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Research Paper

Late Mesozoic topographic evolution of western Transbaikalia: Evidence for rapid geodynamic changes from the Mongol–Okhotsk collision to widespread rifting

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ABSTRACT

The Mesozoic geodynamic evolution of Transbaikalia has been largely controlled by the scissors-like closure of the Mongol–Okhotsk Ocean that separated Siberia from Mongolia–North China continents. Following the oceanic closure, the tectonic evolution of that region was characterized by collisional uplift and subsequent extension that gave rise to the formation of metamorphic core complexes. This complex tectonic setting prevailed simultaneously between 150 Ma and 110 Ma both in Transbaikalia, North Mongolia, and within the North China Craton. Published paleobotanical and paleontological data show that the oldest Mesozoic basins had formed in western Transbaikalia before the estimated age of extension onset. However no precise geochronological age is available for the onset of extension in Transbaikalia. The Tugnuy Basin, as probably the oldest Mesozoic basin in western Transbaikalia, is a key object to date the onset of extension and following changes in tectonic setting. In this study, U–Pb (LA-ICP-MS) dating of detrital zircons from three key Jurassic sediment formations of the Tugnuy Basin are used to identify the potential source areas of the sediments, understand the changes in sediment routing and provide insights on the topographic evolution of western Transbaikalia. Our results show several significant changes in tectonic regime after the closure of the Mongol–Okhotsk Ocean. A wide uplifted plateau formed during the closure of the Mongol–Okhotsk Ocean, determining the Early Jurassic drainage system reaching the Angara-Vitim batholith to the north and shedding sediments to the continental margin to the South. The following collisional event at the end of the Early Jurassic led to the uplift of the collision zone, which partially inverted the drainage system toward the North. A strike-slip displacement induced by the oblique collision initiated some of the early Transbaikalian depressions, such as the Tugnuy Basin at about 168 Ma. A phase of basin inversion, marked by folding and erosion of the Upper Jurassic sediments, could correspond to the short-term collision event that took place during the latest Jurassic–earliest Cretaceous in the eastern Central Asian Orogenic Belt. The following inversion in tectonic regime from compression to extension is consistent with the mid–lower-crustal extension that led to the formation of the numerous metamorphic core complexes throughout northeastern continental Asia during the Early Cretaceous.

1. Introduction

Transbaikalia is part of the Central Asian Orogenic Belt–one of the largest accretionary complexes of the Earth's that developed southward from the Siberian Craton (Zonenshain et al., 1990; Badarch et al., 2002; Bazhenov et al., 2016) (Fig. 1). A large-scale tectonic event therein was the closure of the Mongol–Okhotsk Ocean that extended between the Siberian and Mongolia–North China continents from central Mongolia to the west to the Sea of Okhotsk to the east (Zonenshain et al., 1990; Sengör and Natal'in, 1996; Yin and Nie, 1996; Zorin, 1999). The time of

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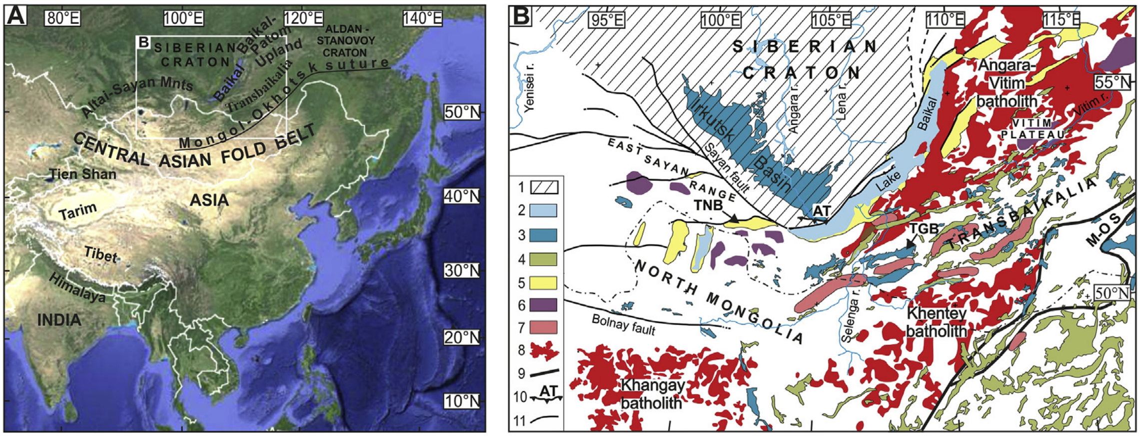


Fig. 1. (A) Location of Transbaikalia on the map of Asia; (B) geological setting of Transbaikalia and adjacent areas (Qi and Wang, 2008; Jolivet et al., 2013; Yarmolyuk et al., 2016). 1–Siberian Craton, 2–Lakes, 3–Jurassic basins (TGB–Tugnuy Basin), 4–Cretaceous basins, 5–Cenozoic basins (TNB–Tunka Basin), 6–Cretaceous and Tertiary volcanic fields, 7–Metamorphic core complexes, 8–Granitoid batholiths, 9–Mongol-Okhotsk suture zone (M−O S), 10–Angara thrust location, 11–Main Cenozoic faults.

the closure of the Mongol–Okhotsk Ocean is subject to considerable discussion and estimates vary from the Permian to the Early Cretaceous (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 Kuzmin, 1999; Zorin, 1999; Darby et al., 2001; Kravchinsky et al., 2002; Parfenov et al., 2003; Cogné et al., 2005; Metelkin et al., 2007; Metelkin et al., 2010; Donskaya et al., 2013; Van der Voo et al., 2015; Yang et al., 2015, Demonterova et al., 2017 and others). Most of the geodynamic models imply a scissor-like closure of the ocean, the associated collision structures getting younger northeastward along the Mongol–Okhotsk suture zone (Zhao et al., 1990; Zonenshain et al., 1990; Scotese, 1991; Kravchinsky et al., 2002; Tomurtogoo et al., 2005; Metelkin et al., 2010). According to Nie et al. (1990), Nie (1991), Yin and Nie (1993, 1996) and Guan et al. (2018), the closure of the Mongol–Okhotsk Ocean occurred in the early Permian at its western termination in central Mongolia and in the latest Jurassic at its eastern termination near the Sea of Okhotsk. However, paleomagnetic data suggest that the final closure of the ocean near the Sea of Okhotsk did not occur until the Early Cretaceous (Kravchinsky et al., 2002; Metelkin et al., 2010).

The Mongol–Okhotsk suture zone is underlined by a laterally extensive accretionary wedge composed primarily of flysch (Parfenov et al., 2001). Geological evidence, such as a switch from marine flysch-type sediments to continental sediments indicate that the closure of the ocean in Transbaikalia occurred at the boundary between the Early and Middle Jurassic (Zorin, 1999). Subduction of the oceanic crust beneath the Siberian continent and the subsequent collision gave rise to significant crustal thickening, magmatism, thrusting and formation of the Mongol–Okhotsk belt, interpreted as a plateau-like uplift (Zorin, 1999). Further from the suture zone, it also induced compressive deformation and denudation on the edge of the Siberian Craton near the Altai–Sayan Mountains (De Grave and Van den haute, 2002; De Grave et al., 2008, 2014) and the Baikal–Patom Upland (Van Der Beek et al., 1996; Jolivet et al., 2009). Paleogeographic maps of the Verkhoyansk margin of North Asia show that the drainage system of the paleo-Lena River transported to the north detrital material from the Sayan region and the northern part of Transbaikalia (the Angara-Vitim batholite) from Pennsylvanian to Middle Jurassic times (Ershova et al., 2005; Prokopiev et al., 2008). U–Pb ages of detrital zircons collected from sandstones of that age in the Verkhoyansk region show a significant increase in the Transbaikalian grains population in the Middle Jurassic deposits compared to the Middle–Upper Triassic sediments. The authors explain this shift towards the Angara-Vitim batholite provenance areas by the uplift and denudation of Transbaikalia due to the collision of the Amuria and North China blocks with Siberia (Prokopiev et al., 2008).

The Middle Jurassic growth of mountain ranges along the southern edge of the Siberian Craton is reflected in the increasing coarseness of sediments upward the section in the Irkutsk Basin along the southern edge of the Craton (Fig. 1B). According to ISC USSR (1981), three sedimentary formations (Fms.) are recognized in the Jurassic deposits of the Irkutsk Basin (from bottom to top)–Cheremkhovo, Prisayan and Kuda (Fig. 2). The lower two formations are composed of rhythmically inter-layered sandstones, siltstones and mudstones. Tuff and thin beds of coal are also found in the Cheremkhovo Fm. The uppermost Kuda Fm. is represented by alternating medium- to coarse-grained sandstones, gravelstones and conglomerates. U–Pb ages of volcanic zircons from tuffs inter-layered within the Cheremkhovo and Kuda Fms. are 194.5 ± 2.6 Ma and 178.3 ± 5.0 Ma, respectively (Mikheeva, 2017). U–Pb detrital zircon ages and Sm–Nd data obtained from all the sedimentary succession of the Irkutsk Basin date the onset of erosion in Transbaikalia to the Early–Middle Jurassic boundary (during deposition of the Kuda Fm.) (Demonterova et al., 2017; Mikheeva et al., 2017).

