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Tectonostratigraphic evolution of the Mohe-Upper Amur Basin reflects the final closure of the Mongol-Okhotsk Ocean in the latest Jurassic–earliest Cretaceous

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ABSTRACT

The Mohe-Upper Amur Basin to the south of the eastern Mongol-Okhotsk Suture Zone contains important stratigraphic records for understanding the closure of the eastern Mongol-Okhotsk Ocean. The basin is crossed by the Russia/China border, and its Chinese and Russian parts are known as the Mohe Basin and Upper Amur Basin, respectively. Using most up-to-date data on stratigraphy, sedimentology, petrography, and detrital zircon U-Pb geochronology, this study establishes the stratigraphic correlation between the two, Mohe and Upper Amur parts of the basin, and analyzes depositional ages, provenance, and paleogeography of their Jurassic–Lower Cretaceous strata. The adopted Middle–Late Jurassic ages for the Xiufeng, Ershierzhan, Emuerhe, and Kaikukang formations in the Mohe Basin, are revised and constrained to late Kimmeridgian, Tithonian, Berriasian–early Valanginian, and late Valanginian ages, respectively. During the late Kimmeridgian–Tithonian, extension occurred in the Mohe-Upper Amur Basin, and sediments were mainly sourced from areas to the south of the basin. Later, in the Berriasian–early Valanginian, the northern margin of the Mohe-Upper Amur Basin was uplifted and started furnishing sediments into the basin. In the late Valanginian, regional uplift of the northern part of the Mohe-Upper Amur Basin transformed the basin into a compressional intermountain basin, with sedimentation localized in its southern part. After the Valanginian, extension and associated volcanism occurred in the basin. We suggest that the evolution of the Mohe-Upper Amur Basin reflects the gradual closure of the eastern Mongol-Okhotsk Ocean and associated collision of the Siberia Craton and the Amuria Block, that occurred from the Kimmeridgian–Tithonian, to the west of the basin through to the Berriasian–Valanginian, to the north and northeast of the basin. The final closure of the Mongol-Okhotsk Ocean to the north of the Mohe-Upper Amur Basin in the earliest Cretaceous significantly affected the sedimentological, structural and tectonic evolution of Northeast Asia.

1. Introduction

The Central Asian Orogenic Belt (CAOB), located between the Siberia Craton to the north and the Tarim and North China cratons to the south, is one of the largest Phanerozoic accretionary collages on earth (Zonenshain et al., 1990; Sengör et al., 1993; Sengör and Natal’in, 1996; Xiao and Santosh, 2014), and is considered to have evolved over about 720 million years from the late Proterozoic to the Mesozoic (Kröner et al., 2007, 2014; Windley et al., 2007). The Mongol-Okhotsk Suture Zone, extending over 3000 km from the Central Mongolia in the southwest to the Sea of Okhotsk in the northeast, is one of the youngest orogenic divisions of the CAOB (Zonenshain et al., 1990) (Fig. 1). The closure of the Mongol-Okhotsk Ocean along the suture zone and associated collision of the Siberia Craton and the Amuria Block in the late Mesozoic significantly affected the stratigraphic, structural and tectonic evolution of the Central and East Asia, involving paleogeographic transformation, folding, thrusting, metamorphism, and magmatism (Zonenshain et al., 1990; Zorin, 1999; Yang et al., 2015a,b). However, two main controversial issues related to the closure of the Mongol-Okhotsk Ocean still remain unresolved.

First, how wide was the Mongol-Okhotsk Ocean in the Late Jurassic? Based on stratigraphic, structural, and magmatic data, geologists suggested that its western part to the west of longitude 120°E closed either in the Late Triassic–Early Jurassic (Zonenshain et al., 1990; Zonenshain and Kuzmin, 1997) or at the Early/Middle Jurassic boundary (Zorin, 1999), leaving to the east a remnant oceanic expanse...
∼300 km wide until the Late Jurassic (Zonenshain et al., 1990) (Fig. 1). However, paleomagnetic data demonstrate that the Late Jurassic to Early Cretaceous convergence between the Siberia Craton and the Amuria Block reached 1000–3000 km, indicating that the ocean remained considerably wide in the Late Jurassic (Enkin et al., 1992; Halim et al., 1998; Cogné et al., 2005; Metelkin et al., 2010; Pei et al., 2011; Van der Voo et al., 2015; Ren et al., 2016).

Second, when did the Mongol-Okhotsk Ocean finally close? As Upper Jurassic thick marine sandstone and shale are widespread in the eastern Mongol-Okhotsk Suture Zone and its neighboring areas where syn-collisional folding, metamorphism, and magmatism occurred in the earliest Cretaceous (Figs. 1 and 2), it was assumed that the eastern part of the ocean closed in the Early Cretaceous (Zonenshain et al., 1990; Zonenshain and Kuzmin, 1997; Nokleberg et al., 2000; Parfenov et al., 2010). Yang et al. (2015a) suggested that the Mongol-Okhotsk Ocean closed rapidly during the latest Jurassic–earliest Cretaceous, which resulted in the formation of a giant fold-and-thrust belt in the northern China and Mongolia. However, geochemical (He et al., 2005) and petrographic (Zhang et al., 2014) studies of the Middle–Upper Jurassic sandstone from the Mohe Basin to the south of the Mongol-Okhotsk Suture Zone indicated that the suture zone was a provenance area, implying that the Mongol-Okhotsk Ocean had closed before the Middle Jurassic, and the neighboring Mohe Basin was either a foreland basin (He et al., 2005; Hou et al., 2010; Zhang et al., 2014) or an intermountain basin (He et al., 2008) (Fig. 2).

The Jurassic–Early Cretaceous Mohe-Upper Amur Basin to the south of the eastern Mongol-Okhotsk Suture Zone (Figs. 1 and 2) is supposed to contain valuable stratigraphic data recording the evolution of the basin as well as the eastern Mongol-Okhotsk Ocean. However, the evolution of the basin has never been investigated in detail, clearly understood, and linked to the final closure of the Mongol-Okhotsk Ocean. As the Mohe Basin and Upper Amur Basin are located in China and Russia, respectively, the stratigraphic correlation between them has not been explored, and the evolution of the basin as a solitary unit remains ambiguous. In this study, we review the stratigraphic and sedimentological characteristics and establish a regional stratigraphic framework for the Mohe-Upper Amur Basin. On the basis of petrographic and detrital zircon U-Pb geochronological analyses of sandstone samples from the Mohe Basin, we reassess the depositional ages and provenance locations for its Middle Jurassic–Lower Cretaceous deposits. Ultimately, we propose a new model for the tectonostratigraphic evolution of the Mohe-Upper Amur Basin linked to the closure of the eastern Mongol-Okhotsk Ocean.

2. Geological setting, stratigraphy and sedimentology of the Mohe-Upper Amur Basin

The Jurassic–Early Cretaceous Mohe-Upper Amur Basin is situated in the northern Erguna Massif, just to the south of the eastern Mongol-Okhotsk Suture Zone and to the north of the Greater Xing’an Range (Fig. 1). The Erguna Massif, the northernmost part of the Amuria Block, has a Precambrian basement composed of amphibolite, gneiss, schist, granulite, marble, and migmatite (Wu et al., 2012; Zhou and Wilde, 2013) overlain by Paleozoic–Mesozoic clastic and volcanic rocks (Zhang et al., 2008). The stratigraphy and sedimentology of the Mohe-Upper Amur Basin are briefly summarized below.
2.1. Mohe Basin

Traditionally, on the basis of loosely constrained biostratigraphic and sparse K-Ar geochronological data, the sedimentary succession of the Mohe Basin is subdivided into the Middle–Upper Jurassic Emuerhe Group and Lower Cretaceous Series (Wu et al., 2003; Xiao et al., 2015) (Figs. 2 and 3). The Emuerhe Group includes, in an ascending order, the Xiufeng, Ershierzhan, Emuerhe, and Kaikukang formations arranged in several fining-upward sequences, and is separated by a parallel to low-angle unconformity between the last two formations (HBGMR, 1993; Qu et al., 1997; Li, 2007; Sun, 2013) (Fig. 3).

