The Heilongjiang Complex as a Fragment of a Jurassic Accretionary Wedge in the Tectonic Windows of the Overlying Plate: A Flat Slab Subduction Model

Article *in* Russian Journal of Pacific Geology · July 2021

DOI: 10.1134/S1819714021040047

Golozubov Vladimir
Far East Geological Institute

Alexander Khanchuk
Far East Geological Institute

ISSN 1819-7140, Russian Journal of Pacific Geology, 2021, Vol. 15, No. 4, pp. 279–292. © Pleiades Publishing, Ltd., 2021.
Russian Text © The Author(s), 2021, published in Tikhookeanskaya Geologiya, 2021, Vol. 40, No. 4, pp. 3–17.

The Heilongjiang Complex as a Fragment of a Jurassic Accretionary Wedge in the Tectonic Windows of the Overlying Plate: A Flat Slab Subduction Model

V. V. Golozubov[a], * and A. I. Khanchuk[b]

[a] *Far East Geological Institute, Far East Branch, Russian Academy of Sciences, Vladivostok, 690022 Russia*
[b] *Geological Institute, Russian Academy of Sciences, Moscow, 119017 Russia*
**e-mail: golozubov@fegi.ru*

Received January 15, 2021; revised February 10, 2021; accepted March 19, 2021

Abstract—The Circum-Pacific Late Albian—Cenomanian orogenic belts (including the Sikhote-Alin—Western Sakhalin belt) were formed as a result of the deformation of mainly epioceanic terranes as fragments of Jurassic—Early Cretaceous accretionary wedges with ophiolites and other fragments of oceanic crust, turbidite basins, and island-arc systems. To the west of the Sikhote-Alin—Northern Sakhalin belt and orthogonally, the previously consolidation structures include the Bureya—Jiamusi—Khanka fragment of the orogenic belt of the Late Cambrian—Early Ordovician consolidation of the Late Proterozoic—Cambrian complexes. Within this belt, four isolated outcrops of the Heilongjiang complex are mapped. This complex combines metamorphic rocks of the epidote—amphibolite and glaucophane—schist facies and represents a fragment of a Jurassic accretionary wedge. It was assumed that these outcrops marked a suture; in particular, they represent the remains of the closed Mudanjiang paleoocean, separating the original Jiamusi terrane (and the Bureya—Jiamusi—Khanka belt) located to the west of Central Asia structures. This paper provides data that indicate that the Heilongjiang complex does not mark a suture, but is an underground near-horizontal continuation of the marginal continental accretionary wedge of the Nadanhada—Bikin terrane (flat subduction model) brought to the surface at the antiform bending site. The unity of the compared parts of the accretionary wedge is emphasized by the close matrix ages, the similarity of detritus zircon populations, and similar composition and age of allochthonous inclusions (limestone, chert, Late Paleozoic, and Early Mesozoic basalt). One important common feature is that Late Paleozoic and Early Mesozoic basalts from allochthonous inclusions occur as the N-MORB and OIB types in both cases, without any suprasubduction volcanism traces in the matrix. The Heilongjiang complex forms, according to this interpretation, a tectonic window among the more ancient structures of the Jiamusi terrane. There is no need to assume the existence of a Mudanjiang Ocean to explain the formation of the Heilongjiang complex. The structural features of this complex and its bedding conditions can be explained by the flat subduction processes of the Pacific slab in the Jurassic and its deformation in the Early Cretaceous.

Keywords: Heilongjiang complex, Jurassic accretionary wedge, high-pressure metamorphism, isotope geochronology, flat subduction, and Northeast China

DOI: 10.1134/S1819714021040047

INTRODUCTION

It can be considered as established that the earliest Circum-Pacific Late Albian—Cenomanian orogenic belts (including the Sikhote-Alin—Western Sakhalin) were formed due to the deformation of predominantly epioceanic terranes as fragments of Jurassic—Early Cretaceous accretionary wedges with ophiolites and other fragments of oceanic crust, turbidite basins, and island arc systems [20]. The Late Albian—Cenomanian orogeny was the final stage of the oblique collision of a relatively motionless continent and the Paleopacific plates actively moved in the Early Cretaceous from the south and southeast to the north and northwest [1, 4, 20]. This collision resulted in a gigantic system of marginal—continental left strike-slips in the Early Cretaceous [7, 13, 65, 66, etc.]. This system includes major faults of the Sikhote-Alin region and the areas located to the west such as Donghua—Mishan (Alchan), Arsen'evsky, and Central Sikhote-Alin [7, 65, 66]. The total displacements along these faults reached hundreds, and according to some estimates [4, 33], even a few thousand kilometers. Terranes as fragments of the Jurassic accretionary wedge (Samarka, Nadanhada—Bikin, etc.) are traced for a

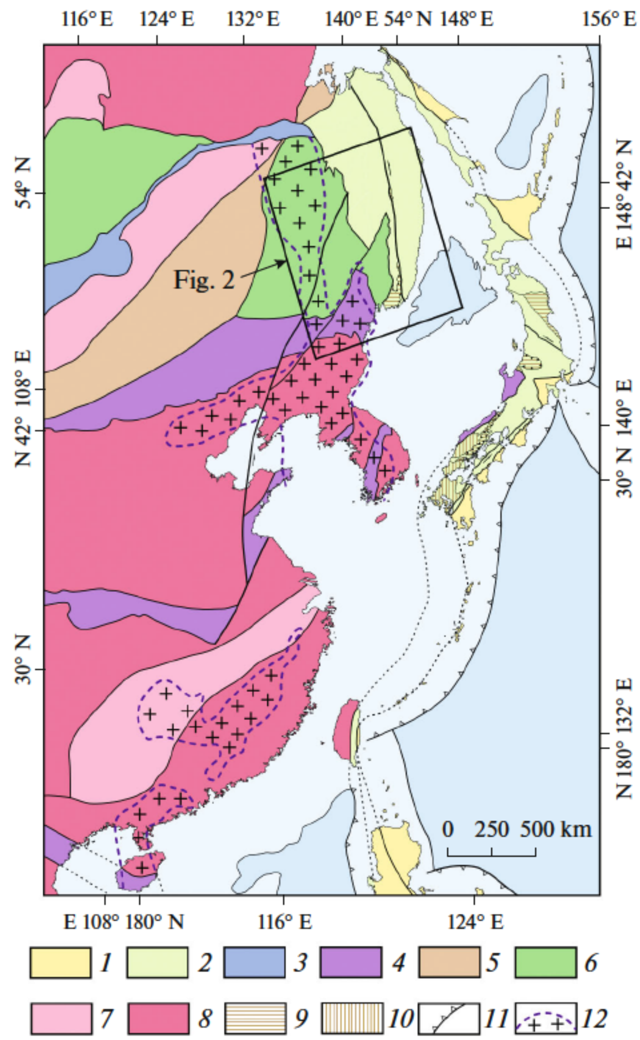

Fig. 1. Cratons and orogenic belts of East Asia. (*1–7*) Orogenic belts of (*1*) Cenozoic, (*2*) Late Albian–Cenomanian, (*3*) Early–Middle Jurassic, (*4*) Middle Triassic, (*5*) Late Paleozoic, (*6*) Late Cambrian, and (*7*) Late Proterozoic age; (*8*) cratons; (*9–10*) Paleozoic klippes and blocks in the Middle–Late Jurassic accretionary complexes: (*9*) continental rocks and (*10*) accretionary wedges; (*11*) subduction zones; (*12*) eastern province of Late Triassic–Early Jurassic (230–190 Ma) postorogenic granitoids.

considerable distance along the northwestern boundary of the pre-Jurassic continent [3, 8].

To the west of the Late Albian–Cenomanian orogenic belt and orthogonally, the earlier consolidation structures include (from north to south) (Fig. 1):

(1) the Mongol–Okhotsk belt of Paleozoic and Early Mesozoic complexes consolidated at the Early–Middle Jurassic boundary [51];

(2) the Bureya–Jiamusi–Khanka (BJK) fragment of the orogenic belt of the Late Cambrian–Early Ordovician consolidation of the Late Proterozoic–Cambrian complexes [10, 44, 68];

(3) the Middle Triassic Solonker orogenic belt of the consolidated Paleozoic and Early Triassic complexes [10, 34].

The Songliao Cretaceous depression is located to the west of the BJK belt; according to the drilling data, its base consists mainly of Paleozoic–Mesozoic granites and Paleozoic volcanic rocks with negligible Mesoproterozoic granite gneisses [44, 60 and references therein]. Between the Jiamusi block and the Songliao depression, the roughly NS-trending uplift of the Minor Xingang–Zhangguangcai ranges is composed of Late Paleozoic and Mesozoic granitoids with rare Paleozoic deposit remains [32, 61]. At the eastern foothills of these ranges, four isolated outcrops of blue and green schists, metabasalts, and other rocks of the Heilongjiang complex, whose age and geodynamic nature were a matter of debate, were mapped [62] (Fig. 2).

In recent years, detailed geological, geochronological, and geochemical studies have made it possible to establish that the Heilongjiang complex is a fragment of a Jurassic accretionary wedge [62].

The Mudanjiang Triassic Ocean has been hypothesized and contradictory reconstructions of its closure with subduction to the west and east [26] or only to the west [32] have been proposed. However, the existence of this paleoocean seems doubtful due to a number of circumstances (the isolation of the Heilongjiang outcrops and the complicated paleotectonic reconstruction of the roughly NS-trending Triassic ocean that are not continued to the south and the north). A different model of the Heilongjiang complex formation is proposed below due to peculiarities of the Jurassic subduction of the Paleopacific plates under the Eurasian Plate.