The present-day geomorphology of Transbaikalia is characterized by a series of NE-trending basins located northwest of the Mongol–Okhotsk suture (Fig. 1B). Geochronological data obtained from the volcanic rocks associated with the opening of the basins as well as paleomagnetic studies show that they formed during or immediately after the closure of the Mongol–Okhotsk Ocean (Gordienko and Klimuk, 1995; Gordienko et al., 1997; Kravchinsky et al., 2002; Cogné et al., 2005; Metelkin et al., 2007, 2010). Based on paleomagnetic data implying a left-lateral displacement along the Mongol–Okhotsk suture zone, several authors explained the formation of the Transbaikalia basins through pull-apart type extension along an oblique continental convergence zone (Parfenov et al., 2001; Metelkin et al., 2004, 2010; Yang et al., 2015). Another model associates the formation of those basins with that of metamorphic core complexes, widely distributed both in Transbaikalia, North Mongolia, and within the North China Craton (Zheng et al., 1991; Sklyarov et al., 1997; Zorin et al., 1997; Zorin, 1999; Donskaya et al., 2008; Daoudene et al., 2009, 2013, 2017; Wang et al., 2011, 2012). Tectonic exhumation of these metamorphic core complexes occurred simultaneously throughout northeastern continental Asia between 145 Ma and 110 Ma, with a peak at 130–125 Ma. The early mid–lower-crustal extension is dated to 150–145 Ma (U–Pb ages on zircons from synkinematic intrusions) (Wang et al., 2012; Daoudene et al., 2017). The spatio–temporal evolution of the Jurassic–Cretaceous granitoids and related intrusions in the Mongol–Okhotsk belt showed a transition from compressive crustal thickening due to the subduction/collision event related to the closure of the Mongol–Okhotsk Ocean during the Early

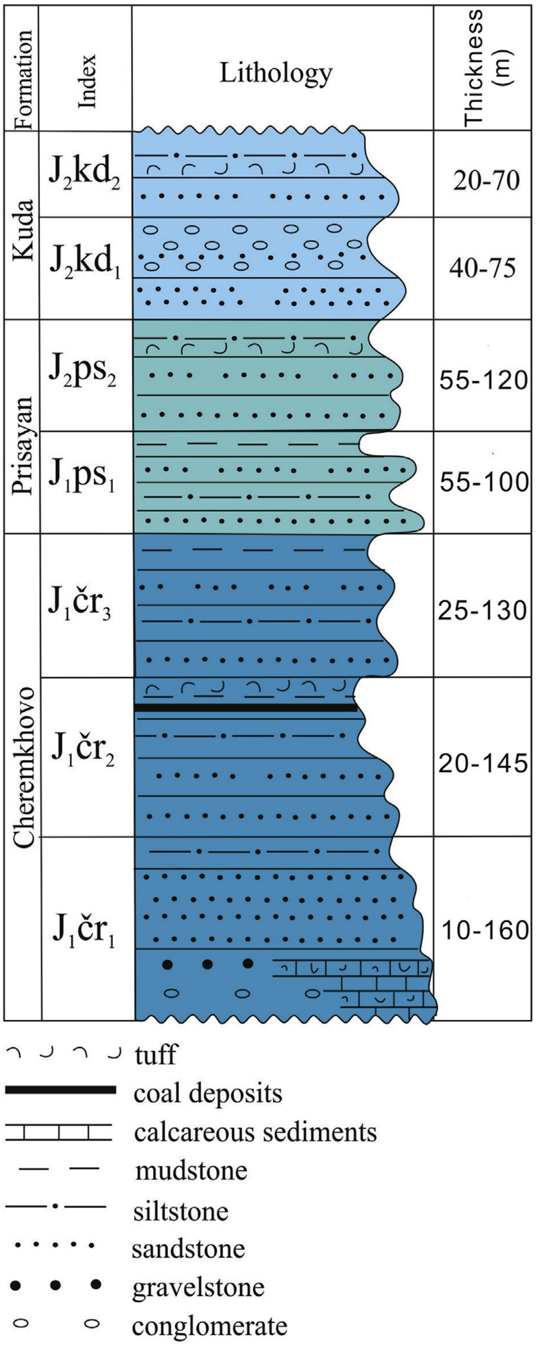


Fig. 2. Lithology of the Jurassic deposits of the Irkutsk Basin (after Mikheeva et al., 2017).

Jurassic to extensional thinning of the continental crust in Late Jurassic–Early Cretaceous times (Wang et al., 2015).

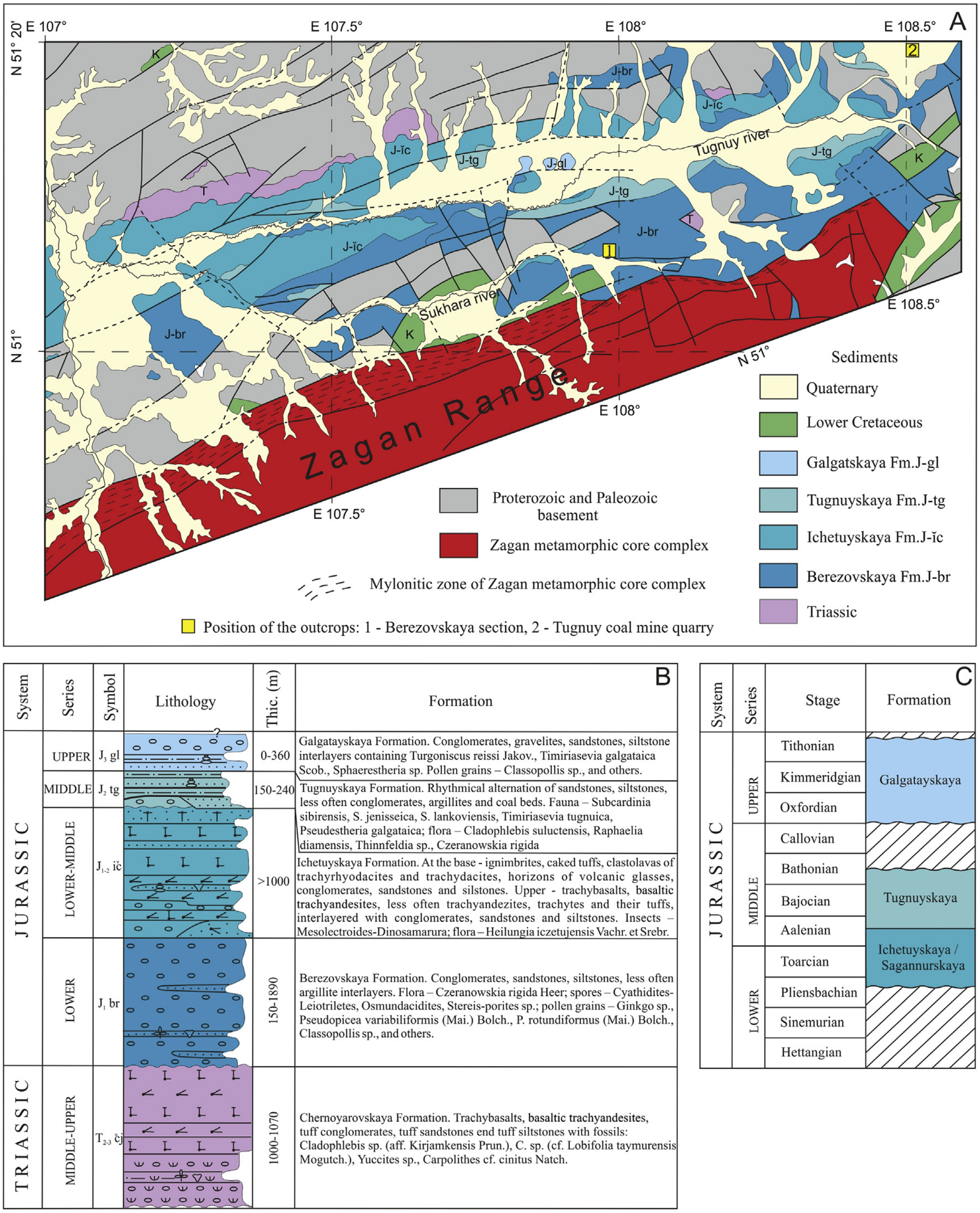
The basins formed in association with metamorphic core complexes are assigned to the Early Cretaceous. However, in Transbaikalia, some basins, older than 150–145 Ma formed during the early stage of this widespread extension. For example, according to paleobotanical and paleontological data, the Tugnuy Basin in western Transbaikalia began to form in the Early Jurassic (Komarov et al., 1965; Leonov, 1983; Skoblo et al., 2001; Novikov, 2005; Qi and Wang, 2008). No precise geochronological age is available for the onset of formation of the Tugnuy Basin, though, as probably the oldest Mesozoic basin in Transbaikalia, it is a key object to date the onset of extension in that region. According to Novikov (2005), four sedimentary formations are recognized in the Jurassic deposits of the Tugnuy Basin (from bottom to top)–Berezovskaya, Ichetuyskaya, Tugnuyskaya and Galgatayskaya (Fig. 3A and B). The conglomerates of the Berezovskaya Fm. in the Tugnuy Basin are sometimes not interpreted as basal but considered as a stratigraphic analogue of the Ichetuyskaya Fm. and referred to as the Sagannurskaya Fm. (Skoblo et al., 2001) (Fig. 3C). K–Ar dating on some volcanic rocks from the Ichetuyskaya Fm. collected within the Tugnuy Basin yielded ages of 145 ± 3 Ma, 150 ± 5 Ma (Ivanov et al., 1995) and 154.5 ± 3.7 Ma (Gordienko et al., 1997). Whole-rock Rb–Sr dating of the same rocks yielded similar ages of 158 ± 8 Ma (Gordienko et al., 1997). Finally, Arzhannikova et al. (2018) re-dated some of those volcanic rocks to 167.7 ± 1.2 Ma (Bajocian–Barthonian) using Ar–Ar analysis on whole rock. The question whether the Berezovskaya Fm. underlies the Ichetuyskaya Fm., or whether it represents a stratigraphic analogue, is crucial to constrain the onset of extension in Transbaikalia. If the Berezovskaya Fm. effectively underlies the Ichetuyskaya Fm., then extension initiated before ~168 Ma.

In this study, we selected samples from three key formations of the Tugnuy Basin (from the basal Berezovskaya Fm., the Tugnuyskaya Fm. and the Galgatayskaya Fm.), and performed U–Pb (LA-ICP-MS) dating of detrital zircons. The U–Pb data are used to assess the still discussed age and stratigraphic position of the conglomerates of the Berezovskaya Fm. and to identify the potential source areas of the sediments. The results allow describing the Jurassic topographic evolution in the area of the Mongol–Okhotsk Ocean suture zone and bring new light on the peculiar geodynamic context that prevailed immediately after the collision.

