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Oceanic Sediments of the Amur Terrane: Their Age and Tectonic Significance

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Abstract—The oceanic pelagic and hemipelagic siliceous and siliceous–clayey sediments play a subordinate role in the Amur Terrane, where they constitute thin tectonic slices separated by thicker terrigenous continental-margin deposits. The analysis of the radiolarian assemblages revealed the Middle–Late Jurassic age of hemipelagic siliceous mudstone and the Early Cretaceous age of similar continental-margin sediments. These new data contribute to the knowledge of the terrane's stratigraphy and demonstrate the progressively younger age of the stratigraphic boundaries between the different sedimentary facies in the southeastern direction. The multiple stacking of the oceanic and continental-margin sediments is characteristic of the accretionary complexes, and precisely such an interpretation of the tectonic nature of the Amur Terrane is consistent with its composition and position in the regional structure.

Keywords: *radiolarians, Jurassic, Cretaceous, oceanic and continental-margin sediments, Amur Terrane.*
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INTRODUCTION

The Mesozoic accretionary complexes that were formed along the East Asian convergent boundary [1, 4, 6–13, 16–19, 21, 22, 25, 27] constitute a significant part of the South Russian Far East (Fig. 1). Their investigation sheds light on many aspects of both the regional geology and the evolution of the convergent boundary as a whole. Biostratigraphic studies based on radiolarian and conodont assemblages play a significant role in reconstructing the structure and stratigraphy of the accretionary complexes, thus providing insight into the accumulation history of the accreted sequences both in the paleoocean and on the convergent boundaries of the lithospheric plates. In this respect, however, the accretionary complexes of the Russian Far East are fragmentarily and irregularly studied due to their poor exposure and the insufficient biostratigraphic investigations. The Amur Terrane with its ambiguously interpreted tectonic nature (accretionary complex vs. turbidite basin) remains the least studied geological object. In this connection, the purpose of the reconnaissance investigations carried out in the northwestern part of the Amur Terrane in the Komsomolsk-on-Amur area and the lower reaches of the Gorin River was obtaining additional information on the composition and age of the sediments constituting this structure.

AMUR TERRANE

B.A. Natal'in was the first to define the Amur Terrane (Fig. 1) and interpret it as a Cretaceous accretionary prism belonging to the Khingan–Okhotsk active continental margin [11, 27]. The terrane 100–120 km wide extends for ~650 km in the northeastern direction along the Amur River valley in its lower reaches. It contacts the Badzhal (Jurassic accretionary complex) and Kiselevka–Manoma (Early Cretaceous accretionary complex) terranes in the northwest and southeast, respectively. The Amur Terrane is composed of Upper Jurassic–Cenomanian [2, 3, 9, 11, 26, 27] largely turbidite sequences that experienced imbricate thrusting and multiphase folding [12]. It is thought that this accretionary complex resulted from the frontal accretion of deep-sea trench sediments [11, 12, 27]. Khanchuk et al. consider this terrane as an element of the larger Zhuravlevka–Amur Terrane formed in the Cretaceous turbidite basin of the transform margin [4, 8, 22]. Thus, the tectonic nature of the terrane is ambiguously interpreted, which is probably related to the fact that accreted oceanic sediments were never recorded in its sections. Nevertheless, such sediments are developed in the terrane, although, since the middle of the last century, they were described together with thick terrigenous sequences and never defined or mapped as autonomous stratigraphic units [2, 20]. Their age remained unknown for a long time as well.

