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Research Paper

Segmental closure of the Mongol-Okhotsk Ocean: Insight from detrital geochronology in the East Transbaikalia Basin

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ABSTRACT

The Late Paleozoic–Early Mesozoic Mongol-Okhotsk Ocean extended between the Siberian and Amur–North China continents. The timing and modalities of the oceanic closure are widely discussed. It is largely accepted that the ocean closed in a scissor-like manner from southwest to northeast (in modern coordinates), though the timing of this process remains uncertain. Recent studies have shown that both western (West Transbaikalia) and eastern (Dzhagda) parts of the ocean closed almost simultaneously at the Early–Middle Jurassic boundary. However, little information on the key central part of the oceanic suture zone is available. We performed U-Pb (LA-ICP-MS) dating of detrital zircon from well-characterized stratigraphic sections of the central part of the Mongol-Okhotsk suture zone. These include the initial marine and final continental sequences of the East Transbaikalia Basin, deposited on the northern Argun-Idemeg terrane basement. We provide new stratigraphic ages for the marine and continental deposits. This revised chronostratigraphy allows assigning an age of ~165–155 Ma, to the collision-related flexure of the northern Argun-Idemeg terrane and the development of a peripheral foreland basin. This collisional process took place 5 to10 million years later than in the western and eastern parts of the ocean. We demonstrate that the northern Argun-Idemeg terrane was the last block to collide with the Siberian continent, challenging the widely supported scissor-like model of closure of the Mongol-Okhotsk Ocean. Different segments of the ocean closed independently, depending on the initial shape of the paleo continental margins.

1. Introduction

The closure of the Late Paleozoic–Early Mesozoic Mongol-Okhotsk Ocean is one of the largest and yet highly discussed paleo-geodynamic events in the tectonic evolution of East Asia. As part of the Paleo-Pacific Ocean, the Mongol-Okhotsk Ocean extended between the Siberian and Amur–North China continents (Zonenshain et al., 1990; Sengör and Natal'in, 1996; Yin and Nie, 1996; Zorin, 1999; Parfenov et al., 2003). Relics of this ocean are exposed as meta-sediments and meta-volcanic rocks in the Mongol-Okhotsk Belt that stretches northeastward from the Hangay Mountains of Central Mongolia to the Sea of Okhotsk (Fig. 1). There is still no consensus on many aspects of the evolution of the Mongol-Okhotsk Ocean (see reviews in Kuzmin and Filippova, 1979; Zorin, 1999; Tomurtogoo et al., 2005; Donskaya et al., 2013). Several models have been proposed for the closure of that ocean but the significance of geochronological ages obtained on the subduction/collision related magmatic complexes is still actively discussed. The proposed age of the oceanic closure varies from the Permian to the Early Cretaceous, mainly because of the wide variety and sometimes inaccuracy of the considered data (Nie et al., 1990; Zonenshain et al., 1990; Nie, 1991; Yin and Nie, 1993, 1996; Kuzmin and Kravchinsky, 1996; Davis et al., 1998; Halim et al., 1998; Zorin et al., 1998; Gordienko and Kuz'min, 1999; Zorin, 1999; Darby et al., 2001; Kravchinsky et al., 2002; Parfenov et al., 2003; Cogné et al., 2005; Metelkin et al., 2007, 2010; Didenko et al., 2013; Donskaya et al., 2013; Van der Voo et al., 2015; Yang et al., 2015; Demonterova et al., 2017; Jolivet et al., 2017; Arzhannikova et al., 2020; Yi and Meert, 2020 and others). More specifically, the lack of absolute stratigraphic age for the marine and continental deposits and numerous

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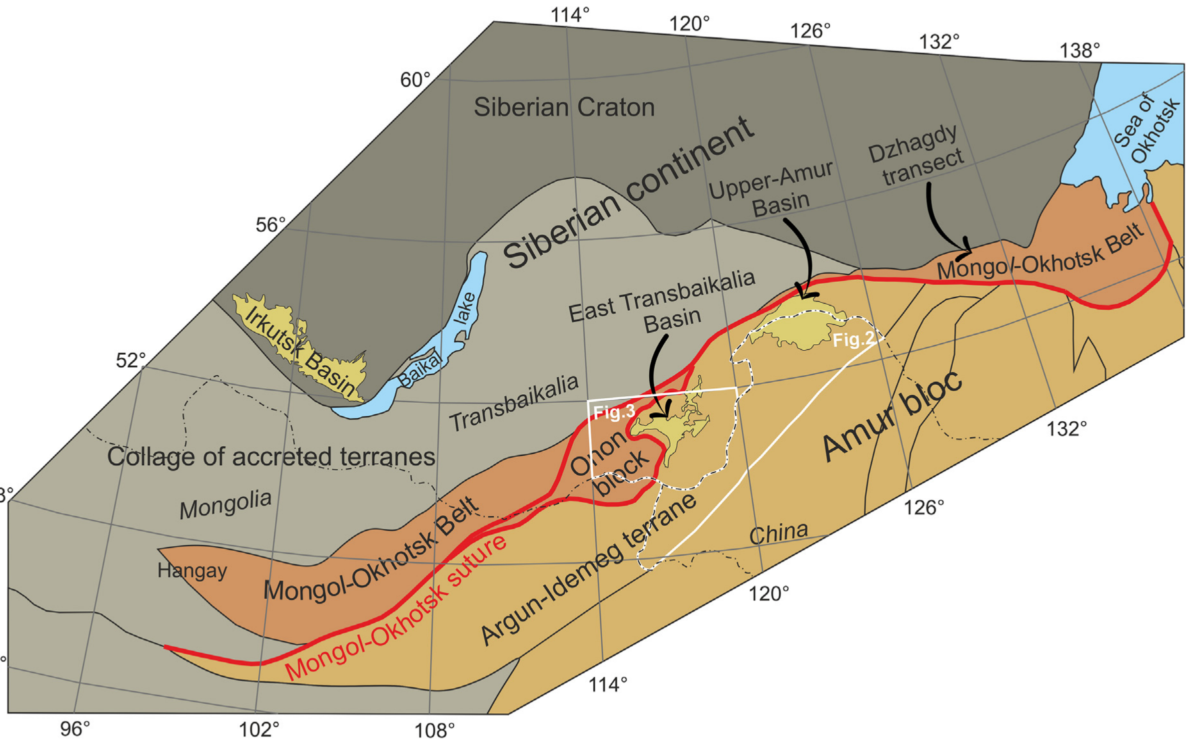

Fig. 1. Tectonic position of the Mongol-Okhotsk Belt (modified from Parfenov et al., 1999). The location of the Mongol-Okhotsk suture (red line) is given after Tomurtogoo et al. (2005).

inconsistencies between the paleomagnetic and geological data prevent drawing final conclusions on the timing of the oceanic closure. Most of the geodynamic models imply gradual (scissor-like as coined by Zonenshain et al., 1990) southwest to northeast (in modern coordinates) closure of the ocean and progressive formation of the Mongol-Okhotsk fold belt as suggested by the northeastward decreasing age of the volcano-sedimentary complexes (Zhao et al., 1990; Zonenshain et al., 1990; Scotese, 1991; Kravchinsky et al., 2002; Parfenov et al., 2003; Tomurtogoo et al., 2005; Metelkin et al., 2010). However, recently published U-Pb detrital zircon dates and isotope-geochemical analysis of marine metasediments in the eastern Mongol-Okhotsk Belt indicate a westward decrease in the age of the oceanic closure. Along the Dzhagdy transect (Fig. 1) the results revealed no detrital zircon grains younger than 171 Ma in the marine sediments and allowed dating the closure of the eastern Mongol-Okhotsk Ocean to the Early–Middle Jurassic boundary (Sorokin et al., 2020). West of the Dzhagdy transect, around the Upper-Amur Basin (Fig. 1), the width of the Mongol-Okhotsk Belt is very restricted and the closure of the ocean seems to have occurred later than in the Dzhagdy region. Indeed, the stratigraphic age of the sediments and the variations in sediment provenance identified based on U-Pb geochronology of detrital zircon suggest a gradual oceanic closure from the Kimmeridgian–Tithonian to the west to the Berriasian–Valanginian to the northeast of the Upper-Amur Basin (Guo et al., 2017).