2. Late Paleozoic–Mesozoic history of Transbaikalia – North Mongolia

As described above, the late Paleozoic–Mesozoic history of Transbaikalia–North Mongolia is largely linked to the closure of the Mongol–Okhotsk Ocean (Zorin et al., 1993, 1994; Zorin, 1999; Gordienko, 2001; Donskaya et al., 2013). The most recent model, based on geochronological and geochemical data available on the late Paleozoic–Mesozoic subduction-related magmatic complexes north of the Mongol–Okhotsk suture in Transbaikalia and Mongolia, implies that subduction began in the Devonian, though the main peak of magmatic activity occurred during the Carboniferous–Late Triassic time interval (Donskaya et al., 2013). During that period, the emplacement of the voluminous granites of the Angara–Vitim batholith (C–P_2) was followed by that of the alkaline granitoids and volcanic rocks of the Western Transbaikalian belt (C_2–P_2), the calc-alkaline granitoids of the Khangay batholith (P_3–T_1) and the Khentey batholith (T_3) near the Mongol–Okhotsk suture, and finally of the alkaline granitoids and bimodal lava series (T_3) in the hinterland of the Mongolian–Transbaikalian volcano-plutonic belt (Fig. 4). Geochemical data show that the early Permian and Late Triassic alkaline granitoids of Transbaikalia are of A_2-type geochemical affinities, typical of active continental margins (Donskaya et al., 2013).

In the Jurassic, the magmatic activity significantly decreased. In western Transbaikalia only a few Jurassic granitoids are reported, spatially confined to metamorphic core complexes but preceding the tectonic exhumation of the cores. These granites are interpreted as marking the switch from subduction to collision following the closure of the Mongol–Okhotsk Ocean in Transbaikalia (Donskaya et al., 2013, 2016). The closure of the ocean in central Mongolia occurred earlier than in Transbaikalia, and most probably corresponds to the Late Triassic–Early Jurassic exhumation event recorded by low temperature thermochronology in the Gobi Altai and the Mongolian Altai (De Grave et al., 2007; Jolivet et al., 2007; Vassallo et al., 2007). The Devonian and Carboniferous flysch-type sediments, widely distributed in the Khangay and Khentey areas, were involved in the collision, intensively folded and metamorphosed under greenschist facies (Zorin, 1999). Daoudene et al. (2017) showed that there is no structural or metamorphic evidence, such as thrusts and associated metamorphic jumps, to attest for the upper crust thrust beneath deeper units in eastern Mongolia. However, the geophysical data obtained from the upper half of the crust (Siberia–Central



System	Series	Symbol	Lithology	Thic. (m)	Formation
JURASSIC	UPPER	J_3 gl		0-360	Galgatayskaya Formation. Conglomerates, gravelites, sandstones, siltstone interlayers containing Turgoniscus reissi Jakov., Timiriasevia galgataica Scob., Sphaerestheria sp. Pollen grains – Classopollis sp., and others.
	MIDDLE	J_2 tg		150-240	Tugnuyskaya Formation. Rhythmical alternation of sandstones, siltstones, less often conglomerates, argillites and coal beds. Fauna – Subcardinia sibirensis, S. jenisseica, S. lankoviensis, Timiriasevia tugnuica, Pseudestheria galgataica; flora – Cladophlebis suluctensis, Raphaelia diamensis, Thinnfeldia sp., Czeranowskia rigida
	LOWER-MIDDLE	$J_{1\text{-}2}$ ič		>1000	Ichetuyskaya Formation. At the base - ignimbrites, caked tuffs, clastolavas of trachyrhyodacites and trachydacites, horizons of volcanic glasses, conglomerates, sandstones and silstones. Upper - trachybasalts, basaltic trachyandesites, less often trachyandezites, trachytes and their tuffs, interlayered with conglomerates, sandstones and siltstones. Insects – Mesolectroides-Dinosamarura; flora – Heilungia iczetujensis Vachr. et Srebr.
	LOWER	J_1 br		150-1890	Berezovskaya Formation. Conglomerates, sandstones, siltstones, less often argillite interlayers. Flora – Czeranowskia rigida Heer; spores – Cyathidites-Leiotriletes, Osmundacidites, Stereis-porites sp.; pollen grains – Ginkgo sp., Pseudopicea variabiliformis (Mai.) Bolch., P. rotundiformus (Mai.) Bolch., Classopollis sp., and others.
TRIASSIC	MIDDLE-UPPER	$T_{2\text{-}3}$ čj		1000-1070	Chernoyarovskaya Formation. Trachybasalts, basaltic trachyandesites, tuff conglomerates, tuff sandstones end tuff siltstones with fossils: Cladophlebis sp. (aff. Kirjamkensis Prun.), C. sp. (cf. Lobifolia taymurensis Mogutch.), Yuccites sp., Carpolithes cf. cinitus Natch.

System	Series	Stage	Formation
JURASSIC	UPPER	Tithonian	Galgatayskaya
		Kimmeridgian	
		Oxfordian	
	MIDDLE	Callovian	▨
		Bathonian	Tugnuyskaya
		Bajocian	
		Aalenian	Ichetuyskaya / Sagannurskaya
	LOWER	Toarcian	
		Pliensbachian	▨
		Sinemurian	
		Hettangian	

Fig. 3. (A) Simplified geological map of the Tugnuy Basin and surrounding area (after Novikov, 2005; Jolivet et al., 2017); (B, C) Triassic–Jurassic stratigraphic section in the Tugnuy Basin: B–after Novikov (2005), C–after Skoblo et al. (2001).

Mongolia and Baikal–Mongolia geophysical transects) indicate that part of the Siberian crust was thrust over the continental margin of the Mongolia–North China continent with an horizontal displacement of at least 150 km in Khangay (Zorin et al., 1993), and about 100 km in Khentey (Zorin et al., 1994). The collision-related thrusts verging towards the Siberian Craton are morphologically less pronounced. The most prominent features are considered to belong to the Angara thrust system, whose frontal part is situated 600 km north of the Mongol–Okhotsk suture on the edge of the Siberian Craton (see location on Fig. 1B). The Precambrian basement of the craton therein was thrust over the Lower Jurassic continental sediments of the Irkutsk Basin. The maximum observed horizontal displacements on the Angara thrust nappe system are of 6–7 km (Sizykh, 2001), with folds and décollement layers affecting the sediments in the frontal part of the wedge. The structural features show displacements from south to north (Mazukabzov and Sizykh, 1987).

Crustal shortening driven by widespread collisional thrusting and abundant calc-alkaline magmatism gave rise to crustal thickening and formation of areas of elevated topography (Zorin, 1999). Although Mesozoic crustal thickening in Eastern Mongolia and NE China is refuted by Daoudene et al. (2017), it is commonly accepted that the formation of metamorphic core complexes requires crustal thickening to at least 50 km (Buck, 1991). Based on correlation of seismic data (Egorkin et al.,

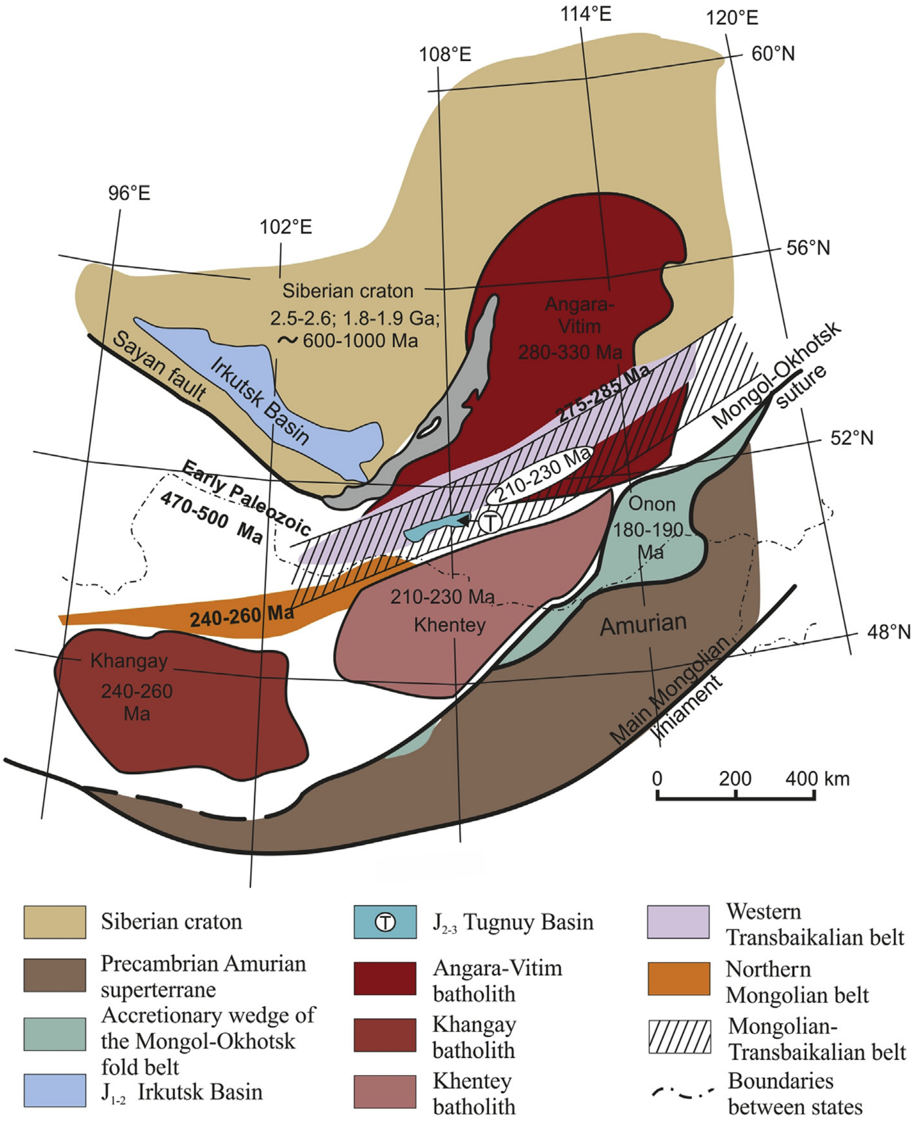


Fig. 4. Distribution of the Late Paleozoic–Early Mesozoic granitoid batholiths and volcano-plutonic belts of Transbaikalia (Russia) and northern and central Mongolia. The figure is modified after (Donskaya et al., 2013) with data from (Zorin, 1999; Parfenov et al., 2001; Yarmolyuk et al., 2002; Demonterova et al., 2017).

1980; Puzyrev, 1981; Kozhevnikov et al., 1990) and gravity anomalies (Stepanov and Volkhonin, 1969; Zorin, 1971), a first crustal thickness map was generated for East Siberia and Mongolia (Zorin et al., 1990, 1999) (Fig. 5) showing that the average crustal thickness in Transbaikalia is 40–50 km. More recent crustal thickness maps based on deep seismic sounding and gravity data show the same result (Suvorov et al., 2002; Petit and Déverchère, 2006; Vinnik et al., 2017).

