to Middle Jurassic cherts and siliceous mudstones
Fragments of the Late Jurassic – Early Cretaceous prism: Taukha terrane Southern Chichibu and Ryukyu terranes Northern Kitakami and Oshima terranes	Sikhote-Alin Ridge, Russia Far East Outer Zone of the Southwest Japan Outer Zone of the Northeast Japan	Tithonian to Early Hauterivian mudstones, siltstones and sandstones	Fragments of the Middle Paleozoic to Early Mesozoic paleoguyots (Late Devonian to Late Triassic limestones associated with high-Ti alkaline basalts), Carboniferous to Early Berriasian cherts, Middle Jurassic MORB-type basalt, Triassic shallow-marine terrigenous rock derived from the continental margin
Fragments of the Early Cretaceous prism: Kiselevka–Manoma terrane Anivo-Gomon and low part of the Western Sakhalin terranes Sorachi Group of the Sorachi-Yezo terrane	Sikhote-Alin Ridge, Russia Far East Sakhalin Island, Russia Far East Hokkaido Island, Japan	Barremian to Middle Albian mudstones, siltstones and sandstones	Fragments of the Early Jurassic to Early Cretaceous seamounts (high-Ti alkaline basalts, Jurassic limestones), Early Jurassic to Aptian cherts and siliceous mudstones Fragments of the Late Jurassic-Early Cretaceous ophiolites of an oceanic plateau (ultramafic, gabbro and basalt rocks), Late Triassic, Early Jurassic to Aptian cherts and siliceous mudstones, Late Triassic and Jurassic limestones

Aalenian–early Bajocian, Bajocian, and Bathonian–Callovian, and for the tectono-stratigraphic complexes of the Taukha terrane, the age of such beds corresponds to Oxfordian–Kimmeridgian, Middle Kimmeridgian–Middle Tithonian, and Early Berriasian. This indicates the successive character of the accretion of different-aged sites of the paleo-oceanic plate to the continental margin. Thus, by using detailed biostratigraphic and structural investigations of the Sikhote-Alin accretionary prisms it has been established that the oldest rocks compose the upper structural level of the prisms, and the youngest ones compose the lowest level. As a whole, the tectonic slices of older rocks are thrust upon slices containing younger rocks. However, within a tectonic slice, the stratigraphic succession of the layers is normal (from more ancient to younger). Such structure in the Sikhote-Alin accretionary prisms is in accordance with modern accretionary prisms being formed at the base of the inner slopes of the trenches of modern convergent margins. In the oceanic plate subduction process, ocean floor crust most remote from the spreading center, and therefore the most ancient, is accreted first. Then underneath these, the fragments of younger areas of oceanic plate are successively accreted, and as a result, a packet of the tectono-stratigraphic slices is formed (Fig. 2*B*).

The study of the ancient accretionary prism fragments of the Sikhote-Alin Orogenic Belt can be used for the reconstruction of a stepwise history of accretion of the differently-aged fragments of oceanic crust, as well as the geological history and main geological events on the eastern margin of the paleo-Asian continent during the Mesozoic. However, more or less objective reconstructions can be made using the geological data not only of the Sikhote-Alin Orogenic Belt, but from the Japanese islands and also the Korean peninsula. Consequently, for more reliable geological and tectonic comparison and correlation between these regions, we need to reconstruct the pre-Miocene configuration (before the opening of the Sea of Japan) of the paleo-Asian continent. This reconstruction (Fig. 18) has been made by taking into account the paleomagnetic data (Otofuji, 1996; and others) and geological data summarized in several major publications (e.g., Ichikawa et al., 1990; Kan et al., 1993; Oh, 2006; Lee, 2008; Moreno et al., 2016; and others).

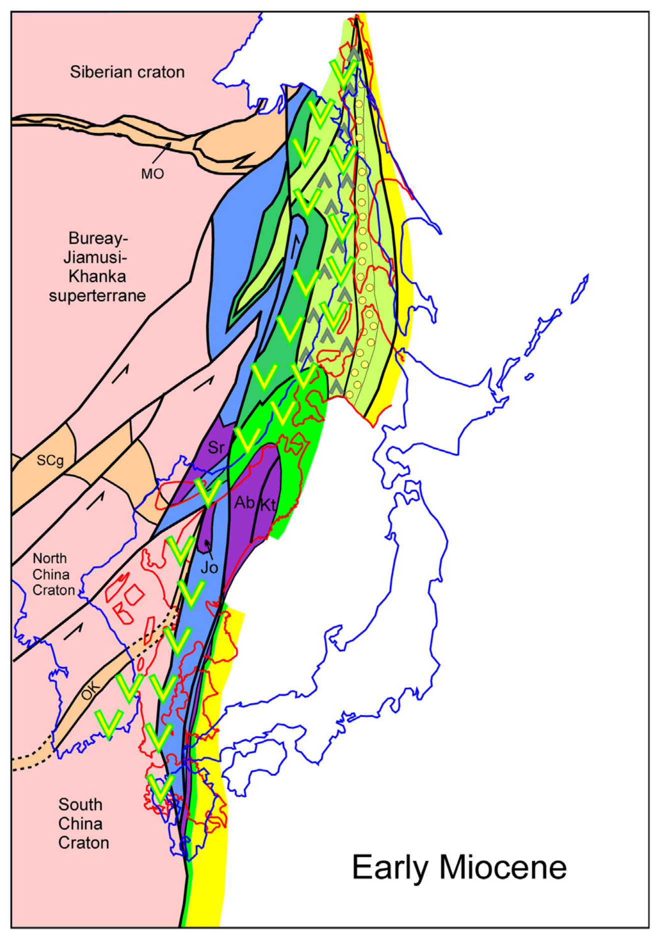

Fig. 18. Paleogeodynamic reconstruction on the Early Miocene time (before opening the Sea of Japan). See legend of Fig. 1.