HEILONGJIANG COMPLEX

The Heilongjiang complex forms a chain of four outcrops extended NS (Fig. 2) [22, 62, 72, 77]. The northern outcrop was found on the right bank of the Amur River (Lyuobei city), two central outcrops occur in the region of Yilan and Hunan cities, while the southern outcrop is located near the Mudanjiang city. On the left bank of the Amur River the Heilongjiang continuation is observed as the Uril Formation (complex) [11]. From the west, these outcrops are constrained by the Mudanjiang fault zone [60].

The Composition and Geodynamic Nature of the Heilongjiang Complex

The Heilongjiang complex is composed of terrigenous, carbonate, siliceous and volcanic rocks metamorphosed in the amphibolite or high-pressure epidote–glaucophane–schist facies. The peak *P–T* values for blue schists were calculated as 8–16 kbar and 320–180°C, while those for amphibolites were calculated as 10.9 kbar and ~622°C. The peak *P–T* condi-

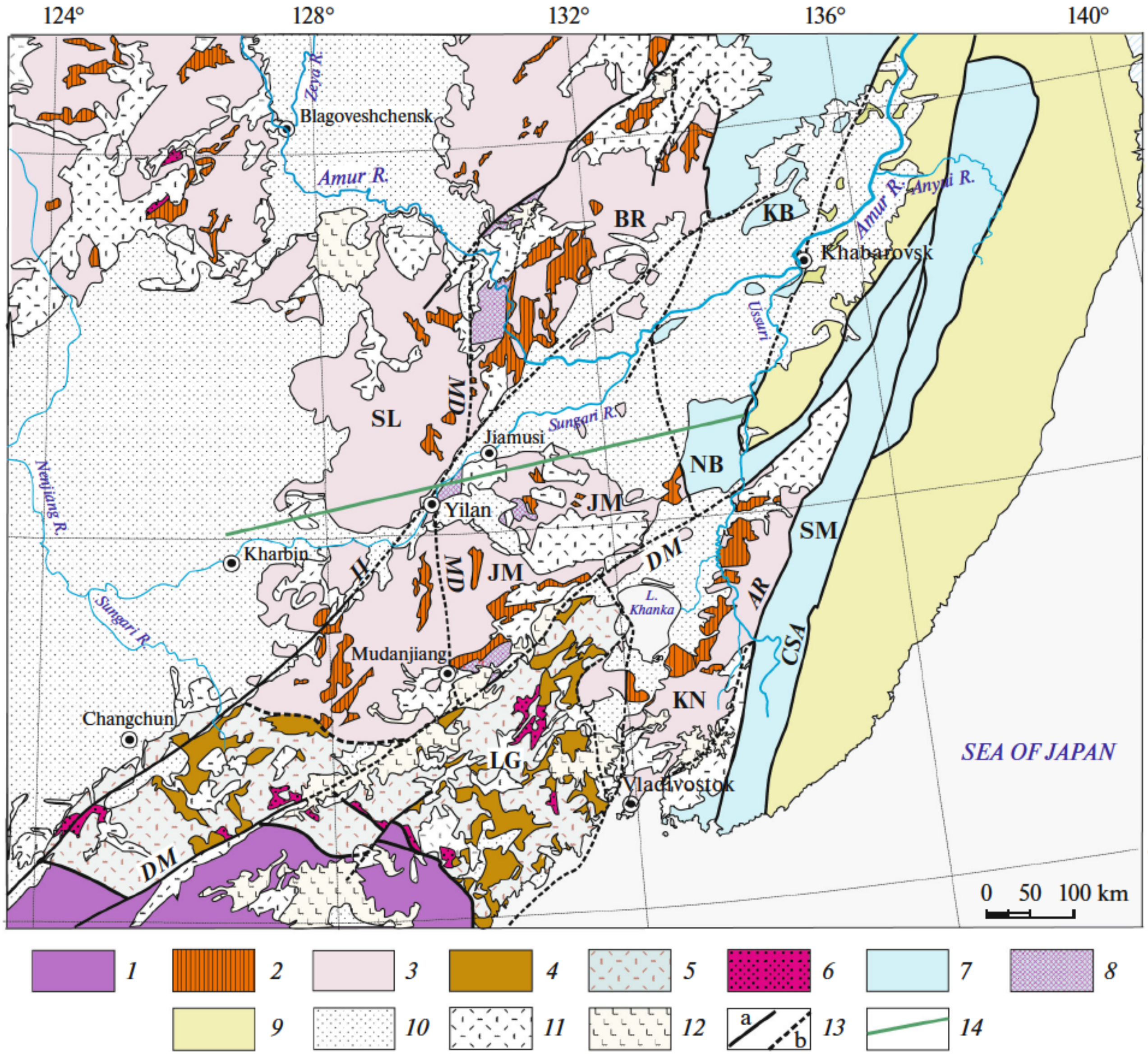

Fig. 2. A tectonic map of Northeast China and adjacent area of the Far East of Russia. According to [5] with additions. (*1*) Sino-Korean craton; (*2–3*) Early Paleozoic orogenic belt including (KN) Khanka and (BR) Bureya superterranes, (JM) Jiamusi terrane, and (SL) Songliao block: (*2*) (PT_3–PZ_1) outcrop remains of terrane-forming complexes, (*3*) Paleozoic and Mesozoic syn- and post-accretionary granitoids, Paleozoic cover fragments; (*4–6*) Late Paleozoic–Early Mesozoic Solonker orogenic belt, (LG) Laoeling–Grodekovsky terrane: (*4*) outcrop remains of the Lower Silurian and Permian structures, (*5*) (P_2–MZ) syn- and post-accretionary granitoids, (*6*) (T_{1-2}?) dynamometamorphism zones; (*7–8*) terranes of the Sikhote-Alin–North Sakhalin orogenic belt: (*7*) Jurassic, including (KB) Khabarovsk, (NB) Nadankhada–Bikin, (SM) Samarka, as well as (K_1–KZ) syn- and post-accretionary structures, (*8*) metamorphic rocks of (J) the Heilongjiang complex; (*9*) Early Cretaceous terranes and (K_2-KZ) syn- and post-accretionary structures; (*10–11*) (*10*) Cenozoic and (*11*) Mesozoic rocks of terrigenous and volcanic cover; (*12*) Cenozoic plateau basalts; (*13*) faults (a) found and (b) suggested, including (II) Yilan–Yitong, (MD) Mudanjiang, (DM) Donghua–Mishan (DM), (AR) Arsen'evsky, (CSA) Central Sikhote-Alin; (*14*) section line shown in Fig. 6.

tions for blue schists in the Yilan area were estimated at 9–11 kbar and 320–450°C, while those for amphibolites were estimated at 10–13 kbar and 500–580°C [22 and references therein]. These estimates correspond to a depth of approximately 30 km. The rocks are dominated by mica–garnet schists formed due to terrigenous, mainly clayey, rocks with different ratios of biotite, muscovite, garnet, feldspar, and quartz. Minor rocks include green and blue schists and amphibolites formed from basic volcanic rocks. The complex also includes tectonic lenses of marble and quartzite (metachert), as well as serpentinite formed from dunite, lherzolite, and harzburgite [76]. From the beginning, this complex was considered as younger than the metamorphic rocks of the Precambrian Mashan Group of the Jiamusi block and it was assigned to the Ordovician–Silurian on the geological map [2]. However, U–Pb isotope dating performed in recent decades by the method of accessory and detrital zircons in the rocks of the complex has led to a complete revision of the ideas of their formation time towards a significant rejuvenation. The youngest detrital zircon populations in metamorphic schists formed from terrigenous rocks cover the age of 190–167 Ma (Early and Middle Jurassic) [77]. Approximately 55% of the detrital zircons are dated from 297 to 180 Ma with peaks at 270–245, 230–200, and 200–180 Ma, while 27% of the detrital zircons are estimated at 544–412 Ma with a peak of 500–480 Ma. Proterozoic detrital zircons (~15%) dated at 2352–595 Ma were also identified and most of them were referred to the Neoproterozoic [26]. The Ar–Ar dates of micaceous minerals (phengite, biotite, and muscovite) of metaterrigenous rocks (making it possible to determine the time of metamorphism) were grouped in a relatively narrow range of 178–146 Ma (end of the Early–Late Jurassic) [22 and references therein].

The Heilongjiang rocks are dominated by green and blue schists and amphibolites as metamorphosed basalts, which sometimes retain a pillow structure, which are geochemically comparable with E-MORB tholeiitic basalts and OIB alkali basalts of seamounts [30, 72, 76]. Based on SHRIMP and LA–ICP–MS U–Pb zircon dating the age of the blue schists and amphibolite protoliths is in the range of 356–195 Ma [22 and references therein, 27, 74]. According to the LA–ICP–MSU–Pb data, the age of magmatic zircons from blue schists is estimated at 162–142 Ma [76].