The main stage of the Middle–Upper Jurassic volcanic activity in Transbaikalia coincides in time with an early phase of tectonic extension and the formation of a series of NE–SW striking grabens, including the Tugnuy Basin (Fig. 1B). Intensive bimodal volcanism, including trachybasalt, trachyandesite, trachydacite and trachyrhyodacite lava flows, produced the volcanogenic material of the Ichetuyskaya Fm. Therein 90% belong to mafic and only 10% to felsic volcanic rocks. The geochemical composition of the basaltoids from the Ichetuyskaya Fm. corresponds to that of continental rift basalts (Gordienko et al., 1997).

A second volcanic stage occurred at the beginning of the Early Cretaceous. The volcanic activity extended towards the NE from North Mongolia to the Vitim Plateau, producing lava flows that formed numerous, up to 1000 m thick subalkaline basalts volcanic fields in western Transbaikalia. This second volcanic stage was associated with the development of a new structural pattern characterized by a system of narrow grabens wherein most of the lava flows occurred (Ivanov et al., 1995). The formation of the Early Cretaceous grabens is still discussed. Daoudene et al. (2017) proposed that the extension was linked to changes in the direction of subduction of the Izanagi plate associated to an anomalously hot continental lithosphere. However, several other researchers consider that the formation of the grabens was associated to the tectonic exhumation of metamorphic core complexes as a result of extension in the overthickened crust (e.g. Zorin, 1999; Donskaya et al., 2008; Wang et al., 2011, 2012). The Early Cretaceous intra-plate basalts are geochemically similar to the Jurassic lavas of the main volcanic stage (Sklyarov et al., 1997; Donskaya et al., 2008, 2013). Tectonic exhumation of the metamorphic core complexes occurred simultaneously both in Transbaikalia–Mongolia and in the Northern China Craton.

The volcanic activity ended during the end of the Early Cretaceous. The lack of reliably dated Upper Cretaceous and Paleogene deposits in Transbaikalia suggests a period of tectonic quiescence (Logatchev et al., 1974). Though later, Logachev (1993) attributed the beginning of the Baikal rifting to the Early Cretaceous based on remnants of a few small basins and the great thickness of sediments in the Southern Baikal Basin. Ivanov et al. (2015) showed that alkaline volcanism initiated simultaneously with the Upper Cretaceous and Paleogene sedimentation.

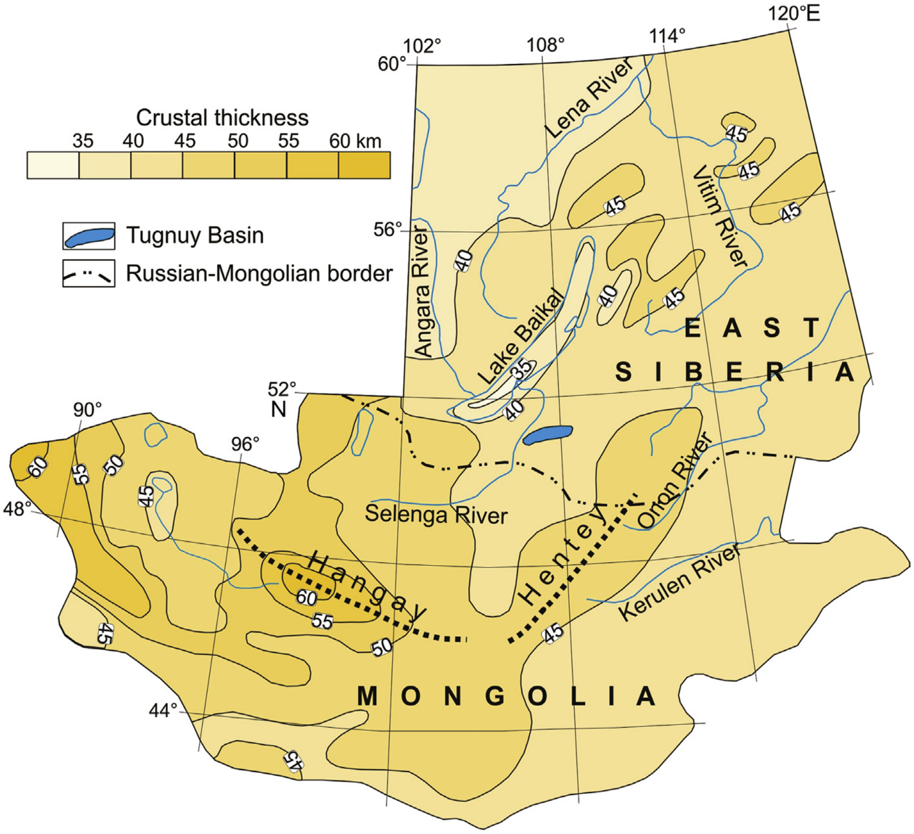


Fig. 5. Crustal thickness of East Siberia and Mongolia (modified after Zorin, 1999).

3. The Jurassic sedimentary deposits in the Tugnuy Basin

The sedimentary deposits in the basins of Transbaikalia were studied intensively in the 1950–1960s (e.g. Martinson, 1955; Kolesnikov, 1961, 1964). The data provided by these studies served as a scientific research basis for some more recent publications (Skoblo et al., 2001; Jolivet et al., 2017). However the ages of the various sediment formations, including those of the Tugnuy Basin, are still disputable (Arzhannikova et al., 2018 and references therein).

The Jurassic stratigraphy of the Tugnuy Basin, is summarized on Fig. 3A based on Skoblo et al. (2001), Novikov (2005) and Jolivet et al. (2017). The base of the section is represented by the 150 m to 1890 m thick Berezovskaya Fm. unconformably overlying the Upper Triassic volcanic rocks and Paleozoic basement. It is conformably overlain by the volcanic-sedimentary Ichetuyskaya Fm. up to 1000 m thick. Up-section, the Ichetuyskaya Fm. is overlain by the 150–240 m thick Tugnuyskaya Fm., either conformably or through an erosion surface. Finally, the Jurassic sequence ends with the up to 360 m thick Galgatayskaya Fm. Small, 100–300 m thick outcrops of Lower Cretaceous proximal alluvial fan deposits are confined to the edge of the Zagan Range (Fig. 3A). The nature of the boundary between the Cretaceous and Jurassic deposits is unknown. The Zagan Range is one of the better-known Lower Cretaceous metamorphic core complexes (Sklyarov et al., 1994, 1997; Donskaya et al., 2008, 2013). The accumulation of the Lower Cretaceous sediments near the edge of the Tugnuy Basin could be related to tectonic exposure of the core complex.

According to Skoblo et al. (2001), the conglomerate deposits of the Berezovskaya Fm. belong to the Sagannurskaya Fm., a stratigraphic analog of the Ichetuyskaya Fm. (Fig. 3C). Following these authors, the Jurassic sedimentation in West Transbaikalia initiated with the deposition of the Pliensbachian to Aalenian Ichetuyskaya and Sagannurskaya Fms., separated from the basement by an erosion surface. The Aalenian-Bathonian Tugnuyskaya Fm. conformably overlies the Ichetuyskaya and Sagannurskaya deposits. Finally, the presumably Oxfordian-Tithonian Galgatayskaya Fm. deposits are separated from the underlying Tugnuyskaya Fm. by an erosion surface (Skoblo et al., 2001) (Fig. 3C). All these ages were estimated based on macro-flora and pollen assemblages. Since the volcanic rocks from the Ichetuyskaya Fm. have been dated to latest Middle Jurassic–latest Late Jurassic using K–Ar, Rb–Sr and Ar–Ar methods (Ivanov et al., 1995; Gordienko et al., 1997; Arzhannikova et al., 2018), all the overlying deposits presented above were formed during or after the Tithonian.

Samples for detrital zircon U–Pb analysis were collected from two locations in the Tugnuy Basin, in order to cover the Berezovskaya, Tugnuyskaya and Galgatayskaya Fms. (Fig. 3A). The Berezovskaya Fm. is exposed in the Berezovskaya section (51°06.065′N, 107°57.929′E) (Fig. 6A). The deposits are composed of poorly sorted pebble to boulder (up to 0.5 m) conglomerates. The clasts are moderately rounded, in a matrix formed by gravels and coarse sandstones. The coarse conglomerates are inter-layered with thin beds of poorly sorted medium-grained sandstones and gravel-conglomerates, both containing loose pebbles. The lithology of the pebbles is dominated by pink and light-gray granites with few mafic and felsic effusive rocks (Fig. 6B). Sample Tug-17-8 was collected from a medium-grained sandstone layer (Fig. 6A). A thin section shows that the polymict sandstone is composed of poorly sorted minerals (quartz, plagioclase, kaolinized feldspar and rare muscovite) and rock fragments (quartzite, felsic and intermediate type of volcanic rocks and granite). The clasts are characterized by varying degrees of roundness, from poor to good. The cement that binds the clasts is made of clay rich-in-iron oxide. These sediments are interpreted as deposited in a braided river to proximal alluvial fan environments. The lithology of the pebbles is dominated by pink and light-gray granites with few mafic and felsic effusive rocks (Fig. 5B). The unit is tectonically disturbed, bedding plunges NW at 30°. Numerous fractures disrupt the conglomerates, some of them with a meter to several meters offset (Fig. 6C).