The Xiufeng Formation, unconformably resting on the Precambrian and Paleozoic metamorphic and granitic rocks (Qu et al., 1997; Li, 2007), is exposed along the southern margin of the Mohe Basin (Fig. 2). A series of planar and listric normal faults controlling deposition of the formation and indicating its extensional setting have been recognized on the basis of gravity and seismic data (Li, 2007; Xu, 2010) (Fig. 2).

The formation is characterized by alluvial fan deposits, and comprises three intervals (Fig. 3). The lower and upper intervals consist of poorly sorted conglomerate and pebbly sandstone, interbedded with medium- to coarse-grained sandstone (Figs. 4 and 5A), whereas the middle interval consists of coarse- to medium-grained sandstone, interbedded with pebbly sandstone and thin laminated siltstone (Li, 2007; Wang, 2015). Its average paleosalinity, estimated from equivalent boron, is relatively low, implying an inland freshwater environment (Zhao et al., 2007). Abundant freshwater faunas, floras, and sporo-pollen assemblages are Aalenian (Xu et al., 2003; Xiao et al., 2015) or early Late Jurassic (Wu et al., 2003) in age.

The Ershierzhan Formation, conformably lying on the Xiufeng Formation, crops out in the central Mohe Basin (Fig. 2) and consists of thick pebbly and coarse- to medium-grained sandstone (Figs. 3 and 4). Ubiquitous rhythmic intervals fining upward from pebbly sandstone to siltstone and mudstone (Fig. 5B) with trough and planar cross-stratification are indicative of a braided river.
depositional environment (Li, 2007). Paleontological studies suggested Bajocian (Xu et al., 2003; Xiao et al., 2015) or early Late Jurassic (Wu et al., 2003) ages. However, U-Pb dating of zircons from a rhyolitic tuff sample in the lower part of the formation yielded the age of 148 ± 2 Ma (Zhao et al., 2014) (Fig. 3). This younger, Tithonian age notably differs from the early Late Jurassic fossil-based ages.

The Emuerhe Formation, conformably overlying the Ershierzhan Formation, occurs in the north of the Mohe Basin (Qu et al., 1997) (Fig. 2). It is composed of medium- to fine-grained sandstone, siltstone, silty mudstone, and shale, with local conglomerate and pebbly sandstone (Wang, 2015) (Fig. 3). Coal and carbonaceous mudstone layers are frequently interbedded throughout the formation, especially in its upper interval (Figs. 3 and 4), reflecting an extensive floodplain swamp environment. Thick-bedded marl, mudstone, and shale (Figs. 4 and 5C), indicate deposition in a shallow lake environment (Li, 2007). Fossil floras and sporo-pollens are Bathonian (Xiao et al., 2015) or Late Jurassic (Wu et al., 2003) in age. Although the lithology and fossils reflect a freshwater depositional environment (Wu et al., 2003; Xiao et al., 2015) or early Late Jurassic (Wu et al., 2003) ages. However, U-Pb dating of zircons from a rhyolitic tuff sample in the lower part of the formation yielded the age of 148 ± 2 Ma (Zhao et al., 2014) (Fig. 3). This younger, Tithonian age notably differs from the early Late Jurassic fossil-based ages.

Fig. 3. Stratigraphic sections of the Mohe Basin and Upper Amur Basin. Data sources: thickness and lithology of the Mohe Basin after Wang (2015); thickness, lithology and sedimentary facies of the Upper Amur Basin after Wolsky et al. (1970) and Petruk et al. (2012); stratigraphic correlations based on this study.
Fig. 4. Outcrop and borehole sections of the Upper Jurassic–Lower Cretaceous formations in the Mohe Basin, with section localities shown on the inset at the lower right. Outcrop sections: SS1, SS2, SS3, and SS5 after Xin et al. (2003); SS4 measured by this study. Borehole sections: MoD1 after Li (2007); XAZK after Wang (2015); MK2 after Zhao et al. (2015); MK3 and MK5 after Wu (2016). Paleosalinity of MK3 and MK5 after Wu (2016): Fresh water < 10, brackish water 10–25, salt water (marine) > 25.

Fig. 5. Photographic images of typical lithofacies in the Mohe Basin, localities shown in Fig. 4. A. Clast-supported, poorly sorted pebble to cobble conglomerate, typical of alluvial fan facies, in the lower interval of the Xiufeng Formation. B. Interbedded fining-upward sandstone–mudstone couplets, typical of fluvial facies, in the Ershierzhan Formation. C. Gray mudstone containing interbedded siltstone, typical of lacustrine facies, in the Emuerhe Formation. D. Clast-supported cobble conglomerate, typical of alluvial fan facies, in the Kaikukang Formation.

<table>
<thead>
<tr>
<th>Xiufeng Formation</th>
<th>Ershierzhan Formation</th>
<th>Emuerhe Formation</th>
<th>Kaikukang</th>
</tr>
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<tbody>
<tr>
<td>SS1</td>
<td>MoD1</td>
<td>XAZK (marker)</td>
<td>MK3</td>
</tr>
<tr>
<td>SS2</td>
<td>SS3</td>
<td>MK2</td>
<td>MK5</td>
</tr>
<tr>
<td>SS3</td>
<td>SS4</td>
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<td>SS4</td>
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</tbody>
</table>

Legend for Fig. 4:
-Conglomerate
-Poorly sorted sandstone
-Sandstone
-Siltstone
-Athyrectic siltstone
-Mudstone
-Carbonateous mudstone
-Coal
-Kryclogypsiferous
-Turbidite sandstone
-Carbonate rock
-Myrtkula

Legend for Fig. 5:
-Floodplain
-Channel
2.2. Upper Amur Basin

The sedimentary fill of the Upper Amur Basin comprises Silurian–Lower Carboniferous and Jurassic–Lower Cretaceous successions (Wolsky et al., 1970; Serezhnikov et al., 2009; Petruk et al., 2012) (Figs. 2 and 3). The Silurian–Lower Carboniferous succession is distributed along the northern margin of the basin (Fig. 2). It rests unconformably on the Precambrian basement of the Erguna Massif and comprises calcareous siltstone and sandstone, interbedded with fossiliferous limestone (Wolsky et al., 1970; Zonenshain et al., 1990; Petruk et al., 2012) (Fig. 3). Abundant felsic tuff and tuffaceous siltstone and sandstone (Petruk et al., 2012) indicate frequent volcanic eruptions in the Silurian–Early Carboniferous.

The Jurassic–Lower Cretaceous succession lies to the south of, and unconformably overlaps the Silurian–Lower Carboniferous succession. It is subdivided into four sequences separated by regional unconformities or abrupt changes in lithology (Fig. 3). The first sequence occurs in the north of basin and includes the Kovali, Skovorodino, and Oshurkova formations, in an ascending order (Fig. 2). It consists of bathyal–shallow-marine flysch-like fine- to medium-grained sandstone, intercalated with siltstone, claystone and acidic ash tuffs (Fig. 3). Scarchogenic foam, bivalve clasts, polycrystalline, and brachiopod weathering constrain the age to Pliensbachian–Bajocian (Petruk et al., 2012) (Fig. 3). Remarkably, U-Pb dating of detrital zircons from a siltstone sample in the Kovali Formation yielded a youngest single-grain age of ca. 170 Ma (Smirnova et al., 2015), suggesting a Bajocian maximum depositional age, which conflicts with the fossil-based Pliensbachian–Toarcian age (Petruk et al., 2012) (Fig. 3), and indicates that the collected fossils are likely not resolutely age-diagnostic and more detailed studies are still needed to establish the absolute age of this formation. A correlative marine succession is differentiated in the western corner of the Upper Amur Basin (Petruk et al., 2012) (Fig. 2). It is composed of interbedded sandstone, siltstone, mudstone, and conglomerate attributed to the Yapan, Mangaley, Tymager, Tsanga, and Buley formations. Their lithologies and fossils are similar to those in the Kovali–Oshurkova formations, signifying deposition in the same time and environments (Petruk et al., 2012).