The Upper Amur Basin is situated in the south-western part of the restricted zone of the Mongol-Okhotsk Belt and belongs to the northern Argun-Idemeg terrane. This terrane forms the northwestern side of the Amur block (Fig. 1) which converged with the Siberian continent during the Late Paleozoic and Mesozoic until complete closure of the Mongol-Okhotsk Ocean (Zonenshain et al., 1990; Parfenov et al., 2003, 2010). A large segment of the most restricted part of the Mongol-Okhotsk Belt to the southwest of the Upper-Amur Basin remains unstudied with respect to determining the absolute age and provenance of the exposed Jurassic sediments. Filling this gap is of major importance: (i) it should help understanding the peculiar geodynamic conditions that lead to such a restricted belt along that segment of the Mongol-Okhotsk collision zone and (ii) it will confirm or infirm that this part of the belt is younger than the Dzhagdy segment, testing the validity of the widely supported hypothesis of a scissor-like northeastward oceanic closure. In this work we present the results of U-Pb (LA-ICP-MS) dating of detrital zircons from both marine terrigenous and continental deposits of the East Transbaikalia Basin on the northern Argun-Idemeg terrane (Fig. 1). We provide new stratigraphic framework for the sediments, identify the source areas, and date the transition from marine to continental depositional environment. Finally, we discuss the timing of complete closure of the Mongol-Okhotsk Ocean in this region and place it within the context of the general evolution of the Mongol-Okhotsk orogeny.

2. Geological setting

2.1. Geology of the Argun-Idemeg terrane and East Transbaikalia Basin

The Argun-Idemeg terrane is located southeast of the Mongol-Okhotsk suture zone (Fig. 1). According to Zonenshain et al. (1990), Parfenov et al. (2010), Wu et al. (2011) and Sun et al. (2013), it has a Neoproterozoic granite-metamorphic basement overlain by sedimentary series showing several unconformities related to tectonic and magmatic events. Recently published U-Pb ages of magmatic zircons from granodiorites and gneisses in the Erguna block (northeastern part of the Argun-Idemeg terrane) revealed the Paleoproterozoic age of the basement (Sun et al., 2019; Liu et al., 2020). Several marine transgressions, resulting in the accumulation of sandstones, clay, and carbonates took place on the Erguna block in the Late Proterozoic–Early Cambrian, from the Silurian to the Early Carboniferous and in the Early–Middle Jurassic. Interruptions in sedimentation are associated with periods of tectonic deformation, erosion, and volcanic activity in the Late Cambrian–Ordovician, at the Middle to Late Paleozoic transition and from the Early Permian to the Early Triassic (Starchenko, 2010). U-Pb dating of magmatic zircons from granitoids of the Erguna block allowed constraining the spatial and temporal distribution of granitic magmatism in the area (Wu et al., 2011) (Fig. 2). According to this data, most of intrusions were emplaced during the Early Paleozoic (416–517 Ma), Late Triassic–Early Jurassic (182–220 Ma) and Early Cretaceous (118–132 Ma). Two minor stages of granitic magmatism occurred in the Neoproterozoic (792–927 Ma) and Late Paleozoic–Early Mesozoic (244–336 Ma).

The last marine stage is associated with the formation of the Mesozoic East Transbaikalia Basin (Fig. 3, see location on Fig. 1) along the Mongol-Okhotsk Ocean subduction zone. As indicated by the occurrence of marine fauna assemblages, marine sedimentation lasted from the Pliensbachian to the Aalenian (Starchenko, 2010). During that period, thick accumulations of marine clastic sediments were deposited, divided into the proximal coastal environments of the Algachi-Kalgan zone and the more distal environments of the Onon-Gazimur zone (Fig. 4). Four depositional stages have been individualized: 1 – initial flexure in the Onon-Gazimur zone with accumulation of psamitic-pelitic deposits of the Ikagiisk Fm., 2 – enhanced subsidence and basin widening with fully marine sedimentation in the Onon-Gazimur zone (Tamenginsky Fm.) and onset of coastal marine sedimentation in the Algachi-Kalagan zone (Akatui Fm.), 3 – marine regression and deposition of the Sivachinsky and Bazanov molasse fms., 4 – a final stage showing an initial deepening (Gosudarevsky Fm.) followed by regression (Kavykuchinsky Fm.) in the Onon-Gazimur marine basin and discontinuous proximal sedimentation in the Algachi-Kalgan zone (Bokhtin Fm.). A hiatus in sedimentation is possibly associated with the transition between the transgression and regression phases in the Onon-Gazimur zone. Based on the large amount of plant macro-fossils preserved in the sediment, complete regression occurred during the Bajocian as marine terrigenous sedimentation was replaced by continental coarse-grained molasse deposits of the Upper Gazimur Fm. (Starchenko, 2010).

Based on this stratigraphy, the closure of the Mongol-Okhotsk Ocean in the East Transbaikalia area is dated to the early Middle Jurassic at the transition from marine to continental sedimentation (Zorin, 1999; Parfenov et al., 2003). The series are dated from paleontological and paleofloristic data (Starchenko, 2010), as no

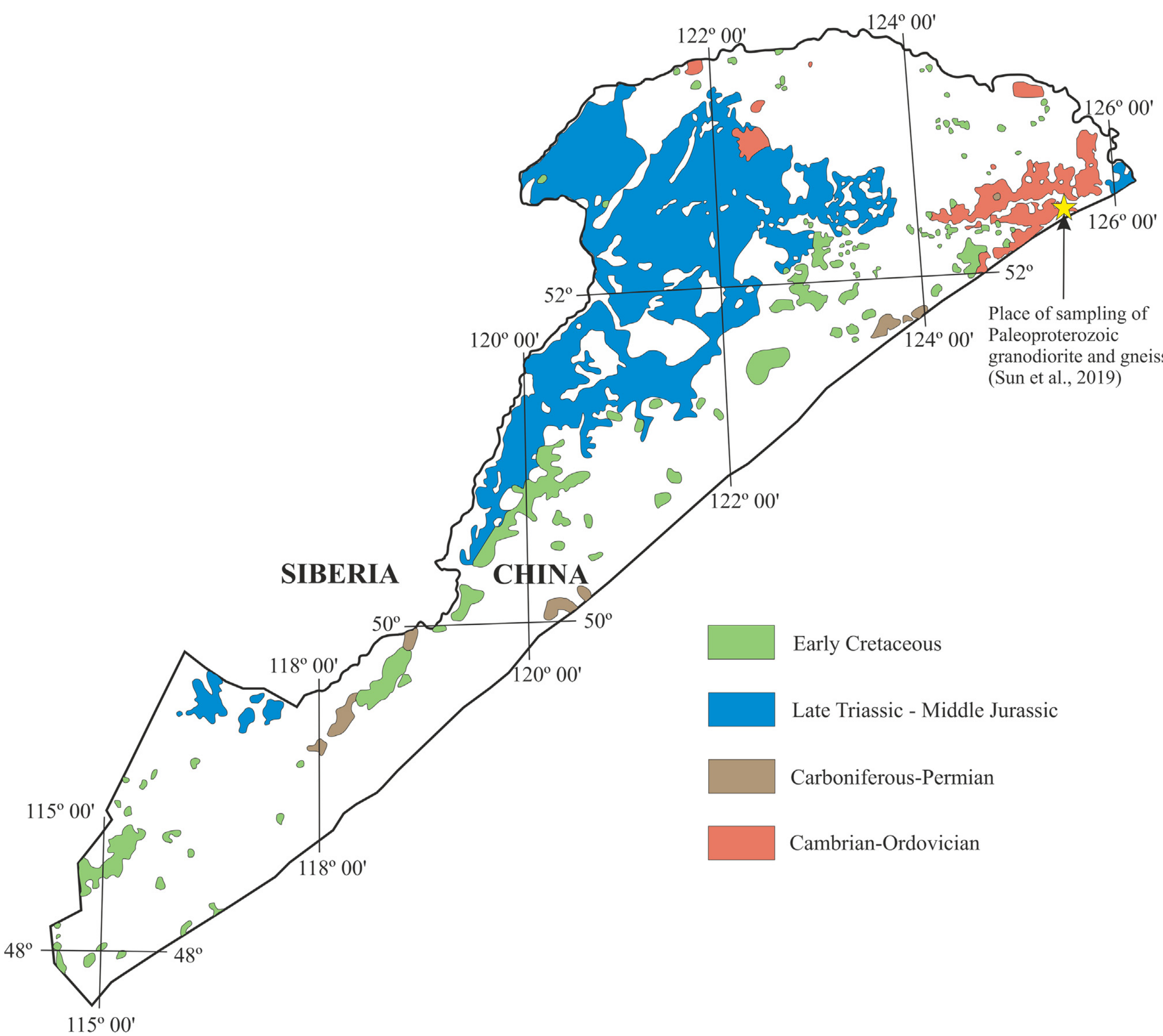

Fig. 2. Temporal-spacial distribution map of Phanerozoic granitoids in the Erguna block (modified after Wu et al., 2011) with the addition of a sampling place of granodiorite and gneiss of Paleoproterozoic age (after Sun et al., 2019).