Samples from the Tugnuyskaya and Galgatayskaya Fms. were taken

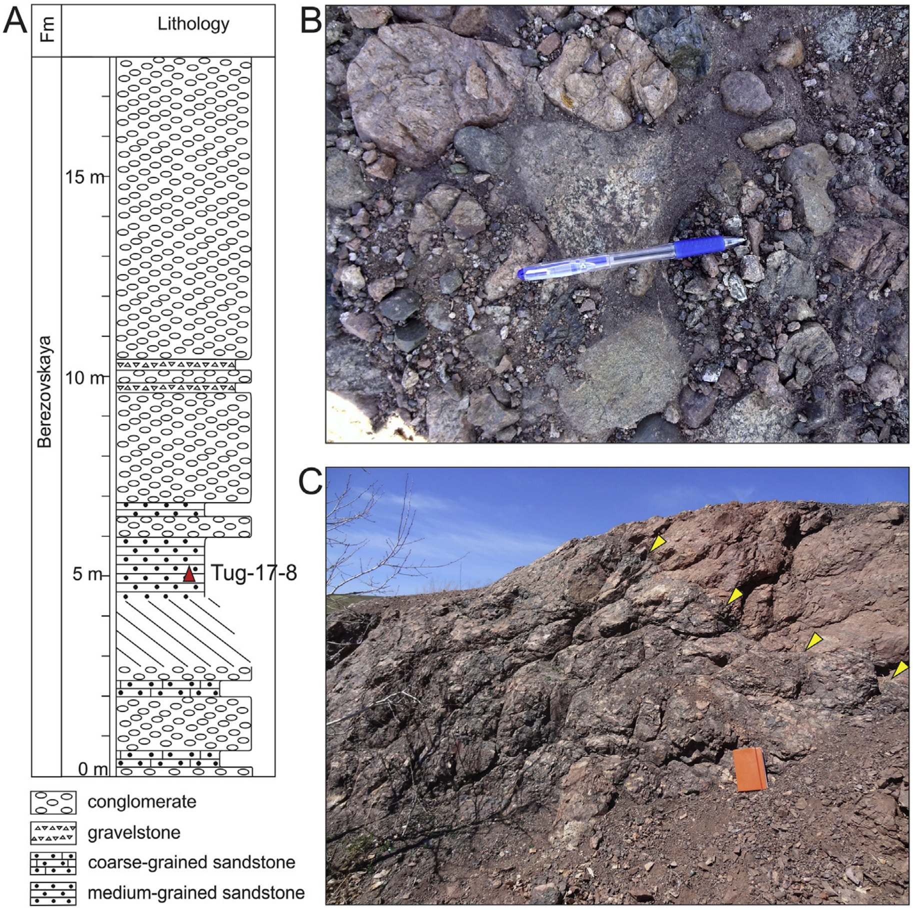


Fig. 6. (A) Berezovskaya sedimentary section. Red triangle–U-Pb Zircon sample; (B) photo of conglomerates; (C) photo of deformed conglomerates with offset of several meters (the rupture is shown by yellow triangles).

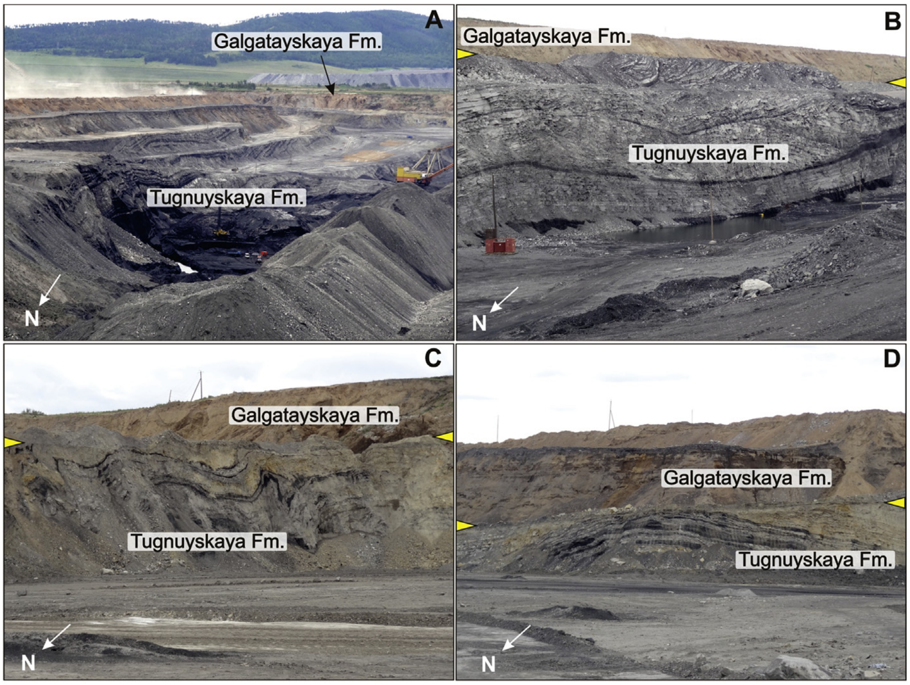


Fig. 7. The folded coal-bearing strata of the Tugnuyskaya Fm. exposed in the Tugnuy coal mine, overlain by the undeformed Galgatayskaya Fm. deposits. The yellow triangles indicate the unconformity between the two formations.

from the Tugnuy coal mine (51°18.690′N, 108°31.426′E). The Tugnuyskaya Fm. is represented by a sequence including 4 groups of economic humic coal beds showing considerable variations in thickness and affected by folds with N–S striking axes. The undeformed Galgatayskaya Fm. unconformably overlies the Tugnuyskaya Fm. through an erosion surface. The sediment sequence is composed of red sandstones and gravel conglomerates, only exposed in the upper part of the quarry (Fig. 7A–D). Samples were collected along two sections.

The first, 12 m thick section in the lower part of the quarry (Fig. 8) is characteristic of most of the Tugnuyskaya Fm. coal-bearing sequence excavated in the mine. The deposits are composed of rhythmically interlayered, well-sorted light-gray medium-grained sandstones, dark-gray siltstones, yellow coarse-grained to gravel sandstones, and thin beds of coal. Medium-grained sandstones are well rounded while coarser-grained ones are less rounded. This facies assemblage is interpreted as representing distal alluvial plain deposits including river and lake environments. The sample Tug-14-3 was collected from a medium-grained sandstone layer (Fig. 8A). It consists of small- to medium-grained polymict sandstone, similar in mineral composition to sample Tug-17-8. However, in contrast, it is well-sorted, has clay cement and mineral grains are well-rounded.

The second, 27 m thick section is located in the upper part of the quarry and contains the contact between the Tugnuyskaya and Galgatayskaya Fms. (Fig. 9). The lower part of the section (0–15 m) corresponds to the Tugnuyskaya Fm. It consists of parallel layers of light-gray medium- and coarse-grained sandstones with intercalations of thin beds of dark-gray siltstones and coal, again interpreted as distal alluvial plain deposits. These are unconformably overlain by deposits of the Galgatayskaya Fm. (15–24 m) represented by intercalated red-yellow medium- to coarse-grained and gravel sandstones with moderately rounded grains characteristic of proximal alluvial plain to distal alluvial fan deposits. The red color suggests a warm, semi-arid climate contrasting with the more humid climate prevailing during deposition of the Tugnuyskaya Fm. (Martinson, 1988). Sample Tug-14-2 was collected from a medium-grained sandstone layer of the Galgatayskaya Fm. (Fig. 9A). The composition of the sample is virtually identical to that of sample Tug-17-8 with minor differences in the cement composition, which is shifted towards iron oxide composition. The uppermost deposits (24–27 m) consist of unsorted Quaternary alluvial sediments.

4. Detrital zircon analysis and results

Detrital zircons were extracted using an electromagnetic separator and heavy liquids. For each sample, more than 100 zircons crystals were mounted without selection based on size (analyzed crystal size vary between 60 μm and 180 μm) or morphology. U–Pb analysis was performed using and ICP-MS Element XR (ThermoFisher Scientific) coupled to an UP-213 laser (New Wave). The instrumental parameters and measurement technique are described in Khubanov et al. (2016) and Buyantuev et al. (2017). The 91500 (1065 Ma) (Wiedenbeck et al., 1995), Plešovice (337 Ma) (Slama et al., 2008) and GJ-1 (608.5 Ma) (Jackson et al., 2004) zircons were used as external standards. Relative errors in the measurement for isotope ratios in the reference standards varied within ranges of 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 $^{207}Pb/^{235}U$. The measurement data were processed using the GLITTER (Griffin et al., 2008) and ISOPLOT (Ludwig, 2003) software. The interpretation only considered the data with <10% discordance. The age data histogram and probability curves for each

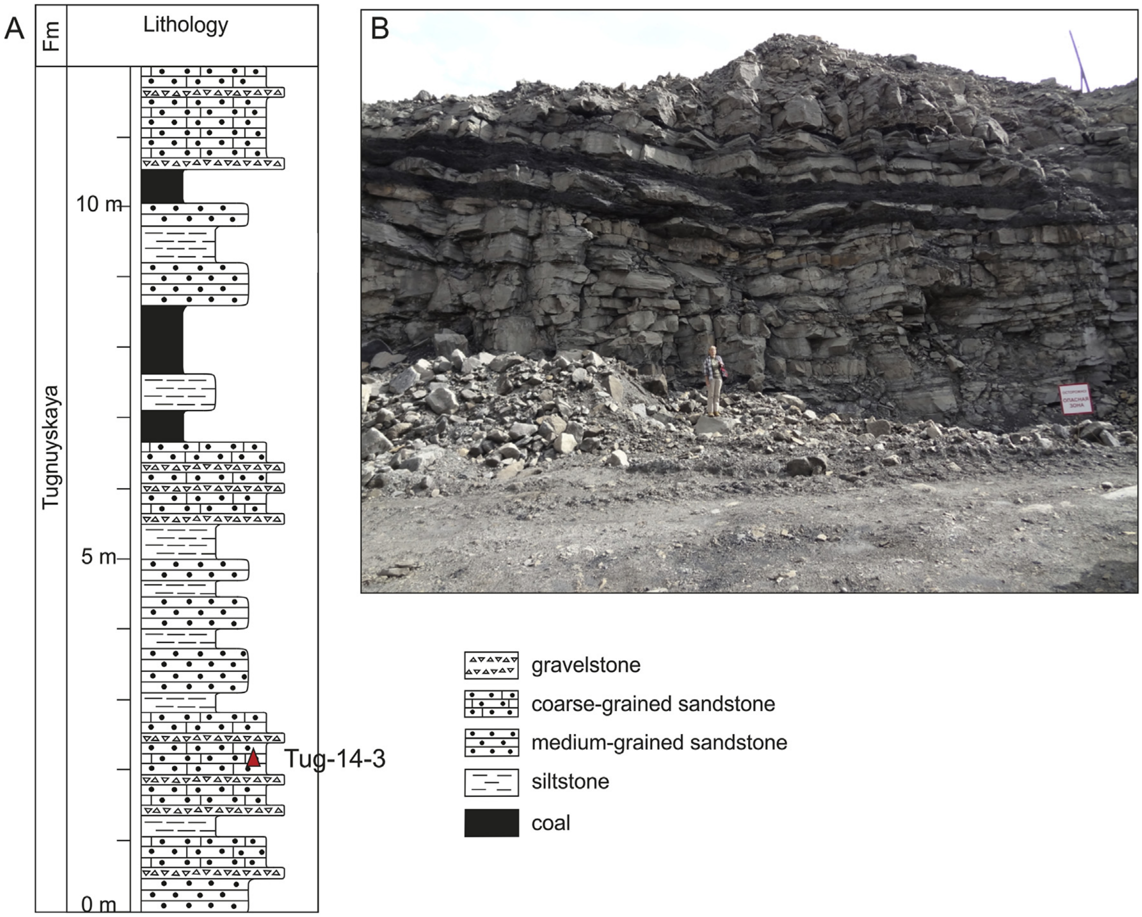


Fig. 8. (A) Sedimentary section of Tugnuyskaya Fm. in sampling site. Red triangle–U-Pb Zircon sample; (B) photo of the logged section.