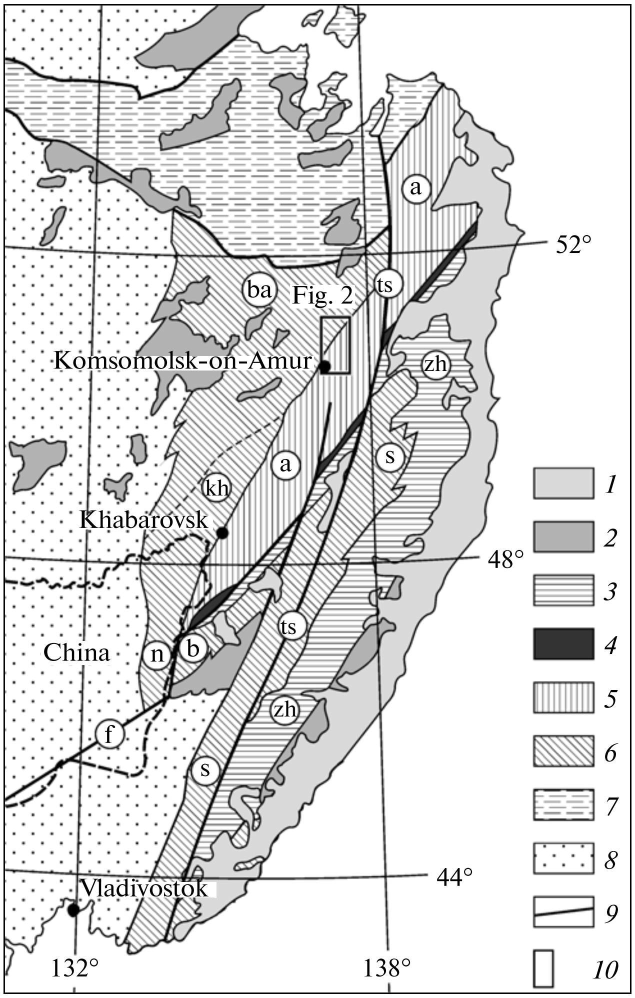


Fig. 1. The schematic tectonic map of the Russian Far East modified after [12, 27] and position of the studied area.
(*1, 2*) subduction-related volcanics: (*1*) Senonian–Paleocene, (*2*) pre-Senonian; (*3*) Zhuravleka Terrane, Early Cretaceous turbidite trough (zh); (*4, 5*) Cretaceous accretionary complexes: (*4*) Kiselevka–Manoma, (*5*) Amur (a); (*6*) Jurassic (Jurassic–Early Cretaceous) accretionary complexes: Badzhal (ba), Bikin (b), Nadan'khada (n) and Samarka (s); (*7*) Mongol–Okhotsk suture zone; (*8*) cratonic areas; (*9*) major faults, including the Central-Sikhote Alin (ts) and Fushun–Mishan faults (f); (*10*) studied area.

In the area under consideration, the most part of the terrane is composed of terrigenous sediments attributed to the Komsomol'sk Group [2, 3, 20], which is now accepted to be the Early Cretaceous (Berriasian–Valanginian) in age [14] (Fig. 1). The Komsomol'sk Group section outcropping in the right bank of the Amur River opposite to the Komsomolsk-on-Amur and characterized by abundant bivalve and ammonite remains is established to also include Upper Jurassic (Volgian) sediments [9, 26]. The southeastern part of the studied area is occupied by terrigenous rocks attributed to the Upper Cretaceous Gornaya Protoka Formation [20] (Fig. 2), whose age is now revised and presently considered as the Early Cretaceous (Barremian–Albian) [3, 14].

OCEANIC SEDIMENTS OF THE AMUR TERRANE

The later studies in the Amur Terrane area revealed that its section includes oceanic siliceous and siliceous–clayey sediments as tectonic slices among the continental-margin terrigenous sequences and dated some of them on the basis of radiolarian finds [19, 24, 26]. The slice of cherts and siliceous mudstones outcropping on the right bank of the Amur River opposite to Komsomolsk-on-Amur (Fig. 2) yielded Aalenian (Middle Jurassic) radiolarians in cherts and middle Callovian–early Kimmeridgian (Middle–Upper Jurassic) radiolarians at the base of a member of hemipelagic siliceous mudstones (approximately 40 m thick) overlying cherts [24, 26]. The host mudstones attributed to the Komsomolsk Group are characterized by Late Tithonian (Upper Jurassic) radiolarians [24, 26].

Easterly, in the Machtovaya River basin, the terrigenous sediments of the Gornaya Protoka Formation also enclose volcanogenic–siliceous rocks (Fig. 2). They were first defined during the large-scale geological mapping by I.P. Boiko (1962), who included them into the terrigenous section of the Cenomanian Sitoga Formation; subsequently, these sediments were attributed in this area to the Barremian–Albian Gornaya Protoka Formation [3, 14]. Based on recent radiolarian finds, the cherts from these sediments were dated back to the late Tithonan and late Tithonian–early Valanginian (Late Jurassic–Early Cretaceous), while clayey cherts from this section were attributed to the Albian (Early Cretaceous) [19].

Tectonic slices of oceanic sediments occur among terrigenous layers also in other areas near Komsomolsk-on-Amur (Fig. 2). For example, on the right bank of the Amur River west of the Verkhnetambovskoe settlement, foliated cherts, basalts, and basalt–limestone breccias are exposed in small outcrops among foliated mudstones of the Komsomolsk Group. In the near-mouth part of the Gorin River, siliceous mudstones constitute two thin tectonic slices. The rocks are intensely foliated being close in their structure to phyllites. The southern slice outcropping near the Bichi settlement is composed of olive-gray siliceous and calcareous mudstones occurring among finely rhythmical turbidites. Some outcrops of these rocks are traceable along the Gorin River in form of a high terrace bench. The slice thickness exceeds 100 m; it is conceivable that its section is made up of stacked sequences. The northern slice approximately 120 m thick is exposed on the left bank of the Gorin River, where it is composed of alternating foliated cherry red and olive gray siliceous mudstones among their phyllite-like dark gray varieties.