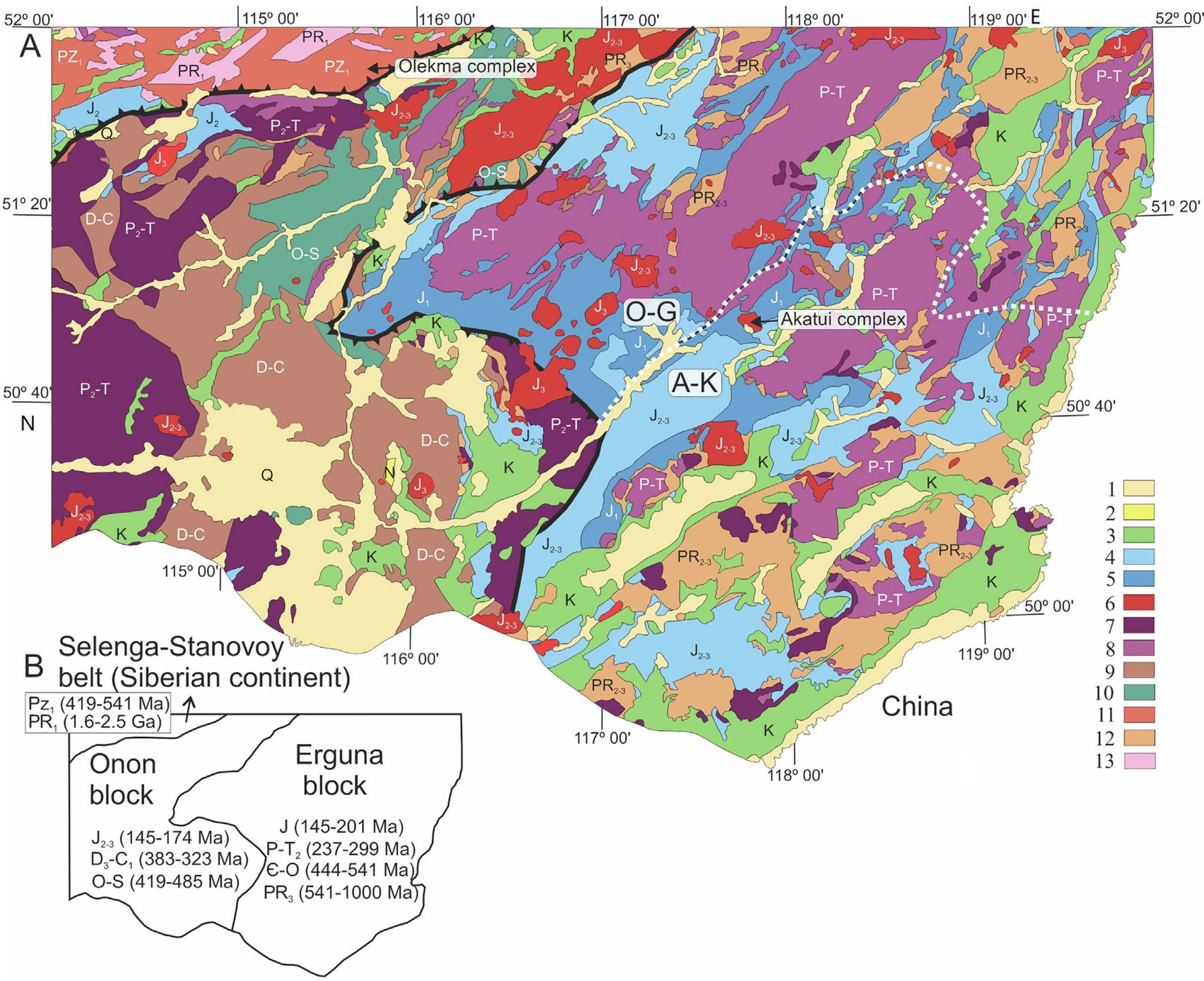

Fig. 3. (A) Geological map of the East Transbaikalia Basin and adjacent area simplified (after Starchenko, 2010) with modification of the age of some geological units (after Sasim et al., 2016; Gordienko et al., 2019). 1 – Quaternary alluvial deposits, 2 – Neogene lacustrine sediments, 3 – Cretaceous sedimentary-volcanic deposits, 4 – Jurassic continental deposits, 5 – Jurassic marine deposits, 6 – Middle–Late Jurassic volcanic rocks, 7 – Permo-Triassic sedimentary rocks, 8 – Permo–Triassic volcanic rocks, 9 – Devonian–Carboniferous sedimentary-volcanic deposits and rhyolites, 10 – Ordovician–Silurian metamorphic sedimentary-volcanic rocks; 11 – Early Paleozoic granitoids, 12 – Mezo- and Neoproterozoic metamorphic sedimentary-volcanic rocks, 13 – Paleoproterozoic metamorphic sedimentary rocks and granitoids. The bold black line shows main thrusts along the Mongol-Okhotsk Suture, the white dotted line indicates the boundary between the Onon-Gazimur (O-G) and Algachi-Kalgan (A-K) zones. (B) Scheme of the tectonic blocks in the study area with ages of magmatic rocks.

absolute age exists. However, a younger age for the oceanic closure can be inferred from the Late Jurassic change in geochemical composition of the East Transbaikalia volcanic rocks from shoshonite-latite, typical of active continental margins, to trachybasalt, typical of intracontinental volcanism (Khlif et al., 2017). ^{40}Ar-^{39}Ar dating of shoshonite-latites of the Akatui intrusive massif within the East Transbaikalia Basin (Fig. 3A) indicates emplacement ages from 162 Ma to 155 Ma (Sasim et al., 2016).

2.2. Stratigraphy of the East Transbaikalia Basin

2.2.1. The proximal Algachi-Kalagan zone

The Akatui Fm. represents the onset of Jurassic coastal-marine deposits and is assigned to the Late Pliensbachian (J_1) (Starchenko, 2010). The basal deposits are composed of conglomerates and breccias resting unconformably on the Devonian basement. The series evolves upward to sandstones, siltstones, and argillites.

The Bazanov Fm. conformably overlies the Akatui Fm., sometimes with gradual transition and evidence of intra-formation erosion phases. The deposits are largely composed of polymictic pebbly conglomerates interlayered with gravel conglomerates and sandstones. Some few siltstone interlayers are also observed. Sandstones are mainly confined to the central part of the formation, while the upper and lower levels consist mainly of conglomerates. The Bazanov Fm. is poorly characterized in terms of paleontology. The age of the formation (Late Pliensbachian–Early Toarcian (J_1)) is assigned based on the correlation with the Sivachinsky Fm. of the distal Onon-Gazimur zone.

Most of the Bokhtin Fm., uppermost among the coastal-marine formations, conformably overlies the Bazanov Fm. and corresponds in age to the Toarcian–Early Aalenian (J_{1-2}) based on faunal remains. The formation is composed of poorly-sorted polymictic and arkosic sandstones, gritstones, siltstones, clay, and pebble conglomerates. The whole series corresponds to turbidite deposits of the inner shelf and coastal plains.