The second sequence includes the Usmanka, Uskali, Osezhina, and Tolbuzino formations, in an ascending order, widely distributed in the Upper Amur Basin (Fig. 2). According to Petruk et al. (2012) (Fig. 3), the Usmanka Formation unconformably lies upon the Oshurkova Formation, and comprises shallow-marine polymeric fine- and medium-grained sandstone, with conglomerate at the base. The Uskali and Osezhina formations consist of fine- to coarse-grained sandstone, interbedded with thin layers of siltstone, claystone, limestone, and dactitic tuff, deposited in a transitional marine to non-marine environment. The Tolbuzino Formation is restricted to the southern basin, and consists of non-marine fine- to coarse-grained sandstone interbedded with thin layers of conglomerate, carbonaceous siltstone, and tuff. Coals occur throughout the Tolbuzino Formation, especially in its lower and upper parts. Based on fossil pelecypods and floras, Petruk et al. (2012) assigned the Usmanka and Uskali formations to the Bathonian, the Osezhina Formation to the Callovian–Oxfordian, and the Tolbuzino Formation to the Oxfordian–Kimmeridgian in age (Fig. 3).

The third sequence, the Peremykino Formation, crops out along the southern margin of the Upper Amur Basin (Fig. 2). Its lower part is composed of alluvial boulder-pebble conglomerate and coarse-grained sandstone, whereas its upper part is dominated by fine-grained sandstone and interbedded siltstone and mudstone (Petruk et al., 2012) (Fig. 3). Fossil spores indicate its Berriasian age (Petruk et al., 2012).

The fourth sequence, the Lower Cretaceous Taldan Formation and upper strata, unconformably overlap underlying Mesozoic and Palaeozoic rocks in both Erguna Massif and Mongol-Okhotsk Suture Zone, and is dominated by volcanic and volcanoclastic rocks (Serezhnikov et al., 2009; Petruk et al., 2012).

2.3. Stratigraphic correlation between the Mohe Basin and the Upper Amur Basin

As the Mohe-Upper Amur Basin is traversed by the Russia/China border, stratigraphic and sedimentological studies of the Mohe Basin were typically published in Chinese, while studies of the Upper Amur Basin were mostly reported in Russian. No study has ever tried to explore a stratigraphic correlation between the two, Mohe and Upper Amur parts of the solitary basin. On the basis of palaeontological data, lithological characteristics, spatial distribution, sequential order, and unconformities, here we make the first attempt to establish the stratigraphic correlation between the two parts of the basin, as follows (Fig. 3).

The Lower–Middle Jurassic bathyal to shallow-marine deposits of the Kovali–Oshurkova and Yapan–Buley formations crop out at the northern margin of the Upper Amur Basin bordering the Mongol-Okhotsk Suture Zone (Fig. 2). No correlative deposits have been recognized in the Mohe Basin.

The Xiufeng–Emuerhe formations in the Mohe Basin are correlated with the Usmanka–Tolbuzino formations in the Upper Amur Basin (Fig. 3). On the basis of palaeontological data, both sedimentary successions were considered Middle–Late Jurassic in age. They are extensively exposed in the south and north of the basin (Fig. 2), and rest unconformably on the underlying strata, denoting the beginning of a new period in the evolution of the solitary basin. In addition, they both comprise fine- to medium-grained sandstone, and are unconformably overlain by coarse-grastic deposits.

Further refining the overall correlation, we tentatively suggest that the Xiufeng Formation is equivalent to the Usmanka Formation, as both formations unconformably rest on the underlying strata and possess a basal layer of poorly sorted conglomerate indicating vigorous deposition at the beginning of a new evolutionary period (Fig. 3). The Ershierzhvan Formation is equivalent to the Uskali Formation, as their areal distributions correspond well. The Emuerhe Formation in the Mohe Basin is correlatable to the Osezhina–Tolbuzino formations in the Upper Amur Basin, as their areal distributions correspond well (Fig. 2) and both the Emuerhe and Tolbuzino formations are rich in coal layers (Fig. 3).

The Kaikukang Formation in the Mohe Basin matches well to the Peremykino Formation in the Upper Amur Basin (Fig. 3). These two formations are exposed next to, and continue into each other across the Russia/China border (Fig. 2). The Peremykino Formation contains Berriasian sporo-pollen assemblages (Petruk et al., 2012), and Early Cretaceous sporo-pollen assemblages, terrestrial floras and faunas characterize the Kaikukang Formation (Wu et al., 2003). Both
formations unconformably rest on the fine-grained coal-bearing deposits, and possess basal layers of boulder-pebble conglomerate with coarse-grained sandstone, indicating an intensive deposition at the beginning of the next evolutionary period. Similarly, they are unconformably overlain by the Lower Cretaceous volcanic rocks.

The Tamulangou Formation in the Mohe Basin correlates well to the Taldan Formation in the Upper Amur Basin. They both are Early Cretaceous in age, rest unconformably on the underlying strata, and are dominated by volcanic and volcanioclastic rocks with conglomerate at the base (Fig. 3). These two formations denote another extensional period of the basin evolution.

Although the available radiometric ages considerably differ from the fossil-based ages of the same deposits, this discrepancy does not affect the accuracy of the presented correlation, as it is substantiated by the similarity of the litho- and bio-stratigraphy, distribution of unconformities, and direct tracing of some formations across the Russia/China border. The attained stratigraphic correlation between the Mohe and Upper Amur basins demonstrates their Jurassic–Cretaceous development as a solitary unit and reveals four periods in its sedimentary evolution (Fig. 3): (1) accumulation of bathyal to shallow marine deposits along its northern margin; (2) non-marine sedimentation in the Mohe Basin to shallow-marine and non-marine sedimentation in the Upper Amur Basin; (3) non-marine mainly alluvial sedimentation; (4) alluvial sedimentation shortly followed by volcanic eruptions.

2.4. Adjacent basins within or bordering the eastern Mongol-Okhotsk Suture Zone

Several small basins are distributed within or boarding the eastern Mongol-Okhotsk Suture Zone. They occur just to the north of the Mohe–Upper Amur Basin and include, from west to east, the Kholodzhikan, Madalan, Streika, Krestovka, and Lesser Tynda basins (Fig. 2). According to Petruk et al. (2012), these basins contain Upper Jurassic–Lower Cretaceous alluvial fan and fluvial conglomerate and coarse-grained sandstone (Fig. 6). These deposits unconformably rest on the underlying and neighboring lower Middle Jurassic or Paleozoic rocks of the Mongol-Okhotsk Suture Zone from which their coarse-grained coal-bearing deposits are derived during the earliest Cretaceous.

Table 1
Recalculated modal petrographic point-count data.

<table>
<thead>
<tr>
<th>Formation</th>
<th>Sample</th>
<th>Qt%</th>
<th>F%</th>
<th>L%</th>
<th>Qm%</th>
<th>F%</th>
<th>Lt%</th>
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</thead>
<tbody>
<tr>
<td>Kaikukang Formation</td>
<td>MH34</td>
<td>44</td>
<td>47</td>
<td>9</td>
<td>43</td>
<td>47</td>
<td>9</td>
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<td>MH35</td>
<td>51</td>
<td>38</td>
<td>12</td>
<td>46</td>
<td>38</td>
<td>16</td>
</tr>
<tr>
<td></td>
<td>MH36</td>
<td>43</td>
<td>44</td>
<td>14</td>
<td>42</td>
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<td>11</td>
<td>42</td>
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<td>MH31</td>
<td>46</td>
<td>42</td>
<td>12</td>
<td>44</td>
<td>42</td>
<td>14</td>
</tr>
<tr>
<td></td>
<td>MH26</td>
<td>44</td>
<td>45</td>
<td>11</td>
<td>41</td>
<td>45</td>
<td>14</td>
</tr>
<tr>
<td>Ershierhan Formation</td>
<td>MH24</td>
<td>49</td>
<td>39</td>
<td>11</td>
<td>47</td>
<td>39</td>
<td>13</td>
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<td></td>
<td>MH22</td>
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<td>43</td>
<td>11</td>
<td>46</td>
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<td>Xuiefeng Formation</td>
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<td>11</td>
<td>44</td>
<td>44</td>
<td>13</td>
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<td>40</td>
<td>50</td>
<td>9</td>
<td>39</td>
<td>50</td>
<td>11</td>
</tr>
</tbody>
</table>

Qt, total quartzose grains = monocrystalline quartz + polycrystalline quartz + Chert; Qm, monocrystalline quartz; F, total feldspar grains = potassium feldspar + plagioclase feldspar; L, total nonquartzose lithic grains; Lt, total lithic grains. Parameters after DeCelles et al. (2014).

3. Sandstone petrography and provenance analysis

Petrographic compositions of sandstone samples from different formations at various localities were studied in the Mohe Basin. The results of this study assist in the provenance analysis, clarifying the provenance nature and location.