The complex also contains quartzites with remains of radiolarians (metachert (?)) and, occasionally, of Fe–Mn nodules [72, 76]. The association of these rocks (as well as tectonic serpentinite lenses), which are considered as ophiolites, is directly indicative of the fact that the Heilongjiang complex is enriched in oceanic material. Detrital zircons in various kinds of mica schists (metamorphosed terrigenous rocks), as mentioned, contain a constant impurity (up to 15%) of magmatic grains with an age of 300–2500 Ma [30, 77]. In other words, this belongs to the sedimentation in the continental margin setting. The combination of fragments of oceanic structures and sedimentary rocks of near-continental origin in one structure, as well as the glaucophane–schist metamorphism in them, lead to the conclusion that the Heilongjiang complex is a metamorphosed mélange zone within the Early–Middle Jurassic accretionary wedge [62, 72, 77]. Jurassic metamorphosed terrigenous rocks (occasionally, serpentinites) likely formed the mélange matrix, while the Carboniferous–Permian and Triassic metabasalts, as well as the associated metamorphosed chert and carbonate rocks, formed blocks and plates in this mélange. Direct evidence of such relationships can be observed in the quarries near Yilan, where mica schists contain blue schist, amphibolite, and quartzite blocks and plates ranging in size from fractions of a meter to 200 m [21]. In addition, the Heilongjiang complex contains the adakite-type monzogranite veins with an age of 175–161 Ma [22].

The Role of the Mudanjiang Fault in the Regional Structure

The Heilongjiang complex is constrained to the west by the roughly NS-trending Mudanjiang Fault, which is thought to separate different terranes. In the east, they include the Jiamusi terrane and the Bureya superterrane, while in the west they form a block with different names (Songliao, Songliao–Xilinhot, and Songnen–Zhangguangcai Range Massif (block)) [28, 60, etc.]. We will use the name "Songliao block."

The Jiamusi terrane and the adjacent Khanka superterrane have a similar structure and good correlation of geological events in the range of approximately 755–115 Ma. The most ancient complexes of the Jiamusi terrane (from 895 Ma) are represented by Late Proterozoic–Early Cambrian protoliths metamorphosed in the granulite facies in the Cambrian–early Ordovician and two complexes of the Early Paleozoic granitoids dated at 530–502 and 490–470 Ma [59, 68 and references therein]. The same Late Proterozoic and Early Paleozoic complexes are distinguished in the Bureya and Khanka superterranes [18, 47, 50]. The Songliao block is assumed to be different from the Jiamusi terrane and the Bureya superterrane in the occurrence of Paleoproterozoic rocks that were uncovered during drilling of the Songliao depression [59]. Meanwhile, the Early Devonian deposits of the Jiamusi terrane and the Songliao block are of the same type in both the facies and age of detrital zircons. This means that these blocks were consolidated before the Early Devonian [44]. The similarity of the facies and detrital zircon distribution spectra in the Permian deposits of the Jiamusi terrane and the Songliao block [63] suggests that this consolidation continued in the Permian as well.

In the Minor Xingang Ridge and to the east of it similar Early Paleozoic granitoids of four intrusion stages in the range of 505–450 Ma are distributed on both sides of the Mudanjiang Fault [58]. This means that the Proterozoic and Cambrian crust was processed in a similar way in the Songliao block and terranes of the Bureya–Jiamusi belt, despite the fact that the Songliao block contains more ancient crustal material than terranes of the Bureya–Jiamusi belt [60]. The Permian granitoids of the Songliao block and the Jiamusi terrane are also of the same type.

The roughly NS-trending band of Late Triassic–beginning of Early Jurassic plutonic and, less often, volcanic rocks is located mainly to the west of the Mudanjiang Fault. However, Late Triassic volcanic rocks are also present east of the Mudanjiang Fault [35]. Late Triassic and Early Jurassic igneous rocks of these regions with ages of 230–190 Ma occur as similar bimodal and alkali ranges with A-type granites and rhyolites [53 and references therein, 54, 55], which are traditionally regarded as resulting from postcollisional extension after the closing of the Paleo-Asian Ocean [35, 54]. The attempt to represent the Triassic–Jurassic igneous rocks of the Zhangguangcai–Minor Xingang ridges as constituting a suprasubduction magmatic arc was related directly to the reconstruction of the Mudanjiang Ocean [31, 32]. Triassic–Early Jurassic igneous rocks of the Zhangguangcai–Minor Xingang ridges make up a large belt of such rocks with ages of approximately 230–190 Ma, which extends from the Bureya superterrane inclusively [49] through the pre-Jurassic continental margin of East Asia [53] to the Southeast China [29] (Fig. 1).

Jurassic igneous rocks younger than 190 Ma, which lack an areal distribution, occur as rare small intrusions of OIB-type dolerites (approximately 188 Ma) [28] and I-type granites (191–163 Ma) in the Zhangguangcai Ridge [75] and as adakite-type and granodiorites (182 and 181 Ma) in the Minor Xingang Ridge [31].

It should be noted that the northern continuation of the Mudanjiang Fault was not found in Russia. The Uril Formation as a continuation of the Heilongjiang complex roughly wedges out on the left bank of the Amur River, subducting under the Early Paleozoic granite metamorphic complex [10]. In the south, this fault joins the zone of the Donghua–Mishan (Alchan in the Primorye area) Fault as a left strike-slip with a horizontal displacement amplitude of at least 250 km [65, 66]. It is noteworthy that due to its small scale the Mudanjiang Fault is not demonstrated at all on the fault diagrams of the Tan-Lu system compiled by the researchers Xu Jaw [65, 66] and V.P. Utkin [13, etc.].

Thus, the Mudanjiang Fault should be considered as a minor branch of the larger left strike-slip as the Donghua–Mishan Fault. It by no means separates blocks with drastically different geological histories and it is impossible to represent it as a continent–ocean boundary for hundreds of millions of years, as suggested in the reconstructions discussed above.

JURASSIC SIKHOTE-ALIN ACCRETIONARY COMPLEXES AS PROBABLE ANALOGS OF THE HEILONGJAING COMPLEX

The Structure of the Jurassic Sikhote-Alin Accretionary Complexes

The Khabarovsk and Nadanhada–Bikin terranes are located east of the Jiamusi terrane and, accordingly, the Heilongjiang outcrops (Fig. 2). They are links in the chain of terranes as fragments of the Jurassic accretionary wedge of the East Asian margin, which were formed in the process of successive subduction of the Paleopacific Plate under the Eurasian Plate [4, 8, 41, 45]. In the area under consideration, the Nadanhada–Bikin terrane is located at the bend of the accretionary wedge, which was formed as a result of the Khanka superterrane extension to the northeast along the Donghua–Mishan (Alchan) Fault [17].

The Khabarovsk terrane consists of repeated varisized tectonic plates and blocks composed of rocks of the oceanic plate and terrigenous mélange structures of the accretionary wedge matrix. The oceanic plate rocks include Triassic and Early Jurassic cherts and jaspers and Aalen–Bajocian siliceous–clayey deposits, which are replaced by Late Bathonian–Middle Callovian mudstones. The accretionary wedge matrix is composed of Oxfordian–Tithonian siltstones and sandstones [39 and references therein]. The subduction mélange, along with varisized fragments and plates of Triassic and Jurassic cherts, contains basalts, gabbroids, Late Carboniferous, Permian, and Late Triassic limestones and metamorphic schists [6 and references therein, 8, 39]. The Tithonian subduction mélange is replaced without visible unconformity by Early Cretaceous sandstones, which we consider as postsubduction deposits [8, 39, 40].

The Nadanhada–Bikin terrane is geographically divided into two parts: the southwestern part (Nadanhada or Wandashan) [70, 73] located in China and the northeastern part (Bikin) located in Russia [8, 40]. In China, the terrane is divided into two structural units. The upper position is occupied by the Yuejinshan complex and the lower position is occupied by the Raohe complex [73]. There are three complexes in Russia: Khor (upper, Toarcian–Callovian analogue of the Yuejinshan complex), Ussuri (middle, Bathonian–Oxfordian analogue of the Raohe top, and Ulitkinsky (lower, Kimmeridgian–Tithonian analogue of the Raohe bottom [8, 40].

The Yuejinshan complex is composed of terrigenous rocks metamorphosed in the greenschist facies with metabasalt, metagabbro, and meta-ultrabasite layers of the ophiolite assemblage, as well as marbles and quartzites that occasionally contain high-pressure and medium-temperature minerals [73]. Ophiolite protolith was formed in the Late Carboniferous–Early Permian [69 and references therein].

Greenschists of the complex are dated by Rb–Sr at 188 ± 4 Ma (Early Jurassic) [67]. Judging from their geochemical characteristics, metabasalts correspond to the MORB and OIB compositions [25, 73]. The age of the Yuejinshan complex matrix was not determined; however, based on the complete analogy of age and composition of paleooceanic inclusions in the Khor complex, as well as the upper and most ancient complexes of the Jurassic accretionary wedge of the Samarka terrane, whose matrix was dated in terms of radiolarians [8, 39, 40], it can be taken as Late Toarcian–Middle Jurassic. The Yuejinshan complex is a complete analogue of the Kalinovsky and Sebuchar complexes located south of the Samarka terrane with the Early–Middle Jurassic terrigenous matrix [8, 40].

The underlying Raohe complex is composed of unmetamorphosed Triassic–Early Jurassic chert, Carboniferous–Permian and Triassic limestone and basalt forming inclusions, blocks, and layers in the Middle–Late Jurassic terrigenous matrix [40, 42]. It should be noted that the Early Cretaceous (Berriasian) deposits of the Raohe complex differ from the Late Jurassic in occurrence of the Late Jurassic detrital zircon population [42].