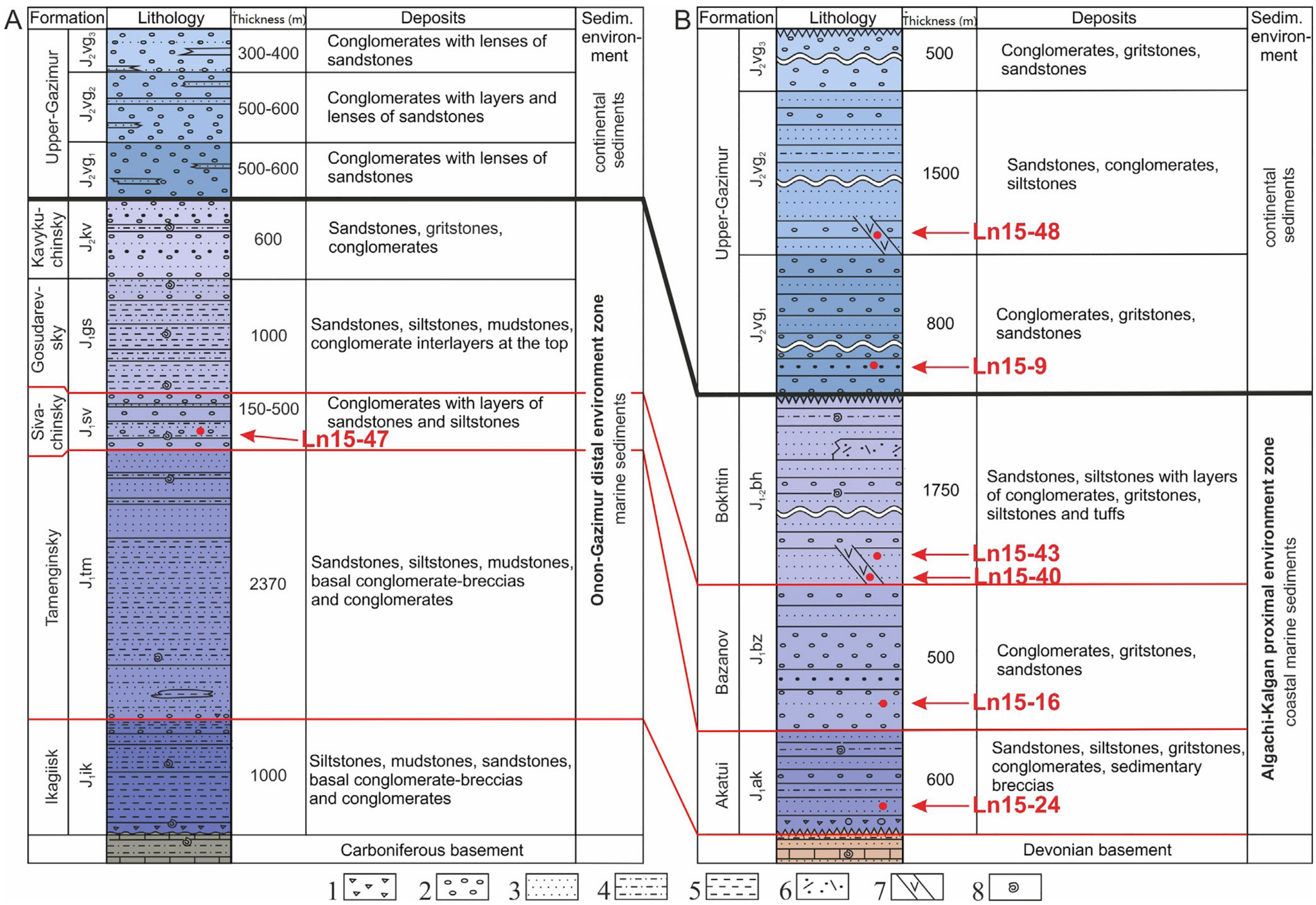

Fig. 4. Jurassic general stratigraphic section in the Est Transbaikalia Basin for distal (A) and proximal (B) environment zones (after Chaban, 2002; Starchenko, 2006). 1 – breccias, 2 – conglomerates, 3 – sandstones, 4 – siltstones, 5 – argillites, 6 – tuffs, 7 – dikes, 8 – remains of fauna. Red points indicate samples position (schematically, without reference to depth and upper/lower parts of fms.)

The Upper Gazimur Fm. that covers both the proximal and distal zone is composed of lacustrine and alluvial coarse-grained deposits and overlies the Jurassic marine deposits conformably or unconformably depending on the location. The deposits are represented by conglomerates with boulder-size clasts rarely interlayered with sandstones in the lower and upper parts of the section and sandstones and gritstones in its central part. Plant remnants are found throughout the deposits but are not allowing dating. According to its position above the Toarcian-Early Aalenian Bazanov Fm., and above the Early Bajocian Kavykuchinsky Fm. in the distal Onon-Gazimur zone (see below in section 2.2.2), the Upper Gazimur Fm. is roughly dated to the Late Bajocian–Early Bathonian (J_2). This sedimentary formation indicates the change of the marine to continental sedimentation mode.

2.2.2. The distal Onon-Gazimur zone

In the distal depositional zone, the Ikagiisk Fm. represents the onset of Jurassic marine sedimentation. The basal deposits rest unconformably on the Carboniferous basement and are composed of conglomerates, gritstones and thin layers of breccia. The rest of the formation consists of argillites and siltstones, the lower part being sandier and the upper part more clay-rich. Based on numerous marine mollusk fossils, the formation is dated to the Pliensbachian.

The Tamenginsky Fm. conformably overlies the Ikagiisk Fm. The base of the Tamenginsky Fm. is composed of a relatively thin layer of breccias and conglomerates. The rest of the deposits consist of interbedded siltstones, argillites and sandstones, with rare interlayers and lenses of gritstones and conglomerates. Again, based on marine mollusk fossils, the formation is dated to the Late Pliensbachian.

The Sivachinsky Fm. is composed of polymictic small-to-large pebble conglomerates interlayered with sandstones, siltstone, and unsorted micro-conglomerates. It conformably overlaps the Tamenginsky Fm., usually through a gradual facies transition. Like the Bazanov Fm. in the proximal area, the Sivachinsky Fm. has a threefold structure in many sections – the tops and bottoms are mainly represented by conglomerates, and the middle part – by sandstones. The age of the formation (end of Pleinsbachian–beginning of Toarcian) was determined from the ammonoid *Amaltheus viligaensis* and clam *Ochotochlamys grandis* found at the base as well as from the Early Toarcian ammonoids *Tiltoniceras* sp. indet. and *Kedonoceras* sp. indet. at the top (Starchenko, 2010).

The Gosudarevsky Fm. in some places overlays the Sivachinsky Fm., while in places it rests directly on the pre-Jurassic basement. In its lower part the formation is represented by interbedded polymictic sandstones, siltstones and argillites, while the upper part is composed of siltstones and argillites with very rare thin interlayers of calcareous sandstones and horizons of small-grained pebble conglomerates. The frequency of conglomerate interlayers and the size of the pebbles increase toward the top of the formation. Based on ammonoids and mollusks fossils, a Toarcian age has been established for that formation.

Being the last marine deposits in the Onon-Gazimur zone, the Kavykuchinsky Fm. overlaps the Gosudarevsky Fm. with a gradual transition. The lower parts of the formation are composed of sandstones, gritstones and conglomerates with interlayers of siltstones. The relatively coarser upper part of the formation is composed of medium- to large-pebble conglomerates and coarse-grained sandstones. Based on the occurrence of bivalve mollusks *Aguilerella khudyavi* in the lower part of the formation and *Mytiloceramus* ex gr. Polyplocus and *Mytiloceramus* ex gr. Lucifer in the upper part, an Early Aalenian to the Early Bajocian age has been ascribed to the Gosudarevsky Fm. (Starchenko, 2010).

3. U-Pb (LA-ICP-MS) dating of detrital and magmatic zircons

Detrital zircon grains were extracted from samples of the marine Akatui, Bazanov, Bokhtin and Sivachinsky fms. as well as from the continental Upper Gazimur Fm. (Fig. 4). Magmatic zircons from dikes cutting through the sediment deposits of the Bokhtin and Upper Gazimur fms. were also dated using the same method. U-Pb dating of those grains will provide absolute age constrains for the sedimentary deposits of the East Transbaikalia Basin and allow tracing the evolution of the sediment source areas. Indeed, U-Pb dating of detrital zircon allows determining the lower age limit for sedimentary deposits and dating of zircon from cutting dikes provides the information on the upper age limit for sediments.

3.1. Methods

Zircon grains were separated using the conventional method before a final hand picking of crystals under a binocular microscope. Over 100 zircon grains were collected from each sediment samples. U-Pb analysis was done at the Geological Institute, Russian Academy of Sciences, Siberian Branch (Ulan-Ude, Russia) by laser ablation inductively coupled plasma mass spectrometry using a high-resolution mass spectrometer Element XR (Thermo Fisher Scientific) coupled to an UP-213 laser (New Wave Research). The instrumental settings and the analytical procedure can be found in Khubanov et al. (2016) and Buyantuev et al. (2017). The ages were calculated relative to the primary zircon standard 91500 (Wiedenbeck et al., 1995) and the quality of the analyses was monitored through analyses of secondary Plešovice (Sláma et al., 2008) and GJ-1 (Jackson et al., 2004) zircon standards. Relative uncertainties for Plešovice and GJ-1 zircon standards were: 1%–2.3% for $^{208}Pb/^{232}Th$, 2.1%–2.6% for $^{207}Pb/^{206}Pb$, 1.1%–2.6% for $^{206}Pb/^{238}U$ and 2%–2.5% for $^{207}Pb/^{235}U$ leading to the calculated age values within 2% of the recommended age values. All data were processed using the GLITTER program (Griffin et al., 2008). For plotting kernel density estimates only ages with less than 10% of discordance were used. Kernel density estimates and Concordia diagrams were plotted using the IsoplotR software (Vermeesch, 2012, 2018).

Zircon separated from acidic dike samples were dated by the same technique at the University of Tasmania (Hobart, Australia). The instrument was an Agilent 7500cs quadrupole ICP-MS with a 193 nm Coherent Ar-F gas laser and the Resonetics S155 ablation cell. The width of the laser beam was 25 μm. The primary standard for age calculation was again the zircon standard 91500 (Wiedenbeck et al., 1995) and the secondary standard was Temora (Black et al., 2003).

3.2. Results

The Akatui Fm. was sampled from an exposure in the interfluve between the Ozoran and Mankechur Rivers (sample Ln-15-24, 50°44.798′E, 117°50.250′E, alt. 950 m) (Fig. 5A). The formation is represented by fine-grained sandstones intercalated with siltstones. Concordant ages were obtained for 51 individual zircon grains (Supplementary Data, Table S1). These ages are distributed into two populations: 162–179 Ma (15% of grains) and 232–268 Ma (65% of grains). Some outliers with ages of 289, 301, 326, 445, 473, 480, 592, 897 and 937 Ma are also present. These outliers do not represent statistically reliable populations (3% or more) and are not considered for discussion. The youngest zircon in the sample has an age of 162.3 ± 4.4 Ma (Fig. 6A).