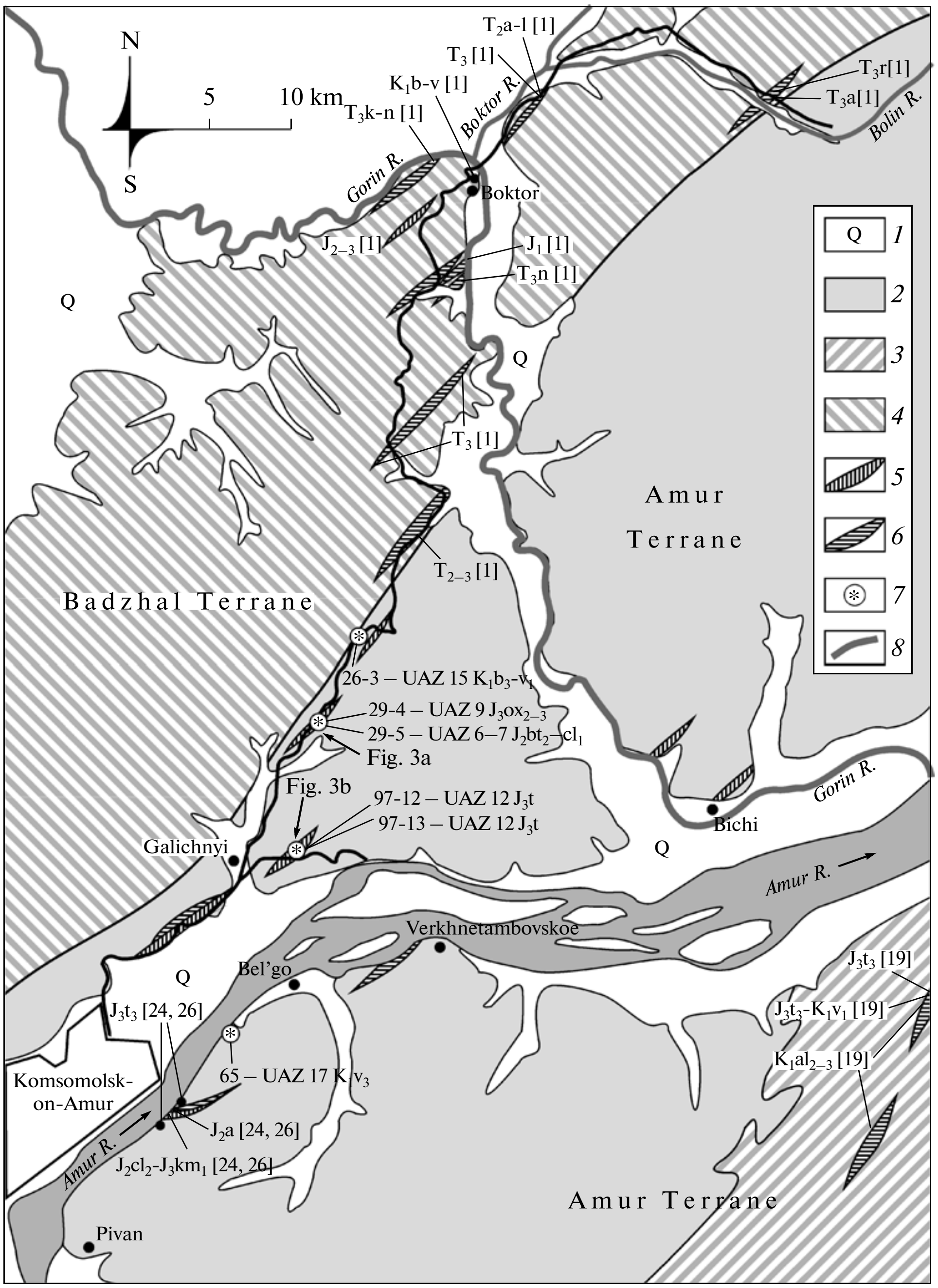


Fig. 2. Tectonic slices of volcanogenic–siliceous sediments among the terrigenous sequences of the Amur and Badzhal terranes. The map is based on geological maps in [2, 3, 20] modified using data from [1, 19, 24, 26] and original observations. The contours of slices are shown conditionally and out of scale; the indices show the available data on the age with the corresponding references. New data on the age are shown by the indices with indication of the sample number and the age according to the UAZ-95 scale [23].

(*1*) Quaternary sediments; (*2, 3*) Amur Terrane: (*2*) Volgian–Valanginian terrigenous sediments of the Komsomolsk Group, (*3*) Barremian–Albian terrigenous sediments of the Gornaya Protoka Formation; (*4*) Badzhal Terrane; (*5, 6*) tectonic slices of oceanic sediments: (*5*) siliceous mudstones, (*6*) cherts and basalts; (*7*) new radiolarian finds; (*8*) road.