One distinctive feature of the Raohe complex is the Middle Jurassic magmatic assemblage of pyroxenite, gabbro, plagioclasite, plagiogranite, and basalt. The age is 172 Ma for basalts and their tuffs in terms of zircons [52] and 167–169 Ma for plagioclasites and plagiogranites [56]. This assemblage is considered as a fragment of an oceanic island of plume origin in the accretionary wedge [52, 56]. The geochemical characteristics of basalts are indicative of their belonging to the OIB type, i.e., seamount basalts [52, 57, 73].

The Jurassic part of the Raohe complex is analogous to that of the Khabarovsk terrane, as well as the lower structural levels of the accretionary wedge of the Samarka terrane with the Middle–Late Jurassic terrigenous matrix. It should be noted that the subduction mélange time was estimated using radiolarian analysis at the Toarcian (approximately 180 Ma), while the subduction completion was referred to the Tithonian in different parts of the Samarka terrane [8, 39, 40]. Berriasian deposits that developed sporadically in fragments of the Sikhote-Alin accretionary wedges occur as terrigenous deposits that build the Tithonian subduction mélange section [8, 39, 40]. They are drastically different from the Jurassic deposits in detrital zircon populations [42]. As an example, the U–Pb age of detrital zircons and the Hf isotopic composition of clastic rocks in the Raohe complex and the Khabarovsk terrane are indicative of considerable differences in the feeding provinces in the Jurassic and Early Cretaceous. In particular, the Middle–Late Jurassic sandstones yield the youngest concordant zircon age of 167 Ma, while the Early Cretaceous sandstones, among others, contain zircons dated at 167–140 Ma [6, 42].

Comparison of the Heilongjiang Complex and the Sikhote-Alin Accretionary Wedges

The age distribution of detrital zircons and monazites in the Heilongjiang complex and in the Sikhote-Alin Jurassic accretion wedges is similar (Fig. 3). The similar ages of the youngest zircons (167 Ma) and their age distribution suggest a consolidated feeding province. It is noteworthy that oceanic plagiogranites are dated at 167–169 Ma in the Raohe complex [56] and the age of the basalts is 172 Ma [52].

One important common feature of the compared Heilongjiang, Khabarovsk, Nadanhada–Bikin, and Samarka accretion complexes is the allochthonous material of Paleozoic basalts of N-MORB and OIB oceanic settings dominated by the latter [3, 12]. The absence of heavy minerals typical of volcanic arcs in the terrigenous matrix of the Samarka terrane is noteworthy [9]. Hence, the compared accretionary wedges are not characterized by the impact of suprasubduction volcanism and traces of a late Early Jurassic–Tithonian suprasubduction volcanic belt (180–150 Ma) related to these wedges [1, 4, 53, 64].

EARLY CRETACEOUS DISLOCATION FEATURES IN THE HEILONGJIANG COMPLEX

The Heilongjiang metamorphic rocks are marked by traces of the most active multistage deformations. According to the investigation results [21, 72, 77], metamorphic rock foliation corresponding to the final deformation stage has a stable ENE (60°–90°) strike and is oriented almost orthogonally with respect to the NS-trending Mudanjiang Fault. Foliation dip angles are from relatively flat (20°–45°) to vertical; overturned bedding should not also be ruled out. Based on the detailed structural studies carried out in the vicinity of Yilan city [21], the Heilongjiang outcrop is observed as an antiform core; the allochthonous complex composed of more ancient rocks of the Jiamusi terrane is located on the wings of this antiform (Figs. 4, 5). The antiform was formed (final deformation stage) in a compression field oriented from SSE to NNW [21]. At such a compression direction, left-sided displacements should be assumed along the Mudanjiang Fault trending NS and restricting outcrops from the west (Fig. 5).

Such paragenesis of structural elements, which is common for the Sikhote-Alin region, records the Early Cretaceous deformation stage (transform margin period) [1, 4, 7, 13]; this means that the described deformations are evidently secondary. The Mudanjiang Fault was likely formed precisely in the Early Cretaceous, and the Heilongjiang outcrops observed along it occur as antiform cores, in fact, strike-slip drag folds rapidly fade at a distance from the maternal fault.

THE FORMATION MODEL OF THE HEILONGJIANG COMPLEX

The correct identification of the Heilongjiang complex as a fragment of the suprasubduction accretionary wedge resulted in far-reaching and, in our opinion, very controversial conclusions that the Heilongjiang is a complex that marks a suture. In other words, the Heilongjiang is suggested to be the remains of the collapsed Mudanjiang Paleoocean, which originally separated the Jiamusi terrane (and the entire Bureya–Jiamusi–Khanka belt) from the structures of the Central Asian orogenic belt (CAOB) located to the west [22, 26, 71, 75]. In addition, it was occasionally

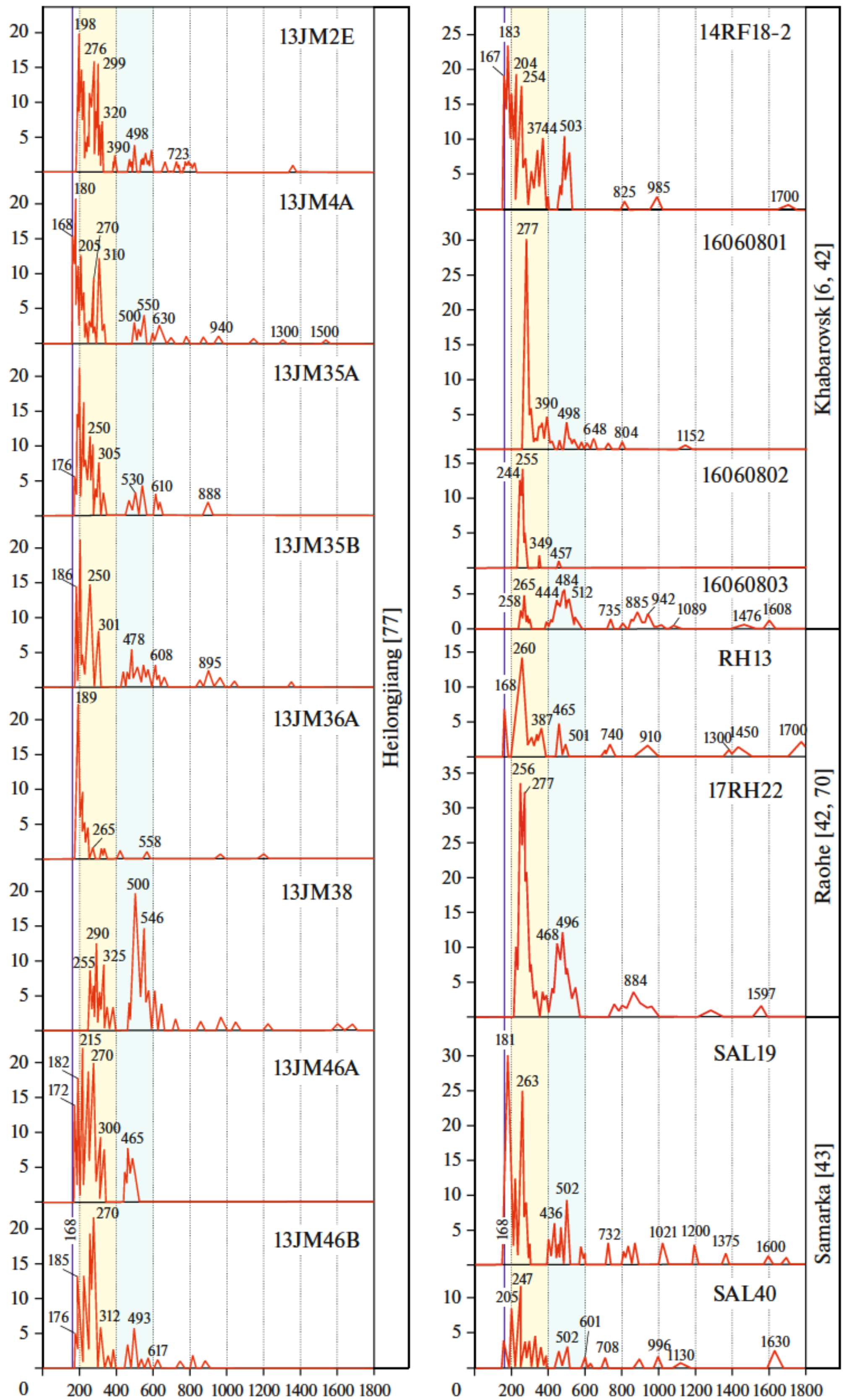

Fig. 3. Compared summed histograms of the probability of age dependences of major detrital zircon generations in the Heilongjiang [77] and Sikhote-Alin [6, 42, 43] accretion complexes.