The Bazanov Fm. was sampled from a sandy interlayer in the conglomerate member exposed near the settlement of Mankechur (sample Ln-15-16, 50°43.752′N, 117°52.112′E, alt. 832 m) (Fig. 5B). The conglomerates are polymictic, with the pebble composition dominated by granites, syenites, and sediments. A total of 94 concordant individual zircon ages were obtained (Supplementary Data, Table S2). The age distribution is similar to that of sample Ln-15-24 with two main populations: 158–192 Ma (35% of grains) and 232–269 Ma (38% of grains). However, a secondary population at 424–491 Ma (9%) is also present together with a few outliers. The youngest zircon has an age of 158.4 ± 4.0 Ma (Fig. 6B).

The Bokhtin Fm. was sampled in a section along the left bank of the Malaya Borzya River (sample Ln-15-43, 50°44.783′N, 118°6.669′E, alt. 739 m). The formation therein is composed of interlayered siltstones, sandstones, gritstones and conglomerates intruded by two acidic dikes (Fig. 5C). One of these dikes (sample Ln-15-40), yielded a U-Pb age of 131.76 ± 0.71 Ma (Supplementary Data, Table S3). The sediment sample was taken from a sandstone interlayer where 110 concordant individual zircon ages (Supplementary Data, Table S4) were obtained. The age distribution shows a unique well-defined peak at 239–268 Ma (93% of grains), and few outliers with ages up to 1066 Ma. The youngest zircon has an age of 166.2 ± 5.0 Ma (Fig. 6C).

The Sivachinsky Fm. was sampled in a small exposure near the settlement of Kirillikha (sample Ln-15-47, 50°55.700′N, 117°28.704′E, alt. 892 m). The series is represented by conglomerates interlayered with sandstones. The sample was taken from a sandstone interlayer (Fig. 5D). Among 51 concordant individual zircon ages (Supplementary Data, Table S5) three young zircon grains with ages of 165, 189 and 190 Ma were found. A major age population at 237–295 Ma (69% of grains) is associated with a secondary population at 480–499 Ma (10% of grains) and few outliers. The youngest zircon in the sample from the Sivachinsky Fm. has an age of 165.0 ± 4.5 Ma (Fig. 6D).

The continental Upper Gazimur Fm. was sampled from a section on the right bank of the Borzya River opposite the settlement of Akurai (sample Ln-15-9, 50°47.433′N, 117°07.210′E, alt. 767 m). The sediment is composed of poorly sorted pebble conglomerates interlayered with sandstones wherefrom the sample for detrital zircon dating was taken (Fig. 5E). A total of 96 concordant individual zircon ages were obtained (Supplementary Data, Table S6). The zircon age distribution differs from that in the marine formation samples. Besides a well-defined population at 231–268 Ma (30% of grains), a second major population of ages is spread between 280 Ma and 512 Ma (52% of grains), with a predominance of Devonian (16%) and Early Paleozoic (15%) ages. Several minor populations are also present with Jurassic: 155–162 Ma (3% of grains, the youngest 155.2 ± 4.0 Ma), and Paleoproterozoic: 1697–1715 Ma (3% of grains) and 1787–1810 Ma (3% of grains) ages. Finally, a few Neo- and Mesoproterozoic single grains are spread between the Paleozoic and Paleoproterozoic populations (Fig. 6E).

A syenite dike intruded through the Upper Gazimur Fm. deposits was sampled near the settlement of Shonoktui (sample Ln-15-48, 50°46.269′N, 117°17.048′E, alt. 846 m) and dated at 127.33 ± 0 .51 Ma (zircon U-Pb) (Fig. 7B, Supplementary Data, Table S3).

4. Discussion

4.1. Depositional age of the sedimentary formations

The detrital geochronology results presented above can be used to discuss the stratigraphy and to better estimate the age of the

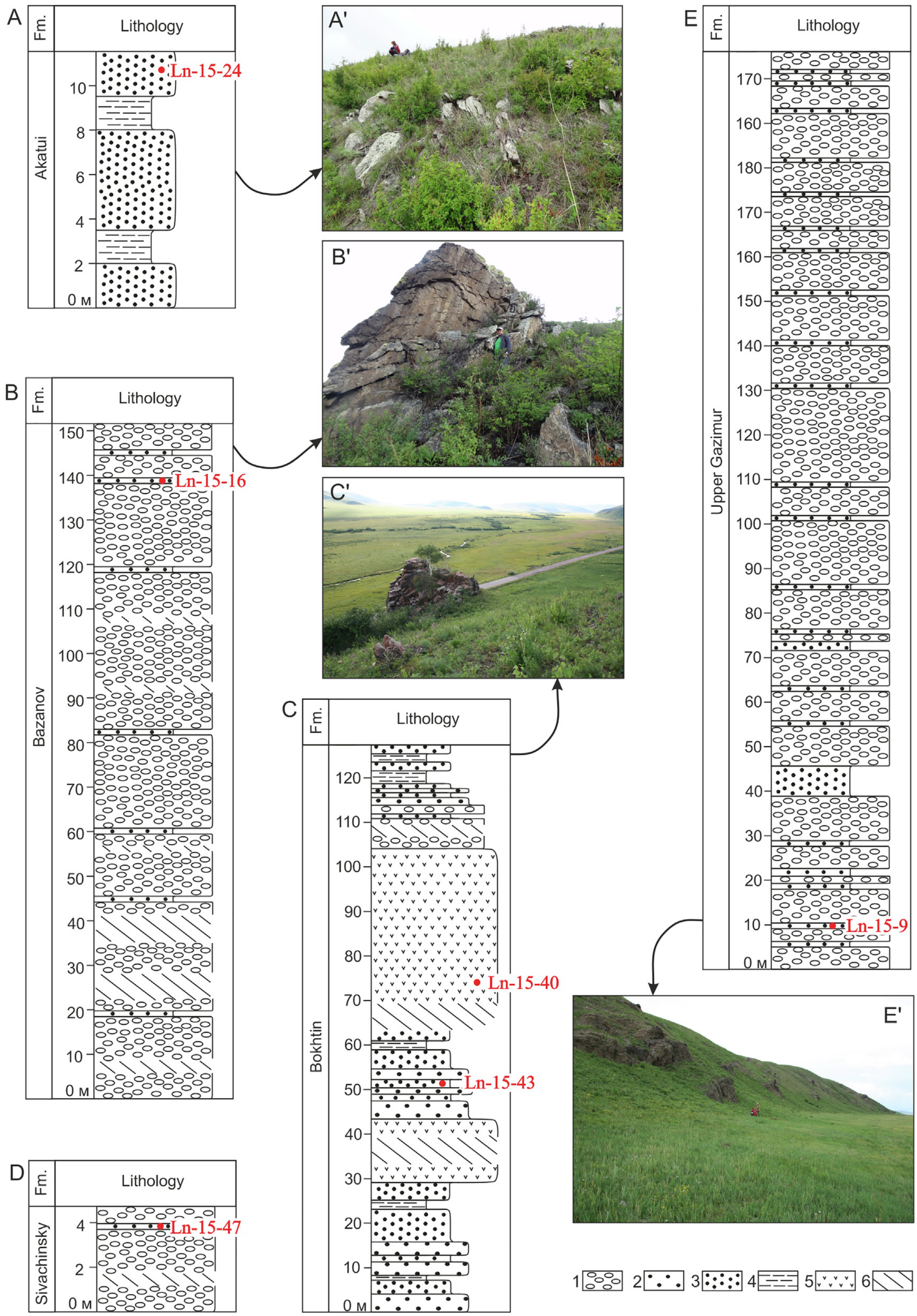

Fig. 5. Sedimentary sections in sampling places (A–E) and field views (A′–E′) of the Akatui (A, A′), Bazanov (B, B′), Bokhtin (C, C′), Sivachinsky (D) and Upper Gazimur (E, E′) formations. Red dots indicate sampling places. 1 – conglomerate, 2 – gritstone, 3 – sandstone, 4 – siltstone, 5 – dike, 6 – cover (no data).