We would like to emphasize that the tectonic correlation between Korea and Japan has been debated for several decades. One of the principal questions is whether the collision zone between the North China and South China blocks (the Dabie-Sulu suture) extends into the Korean Peninsula and Japan? Secondly, which tectonic units represent this collision zone in both regions? According to Hiroi (1981), Isozaki and Maruyama (1991), Tsujimori (2002), Ishiwatari and Tsujimori (2003) and some other researchers, these tectonic units can be the Unazuki Schist (medium-pressure/temperature- type metamorphic rocks in the eastern and south-eastern parts of the Hida Mountain, the Inner Zone of the Southwestern Japan) and the Ogcheon Belt (also medium-pressure/temperature-type metamorphic rocks, South Korea). Alternatively, the Imjingang-Gyeonggi Metamorphic Zone (high-pressure/low- temperature-type metamorphic rocks in the central Korea) and the Renge-Suo Belt (same grade metamorphic rocks of the Inner Zone of the Southwestern Japan) have been proposed to be the eastern extension of the Dabie-Sulu Orogenic Belt (e.g., Chang, 1996; Ree et al., 1996; Oh et al., 2004; Ernst et al., 2007; Sun et al., 2015; and others). However, the tectonic position of the Unazuki Schist is also ambiguous. Some Japanese geologists propose that the Unazuki Schist is a part of the Hida Belt (e.g., Ichikawa et al., 1990; Ehiro et al., 2016) whereas others include it in the Hida-Gaien Belt (e.g., Tsukada et al., 2004; Kojima et al., 2004). In addition, some researchers correlate the Renge Belt with the Hida-Gaien Belt (e.g., Tsujimori, 2002; Matsumoto et al., 2011; Moreno et al., 2016).

Tectonic correlations of the Hida Belt/Terrane and the Oki-Dogo Belt/Terrane are also controversial. According to Isozaki and co-authors (e.g., Isozaki and Maruyama, 1991; Isozaki, 1997) these terranes are fragments of the North China and South China blocks, respectively. The main argument is the Archean and Paleoproterozoic age of the Hida gneisses with no documented Neoproterozoic ages. In contrast, other authors (e.g., Moreno et al., 2016) consider both belts/terranes to be a single tectonic structure. In other words, at the present time the opinions substantially differ about which tectonic units in Korea and Japan are correlated with the North China block, which belong to the South China block, and which represent fragments of the collision zone between them. To improve our knowledge on regional tectonic framework, further detailed studies of geology, petrology, geochemistry and geochronology of metamorphic and associated granitic rocks are required. In our reconstructions of the Mesozoic geodynamic evolution of the eastern margin of the paleo-Asian continent, we adhere to the model of tectonic correlation between the Korea and Japan by Isozaki and Maruyama (1991).

The absence of Triassic accretionary prism fragments within the Sikhote-Alin Orogenic Belt and Japanese islands indicates that during the Early Mesozoic the paleo-Asian continent eastern edge represented a passive (or transform) continental margin (Fig. 19*A*).

It is worth mentioning that it has been proposed, based on lithological and paleontological data, that the Tamba terrane (a fragment of the Jurassic accretionary prism according to most Japanese interpretations) was formed continuously from the early Late Triassic (Sugamori, 2006) as supported by new findings of Permian and Triassic radiolarians in the Kioto Nishiyama area. Late Permian and Middle Triassic radiolarians were extracted from the Takatsuki and Shimamoto Formations, respectively, and Late Triassic radiolarians were extracted from the Tamba terrane. The two first units belong to the Ultra-Tamba terrane and tectonically overlay the Tamba terrane. Tectonic slices of the Permian-Triassic-Jurassic terrigenous (clastic) rocks derived from Sergeevka terrane have been also observed in the Jurassic accretionary prism of the Sikhote-Alin (the Samarka terrane). They are thrusted over the rocks of the Jurassic prism. It is likely that the early Late Triassic radiolarians in the Kioto Nishiyama area were found in similar tectonic slices

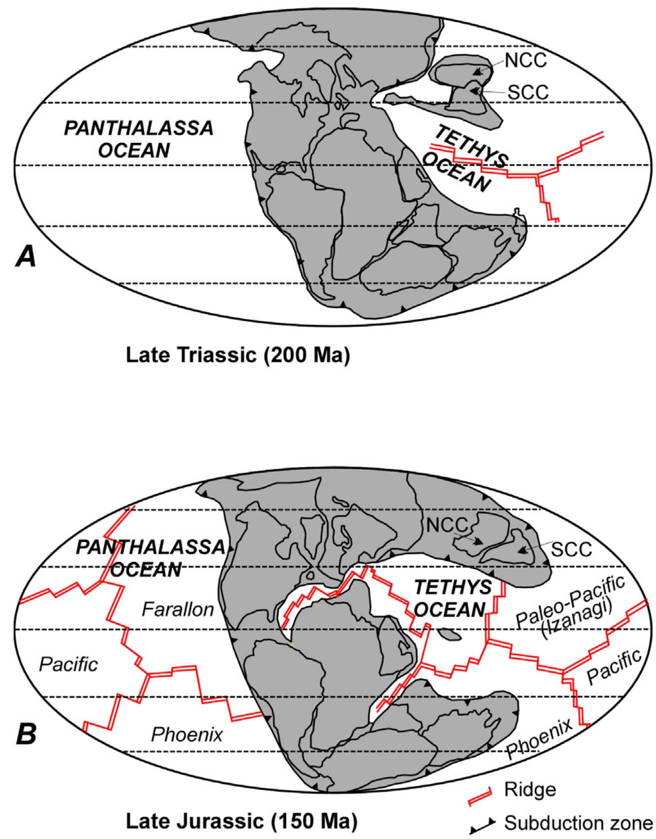

Fig. 19. Paleogeodynamic situation in the Early-Middle Mesozoic (modified after Isozaki, 1997; Taira, 2001; and Metcalfe, 2011).