In the northwestern part of the Amur Terrane adjacent to the Badzhal Terrane, isolated fragments of tectonic slices composed of cherts and siliceous mudstones are exposed in excavations and quarries along the Komsomolsk-on-Amur–Boktor settlement road (Fig. 2). The cherts exhibit scaly cleavage and are deformed into complex folds; some of them are transformed to quartzites. The siliceous mudstones are also characterized by intense scaly cleavage. The relationships between the slices and host rocks were never

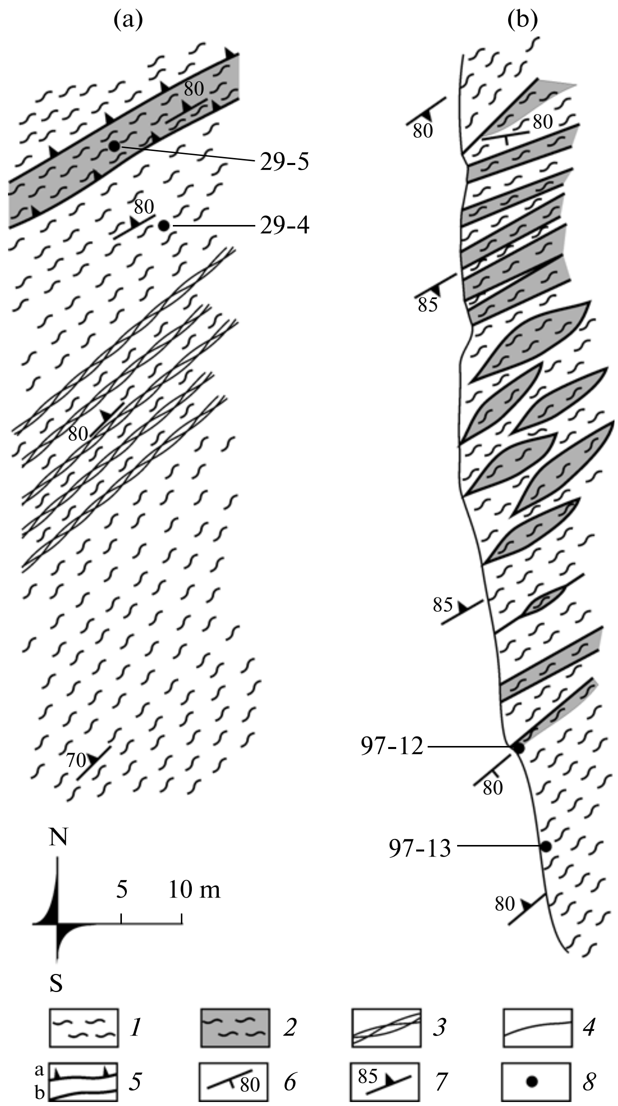


Fig. 3. The structure of the fragments of the tectonic slices composed of siliceous mudstones and the position of the samples with radiolarians.

(a) schematic sketch of the quarry wall (10 km northeast of the Galichnyi Settlement); (b) sketch of the eastern step of the quarry 3 km east of the Galichnyi Settlement (in plan).

(*1*) olive-gray siliceous mudstones; (*2*) red siliceous mudstones; (*3*) zone of intense foliation; (*4*) stratigraphic contacts; (*5*) faults: (a) steep, (b) near-vertical; (*6*) bedding orientation; (*7*) foliation orientation; (*8*) position of the samples with radiolarians.

observed. The internal structure of the slices is exemplified by two relatively extended outcrops in quarries near the Galichnyi settlement. The northern slice (Fig. 3a) is composed of foliated olive-gray siliceous mudstones with a thin (2–4 m) fault-bounded lens of red varieties. The cleavage planes are characterized by steep northwestern dips. The slice thickness estimated in different quarry outcrops exceeds 100 m. The similarly thick southern slice differs in its more complex structure (Fig. 3b). It consists of alternating near-vertical layers of cherry red and olive gray siliceous mudstones. Most of the contacts between these varieties are tectonic with schistosity characterized by steep dips in both the northwestern and southeastern directions. The middle part of the slice exhibits a distinct lenticular structure.

The slices of siliceous–clayey and siliceous rocks are separated by thicker sequences composed of mudstones and turbidites of the Komsomolsk Group. The rocks experienced zoned foliation with the development of parallel and lenticular cleavage. The extended bank outcrops along the Gorin River are complicated by folds of different morphologies and sizes.

This brief review demonstrates that the oceanic pelagic and hemipelagic facies occur in the form of thin tectonic slices among the continental-margin sediments of the Amur Terrane. In this regard, the examined part of the terrane is similar to the adjacent southeastern part of the Badzhal Terrane (Fig. 2), which is unambiguously interpreted as representing an accretionary complex [1, 4, 8, 12, 22, 27]. The only difference between them consists in their lithology: the slices in the Amur Terrane are largely composed of siliceous mudstones, while, in the adjacent segment of the Badzhal Terrane, they are mostly cherty. The occurrence of oceanic sediment slices among the intensely deformed continental-margin facies is characteristic of accretionary complexes and allows precisely such an interpretation of the tectonic nature of the Amur Terrane. In its general structural patterns and the quantitative proportions of the oceanic continental-margin sediments, the Amur Terrane is similar to the Cretaceous part of the Shimanto Terrane in Japan, which is also largely composed of turbidites [28].