Jurassic sedimentary formations in the East Transbaikalia Basin. They also allow discussing the timing of transition between marine and continental depositional environments in the basin (Fig. 8). According to the age of the youngest zircon in the sample, the coastal-marine Bazanov Fm. is younger than 158.4 ± 4.0 Ma. Since the Bokhtin Fm. overlies the Bazanov one, it can be concluded that both formations are younger than ~158 Ma. Similarly, the underlying Akatui Fm. is not older than 162.3 ± 4.4 Ma, in accordance with

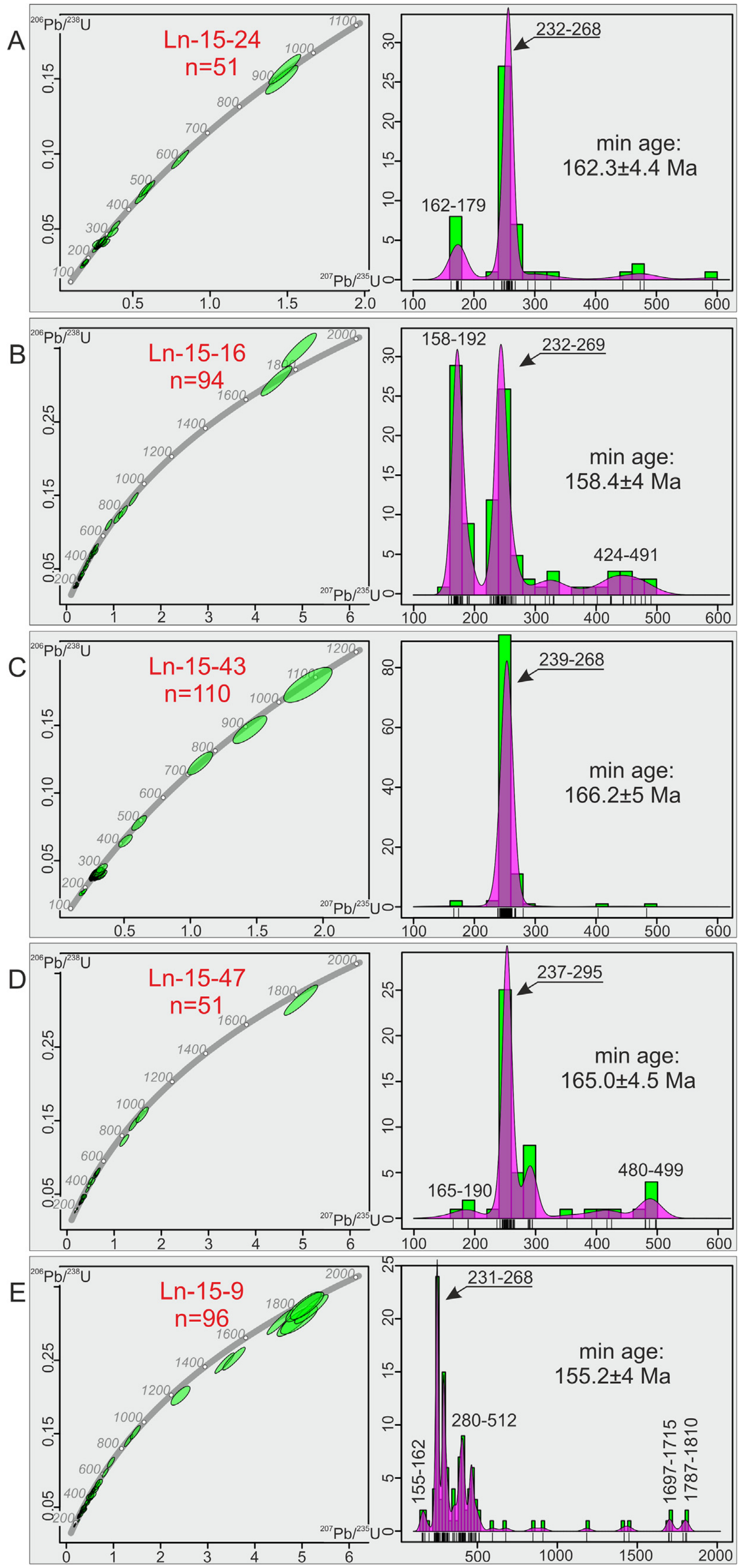

Fig. 6. U-Pb concordia diagrams and histograms coupled with kernel density estimates for zircons from A – Akatui, B – Bazanov, C – Bokhtin, D – Sivachinsky, E – Upper Gazimur Fms. n – numbers of data. The histograms, where there are no statistically significant populations of zircons of Precambrian ages, show only zircons with Paleo- and Mesozoic ages. Frequency histograms for detrital zircons were drawn using bin width of 20 Ma. The lilac area is the kernel density estimates (Vermeesch, 2012, 2018) with bandwidth of 10 Ma.

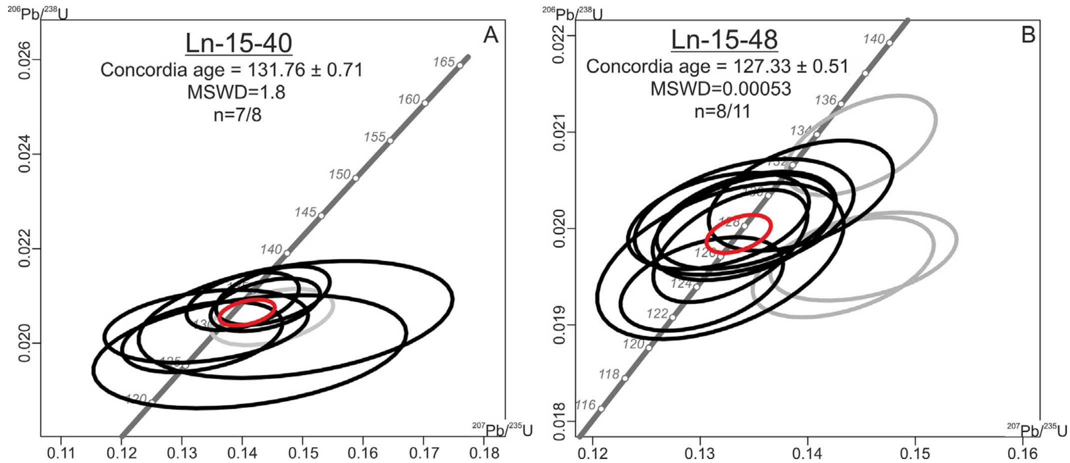

Fig. 7. U-Pb concordia diagrams for zircon from samples Ln-15-40 (A) and Ln-15-48 (B). Black ellipses are used to calculate the concordia age shown by red ellipse using IsoplotR program (Vermeesch, 2018). Grey ellipses are omitted from the calculation. n – is the number of considered individual analysis over the total numbers of data.

the age of the youngest zircon analyzed in sample Ln 15-24. The Akatui Fm. is affected by the Akatui intrusive complex that provided ^{40}Ar-^{39}Ar ages on amphiboles ranging from 162 Ma to 155 Ma (Sasim et al. 2016). Given the maximum age of the overlying Bazanov Fm., we suggest that the Akatui Fm. was deposited between 162 Ma and 158 Ma, synchronal to the magmatic activity. The Sivachinsky Fm. is considered as a distant equivalent of the Bazanov Fm. (Starchenko, 2010), but the age of the youngest detrital zircon in the Sivachinsky Fm. provides an older estimate of the maximum age of the formation at 165.0 ± 4.5 Ma. Again, based on detrital geochronology, the maximum age of the continental Upper Gazimur Fm. is 155.2 ± 4.0 Ma. The data obtained from the dikes (131.76 ± 0.71 Ma and 127.33 ± 0.51 Ma, Fig. 7) intruding into the Bokhtin and Upper Gazimur fms., respectively, provide a very wide range for the minimum age of these upper formations. Considering the widespread occurrence of the Late Jurassic–Early Cretaceous magmatism (ages are distributed between 164 Ma and 118 Ma) in the region, including acidic magmatism with a large number of zircons (Zakharov, 1972; Troshin, 1978; Tauson et al., 1984; Ivanov et al., 2015; Sasim et al., 2016), it should be assumed that zircon grains of these ages found in the sediments are reflecting *syn*-sedimentary volcanism. Thus, in this particular case the ages of the youngest zircons in the sediments can be also considered as the true depositional age (Dickinson and Gehrels, 2009; Rossignol et al., 2019).

To summarize, we propose that the studied marine series were deposited during the late Middle Jurassic rather than the Early Jurassic, as previously assumed (Starchenko, 2010). The change from marine to continental depositional environments occurred in the Oxfordian–Kimmeridgian (formally, between overlapping ages of 158.1 ± 4.0 Ma and 155.2 ± 4.0 Ma).

4.2. Provenance of detrital zircons and time of the final marine regression in Eastern Transbaikalia

The major detrital zircon age populations described above from the sediments fit with local source areas. The youngest age population of 155–192 Ma is present in all the formations but the Bokhtin Fm. where only a single grain of this age was recovered. This population is generally minor, except in the Bazanov Fm. where it represents a major peak. The youngest zircons of this population (155–174 Ma) correspond in age to the Middle–Late Jurassic magmatism widespread in the region and widely intruding the Jurassic marine sedimentary deposits (Starchenko, 2010). As for the Early Jurassic zircon grains, magmatism of this age is absent within the East Transbaikalia Basin (Starchenko, 2010). However, extensive zircon U-Pb dating of volcanic rocks in the Chinese part of the Erguna block revealed Early Jurassic ages of 179–200 Ma (Wu et al., 2011; Sun et al., 2013 and references therein). It is thus probable that Early Jurassic magmatism also took place within the Russian part of the Erguna block, but that the small number of available geochronological data did not yet allow its discovery. Therefore, we suggest that the Early Jurassic zircon grains found in the Akatui and Bazanov formations are also derived from a local source.