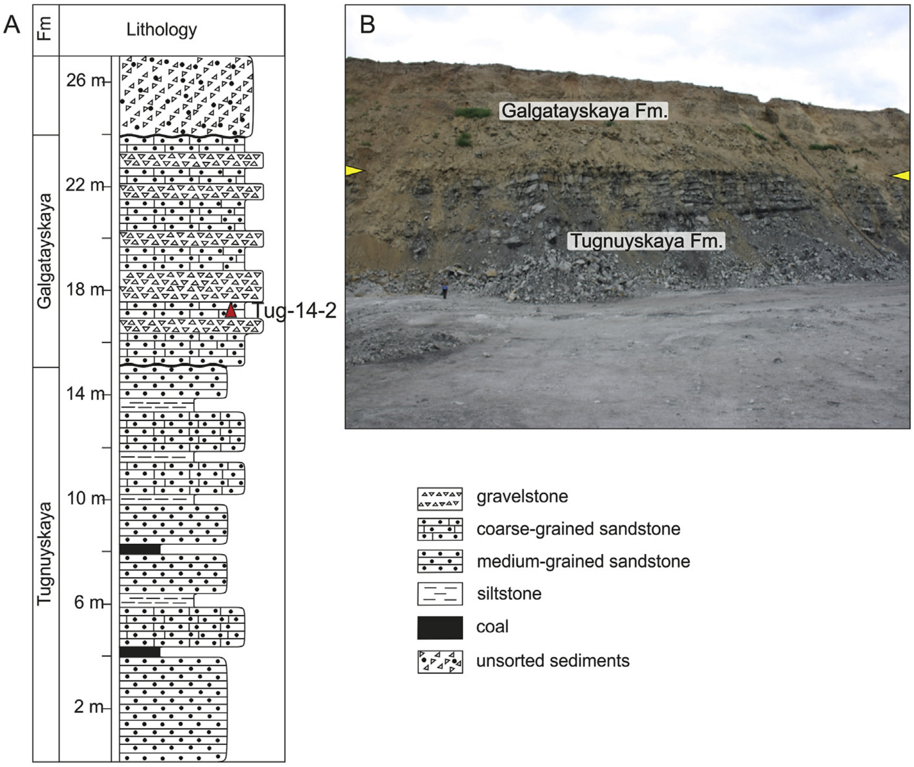


Fig. 9. (A) Sedimentary section of Galgatayskaya and Tugnuyskaya Fms. in their contact zone. Red triangle–U-Pb Zircon sample; (B) photo of the cross-section. The yellow triangles indicate the unconformity between the two formations.

sample were plotted from ^{206}Pb/^{238}U with 2σ error bars (Fig. 10; samples Tug-14-2, Tug-14-3 and Tug-17-8 in Suppl. Material). Backscattered electron imaging (BSE) was used to infer zoning and internal structures of the zircon grains as well as the occurrence of mineral inclusions (Fig. 11).

In general, zircon U–Pb ages from the Tugnuy Basin deposits indicate upper Paleozoic and Mesozoic source rocks. Detrital zircons from the Berezovskaya Fm. (sample Tug-17-8 in Suppl. Material) are transparent, pale yellow to yellow, and contain no more than 5% of fractured grains. Most of the grains are isometric (~35%), short-prismatic (~35%), prismatic (~20%), and some of them are long-prismatic (~10%), most of them are of volcanic affinity. One hundred twelve concordant zircon grains provided U–Pb dates distributed in the following populations: 154–174 Ma (38% of grains), 190–237 Ma (35% of grains), 241–275 Ma (17% of grains), and 288–325 Ma (11% of grains). A few additional single grains with ages of 400 Ma and 1524 Ma have been obtained but they do not represent statistically reliable populations (3% or more) and are not considered for discussion.

Detrital zircons from the Tugnuyskaya Fm. (sample Tug-14-3 in Suppl. Material) are colorless, pale yellow and very seldom yellow. The grains are isometric (~50%), prismatic (~30%) or short-prismatic (~20%). The grains are transparent, with almost no fractures (no more than 5%). One hundred ten U–Pb zircon dates were obtained, distributed in the following populations: 168–177 Ma (3% of grains), 197–270 Ma (91% of grains) and 280–305 Ma (6% of grains).

Detrital zircons from the Galgatayskaya Fm. (sample Tug-14-2 in Suppl. Material), are yellow to pale yellow, less often colorless (~10%). Most of the grains are isometric (~50%) or prismatic (~30%) but some are short-prismatic (~17%) or single long-prismatic (~3%). Fractured grains (predominantly yellow and pale yellow) make up about 20% of the total. One hundred seven U–Pb zircon dates were obtained with age populations of 162–173 Ma (6% of grains), 194–230 Ma (74% of grains) and 233–256 Ma (20% of grains).

5. Discussion

5.1. *Provenance of detrital zircons*

Based on the distribution of the detrital zircon U–Pb ages and the sediment facies and depositional environment we discuss the source area for each formation as well as the topographic evolution of the region surrounding the Tugnuy Basin. The potential sediment source areas have been distinguished based on the geochronological data available in Siberia, North Mongolia and Central Mongolia (Fig. 4).

Based on detrital zircon provenance analysis (Prokopiev et al., 2008; Demonterova et al., 2017; Mikheeva et al., 2017), the topographic evolution of Western Transbaikalia during the Early Jurassic resulted from compressive deformation and denudation on the edge of the Siberian Craton near the Sayan Mountains and the Angara-Vitim batholite area (Fig. 12A) and from the onset of erosion in Western Transbaikalia by ~178 Ma (Fig. 12B). The compressive stress field caused by the Mongol–Okhotsk collision was rapidly inverted; leading to continental rifting which onset age corresponds to the age of the oldest deposits in the Tugnuy Basin.

In the lowest Berezovskaya Fm. (sample Tug-17-8, Fig. 10A), the main zircon ages ranging from 154 Ma to 170 Ma correspond to the age of volcanic rocks of the Ichetuyskaya Fm. (145–168 Ma), widespread within the basin (Ivanov et al., 1995, Gordienko et al., 1997; Arzhannikova et al., 2018). The occurrence of mafic volcanic fragments and the preservation of long-prismatic magmatic zircons of “Ichetuyskaya” age in conglomerates and sandstones of the Berezovskaya Fm. indicate that the latter does not underlie the Ichetuyskaya Fm. but was deposited simultaneously at least during the latest stage of the Ichetuyskaya volcanism. However, the groundmass of pebbles in the Berezovskaya Fm. conglomerates corresponds to felsic magmatic rocks; the percentage of granitoid pebbles (80%) remains unchanged along the investigated cross-section. This is also typical of the other sections logged in the

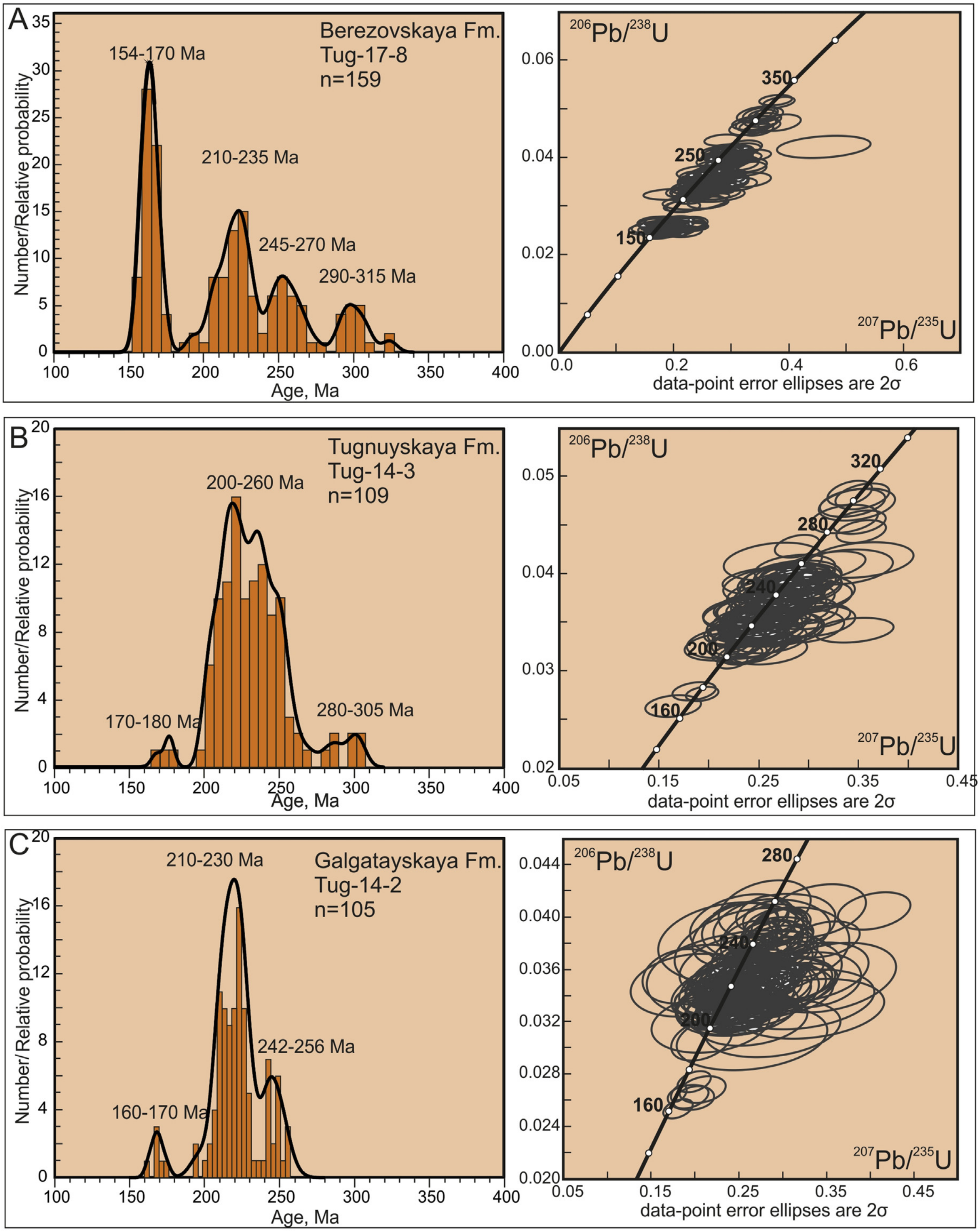


Fig. 10. Histograms coupled with probability density plot (black curve) and U–Pb concordia diagrams for zircons from the (A) Berezovskaya, (B) Tugnuyskaya and (C) Galgatayskaya Fms. n–number of data.