or blocks derived from the Ultra-Tamba or Mayzuru terranes, the lithological composition of which is similar to clastic rocks of the Tamba terrane. We further note that a generally accepted opinion of the Japanese geologists is that the Mino-Tamba-Ashio terranes are Jurassic in age.

At the beginning of the Early Jurassic, the geodynamic mode of the passive continental margin along the east edge of the paleo-Asian continent was replaced with the geodynamic mode of an active continental margin of Andean-type. Starting from this time along the eastern edge of the paleo-Asian continent the tectono-sedimentary complexes of the Jurassic accretionary prism began to be formed (Fig. 19*B*). The fragments of this prism in the modern structure of East and Southeast Asia are represented in the Udsky Gulf south coast in the north, through Sikhote-Alin (Russian South East), Nadanhada-Alin (Northeast China), the Japanese islands, to Palawan island (Philippines) in the south (Zamoras and Matsuoka, 2001). In particular, in the Sikhote-Alin Orogenic Belt, they are represented by the Samarka, Nadanhada-Bikin, Khabarovsk, and Badzhal terranes, and within the Japanese islands (e.g., Ichikawa et al., 1990; Moreno et al., 2016; and others), fragments of the Jurassic prism are known as the Tamba, Mino, Ashio, and Northern Chichibu, and their metamorphosed analogs the Rioke and the Jurassic metamorphosed unit of the Sanbagawa terrane or "Jurassic Sanbagawa Belt" according to Knittel et al., 2014.

It should be noted that the Sanbagawa terrane was previously considered to be a Late Jurassic-Earliest Cretaceous metamorphosed accretionary prism based on the fossil ages of the Oceanic Plate Stratigraphy Sequence fragments constituting this terrane (e.g., Ichikawa et al., 1990; Okamoto et al., 2000). Recent studies based on detrital zircon U-Pb chronology have shown that the Sanbagawa terrane consists not only of metamorphosed Jurassic accretionary prism formations but also of the Lower and Upper

Cretaceous metamorphosed deposits (Otoh et al., 2010; Aoki et al., 2011; Tsutsumi et al., 2012; Knittel et al., 2014).

The terranes of the Jurassic accretionary prism in both the Sikhote-Alin region and the Japanese islands demonstrate the strong similarities of the structures, their lithological compositions, and the ages of certain rock groups. These similarities indicate that during the Jurassic, a single accretionary prism was formed along the paleo-Asia eastern margin (Mizutani and Kojima, 1992; Kojima et al., 2000; Wu et al., 2007; Wakita, 2013; Zhou et al., 2014; and others). This prism marks the convergence zone of the paleo-Asian and paleo-Pacific lithospheric plates in the Jurassic.

Based on data on the composition of the various structural levels of the terranes of the Sikhote-Alin Jurassic prism it is possible to conclude that during the Early Jurassic arrival and subduction of an oceanic plateau took place (Fig. 20*a*). However, being a positive morphostructure, this oceanic plateau could not be completely subducted. During partial underthrusting of the subducting slab, the plateau was dismembered by faults and accreted to the continental margin, analogous to the present accretion of the Dai-ichi Kashima guyot in the Japanese Trench or the Zenisu seamounts in the Nankai Trench (Fujioka et al., 1988). The fragments of this plateau in the Sikhote-Alin are represented by the Kalinovka ophiolite. In the Nadanhada-Alin region, they are represented by the Dahechzhen (or Dongfanghong, according to Sun et al., 2015) ophiolite, and in the Japanese islands, they are represented by the tectonic slabs and blocks of basic volcanites (basalts) associated with Carboniferous-Permian cherts and limestones composing the upper structural level of the Tamba-Mino accretionary complex (Jones et al., 1993; Sano et al., 2001;Koizumi and Ishiwatari, 2006; Ichiyama et al., 2008; and others) and portions of the mafic-ultramafic rocks of the Yakuno ophiolite (e.g., Isozaki, 1997), the petrochemical characteristics of which are identical to the Kalinovka ophiolite (Ishiwatari et al., 2003; Ishiwatari and Tsujimori, 2003; and others). Notably, A. Ishiwatari (e.g., Ishiwatari et al., 2003; Ishiwatari and Tsujimori, 2003) has proposed that the Yakuno ophiolites represent an unusually thick fragment of oceanic crust. According to this interpretation, petrochemical signatures of different parts of the Yakuno ophiolites indicate different geodynamic conditions of their formation (for example, mid-oceanic ridge, arc, back-arc, marginal basin, and/or hotspot). The same authors also correlate the Yakuno ophiolites with the Sikhote-Alin Kalinovka ophiolites based on their petrochemical similarity. Our studies (Khanchuk and Vysotskii, 2016) indicate that the Kalinovka ophiolites are the tectonically disjoined/dismembered (during subduction) fragments of the Paleozoic oceanic plateau. This allows us to interpret a part of the Yakuno ophiolites as a fragment of an oceanic plateau.