The main zircon age population observed within all marine formations and the second largest in the continental formation falls within the range of 231–295 Ma, which corresponds to the Permian–Triassic granitoid magmatism widespread within the Erguna block (Wu et al., 2011; Sun et al., 2013) (Figs. 2, 3). Zircons with ages from 280 Ma to 500 Ma are represented by a very limited number of grains in all marine formations. However, in the continental Upper Gazimur Fm., they represent more than half of the

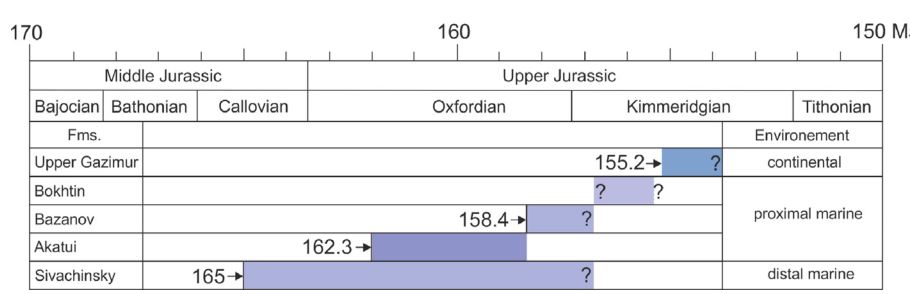

Fig. 8. Timing of marine and continental sedimentation in the Est Transbaikalia Basin.

dated grains with a predominance of Devonian and Early Paleozoic ages. The Early Paleozoic granitoids have a large distribution within the Erguna block (Wu et al., 2011), and are also widely spread throughout the Siberian continent including the Olekma granite complex adjacent to the Mongol-Okhotsk suture to the north (Starchenko, 2010) (Figs. 2, 3). Late Devonian sedimentary-volcanic complexes and rhyolites occur within the Onon block which, being an island-arc, forms one segment of the Mongol-Okhotsk Belt west of the Erguna block (Zorin, 1999), but are almost completely absent from the Erguna block (Starchenko, 2010; Wu et al., 2011; Sun et al., 2013, 2019) (Figs. 2, 3). This observation suggests a source area to the west for the Upper Gazimur continental deposits.

Single zircon grains ranging in age from 500 Ma to 900 Ma distributed in all the formations correspond in age to the Neoproterozoic granites of the Erguna block, again suggesting a local sediment source (Wu et al., 2011; Sun et al., 2013; Smirnova and Sorokin, 2019; Gordienko et al., 2019) (Fig. 3). The oldest zircon grains (1.6 Ga to 1.8 Ga) were found in the continental deposits of the Upper Gazimur Fm. (6% of grains) (Fig. 6E). Paleoproterozoic rocks are only found in the northeastern part of the Erguna block (two samples with ages of 1785 Ma and 1860 Ma (Sun et al., 2019)), far from the study area, but widespread throughout the Siberian continent (Figs. 2, 3). Granitoids with an age of 1.5–2 Ga are found within the Selenga-Stanovoy orogenic belt (Karsakov et al., 2005), located immediately to the north of the Mongol-Okhotsk suture in the study area (Fig. 3A, B). This suggests a more distal source and provenance from the north for the continental Upper Gazimur Fm. deposits.

The evolution of the source area and depositional facies of the Jurassic sediments in the East Transbaikalia Basin reflects the timing and dynamics of switch from marine to continental depositional environment in the East Transbaikalia region. During the deposition of the marine formations, the facies associations indicate proximal depositional environments to the south in the Algachi-Kalgan zone evolving northward to distal environments in the Onon-Gazimur zone (Figs. 3, 4). It should be noted, however, that even the more distal zone periodically received coarse-grained material possibly as turbidites. This geography of the basin is coherent with zircon source areas situated mainly on the Erguna block. Based on facies associations, a shift in basin polarity occurred with the deposition of the Upper Gazimur Fm. and may have initiated during the deposition of the Kavykuchinsky Fm. By that time, the proximal zone was situated to the north in the Onon-Gazimur region while the Algachi-Kalgan region became more distal. This shift in basin polarity is consistent with the shift in detrital zircon provenance from the Erguna block to the Selenga-Stanovoy Belt and Onon block as well as with the change from marine to continental depositional environments.

4.3. Closure of the Mongol-Okhotsk Ocean and tectonic position of the East Transbaikalia Basin

The new chronostratigraphy discussed above for the marine and continental deposits of the East Transbaikalia Basin suggests that, in that region, the final marine regression occurred ~20 Ma later than in Dzhagdy region (Sorokin et al., 2020). To the west, in the Western Transbaikalia region, the closure of the Mongol-Okhotsk Ocean seems to have occurred earlier than in the east. Detrital zircon U-Pb ages and Sm-Nd data from Early–Middle Jurassic sediments in the Irkutsk Basin (southern margin of the Siberian Craton, Fig. 1) showed that the sediment input from Transbaikalia began at the Early–Middle Jurassic boundary (Demonterova et al., 2017). A U-Pb zircon age of 178.3 ± 5.0 Ma was obtained from a volcanic ash interlayer within the youngest formation of the Irkutsk Basin in which detrital zircon grains of Transbaikalian provenance were found (Mikheeva, 2017). These data indicate uplift and volcanic activity in Western Transbaikalia that were interpreted as linked to an orogenic event related to the closure of the Mongol-Okhotsk Ocean and the onset of continental collision (Demonterova et al., 2017; Arzhannikova et al., 2020).

Within the northern Argun-Idemeg terrane, an Oxfordian–Kimmeridgian final marine regression in the East Transbaikalia Basin would slightly precede the Kimmeridgian–Tithonian end of marine sedimentation suggested in the western Upper Amur Basin, itself preceding the Berriasian–Valanginian marine regression in the northeastern Upper Amur Basin (Guo et al., 2017). The segment of the Mongol-Okhotsk Belt extending from the East Transbaikalia Basin to the Upper Amur Basin thus underwent progressive northeastward shift from marine to continental sedimentation from the Oxfordian to the Valanginian, though being long-delayed when compared to more westerly and easterly segments (Fig. 9A–C). Although this late regression should be further documented, the delay may be due to the initial shape of paleo continental margins.

While the western and eastern segments of the Mongol-Okhotsk Ocean had already closed, and the corresponding area passed into the orogenic stage of development with continental sedimentation, the northern part of the Argun-Idemeg terrane underwent marine transgression. Marine environments persisted there from the late Middle Jurassic to the Early Cretaceous, successively being replaced by continental molasses.

Cawood et al. (2012) demonstrated that the age distribution of detrital zircons is partially controlled by transport processes that reflect the tectonic setting of the basin they were deposited in. Convergent margin basins contain a high proportion of detrital zircons with ages close to the deposition age. Basins formed during continental collision (e.g., foreland basins) usually contain zircons with a wider range of age distributions. Extensional basins are dominated by detrital zircons, which ages are much older than the time of sedimentation (Cawood et al., 2012). The detrital zircons within the East Transbaikalia Basin formations provide evidence of deposition in convergence to collisional settings (Fig. 10). The marine Akatui, Bazanov, Bokhtin and Sivachinsky fms. are dominated by detrital zircons with crystallization ages (CA) that are close to their depositional ages (DA). Within the Akatui Fm. sample 78% of the zircon population have CA–DA < 100 Ma. Within the Bazanov, Bokhtin and Sivachinsky fms. of 68%, 92% and 63%, respectively which is consistant with deposition in a convergent setting. In comparison, the detrital zircons from the continental Upper Gazimur Fm. have CA–DA values that are indicative of deposition in a collisional setting (29% of the zircon population within this sample have CA–DA < 100 Ma). This indicates that detrital zircon age distribution patterns changed during the transition from marine to continental deposits, reflecting a change in detrital zircon provenance described above.