3.1. Methods

Eleven samples of fine- to coarse-grained sandstone were collected from outcrops in the Mohe Basin (Fig. 2; Sample localities and descriptions are listed in the Supplementary Table S1) and cut for standard petrographic thin sections in order to obtain modal petrographic data for the provenance analysis. Over 400 framework grains were counted in each thin section following the Gazzi-Dickinson point-counting method (Dickinson and Suczek, 1979; Ingersoll et al., 1984). Grain types, modal parameters, and recalculated data are presented in Table 1 and Fig. 7.

3.2. Results and the provenance nature

Sandstone samples from the Xuiefeng, Ershierzhan, Emuerhe, and Kaikukang formations exhibit similar immature textures and compositions. In terms of major framework constituents, QtFL and QmFLt (Table 1 and Fig. 7), the compositions range from arkose to lithic arkose (McBride, 1963) and fall into the “basement uplift” and “dissected arc”
The Mohe Basin (samples MH13, NH24, MH26, and MH33) do not di

...gas Basin formed after the closure of the eastern Mongol-Okhotsk Ocean. The primary provenance and the continental region to the south of the basin

...Hou et al. (2010) regarded the Mongol-Okhotsk Suture Zone as the

...Both southern Erguna Massif to the south and Mongol-Okhotsk Suture Zone to the north, as they correspond to the

...dissected arc provenance fields (classification scheme of Dickinson et al., 1983). The major framework constituents do not provide an adequate basis for discrimination among different formations, except for sample MH32 with abundant polycrystalline quartz grains, well beyond the standard deviation of other samples, in terms of QtFL. Modal petrographic compositions of the samples collected from the northern margin of the Mohe Basin (MH24 from the Ershierzhanz Formation; MH13, MH26, and MH33 from the Emuerhe Formation) fully overlap those of the samples collected from the southern part of the basin (MH38 and MH19 from the Xiufeng Formation; MH22 from the Ershierzhanz Formation) (Figs. 2 and 7).

3.3. Discussion of the provenance locations

...sandstone samples from different formations at various localities in the Mohe Basin exhibit relatively uniform major framework constituents (Fig. 7), indicating that either no provenance change occurred, or provenances were similar in petrographic compositions, during the deposition of the Xiufeng–Kaikukang formations. Previous investigations presented similar results (He et al., 2008) (Fig. 7). Zhang et al. (2014) suggested that deposits of the Mohe Basin were derived from both southern Erguna Massif to the south and Mongol-Okhotsk Suture Zone to the north, as they correspond to the "basement uplift" and "dissected arc" provenance fields in terms of QtFL, respectively. Furthermore, based on the major and trace element analyses of sandstone samples from the Xiufeng–Kaikukang formations, He et al. (2005) and Hou et al. (2010) regarded the Mongol-Okhotsk Suture Zone as the primary provenance and the continental region to the south of the basin as the secondary one, and interpreted the Mohe Basin as a foreland basin formed after the closure of the eastern Mongol-Okhotsk Ocean.

This dual provenance interpretation is challenged by three recent discoveries. First, the sandstone compositions in the northern margin of the Mohe Basin (samples MH13, NH24, MH26, and MH33) do not differ in terms of QtFL and QmFLt from those in the southern basin (samples MH19, MH22, and MH38) (Figs. 2 and 7, Table 1). Second, the Erguna Massif, overriding the subducting Mongol-Okhotsk oceanic plate in the Early Mesozoic (Tang et al., 2016; Li et al., 2017; Zhang and Li, 2017), contains a significant amount of Mesozoic magmatic rocks (Zhang et al., 2008; Wu et al., 2011; Xu et al., 2011), which could also be a source of immature, lithic-rich sediments characteristic to a "dissected arc" provenance. Third, shallow-marine fossils and deposits of the Usmanuka Formation, equivalent to the Xiufeng Formation, accumulated in the north of the Upper Amur Basin, indicating that a paleo-ocean, probably the Mongol-Okhotsk Ocean, still existed to the north of the Mohe Basin and the suture zone, the supposed provenance, had not formed yet. Following these three key discoveries, we suggest that the previous dual provenance interpretation on the basis of petrographic and geochemical analyses needs to be re-assessed.

4. Detrital zircons: re-assessment of depositional ages and provenance locations

The previously published radiometric age of the Ershierzhanz Formation considerably differs from its fossil-based age (Fig. 3). This discrepancy puts forward the necessity for re-assessment of the established stratigraphic framework and its calibration and tuning to the geochronology based on radiometric age data. We implement U-Pb dating of detrital zircons from different formations in the Mohe Basin, so as to better constrain their depositional ages as well as possible source areas.

4.1. Methods

Eleven samples of fine- to coarse-grained sandstone collected from the Mohe Basin (Fig. 2; Sample localities and descriptions are listed in the Supplementary Table S1) were processed by standard methods of extracting dense minerals, and detrital zircon grains were separated from these dense mineral residues using heavy liquids. Approximately 250 zircon grains for each sample were mounted in epoxy, polished, and examined by cathodoluminescence (CL) imaging. U-Pb dating of zircons was conducted by laser ablation-inductively coupled plasma mass spectrometry (LA-ICP-MS) at the CAS Key Laboratory of Crust-Mantle Materials and Environments at the University of Science and Technology of China, using an ArF excimer laser system (GeoLas Pro, 193 nm wavelength) and a quadrupole ICP-MS (Agilent 7700). A beam size of 32 μm was chosen. Zircon 91500 was used as an external calibration standard for age calculation, and NIST610 was analyzed for concentration calculations of U, Th and Pb. U-Pb isotopic ratios were calculated using the ICPMSDataCal (Liu et al., 2010), and common Pb was corrected by ComPb corr#3-18 (Andersen et al., 2002). The ages assigned to the grains younger than 1000 Ma were based on their 206Pb/238U ratio, whereas ages of the grains older than 1000 Ma were based on their 207Pb/206Pb ratio. Analyses that were > 10% or < −5% discordant were excluded. A total of 849 detrital zircon grains that produced data with acceptable discordance and precision for geochronological interpretation, are listed in the Supplementary Table S2. These data are plotted on the diagrams that combined binned frequency histograms and probability density distributions (Fig. 8). Uncertainties of individual analyses were reported as 1σ. Mean ages for pooled 206Pb/238U ages were calculated by the Isoplot program (Ludwig, 2003) and reported as 2σ.

4.2. Results

4.2.1. Xiufeng Formation (samples MH38 and MH19)

For sample MH38, 100 zircons were analyzed, with 83 yielding analyses that were ≤10% and ≥−5% discordant (Fig. 8K). Zircon ages range from 490 to 150 Ma, and form four major populations of 170–150 Ma, 185–175 Ma, 210–190 Ma, and 260–240 Ma, with three minor populations of 240–220 Ma, 360–340 Ma, and 500–460 Ma.

For sample MH19, 80 zircons were analyzed, with 64 yielding analyses that are ≤10% and ≥−5% discordant (Fig. 8J). Zircon ages range from 471 to 155 Ma, and form a major population of 220–150 Ma, with three minor populations of 250–240 Ma, 280–270 Ma, and 480–470 Ma.

As the youngest single-grain age of sample MH38 (150 ± 4 Ma) overlaps within uncertainty with that of MH19 (155 ± 6 Ma), the mean of the youngest zircon age population of the two samples together...
yields Kimmeridgian maximum depositional age of 154.6 ± 1.9 Ma (mean of 20 youngest zircons).

4.2.2. Ershierzhan Formation (samples MH22 and MH24)

For sample MH22, 100 zircons were analyzed, with 78 yielding analyses that were ≤10% and ≥−5% discordant (Fig. 8I). Zircon ages range from 808 to 152 Ma, and form a major population of 220–160 Ma, with three minor populations of 160–260 Ma, 270–250 Ma, and 480–450 Ma.

For sample MH24, 100 zircons were analyzed, with 81 yielding analyses that were ≤10% and ≥−5% discordant (Fig. 8H). Zircon ages range from 855 to 170 Ma, and form a major population of 230–170 Ma, with a minor population of 530–430 Ma. The population also shows a small peak from 900 to 800 Ma, and an individual age of 375 Ma.