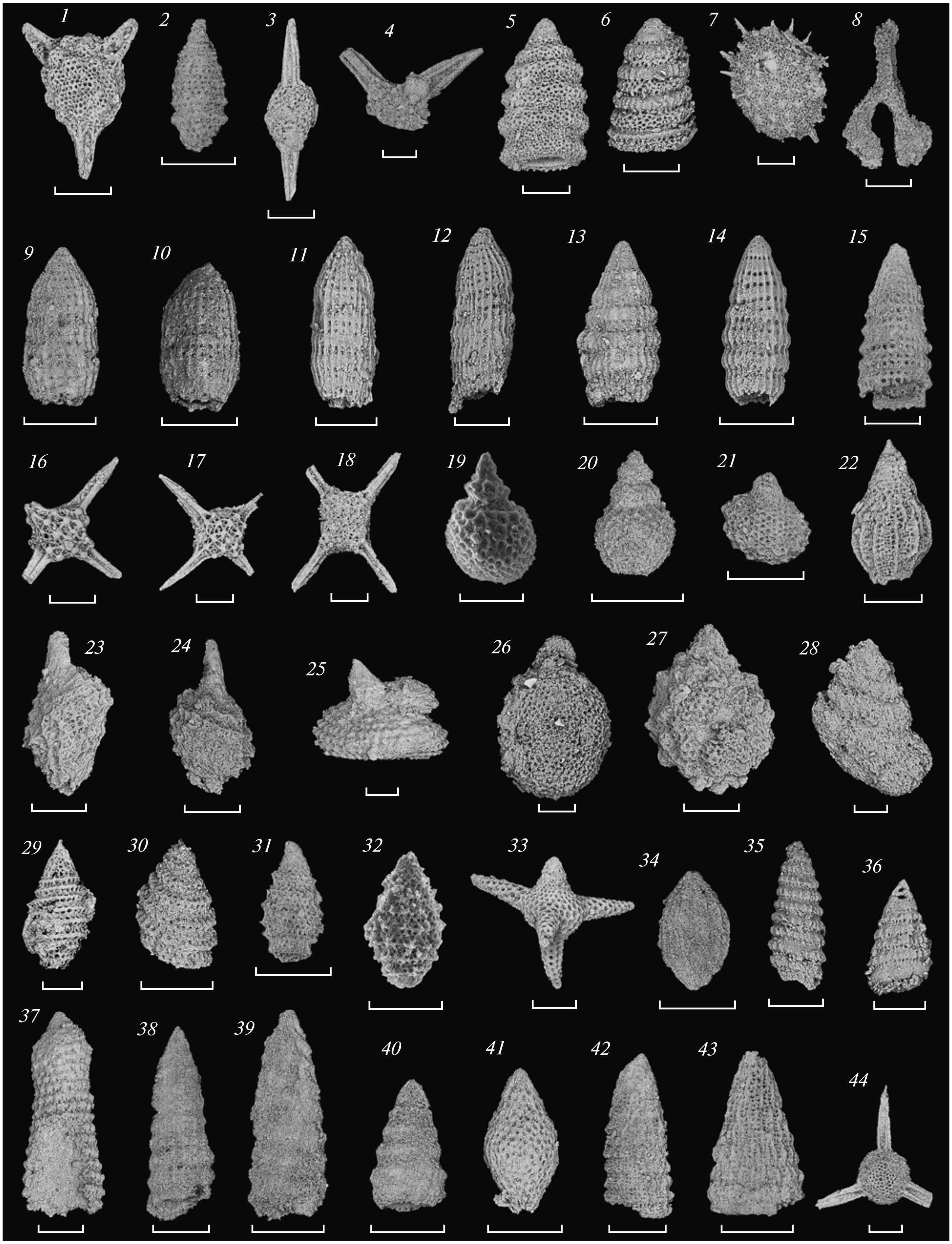
NEW DATA ON THE SEDIMENT AGE

One of the purposes of this work was obtaining additional age data on the sediments constituting the Amur Terrane. For the radiolarian analysis, over 80 samples were taken from the least deformed hemipelagic siliceous mudstones and host terrigenous sediments. The radiolarians were extracted using diluted hydrofluoric acid and then picked from the residue for the subsequent identifying and photographing of their specimens under the scanning electron microscope. Most of the samples contain strongly deformed (elongated and flattened) and recrystallized, although abundant, radiolarian skeletons. Only some of the samples appeared to be suitable for dating of the sediments. The age was determined using the scale of the Unitary Association Zones (UAZ-95) from [23]. The table presents the data on the taxonomic composition of the identified radiolarians, their stratigraphic ranges, and the ages of the sediments. All the mentioned species are provided with their SEM images (plate).