The deposition of marine sediments on the basement of the Argun-Idemeg terrane indicates a collisional setting rather than a subduction one. The upward coarsening and several km-thick successions of the East Transbaikalia Jurassic fms., punctuated in its lower part by a major erosional unconformity (upper Jurassic deposits of the Onon-Gazimur and Algachi-Kalgan zones overlap the Carboniferous and Devonian marine deposits, respectively (Fig. 4)) correspond to a typical stratigraphic pattern of a foreland basin (De Celles, 2012). Sedimentological studies of Late Cenozoic Himalayan peripheral foreland basin described the synorogenic sedimentation under various depositional environments from marine-transitional to fluvial facies (Tandon, 1991; Burbank et al., 1996; Raiverman, 2002). The Siwalik continental molasse overlies the pre-Siwalik marine deposits (Subathu Fm.) with an unconformity. The Subathu Fm. is composed of shallow marine facies and consists of mudstone, sandstone and limestone (Najman et al., 2004). These deposits are similar to the marine sed-

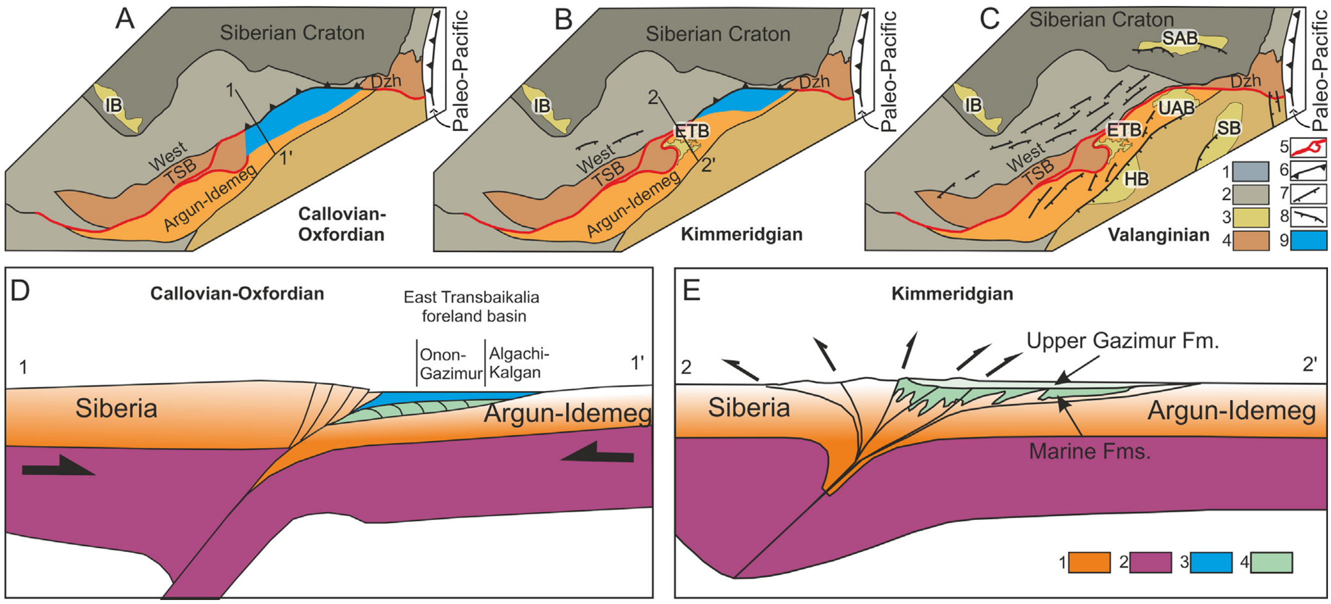

Fig. 9. (A–C) Paleotectonic reconstructions for the Middle Jurassic–Early Cretaceous Mongol-Okhotsk Ocean closure, (A) Callovian-Oxfordian, (B) Kimmerigian, (C) Valanginian. 1 – cratons, 2– collage of accreted terranes, 3 – Mezosoic basins: IB – Irkutsk Basin, ETB – East Transbaikalia Basin, UAB – Upper Amur Basin, SAB – South Aldan Basin, HB – Hailar Basin, SB – Songliao Basin, 4 – Mongol-Okhotsk belt, 5 – Mongol-Okhotsk suture zone, 6 – subduction zone, 7 – normal faults, 8 – reverse faults, 9 – marine space, West TSB – Western Transbaikalia, Dzh – Dzhagdy region. (D–E) Models of the East Transbaikalia Basin sedimentation for marine and continental environment, respectively. 1 – continental crust, 2 – mantle lithosphere, 3 – marine space, 4 – sediments.

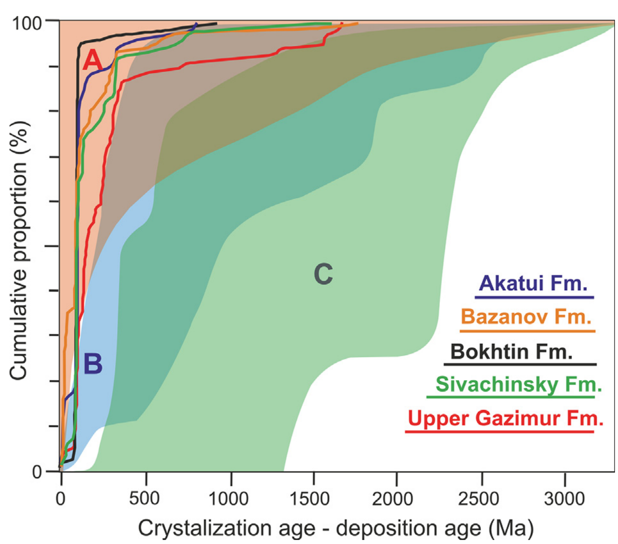

Fig. 10. Tectonic setting diagram for detrital zircons from the marine and continental deposits of the East Transbaikalia Basin (modified after Cawood et al., 2012). (A) Orange field – convergent settings, (B) blue field - collisional settings, (C) green field – extensional settings. CA–DA: difference between the crystallization and depositional ages of the zircons. Color lines show the age distribution of detrital zircons for the studied formations.

iments of the Onon-Gazimur distal environment zone in the Est Transbaikalia Basin (Fig. 4). At the same time, in the Algachi-Kalgan zone, fine-grained sediments were interbedded with conglomerates, which indicates coastal marine sedimentation. The Upper Gazimur Fm., in places unconformably overlying marine sediments, may be an analogue of the Siwalik continental molasse, which represents coarsening upward successions from mudstone–sandstone to conglomerate facies (Kumar et al., 2011 and references therein). Thus, we propose that by ~165–155 Ma, flexure of the northern Argun-Idemeg terrane formed a peripheral foreland basin and resulted in marine transgression and sedimentation on the Paleozoic terrane basement (Fig. 9D). The beginning of the foreland basin subsidence indicates the beginning of the collision (Lin et al., 2017). Thus, the collision in Eastern Transbaikalia began about 165 million years ago, with a significant delay compared to the more western and eastern segments. The reasons for this delay have not yet been clarified but we assume that it may be associated with the original shape of the paleocontinental margins. Between ~158 Ma and ~155 Ma, the marine basin was inverted in East Transbaikalia and turned into a continental foreland basin (Fig. 9E). Marine sedimentation continued in the Upper Amur Basin until the Late Valanginian, and complete disappearance of the marine depositional environments occurred by ~136–133 Ma (Guo et al., 2017).

The inversion of the East Transbaikalia Basin was accompanied by syn-orogenic tectonic deformation (Starchenko, 2010). The marine sediments of the East Transbaikalia were deeply folded and dissected by reverse and thrust faults. The continental deposits of the Upper Gazimur Fm. are conformable with respect to the folds of the Jurassic marine deposits, but form gentle folds. Large thrusts deform the marginal parts of the basin. The contact is characterized by zones of ultramilonites and brecchias up to many hundreds of meters thick and intense tectono-metamorphism. The dip of the thrusts is predominantly to the north and northwest. Late Jurassic intrusions in some places intersect the thrusts and are not affected, limiting the time of thrusting to the Late Jurassic (Starchenko, 2010).

Finally, it should be noted that this portion of the suture zone is the only one that does not include a wide, clearly expressed Mongol-Okhotsk Belt. West of the East Transbaikalia Basin, the suture zone appears double, surrounding the Onon Block. This double subduction is generally documented as being double verging based on the apparent absence of strong collision event between Mongolia and Siberia, although our study does not bring any argument to this model (Wang et al., 2015; Daoudene et al., 2017; Sorokin et al., 2020). However, a double subduction could explain the complete closure of the oceanic domain and formation of a more restricted collision belt (Daoudene et al., 2017).

5. Conclusions

U-Pb (LA-ICP-MS) dating of detrital zircon from Jurassic marine and continental sediments collected from the East Transbaikalia Basin allow for better constrains on the stratigraphic framework of the deposits associated with the final closure of the Mongol-Okhotsk Ocean. The initiation of the East Transbaikalia Basin took place in the Middle Jurassic as a collisional foreland basin rather than in the Early Jurassic, as previously assumed. In the northern Argun-Idemeg terrane region, the disappearance of the marine environments was diachronous from Oxfordian in the western part of the East Transbaikalia Basin, to Late Valanginian NE of the Upper Amur Basin. The northern Argun-Idemeg terrane was the last to collide with the Siberian continent with a 5–10 million-years delay compared to the adjacent southwestern and northeastern regions. This fact does not correspond to the widely supported scissor-like model of the Mongol-Okhotsk Ocean closure, but testifies to its segmental closure. The geodynamic mechanism that led to the delay in collision of the northern Argun-Idemeg terrane must be further documented but could be related to the peculiar double-verging subduction setting inferred for this segment of the Mongol-Okhotsk suture zone or to the peculiar shape of the paleo continental margins.

Declaration of Competing Interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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Appendix A. Supplementary data

Supplementary data to this article can be found online at https://doi.org/10.1016/j.gsf.2021.101254.

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