The mean of the youngest zircon age population of sample MH22 yields Kimmeridgian maximum depositional age of 152.3 ± 3.2 Ma (mean of 3 youngest zircons).

4.2.3. Emuerhe Formation (samples MH8, MH26, MH23, and MH33)

For sample MH8, 100 zircons were analyzed, with 81 yielding analyses that were ≤10% and ≥−5% discordant (Fig. 8G). Zircon ages range from 855 to 170 Ma, and form a major population of 230–170 Ma, with a minor population of 530–430 Ma. The population also shows a small peak from 900 to 800 Ma, and an individual age of 375 Ma.

The mean of the youngest zircon age population of sample MH22 yields Kimmeridgian maximum depositional age of 152.3 ± 3.2 Ma (mean of 3 youngest zircons).

4.2.2. Ershierzhan Formation (samples MH22 and MH24)

For sample MH22, 100 zircons were analyzed, with 78 yielding analyses that were ≤10% and ≥−5% discordant (Fig. 8I). Zircon ages range from 808 to 152 Ma, and form a major population of 220–160 Ma, with three minor populations of 160–260 Ma, 270–250 Ma, and 480–450 Ma.

For sample MH24, 100 zircons were analyzed, with 81 yielding analyses that were ≤10% and ≥−5% discordant (Fig. 8H). Zircon ages range from 855 to 170 Ma, and form a major population of 230–170 Ma, with a minor population of 530–430 Ma. The population also shows a small peak from 900 to 800 Ma, and an individual age of 375 Ma.

The mean of the youngest zircon age population of sample MH22 yields Kimmeridgian maximum depositional age of 152.3 ± 3.2 Ma (mean of 3 youngest zircons).
range from 1557 to 152 Ma, and form four significant populations of 190–150 Ma, 220–190 Ma, 290–240 Ma, and 520–450 Ma, with five individual ages spanning a wide range from 440 to 350 Ma. The age distribution also shows a scattering of ages between 1600 and 600 Ma, including several Neoproterozoic ages (11 ages from 1100 to 600 Ma).

Zircon ages of sample MH26, MH23, and MH33 form four similar populations of 220–170 Ma, 300–220 Ma, 520–430 Ma, and 1000–600 Ma, with some individual ages spanning a wide range (Fig. 8D). Additionally, ages of sample MH23 also form a younger age population of 180–140 Ma and a Paleoproterozoic age population of 1800–1700 Ma.

The youngest single-grain age of sample MH23 is 142 ± 4 Ma, which overlaps within uncertainty with that of MH33 (145 ± 4 Ma). The mean of the youngest zircon ages of these two samples together yields Jurassic/Cretaceous maximum depositional age of 145.4 ± 2.3 Ma (mean of 9 youngest zircons).

4.2.4. Kaikukang Formation (samples MH36, MH35, and MH34)

Zircon ages of sample MH36, MH35, and MH34 form three similar populations of 220–130 Ma, 290–240 Ma, and 410–320 Ma, with some other individual grains (Fig. 8A–C). Furthermore, all three samples contain Paleoproterozoic ages of 2000–1750 Ma. Sample MH34 even contains two Neoarchean ages of 2550–2500 Ma.

The youngest single-grain age of MH36 is 133 ± 4 Ma, which overlaps within uncertainty with that of MH35 (137 ± 3 Ma). The mean of the youngest zircon ages of the two samples together yields Valanginian maximum depositional age of 135.7 ± 3.7 Ma (mean of 3 youngest zircons).

4.3. Constraints on depositional ages

In this study, the maximum depositional ages of the Xiufeng–Kaikukang formations were conservatively estimated by the mean ages of the youngest U-Pb age clusters as follows (Figs. 8 and 9): the Xiufeng Formation ≤ ca. 155 Ma, the Ershierzhan Formation ≤ ca. 152 Ma, the Emuerhe Formation ≤ ca. 145 Ma, and the Kaikukang Formation ≤ ca. 136 Ma. Furthermore, U-Pb dating of zircons from a porphyry intrusion that crosscuts the lower part of the Emuerhe Formation yielded the age of 141.1 ± 0.9 Ma (Li, 2015). Therefore, the depositional age of the lower part of the Emuerhe Formation is constrained to Berriasian (ca. 145–141 Ma). The minimum depositional age of the Kaikukang Formation still remains unconstrained due to scarcity of the direct isotope-geochronological data. Two observations suggest that the Kaikukang Formation was deposited before ca. 133 Ma. Firstly, a basalt sample from the overlying Tamulangou Formation yielded the age of 129.7 ± 1.6 Ma (Zhang et al., 2007), indicating that the Kaikukang Formation ≤ ca. 135 Ma. However, the youngest single-grain age is 133 ± 4 Ma, although intense magmatism occurred throughout the Northeast China since 133 Ma (Zhang et al., 2010; Wu et al., 2011) (Fig. 9J). All these results reveal that the Xiufeng–Kaikukang formations were deposited in the Late Jurassic, late Kimmeridgian through to Early Cretaceous, Valanginian (ca. 155–133 Ma), rather than in the Middle–Late Jurassic as suggested on the basis of paleontological and K-Ar geochronological data (HBGMR, 1993; Wu et al., 2003; Xu et al., 2003; Xiao et al., 2015).

Following the established litho- and bio-stratigraphic correlations between the Mohe and Upper Amur basins, we spread the re-assessed depositional ages (ca. 155–133 Ma) onto the correlative Usmanka–Peremykino formations in the Upper Amur Basin, as shown in Fig. 9. This further constrains the depositional age range of the underlying Koval–Oshurkova formations to Early/Middle Jurassic to Late Jurassic (early Kimmeridgian), which notably differs from their Early–Middle Jurassic fossil-based ages (Fig. 3).

The ages of deposits in the syn-collisional basins to the north of the Mohe–Upper Amur Basin within or bordering the eastern Mongol-Okhotsk Suture Zone (the Kholodzhikan, Madalan, Strelka, Krestovka, and Lesser Tynda basins) (Figs. 2, 6 and 9D) remain mainly constrained with fossils. The radiometric K-Ar ages of an interbedded tuff in the lower part of Kholodzhikan Formation in the Kholodzhikan Basin are latest Jurassic–Valanginian (146–135 Ma) (Petruk et al., 2012). Based on the similarity of fossils, Berriasian deposits in the Krestovka Basin correlate with the Peremykino Formation in the Upper Amur Basin (Petruk et al., 2012). The latter, in turn, is correlative to the Kaikukang Formation in the Mohe Basin with the newly obtained late Valanginian depositional ages, younger than ca. 136 Ma (Fig. 9A). It is entirely possible that the deposits in the other syn-collisional basins formed during the latest Jurassic to Early Cretaceous (mainly during the Berriasian–Valanginian).

4.4. Provenance analysis

Detrital zircon U-Pb ages of sandstone samples from the Xiufeng, Ershierzhan, Emuerhe, and Kaikukang formations exhibit remarkably comparable spectra, and form three common populations of ca. 220–160 Ma, ca. 290–240 Ma, and ca. 520–450 Ma (Fig. 8A–K). These populations are utterly consistent with those of Phanerozoic granitoids in the Northeast China (Wu et al., 2011) (Fig. 8L), suggesting that the Northeast China to the south of the Mohe Basin was a source for the basin’s sediments throughout the deposition of the whole Emuerhe Group. Three samples (MH19, MH22, and MH24) are exceptional as the 220–160 Ma age population is so voluminous that other populations seem subtle (Fig. 8H–J).

Besides these three stationary populations, a distinctive age population of ca. 410–320 Ma is also found in some of these samples (Fig. 8A–H, K). This population shows fairly different proportions in different formations: 0%–4.8% in samples from the Xiufeng Formation, 0%–1.2% in samples from the Ershierzhan Formation, 3.7%–7.2% in samples from the Emuerhe Formation, and 34.3%–64.4% in samples from the Kaikukang Formation. It is reasonable to link the appearance and obvious increase of this population in younger deposits to the emergence of a new source. Potential sources of the 410–320 Ma zircons are recognizable in the areas to the south of the Mohe Basin, and regions to the north including the Siberia Craton and uplifted Devonian–Lower Carboniferous strata at the northern margin of the Upper Amur Basin (Fig. 2).