The distribution of radiolarians in mudstones and their siliceous varieties from the Amur Terrane

Radiolarian species	Zone UAZ-95	Sample					
		26-3	29-4	29-5	65	97-12	97-13
Acaeniotyle diaphorogona Foreman	4-22	+					
Amphipyndax durisaeptum Aita	3-7			+U			
Archaeospongoprunum patricki Jud	13-22	+					
Bernoullius rectispinus s.l. Kito, De Wever, Danelian & Cordey	1-9		+U				
Canoptum banale Jud	13-16	+					
Cinguloturris cylindra Kemkin & Rudenko	12-17				+U	+L	+L
Dactyliodiscus lenticulatus (Jud)	15-22	+L					
Deviatus diamphidius (Foreman)	8-22					+	
Dictyomitra apiarium (Rüst)	8-22				+	+	+
Dictyomitra excellens (Tan)	11-22				+	+	+
Dictyomitra minoensis (Mizutani)	9-12						+U
Dictyomitra pseudoscalaris (Tan) sensu Schaaf	17-22				+L		
Dictyomitrella (?) *kamoensis* Mizutani & Kido	3-7			+U			
Emiluvia chica Foreman	3-18	+				+	
Emiluvia pessagnoi Foreman	4-17	+				+	
Hiscocapsa funatoensis (Aita)	3-11			+			
Hiscocapsa uterculus (Parona)	11-22					+	
Hiscocapsa zweilii (Jud)	14-19				+		
Hsuum raricostatum Jud	13-15	+U					
Mirifusus chenodes (Renz)	6-22					+	
Mirifusus minor Baumgartner	9-20				+	+	
Obesacapsula bullata Steiger	13-19				+		
Obesacapsula cetia (Foreman)	10-17					+	
Obesacapsula verbana (Parona)	11-20	+			+		
Parvicingula boesii (Parona)	9-22	+	+L		+	+	
Parvicingula dhimenaensis Baumgartner	3-11		+	+			
Parvicingula usotanensis Tumanda	15-22				+		
Podocapsa amphitreptera Foreman	9-18	+				+	
Protunuma japonicus Matsuoka & Yao	7-12		+			+U	
Pseudodictyomitra carpatica (Lozyniak)	11-21				+		+
Pseudodictyomitra nuda (Schaaf)	16-22				+		
Ristola altissima s.l. (Rüst)	5-12					+U	
Spongocapsula palmerae Pessagno	6-13		+	+L			
Spongocapsula perampla (Rüst)	6-11		+	+L			
Stichocapsa pulchella (Rüst)	17-22				+U		
Transhsuum hisuikyoense (Isozaki & Matsuda)	3-7			+			
Transhsuum maxwelli gr. (Pessagno)	3-10		+				
Triactoma tithonianum Rüst	6-22	+					
Sample age in the UAZ-95 scale		15	9	6-7	17	12	12

Note: (+) identified species; (L) the lower age limit; (U) the upper age limit.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Radiolarians from siliceous mudstones and mudstones of the Amur Terrane. The bar is 100 μm.

(*1*) *Acaeniotyle diaphorogona* Foreman, sample 26-3; (*2*) *Amphipyndax durisaeptum* Aita, sample 29-5; (*3*) *Archaeospongoprunum patricki* Jud, sample 26-3; (*4*) *Bernoullius rectispinus* s.l. Kito, De Wever, Danelian et Cordey, sample 29-4; (*5*) *Canoptum banale* Jud, sample 26-3; (*6*) *Cinguloturris cylindra* Kemkin et Rudenko, sample 65; (*7*) *Dactyliodiscus lenticulatus* (Jud), sample 97-12; (*8*) *Deviatus diamphidius* (Foreman), sample 97-12; (*9*, *10*) *Dictyiomitra apiarium* (Rüst), samples 97-13 and 97-12, respectively; (*11*, *12*) *Dictyiomitra excellens* (Tan), samples 97-12 and 97-13, respectively; (*13*) *Dictyiomitra minoensis* (Mizutani), sample 97-13; (*14*) *Dictyomitra pseudoscalaris* (Tan) sensu Schaaf, sample 65; (*15*) *Dictyiomitrella* (?) *kamoensis* Mizutani et Kito, sample 29-5; (*16*, *17*) *Emiluvia chica* Foreman, samples 26-3 and 97-12, respectively; (*18*) *Emiluvia pessagnoi*, sample 26-3; (*19*) *Hiscocapsa uterculus* (Parona), sample 97-12; (*20*) *Hiscocapsa zweilii* (Jud), sample 65; (*21*) *Hiscocapsa funatoensis* (Aita), sample 29-5; (*22*) *Hsuum raricostatum* Jud, sample 26-3; (*23*, *24*) *Mirifusus chenodes* (Renz), sample 97-12; (*25*) *Mirifusus minor* Baumgartner, Sample 97-12; (*26*) *Obesacapsula bullata* Steiger, sample 65; (*27*) *Obesacapsula cetia* (Foreman), sample 97-12; (*28*) *Obesacapsula verbana* (Parona), sample 65; (*29*, *30*) *Parvicingula* ex gr. *boesii* (Parona), samples 26-3 and 97-12, respectively; (*31*) *Parvicingula dhimenaensis* Baumgartner, sample 29-5; (*32*) *Parvicingula usotanensis* Tumanda, sample 65; (*33*) *Podocapsa amphitreptera* Foreman, sample 26-3; (*34*) *Protunuma japonicus* Matsuoka et Yao, sample 29-4; (*35*) *Pseudodictyomitra carpatica* (Lozyniak), sample 65; (*36*) *Pseudodictyomitra nuda* (Schaaf), sample 65; (*37*) *Ristola altissima* s.l. (Rüst), sample 97-12; (*38*, *39*) *Spongocapsula palmerae* Pessagno, samples 29-4 and 29-5, respectively; (*40*) *Spongocapsula perampla* (Rüst), sample 29-5; (*41*) *Stichocapsa pulchella* (Rüst), sample 65; (*42*) *Transhsuum hisuikyoense* (Isozaki et Matsuda), Sample 29-5; (*43*) *Transhsuum maxwelli* gr. (Pessagno), sample 29-4; (*44*) *Triactoma tithonianum* Rüst, sample 26-3.