conglomerates of the Berezovskaya Fm. (Skoblo et al., 2001), indicating a continuous erosion of the granitoid provinces. The age peaks of 210–235 Ma and 245–270 Ma correspond to the erosion of the southern magmatic provinces including the Mongolian-Transbaikalian belt, the Northern Mongolian belt, the Khentey batholith, and the Khangay batholith. Only the Onon province farther to the east seems not to be represented (Fig. 4). As proposed by Donskaya et al. (2013), some of these belts presented relatively high relief that could explain the coarse material transported to the Transbaikalian basins (Fig. 12C). The more restricted zircon ages ranging from 290 Ma to 315 Ma only correspond to the Angara–Vitim batholith situated to the north of the Tugnuy Basin. As indicated by the significant occurrence of late Carboniferous–early Permian detrital zircon U–Pb ages in the Lower–Middle Jurassic deposits of the Verkhoyansk margin and Irkutsk Basin, the Angara-Vitim batholith area was also an uplifted region at the Early–Middle Jurassic boundary (Prokopiev et al., 2008; Demonterova et al., 2017; Mikheeva, 2017) (Fig. 12B). However, the occurrence of age peaks corresponding to sources both to the north and south of the Transbaikal Province in a single sample

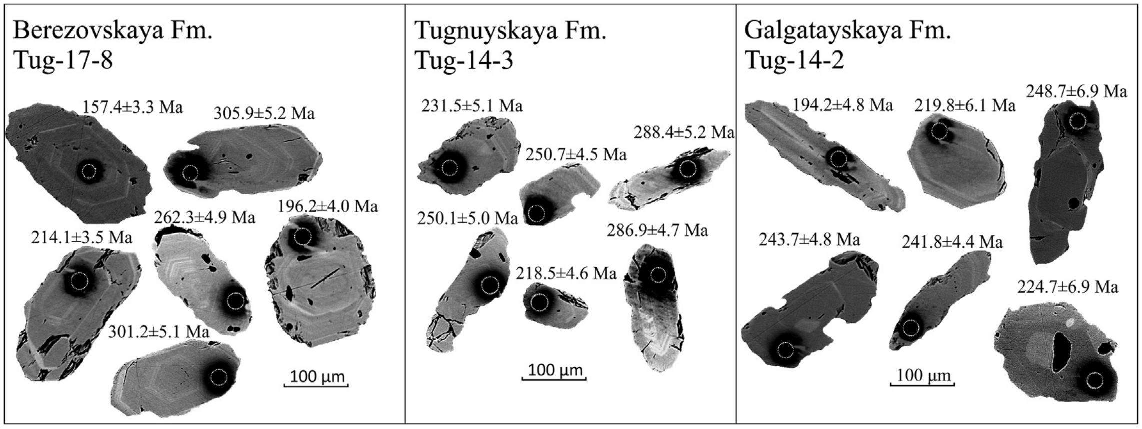


Fig. 11. BSE images of some representative igneous zircons from the Berezovskaya, Tugnuyskaya and Galgatayskaya Fms. The white circles indicate the locations of the laser ablation spots.

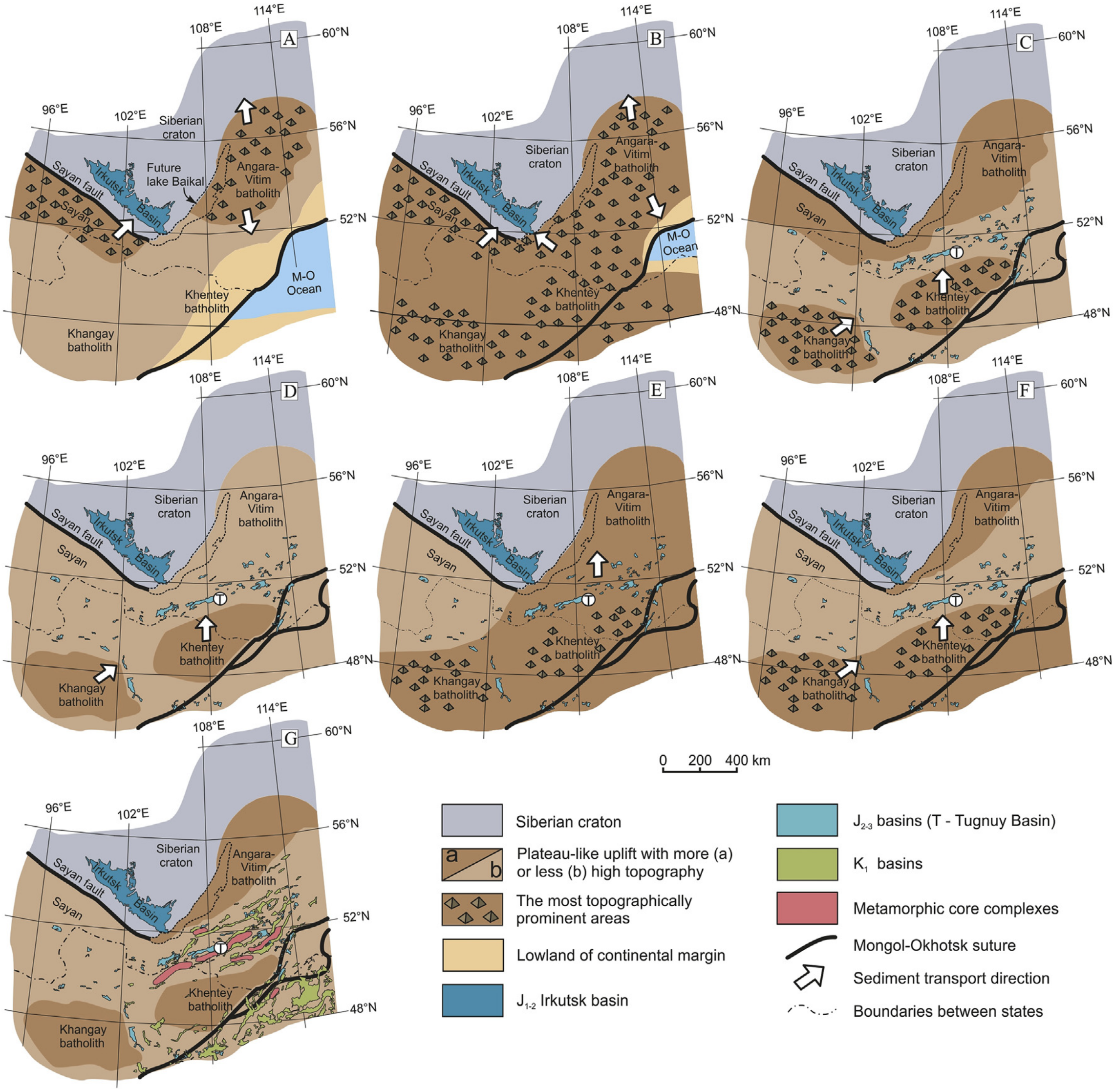


Fig. 12. Schematic paleogeographic reconstruction of Transbaikalia and North Mongolia during the Early Jurassic–Early Cretaceous. (A) Onset of sediment deposition in the Irkutsk Basin (~194 Ma). (B) Final period of deposition in the Irkutsk Basin (~178 Ma); the compressive stress field was caused by the Mongol-Okhotsk collision. (C) "Ichetuyskaya/Berezovskaya" period (~168–145 Ma), onset of continental rifting. (D) "Tugnuyskaya tectonically quiet period (during or after the Tithonian). (E) Erosional phase in Western Transbaikalia (latest Jurassic–earliest Cretaceous) related to a short-term collision event (Yang et al., 2015). (F) "Galgatayskaya" period (Early Cretaceous), increasing of basin subsidence. (G) "Metamorphic core complexes" period (Early Cretaceous).

suggest sediment recycling from previous deposits (Yang et al., 2013). The large amount of granitoid fragments derived from the southern provinces, associated to the short transport distance suggested by the alluvial fan depositional environment advocates for a river system flowing from the south and mainly eroding the basement. Nonetheless, as the Berezovskaya Fm. corresponds to the onset of extension, the previously existing cover sequence, containing zircons derived from sources to the north was probably still preserved and participated to the clastic material source (Fig. 12C). The presence of detrital zircons with ages typical of the Angara-Vitim batholith south of the Tugnuy Basin further implies that a river system sourced in the Angara-Vitim area had reached this region prior to Middle Jurassic times (Fig. 12A). This South-directed drainage system seems to have been at least partially inverted during the Middle Jurassic (Fig. 12C). This is consistent with the southward shift in the zircon sources observed by Prokopiev et al. (2008) in the late Lower to Middle Jurassic deposits of the paleo-Lena River system.