The areas to the south of the Mohe Basin seem to contain a small amount of 410–320 Ma zircons, as the proportion of the coeval granitoids among the Phanerozoic granitoids in the Northeast China is limited to ca. 3.5% (Wu et al., 2011) (Fig. 8L). This is further confirmed by the little 1.9% relative abundance of the 410–320 Ma zircon grains in a modern sand sample from the Huma River to the south of the basin (Li, 2010) (Figs. 1 and 8M). Paleocurrent studies indicate that deposits of the Xiufeng and Ershierzhan formations were mainly derived from the areas to the south of the basin (Hou, 2007; Hou et al., 2010) (Fig. 10B–C). The relative abundances of the 410–320 Ma zircon grains in the Xiufeng (0%–4.8%; Fig. 8J–K) and Ershierzhan (0%–1.2%; Fig. 8H–I) formations are commensurate with those of the southern Erguna Massif and Northeast China (1.9%–3.5%; Fig. 8L–M), signifying that areas to the south of the Mohe Basin were the likely provenance during deposition of the Xiufeng–Ershierzhan formations. Notably, the relative abundances of the 410–320 Ma zircon grains in the Emuerhe (3.7%–7.2%; Fig. 8D–G) and Kaikukang (34.3%–64.4%; Fig. 8A–C) formations exceed those in the southern Erguna Massif and Northeast China (1.9%–3.5%; Fig. 8L–M), which points to the existence of another source during their deposition.

The Siberia Craton could doubtfully be the source supplying an adequate amount of 410–320 Ma zircons to the Mohe Basin during deposition of the Emuerhe–Kaikukang formations. The abundance of the 410–320 Ma zircon grains in a modern sand sample from the Lena River flowing through the Siberia Craton (Fig. 1) merely attains ca. 2.6% (Wang et al., 2011) (Fig. 8Q). Even if there were abundant
Fig. 9. Summary of the tectonostratigraphic events occurred in the Northeast Asia during the Late Jurassic–Early Cretaceous.
410–320 Ma zircons in the Siberia Craton, either the remnant Mongol-Okhotsk Ocean or rising Mongol-Okhotsk collisional orogen would have represented a barrier for their delivery into the Mohe-Upper Amur Basin (Figs. 1 and 2).

The Devonian–Lower Carboniferous strata at the northern Upper Amur Basin are regarded as a potential source of the copious 410–320 Ma zircons in the Emuerhe–Kaikukang formations (Figs. 2 and 3). There are numerous felsic tuff and tuffaceous siltstone and sandstone layers in these Paleozoic deposits. It has been suggested that the acid and intermedia volcanogenic rocks of the Devonian Oldoy Formation (Figs. 2 and 3) belong to the Devonian Norovlinskiy continental margin magmatic arc along the northern margin of the Amuria Block facing the Mongol-Okhotsk Ocean (Khanchuk et al., 2015). Sandstone samples from the Oldoy and Tipara formations contain a relatively high abundance of 410–320 Ma zircon grains (Sorokin et al., 2015) (Figs. 2 and 8O–P). The abundances of 410–320 Ma zircon grains in the Emuerhe Formation (3.7–7.2%) are higher than in the underlying Xiufeng–Ershierzhan formations (0.4–8.8%) and in the southern Erguna Massif and Northeast China (Fig. 8). This suggests that the unroofing Devonian–Lower Carboniferous strata started supplying sediments into the Mohe Basin during the deposition of the Emuerhe Formation, since the Early Cretaceous, Berriasian. The abundances of 410–320 Ma zircon grains remarkably increased to ca. 34.3–64.4% in the Kaikukang Formation, which indicates that the Devonian–Lower Carboniferous strata became the main provenance during the deposition of the Kaikukang Formation in the late Valanginian. This is supported by the occurrence of south-directed paleocurrents revealed in the fluvial sandstones of this formation (Hou, 2007; Hou et al., 2010) (Fig. 10E).

It is remarkable that virtually no zircon grains of 410–320 Ma were found in the siltstone sample from the Kovali Formation at the northern margin of the Upper Amur Basin (Smirnova et al., 2015) (Figs. 2 and 8N), signifying that the adjacent Devonian–Lower Carboniferous strata did not supply sediments into the basin during the deposition of the Kovali Formation in the Early/Middle Jurassic. Obviously, the area composed of the Paleozoic deposits appeared as a provenance much later, in the Berriasian, and became predominant in the late Valanginian. Thus, the emergence of the northern source area took place in the earliest Cretaceous.

5. Evolution of the Mohe-Upper Amur Basin and the gradual closure of the eastern Mongol-Okhotsk Ocean

On the basis of the reviewed stratigraphic and sedimentological characteristics, established stratigraphic correlations, re-assessed...
Fig. 11. New tectonic model for the evolution of the Mohe-Upper Amur Basin and the gradual closure of the eastern Mongol-Okhotsk Ocean. A. During the Middle–early Late Jurassic, a remnant Mongol-Okhotsk Ocean existed to the north of the Mohe-Upper Amur Basin, and the Mongol-Okhotsk oceanic plate was subducted beneath both the Siberia Craton and the Amuria Block. B. During the late Kimmeridgian–Tithonian (ca. 155–145 Ma), the Kolyma-Omolon composite terrane collided with the Siberian margin, intensifying the clockwise rotation of the Siberia Craton and resulting in the closure of the Mongol-Okhotsk Ocean just to the west of the Mohe-Upper Amur Basin, the southwestward retreat of the Amuria Block, and the initial extension in the Mohe-Upper Amur Basin. C. During the Berriasian–early Valanginian (ca. 145–136 Ma), the eastern Mongol-Okhotsk Ocean gradually closed from west to east, and the Devonian–Lower Carboniferous strata along the northern margin of the Upper Amur Basin were gradually unroofed and started furnishing sediments into the Mohe-Upper Amur Basin. D. During the late Valanginian (ca. 136–133 Ma), the eastern Mongol-Okhotsk Ocean completely closed and the ensuing Siberia-Amuria collision transformed the Mohe-Upper Amur Basin into a compressional intermountain basin.
depositional ages and provenance records, we reconstruct the essential features of tectonostratigraphic (Fig. 9) and paleogeographic (Fig. 10) evolution of the Mohe-Upper Amur Basin from the Middle Jurassic through to Early Cretaceous. This provides a firm ground for developing a new tectonic model that links the tectonostratigraphic evolution of the Mohe-Upper Amur Basin to the closure of the eastern Mongol-Okhotsk Ocean (Fig. 11).

5.1. During the Middle–early Late Jurassic

After the closure of the western part (to the west of longitude 120°E) of the Mongol-Okhotsk Ocean in the Late Triassic–Early Jurassic (Zonenshain et al., 1990; Zonenshain and Kuzmin, 1997), or at the Early/Middle Jurassic boundary (Zorin, 1999), a several-hundred-kilometer-wide ocean remained to the east (Zonenshain et al., 1990) (Figs. 1, 10A and 11A). The Early–Late Jurassic subduction-related magmatism occurred both to the north and to the south of the Mongol-Okhotsk Suture Zone (Donskaya et al., 2013; Tang et al., 2016; Zhang and Li, 2017), indicating that the Mongol-Okhotsk oceanic plate subducted beneath the Siberia Craton and the Amuria Block (Fig. 11A). During the Middle–early Late Jurassic, bathyal–shallow-marine deposits of the Kovali, Skovorodino, and Oshurkova formations and their correlatives accumulated above the Silurian–Lower Carboniferous strata at the northern margin of the Mohe-Upper Amur Basin bordering the Mongol-Okhotsk Ocean (Petruk et al., 2012) (Figs. 2, 3 and 10A). To the southwest of the basin, no Middle–Upper Jurassic marine deposits are recognized (Zonenshain et al., 1990; Zorin, 1999; Petruk et al., 2012), limiting the expanse of the remnant Mongol-Okhotsk Ocean just to the west of the basin (Figs. 2, 10A and 11A). The wide regions south of the coastal margin were uplifted and eroded, supplying sediments to the ocean (Fig. 10A). Therefore, siltstone of the Kovali Formation contains abundant 220–160 Ma, 290–240 Ma, and 520–450 Ma detrital zircon grains (Smirnova et al., 2015) (Fig. 5N) sourced from areas to the south of the basin. It virtually lacks 410–320 Ma zircons, as their source, the tuff-bearing Devonian–Lower Carboniferous strata, were still buried that time.