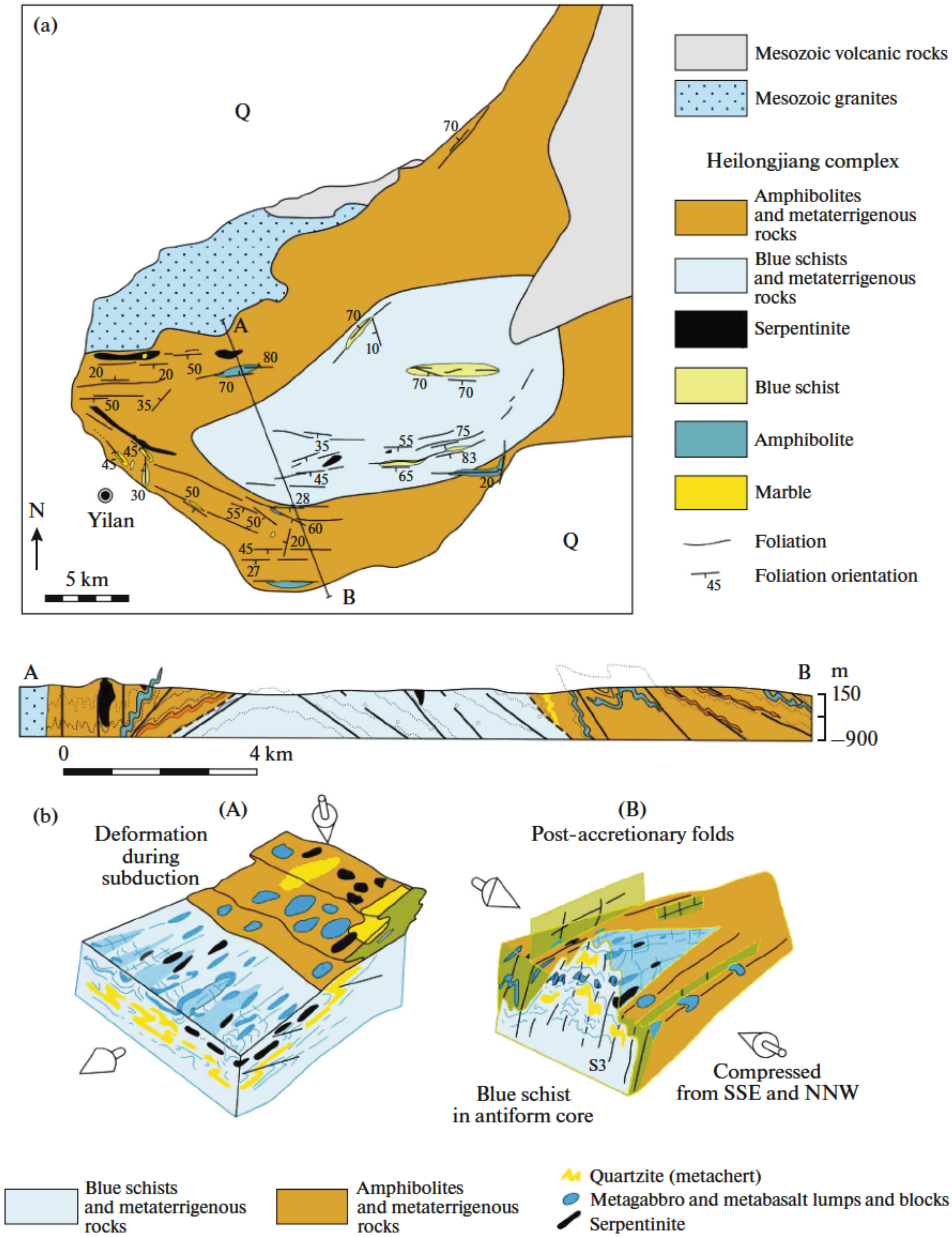

Fig. 4. An antiform formed by the Heilongjiang complex in the Yilan area (according to [21]). (a) Geological map and section of Heilongjiang outcrops, (b) structural block diagrams showing regional compression directions in the Jurassic and Early Cretaceous.

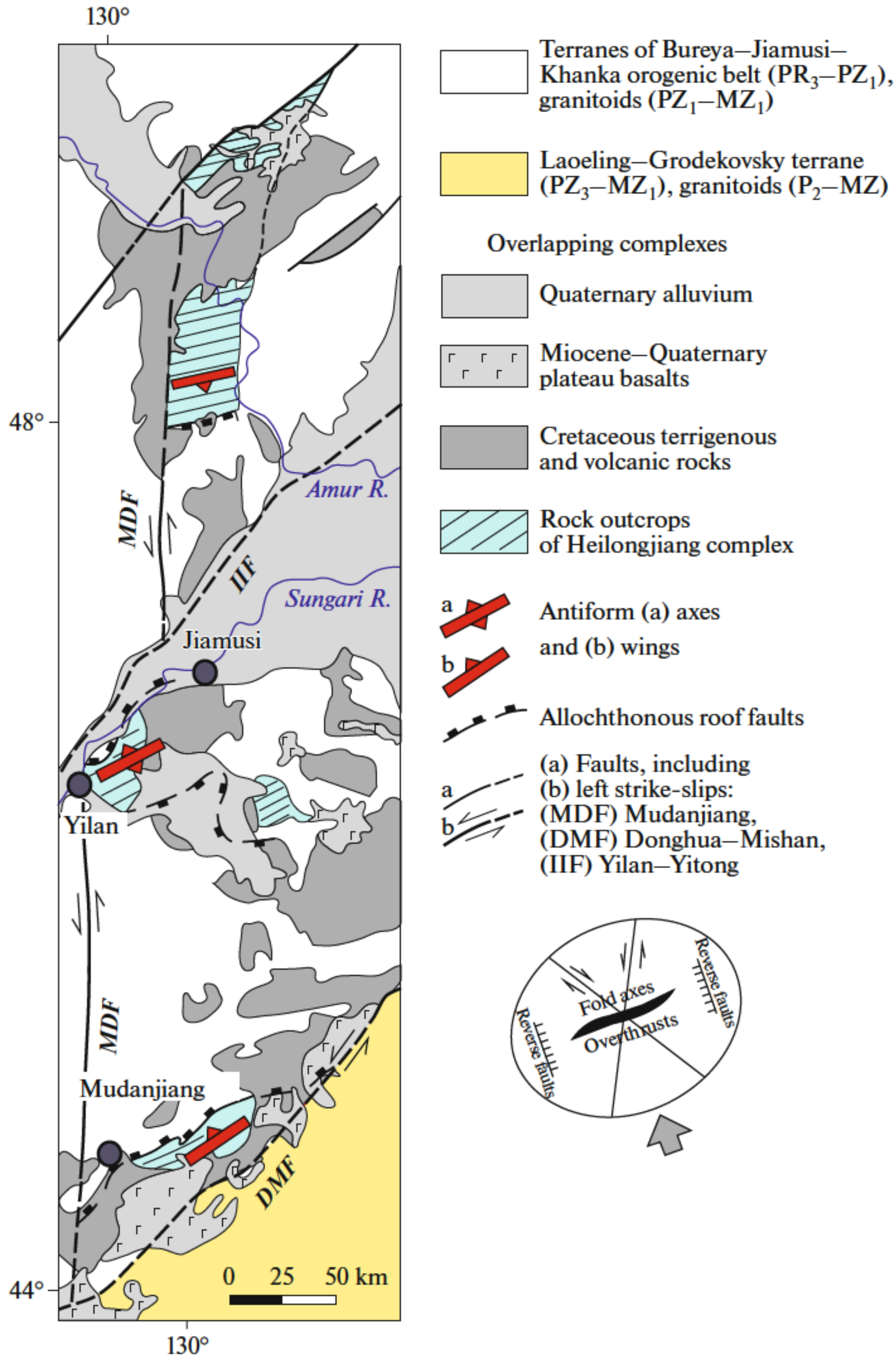

Fig. 5. The Mudanjiang Fault and Heilongjiang outcrops adjacent to it from the east in the antiform cores. The location of the studied region is shown in Fig. 2. At the bottom right, the Cretaceous deformation ellipsoid illustrates the paragenesis of structures in the unilateral compression setting.

assumed that the Bureya–Jiamusi–Khanka orogenic belt was an exotic formation as a fragment of Gondwana accreted to CAOB in the Early–Middle Jurassic [62]. In some reconstructions, based on the above dates of ophiolite protoliths, the Mudanjiang Ocean existed from the Early Carboniferous to the Early Cre-