The Middle and Late Jurassic time interval was characterized by the subduction, in morphological aspect, of the poorly disjointed part of the paleo-oceanic plate. The accreted paleo-oceanic fragments of this time interval are recorded by chert-clastic sequences that differ from each other only by the different ages of the transition from siliceous beds to clastic layers. At the end of the Jurassic, in the southern part of the Jurassic suduction zone, accretion of one more oceanic plateau took place (Fig. 20*b*) the fragments of which (Mikabu ophiolites) are described as a part of the "Jurassic Sanbagawa Belt" (Kimura et al., 1994; Kimura, 1997).

In the latest Jurassic (probably in the Tithonian) the geodynamic mode of subduction along most part of the paleo-Asian continent eastern margin was changed to the geodynamic mode of transform sliding of the paleo-oceanic plate towards the north direction. The evidence for this is as the follows: 1) termination of the Jurassic prism formation; 2) drastic change in the conditions of sedimentation near the continent–ocean boundary and beginning of the formation of a thick section (more than 11000 m) of turbidites of the Zhouravlevka–Amur terrane with extremely high rates of sedimentation (about 500 mm per 1000 years); 3) intrusion into the Jurassic prism sediments (Fig. 21) of Late Jurassic–Early Cretaceous alkaline ultramafic and mafic plutons (Koksharovsky, Ariadninsky, Shoumninsky and others massifs) and effusion of Late Jurassic alkaline picrites and meimechites (Poga, Malyanovka, Koultoukha and others suites) which are related to the mantle injection through a slab window or slab break-off (Khanchuk, 2006).

Replacement of the geodynamic mode in the latest Jurassic was caused, most likely, by a change of direction of the paleo-Pacific plate motion from northwest to the north (Engebretson et al., 1985). Thus, since the latest Jurassic the paleo-Asian continent eastern edge represented a transform margin. On the contrary, along the southern edge of the paleo-Asian continent, due to sub-lateral orientation of the continent-ocean boundary, a new subduction zone has been arising (Fig. 20*c*). During the Tithonian-Early Hauterivian along this subduction zone the tectono-sedimentary complexes of the Late Jurassic-Early Cretaceous accretionary prism were formed (Fig. 20*d*). In the modern structure of the Asia Pacific margin this prism is represented by the Taukha terrane (Sikhote-Alin Orogenic Belt, Russia Far East), Southern Chichibu and Ryukyu terranes (Outer Zone of Southwest Japan), and Northern Kitakami and Oshima terranes (Northeast Japan). The data on composition and age of rocks in the tectonic slices of the Taukha terrane show that fragments of Late Devonian to Late Triassic guyots and their associated sedimentary cover were consistently accreted onto the eastern margin of the paleo-Asian continent during the first half of the Early Cretaceous. We suggest that the time of approach to a convergence zone and the beginning of the subduction of differently-aged sites of the paleo-oceanic plate and, correspondingly, the subsequent accretion of each marine structural slice is correlated with the age of the terrigenous rocks overlapping the marine formations. Consequently, in the Late Tithonian-Early Berriasian, fragments of the Paleozoic part of the oceanic plate, i.e. fragments of Devonian to Permian guyots and sites of the abyssal plain surrounding them (Skalistorechenka complex), were accreted. In the Berriasian-Valanginian the Triassic to Middle Jurassic part of the oceanic plate, which morphologically also represented an abyssal plain with several Middle to Upper Triassic guyots (Gorbousha Formation), was accreted. Correspondingly, accretion of the Late Jurassic to Berriasian part of the oceanic plate that is represented in the Taukha terrane by the fragments of a mid-oceanic spreading ridge with overlapping Middle Oxfordian to Middle Berriasian pelagic deposits (Erdagou Formation), which began in the earliest Hauterivian.

It should be noted that the composition of accreted marine formations composing the Jurassic and Late Jurassic-Early Cretaceous prism differ significantly. In particular, the Paleozoic oceanic fragments of the Jurassic prism are represented by tectonic slices of an oceanic plateau, whereas in the Late Jurassic-Early Cretaceous prism they consist of fragments of paleoguyots. These data indicate that along the paleo-Asian continent eastern margin, but in its different parts, the accretion of fragments of differently-structured areas of oceanic crust took place. In other words, oceanic plateaus were the main structural elements of the northern part of the paleo-Pacific plate, whereas within the southern part of the paleo-Pacific plate paleoguyots were widespread. Although it cannot excluded be that there might have been two different paleo-oceanic plates.

In Hauterivian time, the southern subduction zone, where the Late Jurassic-Early Cretaceous accretionary prism had been forming, was blocked by a spreading ridge which separated the paleo-Pacific plate (some geologists call it Izanagi) and the Pacific plate (Fig. 20*d*). Fragments of this ridge are represented in the youngest structural unit (Erdagou complex) of the Taukha terrane (Kemkin, 2006; Kemkin and Taketani, 2008). The blocking of the southern subduction zone was a reason for the termination of the Late Jurassic-Early Cretaceous accretionary prism formation and also a reason of arising of a series of left-lateral strike-slip faults on the paleo-Asian continent eastern margin. Along one of these