Previous paleomagnetic studies show that the Late Jurassic to Early Cretaceous convergence between the Siberia Craton and the Amuria Block amounted to 1000–3000 km, suggesting that a wide Mongol-Okhotsk Ocean existed at that time (Enkin et al., 1992; Cogné et al., 2005; Metelkin et al., 2010; Pei et al., 2011; Ren et al., 2016). However, stratigraphic, structural, and magmatic evidences along the Mongol-Okhotsk Suture Zone indicate that the western part of the ocean had closed prior to the Middle Jurassic (Zonenshain et al., 1990; Zonenshain and Kuzmin, 1997; Zorin, 1999; Chen et al., 2011) (Figs. 1 and 11A). The closure of the western ocean and the subsequent collision between the Siberia Craton and the Amuria Block to the northwest of the Erguna Massif are also evidenced by the Middle Jurassic compressional setting in the northern Greater Xing’an Range revealed by the occurrence of S-type granitoids and the absence of contemporaneous sedimentary strata (Li et al., 2015). As Middle–Upper Jurassic marine deposits are only distributed along the northern margin of the Mohe-Upper Amur Basin and none to its southwest, further along the Mongol-Okhotsk Suture Zone (Parfenov and Natalin, 1977; Parfenov et al., 1978; Zonenshain et al., 1990; Zorin, 1999; Petruk et al., 2012), we sustain the interpretation that the western part of the suture zone had been formed by the Middle Jurassic (Fig. 11A), and suppose that the convergence inferred from the paleomagnetic data was accomplished by the sinistral strike-slip motion of the Siberia Craton (Natal’in, 1993; Sengör and Natalin, 1996; Metelkin et al., 2010; Ren et al., 2016) relative to the East Asia (Yang et al., 2015a, 2017), as well as the closure of the eastern Mongol-Okhotsk Ocean and associated crustal shortening in the northern China and Mongolia (Yang et al., 2015a,b) during the Late Jurassic–Early Cretaceous.

5.2. During the latest Jurassic–earliest Cretaceous (ca. 155–133 Ma)

5.2.1. Evolution of the Mohe-Upper Amur Basin

During the late Kimmeridgian–Tithonian (ca. 155–145 Ma), the Mohe-Upper Amur Basin experienced an extensional phase with sedimentation sourced from the southern provenance (Figs. 9A–B, 10B–C and 11B). Alluvial-fluv, fluvial, deltaic, coastal-marine, and shallow-marine depositional environments sequentially passed into each other from the uplifted areas south of the Mohe Basin towards the Mongol-Okhotsk Ocean (Figs. 10B–C and 11B). Sedimentation was likely controlled by the series of normal faults recognized in the Mohe Basin (Li, 2007; Xu, 2010; Shi et al., 2014) (Fig. 2). Terrestrial alluvial fan conglomerate and pebbly sandstone of the Xiufeng Formation and braided river pebbly to medium-grained sandstone of the Ershierzhan Formation were widely deposited in the southern Mohe-Upper Amur Basin (Qu et al., 1997; Li, 2007) (Figs. 2, 3, 4, 5A–B, and 10B). Marine depositional environment along the western margin of the basin gave way to the terrestrial alluvial-fluv and fluvial environments of the Xiufeng Formation (Figs. 2 and 10A–B). Shallow-marine deposits of the Usmanka Formation and marine-to-nonmarine deposits of the Uskali Formation were accumulated in the northern part of the basin (Petruk et al., 2012) (Figs. 2 and 10B–C). Detrital zircon U-Pb ages of sandstone samples from the Xiufeng and Ershierzhan formations exhibiting comparable spectra with those of the Phanerozoic granitoids in the Northeast China (Wu et al., 2011) (Fig. 6–1), in combination with the southerly paleocurrents in the Mohe Basin (Hou, 2007; Hou et al., 2010) (Fig. 10B–C), indicate that the sediments of the Mohe-Upper Amur Basin were mainly sourced from the areas to the south of the basin. The Paleozoic strata in the north of the basin, the other inferred source, have not been unroofed yet.

During the Berrriasian–early Valanginian (ca. 145–136 Ma), a closed lake formed in the Mohe-Upper Amur Basin, between the uplifted areas to the north and south, and the northern provenance emerged (Figs. 9A–B, 10D and 11C). Lacustrine thick-bedded marl, mudstone, and shale of the Emuerhe Formation accumulated in the closed lake (Figs. 2, 3, 4, and 5C). Episodic marine transgressions are evidenced by the paleosalinity recorded in the formation (Wu, 2016) (Fig. 4). Detrital zircon U-Pb ages of samples from the Emuerhe Formation possess not only three common populations of 220–160 Ma, 290–240 Ma, and 520–450 Ma, but also the large population of 410–320 Ma, indicating the eroding Devonian–Lower Carboniferous strata at the northern margin of the Upper Amur Basin started furnishing sediments into the basin (Figs. 2, 10D and 11C).

During the Valanginian (ca. 136–133 Ma), the northern part of the Mohe-Upper Amur Basin experienced a regional uplift, transforming the basin into a compressional basin with sedimentation derived from both the southern and northern provenances (Figs. 9A–B, 10E and 11D). A series of northeast-east and east trending thrust faults developed in the western Mohe Basin (Li, 2007; Sun, 2013) (Fig. 2). Accumulation of alluvial fan deposits of the Kaikukang and Peremynko formations was confined to the southeastern part of the basin (Figs. 2, 3, 4, and 5D, and 10E), where they unconformably rested on the underlying fine-grained deposits (Fig. 3). The large population of 410–320 Ma detrital zircons within the sandstone samples of the Kaikukang Formation (Fig. 8A–C), in combination with the northerly paleocurrents (Hou, 2007) (Fig. 10E), indicates that the Devonian–Lower Carboniferous strata at the northern margin of the basin were fully uplifted and became a dominating provenance (Fig. 11D). The uplift and exhumation of the basin is also evidenced by the fission-track analyses of zircons from sandstone and volcanic rocks in the Mohe Basin, which yielded ages of ca. 144–132 Ma (Sun, 2013) (Fig. 9C).

5.2.2. Gradual closure of the eastern Mongol-Okhotsk Ocean

During the Late Jurassic, the Kolyma-Omolon composite terrane (Northeast Russia) began to collide with the Siberian margin (Fig. 11B), causing intense thrusting, folding, and magmatism along the
northeastern margin of the Siberia Craton (Parfenov and Natal’ in, 1986; Parfenov et al., 1993; Prokopiev, 2000; Oxman, 2003; Prokopiev and Oxman, 2009; Fridovsky, 2017). The collisional event might have intensified the clockwise rotation of the Siberia Craton, causing the closure of the Mongol-Okhotsk Ocean just to the west of the Mohe-Upper Amur Basin and the eastward migration of the marine depositional environment along the northern margin of the basin during the Kimmeridgian–Tithonian (Figs. 10A–C and 11B). The clockwise rotation and associated sinistral transpressional motion of the Siberia Craton along the western Mongol-Okhotsk Suture Zone (Metelkin et al., 2010) probably induced a significant southwestward retreat of the Amuria Block toward the trench in the subduction zone of the remnant Mongol-Okhotsk Ocean, creating an extensional setting in the back-arc region of the Amuria Block (Fig. 11B). Therefore, the Mohe-Upper Amur Basin, an extensional basin, formed near the northern margin of the Amuria Block during the Kimmeridgian–Tithonian. In this view, development of the basin during the late Kimmeridgian–Tithonian (ca. 155–145 Ma) resembles the Andaman Basin formed during the India-Asia collision in the Cenozoic, and is consistent with the upper plate motion controlled model (Heuret and Lallemand, 2005). This Late Jurassic extension in the northern margin of the Amuria Block is further testified by the formation of the Late Jurassic alkaline–subalkaline volcanic rocks in the northern Greater Xing’ an Range (Xu et al., 2013; Tang et al., 2015).