The age of the siliceous mudstones was established for two tectonic slices in the northwestern part of the terrane in the Galichnyi settlement area (Fig. 2, table). The stratigraphic position of these samples is shown in Fig. 3. In the northern slice (Fig. 3a), red mudstones (sample 29-5) contain middle Bathonian–early Callovian samples (Middle Jurassic, zones 6–7 of the UAZ-95 scale), which is evident from the cooccurrence of *Amphipyndax durisaeptum* Aita, *Dictyomitrella (?) kamoensis* Mizutani et Kido, *Spongocapsula palmerae* Pessagno, and *S. perampla* (Rüst). Olive-gray siliceous mudstones contacting the last variety along the fault (sample 29-4) are characterized by middle-late Oxfordian radiolarians (Late Jurassic, Zone 9 of the UAZ-95 scale). Their age is derived from the cooccurrence of *Bernoullius rectispinus* s.l. Kito, De Wever, Danelian, et Cordey, and *Parvicingula boesii* (Parona). In the southern slice, samples from red (97-12) and olive-gray (97-13) siliceous mudstones are dated back to the Tithonian (Late Jurassic, zone 12 of the UAZ-95 scale). The lower age limit is determined by the occurrence of *Cinguloturris cylindra* Kemkin et Rudenko in both samples, and the upper one, by the finds of *Ristola altissima* (Rüst) and *Protunuma japonicus* Matsuoka et Yao in sample 97-12 and *Dictyomitra minoensis* (Mizutani) in sample 97-13.

The mudstones from the thick sequence of terrigenous sediments (Fig. 2) were dated in the northwestern part of the Amur Terrane near its boundary with the Badzhal Terrane (sample 26-3) and, southerly, on the right bank of the Amur River (sample 65). Sample 26-3 was taken in the small near-road quarry 15 km northeast of the Galichnyi settlement from a mudstone member with numerous silty laminae. Similar rocks are observed also southerly, where they alternate with bioturbated mudstones and rare turbidite beds. The late Berriasian–early Valanginian age of these rocks (Early Cretaceous, zone 15 of the UAZ-95 scale) is established from the radiolarian assemblage with cooccurring *Dactyliodiscus lenticulatus* (Jud) and *Hsuum raricostatum* Jud (table). Sample 65 was taken from the sequence (a few hundreds of meters thick) of alternating mudstones and tuffaceous siltstones with rare turbidite layers outcropping 3 km southwest of the Bel'go

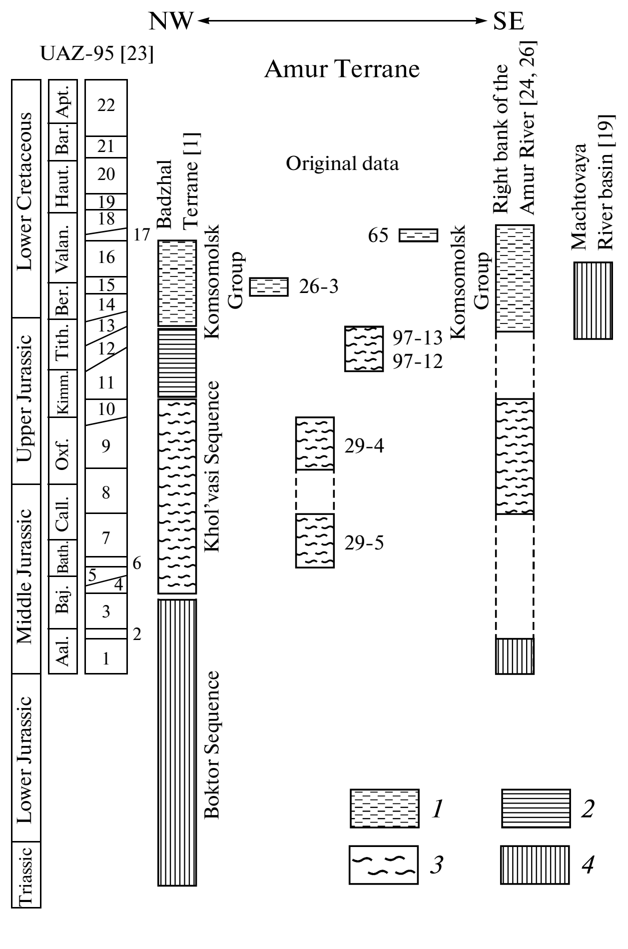

Fig. 4. Stratigraphic correlation of the oceanic and continental-margin sediments of the Amur Terrane and the adjacent part of the Badzhal Terrane.