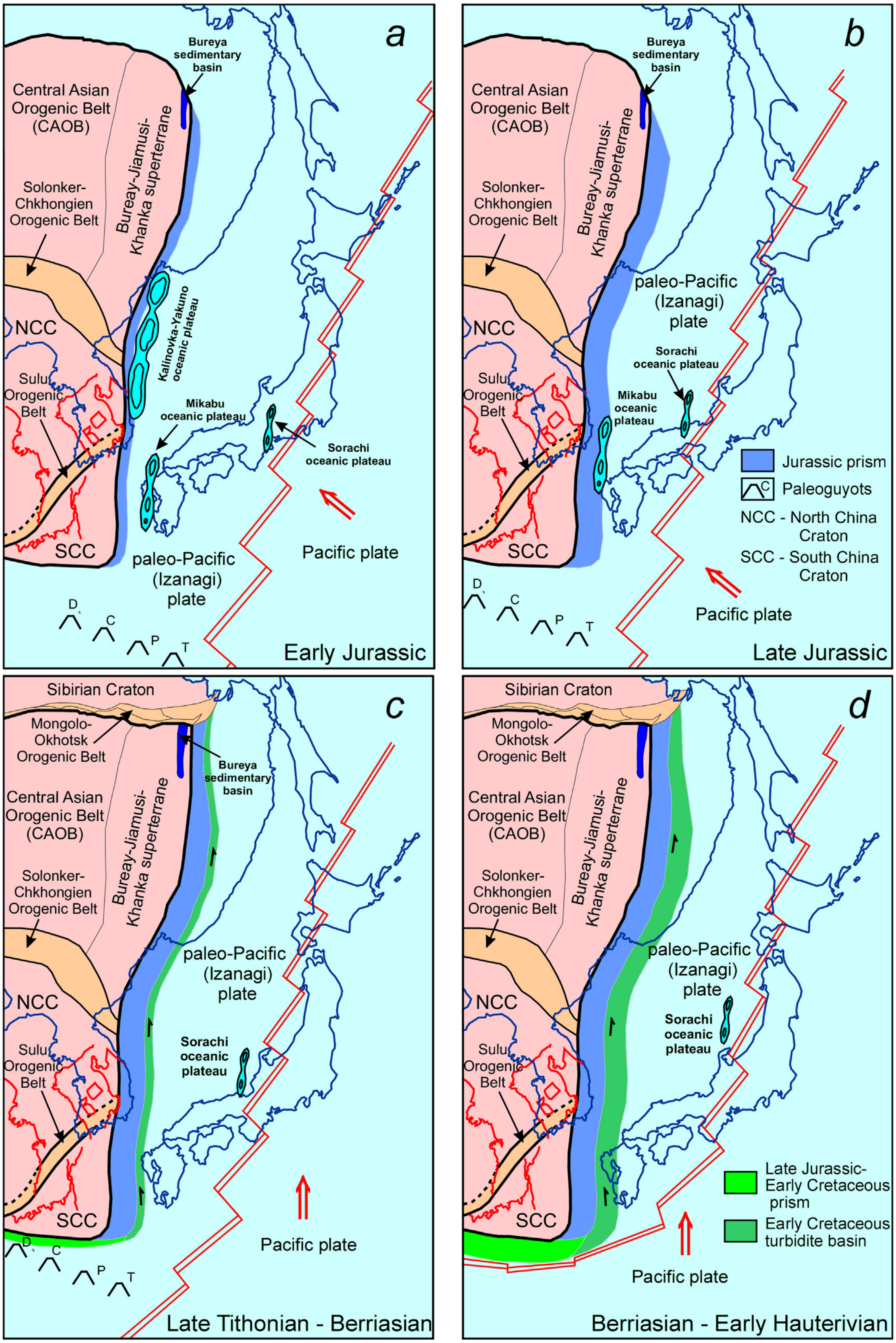

Fig. 20. Paleogeodynamic reconstruction on the Jurassic – Early Hauterivian time.