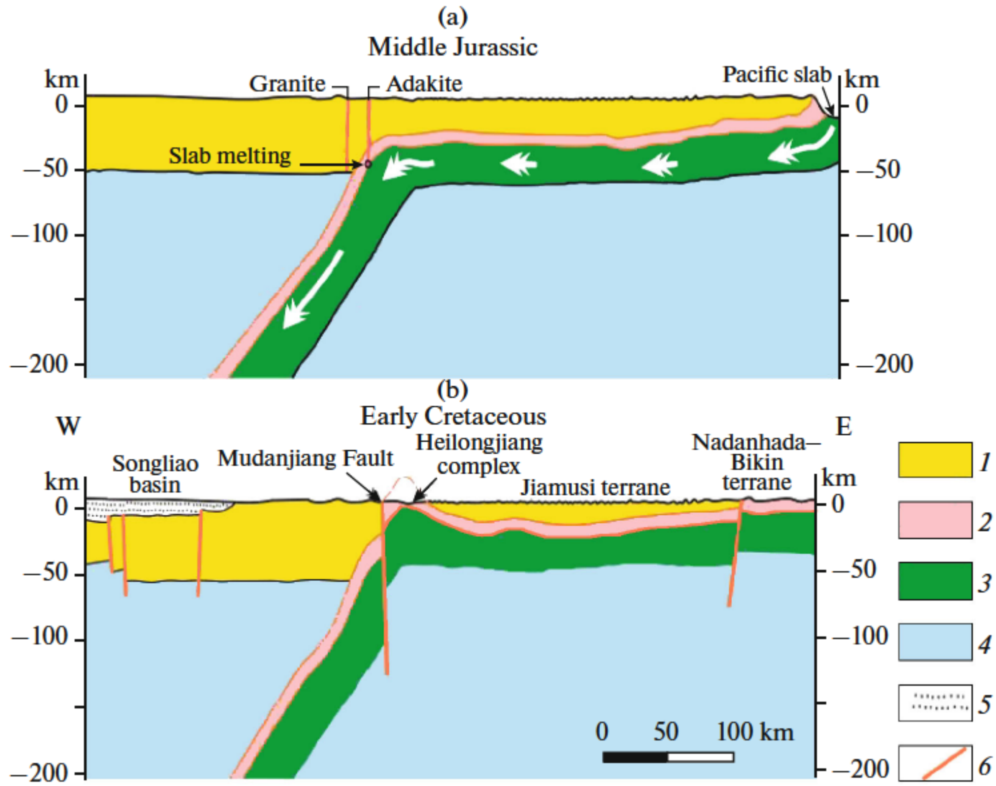

Fig. 6. The proposed formation model of the Heilongjiang complex in the flat subduction setting and subsequent dislocations. Section positions are shown in Fig. 2. (*1*) Continental lithosphere; (*2*) accretionary prism; (*3*) Pacific slab; (*4*) mantle; (*5*) Cretaceous and Cenozoic deposits of the Songliao basin; (*6*) faults.

taceous (more than 200 Ma) [22]. In other words, its age and area exceeded those, for example, of the recent Atlantic Ocean, which is unlikely.

The above data on analogous compositions of the Heilongjiang complex and the Sikhote-Alin Jurassic accretionary wedge (without a parallel volcanic arc) give grounds for the use of the flat subduction (flat slab subduction) model. Recent examples of such avolcanic subduction zones include individual sections of the Andes-type margin. The suprasubduction volcanic belts were not formed without the asthenospheric wedge between the slab and the continental plate. The flat subduction followed the submergence of a thickened, low-density, and therefore floating lithosphere (aseismic ridges, seamounts, etc.) [14, 23, 24, 37, 48]. According to [36], in the course of the flat subduction, the lower plate moved a few hundreds of kilometers at almost the same depth, reaching the melting pressure–temperature of the slab. In the course of flat subduction, magmatic complexes were formed on a small scale deep in the continent above the region where the slab was bent and ruptured; they were different in geochemistry from typical suprasubduction complexes [36, 46]. Such a thickened oceanic plate subducted in the Jurassic under the Eurasian Continent can be proposed relatively definitely due to the fragments of the large Late Paleozoic oceanic plume plateau (Kalinovsky and Sebuchar complexes) in the Samarka and Nadanhada–Bikin terranes. They occur as different-depth gabbro–ultrabasic assemblages, high-Ti and high-Fe basalts comparable to those of the Ontong–Java plateau and nonreef limestones typical of oceanic plateaus [15, 16, 19]. Fragments of this plateau (ultrabasic rocks, gabbro, basalt, and Late Paleozoic limestone) are also present in the Yuejinshan complex of the Nadanhada–Bikin terrane, where they are considered as a part of the oceanic plume seamount [25, 38, 69]. Fragments of the Middle Jurassic oceanic island were described in the Raohe complex [49, 57].

Hence, the Jiamusi terrane is constrained from the west and east by fragments of Jurassic accretionary wedges that are similar in composition and age. In the west, this is a fragment formed by the Heilongjiang complex, which was mentioned above, and in the east, the terrane borders on the accretion complexes of the Sikhote-Alin–North Sakhalin belt. With regard to these accretionary complexes, it is quite possible that the Heilongjiang complex is an underground, near-horizontal continuation of the accretionary complex of the Nadanhada–Bikin terrane, which was brought to the surface in the antiform bend area (flat subduction model) (Fig. 6).

The unity of the accretionary complexes that are being compared is emphasized by their similar matrix age, analogous age groups of detrital zircons, and identical compositions and ages of allochthonous inclusions (limestone, chert, Late Paleozoic and Early Mesozoic basalts). The Heilongjiang complex is exposed, according to this interpretation, in the tectonic window among more ancient rocks of the Jiamusi terrane. Additional confirmation is seen in the fact that granites and volcanic rocks in the western and southern that frame the Heilongjiang outcrops are dated as Triassic–early Jurassic (246–190 Ma) [49, 51, 52, 67]; in other words, they are more ancient than the synsubduction metamorphic rocks of this complex. This model also explains sporadic Jurassic adakites [21] in association with granitoids in the western framing of the Heilongjiang complex [75].

CONCLUSIONS

There is no need to assume a Mudanjiang Ocean to explain the formation of the Heilongjiang complex. The structural features of this complex and its bedding conditions can be explained by flat subduction processes of the Pacific slab in the Jurassic and its deformation in the Early Cretaceous.

FUNDING

The work was supported by the Russian Foundation for Basic Research (project no. 19-05-00229).

REFERENCES

1. *Geodynamics, Magmatism, and Metallogeny of East Russia*, Ed. by A. I. Khanchuk (Dal'nauka, Vladivostok, 2006) [in Russian].
2. *Geological Map of the Amur Region and Adjacent Territories. 1 : 2500000* (VSEGEI, St. Petersburg, 1999) [in Russian].
3. V. V. Golozubov and N. G. Mel'nikov, *Tectonics of the Geosynclinal Complexes of Southern Sikhote-Alin* (DVNTs AN SSSR, Vladivostok, 1986) [in Russian].
4. V. V. Golozubov, *Tectonics of the Jurassic and Lower Cretaceous Complexes of the Northwestern Pacific Margin* (Dal'nauka, Vladivostok, 2006) [in Russian].
5. V. V. Golozubov, "Terranes of Northeastern China and adjacent areas of the Russian Far East," in *Fundamental Problems of Tectonics and Geodynamics. Proc. 52th Tectonic Conference* (GEOS, Moscow, 2020), Vol. 1, pp. 182–185 [in Russian].
6. A. N. Didenko, Sh. Oto, A. V. Kudymov, A. Yu. Peskov, M. V. Arkhipov, Yu. Miyake, and M. Nagata, "Tectonic implications: zircon age of sedimentary rocks from Khabarovsk, Samarka, and Zhuravlevka–Amur terranes in the northern Sikhote–Alin Orogenic Belt," Russ. J. Pac. Geol. **39** (1), 1–19 (2020).
7. B. A. Ivanov, *Central Sikhote-Alin Fault* (PGU, Vladivostok, 1972) [in Russian].
8. I. V. Kemkin, *Geodynamic Evolution of Sikhote-Alin and Sea of Japan Region in the Mesozoic* (Nauka, Moscow, 2006) [in Russian].
9. V. P. Nechaev, M. Musashino, and D. U. Li, "Jurassic–Lower Cretaceous geodynamic evolution of the Eastern Asian margin: reconstruction from heavy mineral assemblages of sedimentary rocks," Tikhookean. Geol. **16** (6), 21–35 (1997).
10. L. M. Parfenov, N. A. Berzin, A. I. Khanchuk, G. Badarch, V. G. Belichenko, A. N. Bulgatov, S. I. Dril', G. L. Kirillova, M. I. Kuzmin, U. J. Nokleberg, A. V. Prokop'ev, V. F. Timofeev, O. Tomurtogoo, and H. Yan, "Models of formation of orogenic belts of central and northeastern Asia," Tikhookean. Geol. **22** (6), 7–41 (2003).
11. E. B. Sal'nikova, A. B. Kotov, V. P. Kovach, S. D. Velikoslavinskii, B.-M. Dzhan, A. A. Sorokin, A. P. Sorokin, K.-L. Van, S.-L. Chan, Kh.-Ya. Li, and E. V. Tolmacheva, "Mesozoic Age of the Uril Formation of the Amur Group, Lesser Khingan Terrane of the Central Asian Foldbelt: results of U–Pb and Lu–Hf isotopic studies of detrital zircons," Dokl. Earth Sci. **453** (2), 1181–1184 (2013).
12. V. P. Simanenko, A. N. Filippov, and A. A. Chashchin, "Basalts of the Pantalassa Ocean in the Samarka Terrane, Central Sikhote Alin," Russ. J. Pac. Geol. **28** (3), 220–233 (2009).
13. V. P. Utkin, "Tan-Lu and Sikhote-Alin transregional structural paragenesis and its role in continental riftogenesis," Dokl. Earth Sci. **444** (2), 687–691 (2012).
14. V. E. Khain and M. G. Lomize, *Geotectonics on the Geodynamic Basis* (MGU, Moscow, 1995) [in Russian].
15. A. I. Khanchuk, I. V. Panchenko, and I. V. Kemkin, "Geodynamic Evolution of Sikhote-Alin and Sakhalin in the Paleozoic and Mesozoic," *Asian Pacific Margin. Geology*, Ed. by A. I. Khanchuk (Nauka, Moscow, 1989), pp. 218–254 [in Russian].
16. A. I. Khanchuk and I. V. Panchenko, "Garnet gabbro in the ophiolites of Southern Sikhote Alin," Dokl. Earth Sci. SSSR **321** (4), 800–803 (1991).
17. A. I. Khanchuk, V. V. Golozubov, V. P. Simanenko, and A. I. Malinovskii, "Giant folds with steeply dipping hinges in structures of orogenic belts: evidence from Sikhote Alin," Dokl. Earth Sci. **395** (2), 165–169 (2004).
18. A. I. Khanchuk, G. M. Vovna, V. I. Kiselev, M. A. Mishkin, and S. N. Lavrik, "First results of zircon LA-ICP-MS U–Pb dating of the rocks from the granulite complex of Khanka Massif in the Primorye Region," Dokl. Earth Sci. **434** (1), 1164–1167 (2010).
19. A. I. Khanchuk and S. V. Vysotskiy, "Different-depth gabbro-ultrabasite associations in the Sikhote-Alin ophiolites (Russian Far East)," Russ. Geol. Geophys. **57** (1), 141–154 (2016).
20. A. I. Khanchuk, A. V. Grebennikov, and V. V. Ivanov, "Albian–Cenomanian orogenic belt and igneous province of Pacific Asia," Tikhookean. Geol. **13** (3), 187–219 (2019).
21. A. Aouizerat, W. Xiao, K. Schulmann, P. Jerabek, P. Monie, J.-B. Zhou, J. Zhang, S. Ao, R. Li, Y. Li, and R. Esmaeili, "Structures, strain analyses, and $^{40}Ar/^{39}Ar$