(*1*) mudstones and turbidites; (*2*) shales and siltstones; (*3*) siliceous mudstones; (*4*) cherts and basalts.

settlement; these rocks were previously referred to the Upper Jurassic [20]. This sample yielded the late Valanginian radiolarian assemblage (Early Cretaceous, zone 17 of the UAZ-95 scale), which follows from the finding of *Dictyomitra pseudoscalaris* (Tan) and *Cinguloturris cylindra* Kemkin et Rudenko (table).

DISCUSSION

The new age data supplement and widen the available views on the accumulation time of the hemipelagic oceanic sediments in the examined part of the Amur Terrane (Fig. 4). The fragmentary character of these data allows only general stratigraphic correlations and inferences. The age of the siliceous–clayey sediments was established only for separate fragments of tectonically disturbed sedimentary successions. It should be taken into consideration that the correlation model in Fig. 4 demonstrates only the age limits of the samples and not the stratigraphic ranges of the corresponding units. According to these data, the accumulation of the hemipelagic siliceous mudstones that are included into the structure of the northwestern Amur Terrane was in progress at least since the middle Bathonian–early Callovian until the Tithonian. The commencement of the deposition of the siliceous mudstones that outcrop southerly on the right bank of the Amur River [24] is dated more reliably, although within a wider period. In this area, their succession is estimated to be the Middle Callovian to early Kimmeridgian in age. Thus, the lower boundary of the hemipelagic siliceous mudstones becomes younger in the NW–SE direction transversely to the terrane's strike. In the late Tithonian, the hemipelagic sedimentation gave way to the accumulation of mudstones and turbidites in the deep-sea trench [24, 26]. The late Berriasian–early Valanginian and late Valanginian dates of the mudstones correspond to different stratigraphic levels of these terrigenous sediments attributed to the Komsomol'sk Group. The terrigenous sediments constituting the northwestern segment of the Amur Terrane are coeval with the upper Tithonian–lower Valanginian volcanogenic–siliceous strata outcropping in the Machtovaya River basin in the southeastern part of the area under consideration [19] (Fig. 4), which implies substantially younger ages for the lower boundaries of the pelagic, hemipelagic, and continental-margin successions in the southeastern direction.

The comparison between the accumulation patterns of the different-facies sediments in the neighboring segments of the Amur and Badzhal terranes is also complicated by the few and too fragmentary biostratigraphic data. The geological mapping carried out in the southeastern part of the Badzhal Terrane in the middle of the last century revealed Middle–Upper Jurassic substantially terrigenous sediments, which also included volcanogenic–siliceous facies [2]. Anoikin [1], who conducted special studies in this area, proposed a new stratigraphic scheme [1] where the volcanogenic–siliceous sediments were attributed to the Middle Triassic–Middle Jurassic Boktor sequence, while the siliceous mudstones, shales, and siltstones were included into the Middle–Upper Jurassic Khol'vasi Sequence (Fig. 4). A significant part of the terrigenous sediments was also referred to the Upper Jurassic–Lower Cretaceous Komsomol'sk Group. The age of these stratigraphic units was substantiated by new radiolarian and conodont finds [1], as well as by previously obtained data [5, 15]. The positions of the boundaries between the sedimentary sequences (Fig. 4) are relatively conditional, since the age of their isolated fragments is frequently determined within wide limits. The boundary between the hemipelagic siliceous mudstones and the terrigenous shales and siltstones united into the Khol'vasi Sequence is drawn in accordance with the dates obtained for the siliceous mudstones [1] (Fig. 4). The available data indicate that both the hemipelagic and terrigenous sedimentation commenced in the southeastern part of the Badzhal Terrane slightly earlier as compared with that in the Amur Terrane area (Fig. 4). This contributes to the general diachronic pattern of the stratigraphic boundaries characteristic of the accretionary complexes.

CONCLUSIONS

The terrigenous continental-margin sequences of the Amur Terrane enclose thin tectonic slices composed of oceanic pelagic and hemipelagic sediments. Together with the imbricate–thrust structure of the terrane, the occurrence of such slices allows the Amur Terrane to be interpreted as an accretionary complex. The presented data on the Middle–Late Jurassic age of the hemipelagic oceanic sediments contribute to the knowledge of the terrane's stratigraphy and indicate the progressively younger position of the stratigraphic boundaries between the different-facies sequences in the southeastern direction toward the assumed area of the subducting lithospheric plate.

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