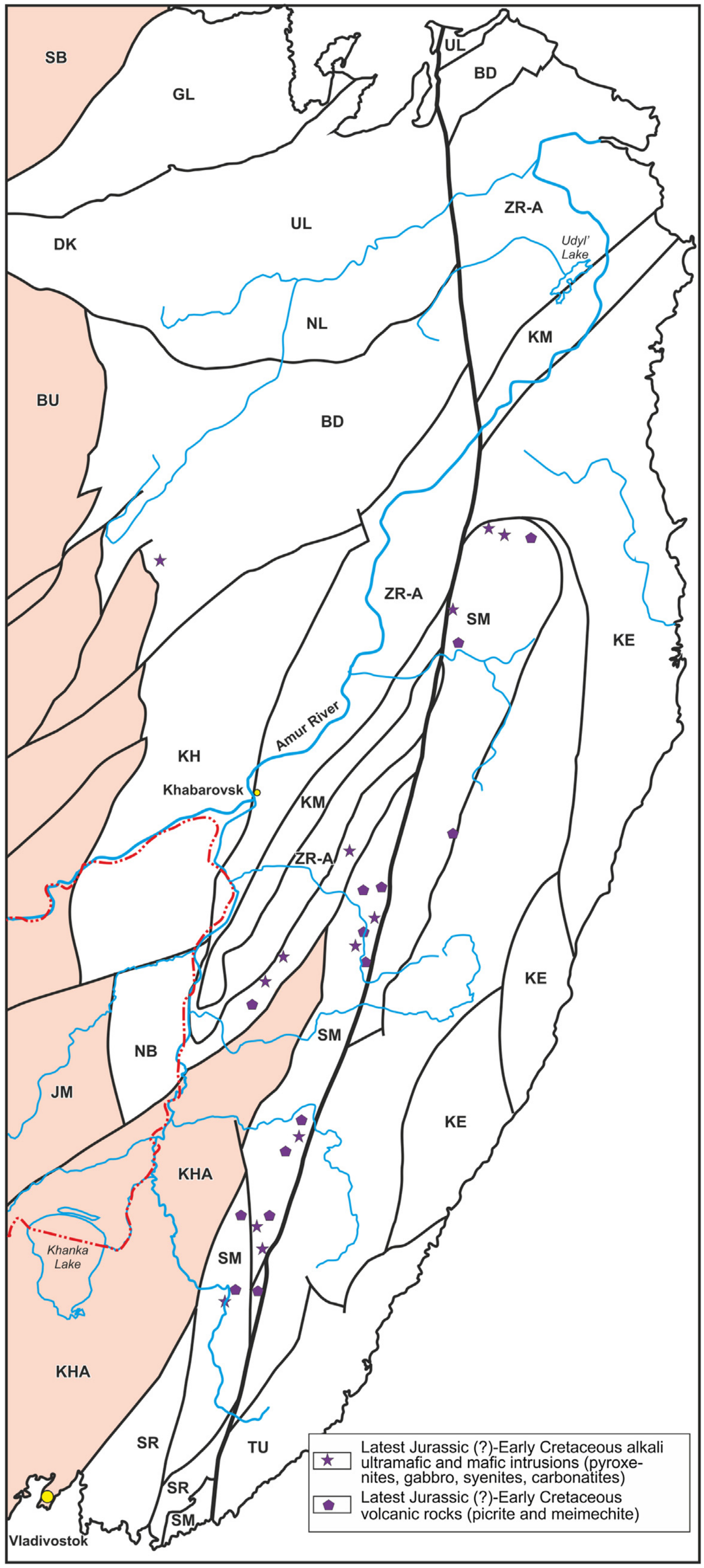

Fig. 21. Distribution of Late Jurassic(?)-Early Cretaceous alkali mafic and ultramafic rocks.

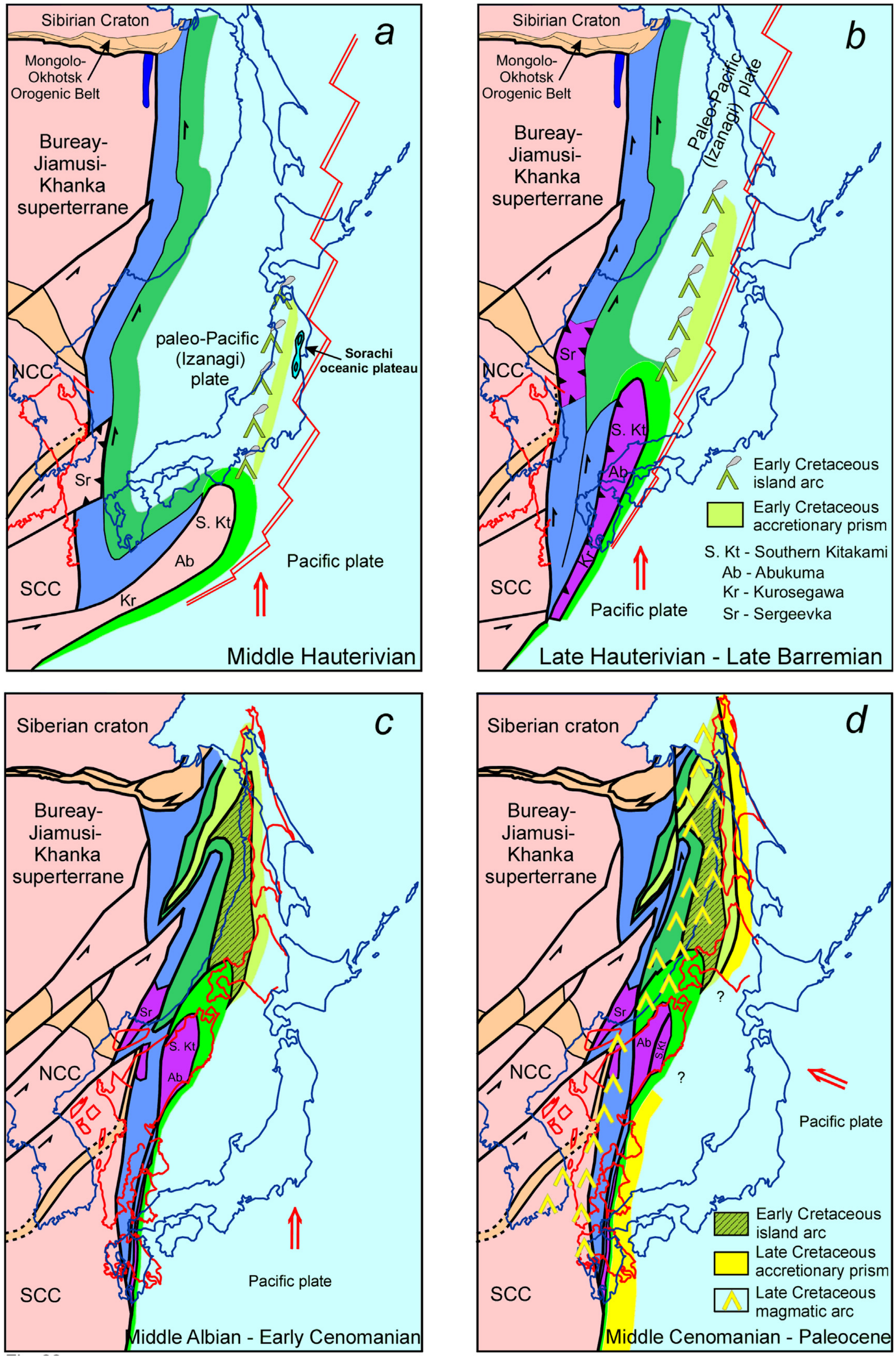

Fig. 22. Paleogeodynamic reconstruction on the Middle Hauterivian – Paleocene time.