The distal alluvial plain to lacustrine, coal-bearing facies of the Tugnuyskaya Fm., suggests that by that time, Transbaikalia was already a tectonically quiet area with a flat, poorly dissected topography mainly characterized by wide alluvial valleys (Butova, 1963; this study). Volcanism had ceased by that time (Donskaya et al., 2013), and the volcanic deposits were already largely overlain by younger clastic sediments. We suppose that for this reason we do not observe zircon age population corresponding to the Ichetuyskaya Fm. time-span in the Tugnuyskaya Fm. Sample Tug-14-3 is characterized by a major population of zircons issued from the southern provinces (200–260 Ma, Fig. 10B), which indicates that erosion in the uplifted areas to the south still continued (Fig. 12D). This is consistent with the occurrence of a few Jurassic (170–180 Ma) and late Carboniferous–early Permian (280–305 Ma) ages (Fig. 10B) most probably representing, like in sample Tug-17-8 (Berezovskaya Fm.) recycling of previous deposits. Finally, this result supports the idea that the Berezovskaya and Tugnuyskaya Fms. correspond to a single, continuous topographic and erosional stage: the lower proportions of Jurassic and late Paleozoic zircon ages observed in sample Tug-14-3 compared to sample Tug-17-8 indicate a deepening of the erosion level associated with the progressive removal of the previously existing sediment cover in the southern provinces.

The tectonic deformation (folding) observed in the Tugnuyskaya Fm. deposits and the unconformable erosional contact with the overlying Galgatayskaya Fm. indicate an episode of compression and erosion in the Tugnuy Basin area (Fig. 12E). The roughly N–S folds axes imply E–W compression coherent with the contemporaneous collision-related compressive deformations described in the eastern part of the Mongol–Okhotsk suture zone, east of Transbaikalia. Based on geophysical studies, the results of Shevchenko et al. (2011) and Didenko et al. (2013) showed multiple trusting on the Aldan-Stanovoy craton where the South Aldan Jurassic coal basin was partly overthrusted by metamorphic rocks. Yang et al. (2015) described Upper Jurassic–Lower Cretaceous folding and erosion in some basins of Mongolia and North China. They related this compression phase, enclosed between two episodes of extension, to a short-term collision event lasting about 10 million years during the latest Jurassic–earliest Cretaceous in the eastern Central Asian Orogenic Belt. The folding of the Tugnuyskaya Fm. can be a response to this collision event in the central part of the Mongol–Okhotsk fold belt.

The compression and erosion phase was followed by the deposition of the Galgatayskaya Fm. terminating the Tugnuy sequence. The upward coarsening of the deposits and the progressive shift toward more proximal depositional environments suggest a renewed relief building associated with an increasing rate of basin subsidence (Fig. 12F). The zircon U–Pb age distribution again shows a small peak of recycled Jurassic volcanic zircons (160–170 Ma) and two main peaks corresponding to sources in the magmatic provinces of North Mongolia (210–230 Ma and 242–256 Ma) (Fig. 10C). The absence of upper Paleozoic zircons suggests that most of the previously deposited sediment cover containing those zircons had been removed by Middle–Late Jurassic times.

Finally, by Early Cretaceous time, further extension led to the tectonic exhumation of metamorphic core complexes and the formation of the Lower Cretaceous grabens widespread in Transbaikalia and North Mongolia (Sklyarov et al., 1997; Donskaya et al., 2008, 2013) (Fig. 12G).

5.2. *Formation mechanism of the Jurassic basins in Transbaikalia*

Based on detrital U–Pb zircon geochronology data and sediment analysis presented above, extension in the Tugnuy Basin started around 168 Ma, participating to the initial degradation of the post-collision relief in the Transbaikal region. This is ~10–12 million years later than the latest Early Jurassic age proposed for the onset of the collision-related topography in Transbaikalia (Demonterova et al., 2017; Mikheeva et al., 2017; Mikheeva, 2017). However, the Tugnuy Basin initiated earlier than the mid–lower-crustal extension that led to the tectonic exhumation of the Lower Cretaceous metamorphic core complexes in Southeast Siberia and North Mongolia (Donskaya et al., 2008; Wang et al., 2012; Daoudene et al., 2017). In that respect, the model relating the formation of the Transbaikalian basins to post-collisional collapse of the thickened continental crust, can only explain the evolution of the Lower Cretaceous basins widespread in Transbaikalia, North Mongolia and within the North China Craton (Zheng et al., 1991; Sklyarov et al., 1997; Zorin et al., 1997; Zorin, 1999; Donskaya et al., 2008; Wang et al., 2011, 2012). The formation of the Jurassic basins, however, seems to have had a more local character, and their spatial location is often unrelated to any metamorphic complex.

The Jurassic evolution of the Tugnuy Basin can be divided in three stages. Following the Bathonian initiation of the basin, the deposition of the at least 1 km thick volcano-sedimentary deposits of the Berezovskaya/Ichetuyskaya and Tugnuyskaya Fms. shows a generally retrograding trend from coarse, proximal alluvial fan deposits to sandy, coal bearing alluvial plain and lacustrine deposits. This retrogradation trend suggests a decrease in subsidence rate and thus in tectonic extension rate. In the latest Jurassic–earliest Cretaceous, the basin was affected by E–W compression leading to basin inversion and erosion of the Tugnuyskaya Fm. Renewed extension in Early Cretaceous finally allowed the deposition of the prograding Galgatayskaya Fm.

Such a long-term deformation pattern, with the simultaneous or alternating occurrence of short-term compression and extension phases, is typical of basins forming along large shear zones. For example, the Tunka Basin in the southwestern flank of the Baikal rift (see location on Fig. 1B), which began to subside during late Oligocene and accumulated about 3 km of sediment in a regionally transtensive tectonic setting (Sherman et al., 1973; Mazilov et al., 1993), was locally inverted during the late Pleistocene–Holocene (Larroque et al., 2001; Arjannikova et al., 2004; Arzhannikova et al., 2005; Shchetnikov, 2017; Ritz et al., 2018). To a larger scale, a similar deformation pattern, associating contemporaneous extension and compression along a large-scale strike-slip system has been put forward to explain the Cenozoic evolution of the Baikal rift –the Transbaikal system (Jolivet et al., 2013). Paleomagnetic data obtained from the Mesozoic deposits of Southeast Siberia and North Mongolia evidence left-lateral strike-slip motion along the Mongol–Okhotsk suture zone during and after the collision due to clockwise rotation of the Siberian continent (Parfenov et al., 2001; Metelkin et al., 2004, 2010). Yang et al. (2015) proposed that this major left-lateral strike-slip motion triggered the gravitational collapse of the thickened upper crust, leading to the development of rift basins. The oblique closure of the Mongol–Okhotsk Ocean has been put forward to explain the simultaneous formation of compressional structures along the edge of the Siberian Craton and that of extensional structures in Transbaikalia (Jolivet et al., 2017). However, as indicated in the introduction, newly obtained data show that compression and positive relief building in Transbaikalia began about 12 million years earlier than extension (Demonterova et al., 2017; Mikheeva, 2017; this study). The basin formation in Transbaikalia as the extension along strike-slip fault systems seems probable, though it relates only to the Jurassic basins. Finally, the Cretaceous basins widespread throughout northeastern continental Asia are tightly related in space and time with metamorphic core complexes and correspond to an extensional mechanism not limited to the Mongol–Okhotsk suture zone. To the east, the Mongol–Okhotsk oceanic plate was directly connected to the Farallon plate itself separated from the Izanagi plate to the south. By Late Jurassic, the Farallon plate had completely subducted, replaced by the Izanagi plate moving northwestward and connected to the Pacific plate to the south (Cogné et al., 2005; Daoudene et al., 2017). It is largely admitted that this widespread extension phase is related both to collisional uplift collapse and far-field effects of the Cretaceous Pacific and the Izanagi plate subduction processes (Zheng et al., 1991; Sklyarov et al., 1997; Zorin et al., 1997; Zorin, 1999; Donskaya et al., 2008; Wang et al., 2011, 2012; Daoudene et al., 2017). This last event was superimposed to the more local, Jurassic extension in Transbaikalia similarly to the Cenozoic superimposition of the Baikal system to the Mesozoic Transbaikal basins (Jolivet et al., 2013).

6. Conclusions

The Jurassic–Lower Cretaceous sedimentary and topographic evolution of Transbaikalia provides key information on the rapid change in tectonic setting between the final closure of the Mongol–Okhotsk Ocean and the onset of the continental-scale extension in northeastern Asia.

A wide uplifted plateau reaching the southern edge of the Siberian craton by ~178 Ma characterized the topography that resulted from the closure of the Mongol–Okhotsk Ocean at the end of the Early Jurassic. The main sediment sources in Transbaikalia were the exhumed granitic batholiths of North Mongolia and Transbaikalia. Sedimentation occurred in a wide area including Transbaikalia, the Irkutsk Basin and the Verkhoyansk margin. Nonetheless, while this topography was evolving, strike-slip displacement induced by the oblique closure of the Mongol–Okhotsk Ocean initiated some of the Transbaikalian depressions, such as the Tugnuy Basin at about 168 Ma, associated to igneous activity. Our results on detrital zircon geochronology of the Tugnuy Basin sediments together with published ^{40}Ar/^{39}Ar data on volcanic rocks clearly demonstrate that the Berezovskaya Fm. was deposited simultaneously with the Ichetuyskaya Fm. during the final stage of volcanic activity from Kimmeridgian to Tithonian. They contain material partially recycled from a previous vast Lower Jurassic drainage system reaching the Angara-Vitim batholith to the north and shedding sediments to the continental margin of the Mongol–Okhotsk Ocean in Early Jurassic. The collisional event at the end of the Early Jurassic led to the uplift of the continental margin, which partially inverted the drainage system toward the North. The main zircon age populations in the Berezovskaya and Tugnuyskaya Fms. correspond to the erosion of the southern (North Mongolian) granite batholites. A phase of basin inversion marked by folding of the Tugnuyskaya Fm., could correspond to the short-term collision event that took place during the latest Jurassic–earliest Cretaceous in the eastern Central Asian Orogenic Belt (Yang et al., 2015).

The following inversion in tectonic regime from compression to extension occurred in Transbaikalia in Early Cretaceous. This is consistent with the crustal extension that led to the formation of the numerous metamorphic core complexes throughout northeastern continental Asia during the Early Cretaceous. We propose that this extension was driven by a combination between the Mongol–Okhotsk orogenic collapse and the far field effects of the paleo-Pacific–Izanagi plate subduction to the east. A pattern similar to the combination between the India-Asia collision and Pacific subduction stress fields opening the Cenozoic Baikal rift system.

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

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