ages of blueschist-bearing Heilongjiang Complex (NE China): implications for the Mesozoic tectonic evolution of NE China," Geol. J. **54**, 716–745 (2018).

22. A. Aouizerat, W. Xiao, K. Schulmann, B. F. Windley, J. Zhou, J. Zhang, S. Aoa, D. Song, P. Monie, and K. Liu, "Accretion, subduction erosion, and tectonic extrusion during Late Paleozoic to Mesozoic orogenesis in NE China," J. Asian Earth Sci. **194**, 104258 (2020).
23. G. Axen, V. W. Jolante, and C. C. Currie, "Basal continental mantle lithosphere displaced by flat-slab subduction," Nature Geosci. **11**, 961–964 (2018).
24. M. Barazangi and B. Isacks, "Spatial distribution of earthquakes and subduction of the Nazca Plate beneath South America," Geology **4**, 686–692 (1976).
25. J. H. Bi, W. C. Ge, H. Yang, Z. H. Wang, D. X. Tian, X. W. Liu, W. L. Xu, and D. H. Xing, "Geochemistry of MORB and OIB in the Yuejinshan Complex, NE China: implications for petrogenesis and tectonic setting," J Asian Earth Sci. **145**, 475–473 (2017).
26. Y. Dong, W. C. Ge, H. Yang, Z. Ji, D. Zhao, and W. Xu, "Convergence history of the Jiamusi and Songnen–Zhangguangcai Range massifs: insights from detrital zircon U-Pb geochronology of the Yilan Heilongjiang Complex, NE China," Gondwana Res. **56**, 51–68 (2018).
27. Y. Dong, W. C. Ge, H. Yang, X. Liu, Z. Ji, and W. Xu, "Geochemical and SIMS U-Pb rutile and LA-ICP-MS U-Pb zircon geochronological evidence of the tectonic evolution of the Mudanjiang Ocean from amphibolites of the Heilongjiang Complex, NE China," Gondwana Res. **60**, 25–44 (2019).
28. G. Feng, Y. Dilek, X. Niu, F. Liu, and J. Yang, "Geochemistry and geochronology of OIB-type, Early Jurassic magmatism in the Zhangguangcai Range, NE China, as a result of continental back-arc extension," Geol. Mag. **158**, 143–157 (2018).
29. P. Gao, Y.-F. Zheng, and Z.-F. Zhao, "Triassic granites in South China: a geochemical perspective on their characteristics, petrogenesis and tectonic significance," Earth-Sci. Rev. **173**, 266–294 (2017).
30. M. H. Ge, J.-J. Zhang, L. Li, K. Liu, Y.-Y. Ling, J.-M. Wang, and M. Wang, "Geochronology and geochemistry of the Heilongjiang Complex and the granitoids from the Lesser Xing'an–Zhangguangcai Range: implications for the Late Paleozoic–Mesozoic tectonics of eastern NE China," Tectonophysics **717**, 565–584 (2017).
31. M. H. Ge, J. J. Zhang, L. Li, and K. A. Liu, "Triassic–Jurassic westward scissor-like subduction history of the Mudanjiang Ocean and amalgamation of the Jiamusi Block in NE China: constraints from whole-rock geochemistry and zircon U-Pb and Lu-Hf isotopes of the Lesser Xing'an–Zhangguangcai Range granitoids," Lithos **302–303**, 263–277 (2018).
32. M. H. Ge, J. J. Zhang, L. Li, and K. Liu, "Ages and Geochemistry of Early Jurassic granitoids in the Lesser Xing'an–Zhangguangcai Ranges, NE China: petrogenesis and tectonic implications," Lithosphere **11** (6), 804–820 (2019).
33. V. V. Golozoubov, V. S. Markevich, and E. V. Bugdaeva, "Early Cretaceous changes of vegetation and environment in East Asia," Palaegeogr., Palaeclimat., Palaeecol **153**, 139–146 (1999).
34. C. Gu, G. Zhu, Y. Li, N. Su, S. Xiao, S. Zhang, and C. Liu, "Timing of deformation and location of the eastern Liaoyuan Terrane, NE China: constraints on the final closure time of the Paleo-Asian Ocean," Gondwana Res. **60**, 194–212 (2018).
35. P. Guo, W. L. Xu, J. J. Yu, F. Wang, J. Tang, and Y. Li, "Geochronology and geochemistry of Late Triassic bimodal igneous rocks at the eastern margin of the Songnen–Zhangguangcai Range Massif, Northeast China: petrogenesis and tectonic implications," Int. Geol. Rev. **58** (2), 196–215 (2016).
36. M. A. Gutscher, R. Maury, J. P. Eissen, and E. Bourdon, "Can slab melting be caused by flat subduction?," Geol **28** (6), 535–538 (2000).
37. A. Hasegawa and I. S. Sacks, "Subduction of the Nazca Plate beneath Peru as determined from seismic observations," J. Geophys. Res. **86**, 4971–4980 (1981).
38. A. Ishiwatari and Y. Ichiyama, "Alaskan-type plutons and ultramafic lavas in Far East Russia, Northeast China, and Japan," Int. Geol. Rev. **46**, 316–331 (2004).
39. I. V. Kemkin, A. I. Khanchuk, and R. A. Kemkina, "Accretionary prisms of the Sikhote-Alin orogenic belt: composition, structure and significance for reconstruction of the geodynamic evolution of the Eastern Asian margin," J. Geodynam. **102**, 202–230 (2016).
40. A. I. Khanchuk, I. V. Kemkin, and N. N. Kruk, "The Sikhote-Alin orogenic belt, Russian South East: terranes and the formation of continental lithosphere based on geological and isotopic data," J. Asian Earth Sci. **120**, 117–138 (2016).
41. S. Kojima, "Mezozoic Terrane Accretion in Northeast China, Sikhote-Alin and Japan Regions," Palaegeogr., Palaeclimatol., Palaeecol. **69**, 213–232 (1989).
42. Y. Li, W.-L. Xu, R.-X. Zhu, F. Wang, W.-C. Ge, and A. A. Sorokin, "Late Jurassic to Early Cretaceous tectonic nature on the NE Asian continental margin: constraints from Mesozoic accretionary complexes," Earth-Sci. Rev. **200**, 103042 (2020).
43. K. Liu, J. J. Zhang, S. A. Wilde, S. R. Liu, F. Guo, S. A. Kasatkin, V. V. Golozoubov, M. H. Ge, M. Wang, and J. M. Wang, "U-Pb dating and Lu-Hf isotopes of detrital zircons from the southern Sikhote-Alin orogenic belt, Russian Far East: tectonic implications for the Early Cretaceous evolution of the Northwest Pacific margin," Tectonics **36**, 2555–2598 (2017).
44. Y. Liu, W. Li, Z. Feng, Q. Wen, F. Neubauer, C. Y. Liang, "A review of the Paleozoic tectonics in the eastern part of Central Asian Orogenic Belt," Gondwana Res. **43**, 123–148 (2017).
45. Z. Qinlong, "The Nadanhada Terrane in relation to Mesozoic tectonics of continental margins of East Asia," Acta Geol. Sinica **3** (1), 15–29 (1990).
46. L. Mori, A. Gomez-Tuena, and Y. Cai, and S. L. Goldstein, "Effects of prolonged flat subduction on the Miocene magmatic record of the central Trans-Mexican Volcanic Belt," Chem. Geol. **244** (3–4), 452–473 (2007).
47. R. O. Ovchinnikov, A. A. Sorokin, N. M. Kudryashov, V. P. Kovach, Yu. V. Plotkina, and T. M. Skovitina, "Age of the Early Paleozoic granitoid magmatism in the

central part of the Bureya continental massif, Central Asian Fold Belt," Geodynamics & Tectonophysics **11** (1), 89–106 (2020).