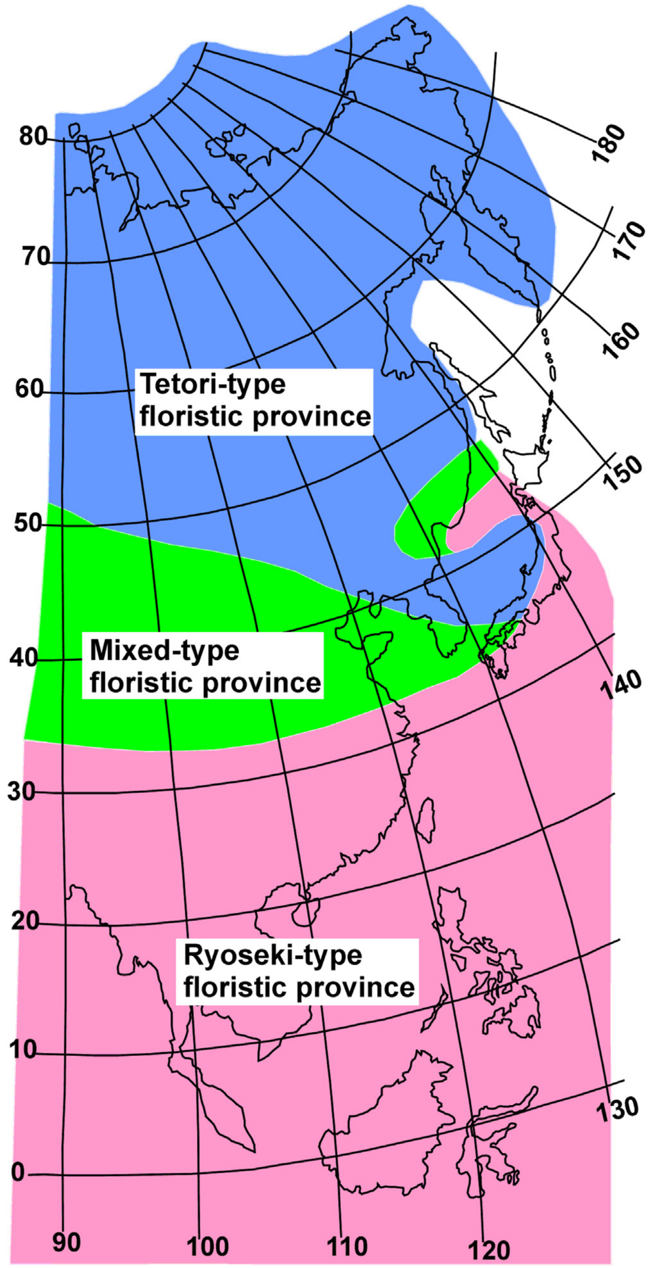

Fig. 23. Distribution of paleofloristic zones on the paleo-Asian continent east margin (after Kimura, 2000).

faults the southeastern part of the paleo-Asian continent moved to the northeast (see Fig. 22*a*), analogous to the way the Alchan block of the Bureya-Jiamusi-Khanka superterrane moved forward along the Misha-Fushung-Alchan fault at the end of Albian (see Fig. 3).

The large-scale displacement of the southern part of the paleo-Asian continent eastern margin along the left-lateral strike-slip faults also caused the crumpling of the Jurassic prism southern flank into the giant fold with a steeply plunging axis (oroclinal fold) (see Fig. 22*a*). The right (southeastern) wing of this fold became the future Jurassic portion of the Sanbagawa terrane and the Northern Chichibu terranes.

The blocking of the southern subduction zone was probably a reason for the initiation of the growth of the Early Cretaceous island arc (Kema and Rebun-Kabato terranes) and the synchronous Early Cretaceous accretionary prism (Kiselevka-Manoma terrane) nearby on the continental margin (Fig. 22*a*). The terrigenous (clastic) rocks of the Kiselevka–Manoma terrane (i.e., siltstones, sandstones, and mélange) are represented by greywackes that lack any arkosic component (Markevich et al., 1997; Filippov, 2001; Filippov and Kemkin, 2009). This indicates that the paleo-oceanic formations of the Kiselevka–Manoma terrane were not subducted under the Paleo-Asian continent, but under an island arc located to the east of the continent, and which made a peculiar barrier to arkosic detritus. The products of volcanic activity in this arc are found among the upper horizons of chert and siliceous mudstone in the form of interbeds of tuff (Filippov, 2001; Filippov and Kemkin, 2009).

The southern part of this island arc probably had a junction with the continental margin (analogous to the modern situation in the area of the Kamchatka Peninsula – Kuril Islands, but rotated by 180°) because according to available data (Minoura, 1990), the Hauterivian volcanic rocks of the Rebun-Kabato arc unconformably overlie the chert-terrigenous sequences of the Late Jurassic-Early Cretaceous accretionary prism (Northern Kitakami terrane). Thus, at that time the southern part of the Zhouravlevka–Amur turbidite basin had developed into a back-arc basin (Fig. 22*a, b*).

During the Hauterivian-Albian all these complexes (Jurassic and Late Jurassic-Early Cretaceous prisms, Early Cretaceous turbidite basin, Early Cretaceous island arc and Early Cretaceous accretionary prism) were displacing along the paleo-Asian continent eastern margin to the north, being moved by the Pacific plate (Fig. 22*b*). As a result of this displacement the giant fold of the Jurassic prism was transformed into the isocline (closely compressed) fold (Fig. 22*b*). At the beginning of the Late Albian, the Early Cretaceous island arc and the Early Cretaceous accretionary prism approached the continent and were accreted. As a result a new transform continental margin was formed (Fig. 22*c*).