During the earliest Cretaceous, the remnant Mongol-Okhotsk Ocean gradually closed by zipping of oceanic space between the Siberia Craton and the Amuria Block, or in a scissors-like manner, driven by the continuous clockwise rotation and sinistral transpressional motion of the Siberia Craton (Parfenov and Natal’ in, 1977; Parfenov et al., 1978; Metelkin et al., 2010; Yang et al., 2015a) and northeastward movement of East Asia associated with the collision of the Lhasa microcontinent with Asia (Yin and Harrison, 2000; Yang et al., 2015a, 2017) (Fig. 11C–D). The eastward retreat and gradual closure of the remnant Mongol-Okhotsk Ocean is evident in the evolving paleogeography of the Mohe-Upper Amur Basin (Fig. 10), and was followed by the eastward propagating collision. In the Berriasian–early Valanginian (ca. 145–136 Ma), the collision between the Siberia Craton and the Amuria Block occurred to the north of the Mohe-Upper Amur Basin, whose uplifting and unroofed northern margin started furnishing sediments into the basin (Figs. 9, 10D and 11C). In the late Valanginian (ca. 136–133 Ma), the collision between the Siberia Craton and the Amuria Block propagated eastward and enhanced the uplift and erosion of the northern edge of the Erguna Massif, transforming the Mohe-Upper Amur Basin into a compressional intermountain basin to the south of the collisional orogen, and the adjacent Mongol-Okhotsk Ocean completely vanished (Figs. 9, 10E and 11D). The collision terminated in the Hauterivian as constrained by deposition of the Hauterivian Taldan Formation on both Mongol-Okhotsk Suture Zone and Erguna Massif (Serezhnikov et al., 2009) (Fig. 3).

5.2.3. Regional effects of the Siberia-Amuria collision in Northeast Asia

The effects of the Siberia–Amuria collision to the north and northeast of the Mohe-Upper Amur Basin during the earliest Cretaceous are discernible throughout Northeast Asia (Fig. 11C–D). Within or bordering the Mongol-Okhotsk Suture Zone to the north of the Mohe-Upper Amur Basin, a series of syn-collisional basins (Kholodzhikan, Madalan, Sterelka, Krestovka, and Lesser Tynda basins) formed during the earliest Cretaceous (Petruk et al., 2012) (Figs. 2, 6 and 9D). The Bokon Basin, also referred to as the Uda Basin (Kirillova, 2003, 2008), nearly borders the Mongol-Okhotsk Suture Zone and bears close resemblance to the syn-collisional basins to the north of the Mohe-Upper Amur Basin (Figs. 1, 2 and 6). In the basin, thick Berriasian–Valanginian terrestrial conglomerate (~1000 m) interbedded with coal-bearing sandstone and coalyferous mudstone unconformably rest on the Upper Jurassic volcanic, coastal-marine and terrestrial deposits (Kirillova, 2003; Zabrodin et al., 2007; Serezhnikov et al., 2009) (Figs. 1 and 9E). The clasts in conglomerate are composed of pebbles of gneiss, granites, migmatites, amphibolites, and gabbro shed off the early Precambrian metamorphic complexes of the Stanovoy Group along the southeastern margin of the Siberia Craton, indicating a rapid unroofing of the southeastern margin of the Siberia Craton during the earliest Cretaceous (Kirillova, 2003; Serezhnikov et al., 2009). Further north, a regional amphibolite-facies metamorphism of the Stanovoy Group occurred at about 140 ± 1 Ma (Larin et al., 2006) (Figs. 1 and 9F). Additionally, in the South Aldan Basins, the Jurassic–Lowermost Cretaceous terrestrial deposits were intensely folded and overthrust by metamorphic rocks of the Stanovoy Group in the Neocomian (Prokopiev et al., 2001; Nikishin et al., 2010) (Fig. 1).

To the south of the Mongol-Okhotsk Suture Zone, in the Hailar-Tamsag Basin, an extended sedimentation hiatus, ca. 145–133 Ma separated deposition of the Tamulangou and Tonggbomiao formations (Zhang et al., 2016) (Figs. 1 and 9G). In the Songliao Basin, the Taonan Formation composed of andesite and tuff with K-Ar ages of 148–146 Ma (Xu et al., 2003) is unconformably overlapped by the Huoshiling Formation with zircon U-Pb ages of 133–125 Ma (Pei et al., 2008; Xu, 2010; Huang et al., 2011) (Figs. 1 and 9H). In the Sanjiang-Middle Amur Basin, after the deposition of the Suibin–Dongrong formations in the Callovian–Berriasian, the basin underwent a tectonic inversion and uplift, and deposition resumed in the Hauterivian when the basal conglomerate of the Didao Formation accumulated in half-grabens (Zhang et al., 2012) (Figs. 1 and 9I).

5.3. During the late Early Cretaceous (after ca. 133 Ma)

During the late Early Cretaceous (after ca. 133 Ma), the Mohe-Upper Amur Basin entered into an extensional setting. A series of normal faults developed in the eastern Mohe Basin (Li, 2007). Volcanic and volcaniclastic rocks of the Tamulangou and Taldan formations accumulated on the underlying deposits with basal unconformity and conglomerate (Figs. 3 and 9A–B). In a broader tectonic perspective, extensional events were facilitated throughout Northeast Asia during the same time. Extrusive and intrusive magmatism was spread on the both sides of the Mongol-Okhotsk Suture Zone (Serezhnikov et al., 2009; Petruk et al., 2012; Wang et al., 2015; Ling et al., 2017). Rift basins and metamorphic core complexes were widely generated in Transbaikalia, East Mongolia and Northeast China (Meng et al., 2003; Lin and Wang, 2006; Wang et al., 2012; Daoudene et al., 2013; Johnson, 2015).

The extensive extension in Northeast Asia reflects the termination of the Siberia-Amuria collision (Zonenshain et al., 1990; Yang et al., 2015a), concurrently with the termination of the collision between the Siberia Craton and Kolyma-Omolon composite terrane (Oxman, 2003). This regional extension was likely resulted from the tectonic escape of East Asia, driven by the continental collision of the Lhasa Block along the southern margin of Asia (Yang et al., 2015a, 2017). Strike-slip faulting triggered gravitational collapse of upper crust and delamination of lower crust and mantle lithosphere thickened during the Siberia-Amuria collision.

6. Conclusions

This study established a stratigraphic correlation between the Mohe Basin and the Upper Amur Basin, and refined the depositional ages and provenances of their Middle Jurassic–Lower Cretaceous strata. The Upper Jurassic, upper Kimmeridgian–Tithonian deposits of the Xiufeng–Ershierzhan formations were mainly sourced from the southern provenance, areas to the south of the Mohe Basin, whereas the Lower Cretaceous deposits of the Emuerhe–Kaikukang formations were derived from not only the southern provenance, but also the northern provenance, the Devonian–Lower Carboniferous strata at the northern margin of the Upper Amur Basin. The northern provenance started furnishing sediments into the Mohe-Upper Amur Basin during the accumulation of the Emuerhe Formation in the Berriasian–early
Valanginian and dominated in sediment supply during the accumulation of the Kaikulang Formation in the late Valanginian.

The reconstructed paleogeographic evolution of the Mohe-Upper Amur Basin revealed the gradual closure of the eastern Mongol-Okhotsk Ocean, and a new model linking the tectonostратigraphic evolution of the basin with the final closure of the Mongol-Okhotsk Ocean is proposed. During the late Kimmeridgian–Tithonian (ca. 155–145 Ma), the clockwise rotation of the Siberia Craton driven by the collision between the Kolyma-Okhotsk composite terrane with the Siberian margin, led to the closure of the Mongol-Okhotsk Ocean just to the west of the Mohe-Upper Amur Basin, the southwestward retreat of the Amuria Block, and the initial extension in the Mohe-Upper Amur Basin. During the Berriasian–early Valanginian (ca. 145–136 Ma), the Mongol-Okhotsk Ocean was closing to the north of the Mohe-Upper Amur Basin, whose uplifted and unroofed northern margin started furnishing sediments into the basin. During the late Valanginian (ca. 136–133 Ma), the Mongol-Okhotsk Ocean completely closed and the ensuing Siberia-Amuria collision transformed the Mohe-Upper Amur Basin into a compressional intermountain basin. After the Siberia-Amuria collision terminated in the Hauterivian at ca. 133 Ma, the East Asia including the Mohe-Upper Amur Basin entered into a regional extensional setting, driven by the continental collision of the Lhasa Block along the southern margin of Asia.

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Appendix A. Supplemental material

Supplemental data associated with this article can be found, in the online version, at http://dx.doi.org/10.1016/j.jseaes.2016.07.020.

References