48. V. A. Ramos and A. Folguera, "Andean flat-slab subduction through time," *Ancient Orogens and Modern Analogues*, Ed. by J. B. Murphy, Geol. Soc. London. Spec. Publ. **327** (1), 31–54 (2009).
49. A. A. Sorokin, A. B. Kotov, N. M. Kudryashov, and V. P. Kovach, "Early Mesozoic granitoid and rhyolite magmatism of the Bureya Terrane of the Central Asian Orogenic Belt: age and geodynamic setting," Lithos **261**, 181–194 (2016).
50. A. A. Sorokin, R. O. Ovchinnikov, W. L. Xu, V. P. Kovach, H. Yang, A. B. Kotov, V. A. Ponomarchuk, A. V. Travin, and Yu. V. Plotkina, "Ages and nature of the protolith of the Tulovchikha metamorphic complex in the Bureya Massif, Central Asian Orogenic Belt, Russia: evidence from U-Th-Pb, Lu-Hf, Sm-Nd, and $^{40}Ar/^{39}Ar$ Data," Lithos **332–333**, 340–354 (2019).
51. A. A. Sorokin, V. A. Zaika, V. P. Kovach, A. B. Kotov, W. Xu, and H. Yang, "Timing of closure of the eastern Mongol–Okhotsk Ocean: constraints from U-Pb and Hf isotopic data of detrital zircons from metasediments along the Dzhagdy transect," Gondwana Res. **81**, 58–78 (2020).
52. M.-D. Sun, Y.-G. Xu, and H.-L. Chen, "Subaqueous Volcanism in the Paleo-Pacific ocean based on Jurassic basaltic tuff and pillow basalt in the Raohe Complex, NE China," Sci. China Earth Sci. **61**, 1042–1056 (2018).
53. J. Tang, W. Xu, F. Wang, and W. Ge, "Subduction history of the paleo-Pacific slab beneath Eurasian continent: Mesozoic–Paleogene magmatic records in Northeast Asia," Sci. China Earth Sci. **61** (5), 527–559 (2018).
54. F. Wang, W. L. Xu, Y. G. Xu, F. Gao, and W. Ge, "Late Triassic bimodal igneous rocks in Eastern Heilongjiang Province, NE China: implications for the initiation of subduction of the Paleo-Pacific Plate beneath Eurasia," J. Asian Earth Sci. **97**, 406–423 (2015).
55. F. Wang, Y. G. Xu, W. L. Xu, L. Yang, W. Wu, and C. Y. Sun, "Early Jurassic calc-alkaline magmatism in Northeast China: magmatic response to subduction of the Paleo-Pacific Plate beneath the Eurasian continent," J. Asian Earth Sci. **143**, 249–268 (2017).
56. J. Y. Wang, Y. C. Yang, Y. W. Huang, Y. S. Hou, Y. Tan, and G. B. Zhang, "Formation ages and tectonic significance of ophiolites in Wandashan Terrane of the Eastern Heilongjiang," J. Earth Sci. Environ. **38** (2), 182–195 (2016).
57. Z. H. Wang, W. C. Ge, H. Yang, Y. L. Zhang, J. H. Bi, D. X. Tian, and W. L. Xu, Middle Jurassic oceanic island igneous rocks of the Raohe accretionary complex, northeastern China: petrogenesis and tectonic implications," J. Asian Earth Sci. **111**, 120–137 (2015).
58. Z.-W. Wang, W.-L. Xu, F.-P. Pei, F. Wang, and P. Guoa, "Geochronology and geochemistry of Early Paleozoic igneous rocks of the Lesser Xing'an Range, NE China: implications for the tectonic evolution of the eastern Central Asian Orogenic Belt," Lithos **261**, 144–163 (2016).
59. S. A. Wilde, H. L. Dorsett-Bain, and J. Liu, "The шdentification of a Late Pan-African granulite facies event in Northeastern China: SHRIMP U-Pb zircon dating of the Mashan Group at Liu Mao, Heilongjiang Province, China," *Proceedings of the 30th International Geological Congress, Beijing, 1997* (VSP Intern. Sci. Publ, Beijing, 1997), pp. 59–74.
60. S. A. Wilde, "Final amalgamation of the Central Asian Orogenic Belt in NE China: Paleo-Asian Ocean closure versus Paleo-Pacific plate subduction—a review of the evidence," Tectonophysics **662**, 345–362 (2015).
61. F. Y. Wu, D. Y. Sun, H. M. Li, B. M. Jahn, and S. A. Wilde, "A-type granites in Northeastern China: age and geochemical constraints on their petrogenesis," Chem. Geol. **187**, 143–173 (2002).
62. F. Y. Wu, J. H. Yang, C. H. Lo, S. A. Wilde, D. Y. Sun, and B. M. Jahn, "The Heilongjiang Group: a Jurassic accretionary complex in the Jiamusi Massif at the Western Pacific Margin of Northeastern China," Island Arc **16**, 156–172 (2007).
63. K. C. Xing, F. Wang, W. -L. Xu, and F. H. Gao, "Tectonic affinity of the Khanka Massif in the easternmost Central Aian Orogenic Belt: evidence from detrital zircon geochronology of Permian sedimentary rocks," Int. Geol. Rev. **62** ((4)), 428–445 (2020).
64. W. L. Xu, F. P. Pei, F. Wang, E. Meng, W. Q. Ji, D. B. Yang, and W. Wang, "Spatial-temporal relationships of Mesozoic volcanic rocks in NE China: constraints on tectonic overprinting and transformations between multiple tectonic regimes," J. Asian Earth Sci. **74**, 167–193 (2013).
65. J. Xu, W. Tong, G. Zhu, S. Lin, and C. Ma, "An outline of the pre-Jurassic tectonic framework in East Asia," J. Southeast Asia Earth Sci. **3** (1–4), 29–45 (1989).
66. J. Xu, "Basic characteristics and tectonic evolution of the Tancheng–Lujiang Fault Zone," *Tancheng–Lujiang Wrench Fault System*, Ed. by J. Xu (John Wileys, 1993), pp. 17–51.
67. J. Z. Yang, H. J. Qiu, J. P. Sun, and X. Z. Zhang, "Juejinshan Complex and its tectonic significance," J. Changchun Univ. Sci. Tec. **28** ((4)), 380–385 (1998).
68. H. Yang, W.-C. Ge, J.-H. Bi, Z.-H. Wang, D.-.X. Tian, and Y. Dong, "The Neoproterozoic–Early Paleozoic evolution of the Jiamusi Block, NE China and its east Gondwana connection: geochemical and zircon U-Pb-Hf isotopic constraints from the Mashan Complex," Gondwana Res. **54**, 102–121 (2018).
69. Q. Zhang and G. Q. Zhou, *Ophiolites in China* (Sci. Press, Beijing, 2001).
70. D. Zhang, Y.-J. Liu, W-.M. Li, S.-Z. Li, M. Z. Iqbal, and Z.-X. Chen, "Marginal accretion processes of Jiamusi Block in NE China: evidences from detrital zircon U-Pb Age and deformation of the Wandashan Terrane," Gondwana Res. **78**, 92–109 (2020).
71. D. Zhao, W. Ge, H. Yang, Yu. Dong, J. Bi, and Y. He, "Petrology, geochemistry, and zircon U–Pb–Hf isotopes of Late Triassic enclaves and host granitoids at the southeastern margin of the Songnen–Zhangguangcai Range Massif, Northeast China: evidence for magma mixing during subduction of the Mudanjiang Oceanic Plate," Lithos **312–313**, 358–374 (2018).

72. J. B. Zhou, S. A. Wilde, X. Z. Zhang, G. C. Zhao, C. Q. Zheng, Y. J. Wang, and X. H. Zhang, "The onset of Pacific margin accretion in NE China: evidence from the Heilongjiang high-pressure metamorphic belt," Tectonophysics **478**, 230–246 (2009).
73. J. B. Zhou, J. L. Cao, S. A. Wilde, G. C. Zhao, J. J. Zhang, and B. Wang, "Paleo-Pacific subduction-accretion: evidence from geochemical and U-Pb zircon dating of the Nadanhada accretionary complex, NE China," Tectonics **33**, 2444–2466 (2014).
74. C. Y. Zhu, G. Zhao, M. Sun, Q. Liu, Y. Han, W. Hou, X. Zhang, and P. R. Eizenhofer, "Geochronology and geochemistry of the Yilan blueschists in the Heilongjiang Complex, Northeastern China and tectonic implications," Lithos **216**, 241–253 (2015).
75. C. Y. Zhu, G. Zhao, M. Sun, P. R., Eizenhöfer, Y. Han, Q. Liu, and D. X. Liu, "Subduction between the Jiamusi and Songliao blocks: geochronological and geochemical constraints from granitoids within the Zhangguangcailing Orogen, Northeastern China," Lithosphere **9** (4), 515–533 (2017).
76. C. Y. Zhu, G. Zhao, M. Sun, P. R., Eizenhöfer, Q. Liu, X. Zhang, Y. Han, and W. Hou, "Geochronology and geochemistry of the Yilan greenschists and amphibolites in the Heilongjiang Complex, Northeastern China and tectonic implications," Gondwana Res. **43**, 213–228 (2017).
77. C. Y. Zhu, G. Zhao, M. Sun, Y. Han, Q. Liu, P. R. Eizenhofer, X. Zhang, and W. Hou, "Detrital zircon U-Pb isotopic data for meta-sedimentary rocks from the Heilongjiang Complex, Northeastern China and Tectonic Implications," Lithos **282–283**, 23–32 (2017).

Recommended for publishing by A.A. Sorokin
Translated by E. Maslennikova