Paleophytogeographic studies of T. Kimura (Ohana and Kimura, 1995; Kimura, 2000; and others) provide direct evidence of the large-scale displacement of the abovementioned complexes along the paleo-Asian continent eastern margin. According to his data, there were three distinct coeval floristic provinces within the paleo-Asian continent during the Late Jurassic and Early Cretaceous (Fig. 23). They are the Ryoseki-type, Tetori-type and the Mixed-type floristic provinces. The Ryoseki-type was characterized by typical subtropical-tropical climatic conditions with a fairly long-term arid season. The Tetori-type existed under warm-temperate and humid climatic conditions. The Mixed-type had intermediate climatic conditions. The border between the Mixed-type and Ryoseki-type is situated (in modern coordinates) approximately at 33^0 north latitude. But if we look at the Sikhote-Alin, we can see that here this border is displaced up to 44^0 north latitude. Thus, it appears that the Taukha terrane containing the Ryoseki-type flora and the Zhouravlevka-Amur terrane containing the Mixed-type flora were displaced from their points of origin by a distance of about 1500 km (from 33^0 to 44^0 northern latitude). Paleomagnetic data (Didenko et al., 2014, 2015) supports this. These data indicate that the Kiselevka–Manoma terrane moved during the Early Cretaceous from 40^0 to about 52^0 northern latitude.

The Late Albian-Early Cenomanian time interval is characterized by a large scale left-lateral translation of the paleo-Asian continent eastern margin along the numerous faults of the Tan–Lu Fault system (Fig. 22*c*), the largest of which are the Misha-Fushung-Alchan, Ilan-Itoun, Kondzhu-Ymsong, Central Sikhote-Alin and their continuation in the Japan Tanakura Tectonic Line, Hatagawa Tectonic Line and Median Tectonic Line faults (e.g., Sakashima et al., 2003; and others). As a result of these left-lateral dislocations, the rock associations of the Mesozoic accretionary prisms, turbidite basin and island arc were crumpled into multiple folds of various scales with steeply plunging axes (oroclinal folds). During the oroclinal orogeny, the vertical thickness of sediments of the abovementioned terranes increased multifold. The lower part of these terranes experienced temperatures and pressures that were high enough to create large volumes of granitic magma. These orogenic granites were intruded into all the Sikhote-Alin terranes, and new continental crust was formed along the paleo-Asian continent eastern margin (Khanchuk et al., 2013).

At the beginning of the Late Cretaceous (Middle Cenomanian), the geodynamic mode of the transform margin along the paleo-Asian continent eastern edge was changed again to the geodynamic mode of subduction of an oceanic (Pacific) plate (Fig. 22*d*). During the Late Cretaceous–Paleocene along the paleo-Asian continent eastern margin the following lateral series was formed: an epi-continental (marginal-continental) volcanic arc (East Sikhote-Alin volcanic belt), a forearc basin (West Sakhalin and Sorachi–Ezo terranes) and accretionary prism (the Nabil terrane (Sakhalin Island), the East Hidaka terrane (Hokkaido Island), and the Simanto terrane (Outer Zone of the Southwest Japan)).

7. Conclusion

Using the detailed lithological-biostratigraphic and structural studies of the terranes of the ancient accretionary prisms of the Sikhote-Alin Orogenic Belt, the composition, structure and evolutionary succession of their formations have been revealed. In particular, it is established that they represent complex-structured tectono-sedimentary complexes (imbricate-underthrusted sedimentary packets) consisting of different-aged tectono-stratigraphic units. Each unit contains many repeated fault-bounded tectonic slices composed of oceanic (pelagic and hemipelagic deposits and fragments of seamount and rises), marginal-oceanic (siltstones and sandstones), and chaotic (subduction mélange) formations. These tectono-stratigraphic units differ in age from the accreted paleooceanic fragments and in their time of their accretion. The oldest paleooceanic formations and terrigenous rocks overlapping them compose the upper structural levels of accretionary prism terranes, and the youngest ones compose the lowermost.

Analysis of the data on the structure and composition of the Sikhote-Alin accretionary prism fragments and adjoining terranes allowed us to decipher the geological history on the eastern margin of the paleo-Asian continent during the Mesozoic. The formation of the continental crust of the Pacific margin of Asia in the Mesozoic includes several stages which are characterized by different geodynamic modes. In chronological order they correspond to: a passive continental margin (Pre-Jurassic, at least Permian-Triassic time); an active continental margin of Andean-type (Early-Late Jurassic); a transform continental margin in combination with an active continental margin of Andean-type (Tithonian-Early Hauterivian); a transform margin in combination with an active continental margin of Japanese-type (Middle Hauterivian-Early Albian); a transform continental margin (Middle Albian-Early Cenomanian); and again an active continental margin of Andean-type (Middle Cenomanian-Paleocene). Thus, the main Mesozoic geological processes of the formation of the continental crust of the eastern Asian edge were: accretion of paleo-oceanic fragments to the continental margin (which was realized as a result of the subduction of the paleo-Pacific plate along the convergent borders); subsequent intense deformation of the rocks composing the accretionary prisms including crumpling into oroclinal folds and multiple thrusts under conditions of the transform margin (which gave rise to multifold increase in the vertical thickness of sediments); as well as formation of granitic–metamorphic complexes due to intrusion of orogenic granite of *S* to *I*-type into the accretionary prisms rocks.

Acknowledgments

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