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D. Jiang, K. Schulmann, A. Kröner, M. Sun, O. Lexa, et al.. Neoproterozoic-Early Paleozoic Peri-Pacific Accretionary Evolution of the Mongolian Collage System: Insights From Geochemical and U-Pb Zircon Data From the Ordovician Sedimentary Wedge in the Mongolian Altai. *Tectonics*, 2017, 36 (11), pp.2305 - 2331. 10.1002/2017TC004533 . hal-01896742

HAL Id: hal-01896742

<https://hal.science/hal-01896742v1>

Submitted on 18 Nov 2021

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RESEARCH ARTICLE

10.1002/2017TC004533

Key Points:

- The Mongolian Altai represents an Ordovician accretionary wedge rimming the active margins of the northerly Precambrian blocks
- Western margins of Mongolian Precambrian blocks switched from an Early Cambrian passive margin to a Late Cambrian-Ordovician active one
- The Mongolian collage system and southern Siberia probably evolved from a peri-Pacific subduction system in Cambro-Ordovician

Supporting Information:

- Supporting Information S1
- Table S1
- Table S2

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Citation:

Jiang, Y. D., Schulmann, K., Kröner, A., Sun, M., Lexa, O., Janoušek, V., ... Hanzl, P. (2017). Neoproterozoic-early Paleozoic peri-Pacific accretionary evolution of the Mongolian collage system: Insights from geochemical and U-Pb zircon data from the Ordovician sedimentary wedge in the Mongolian Altai. *Tectonics*, 36, 2305–2331. <https://doi.org/10.1002/2017TC004533>

Received 25 FEB 2017

Accepted 27 SEP 2017

Accepted article online 4 OCT 2017

Published online 3 NOV 2017

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Neoproterozoic-Early Paleozoic Peri-Pacific Accretionary Evolution of the Mongolian Collage System: Insights From Geochemical and U-Pb Zircon Data From the Ordovician Sedimentary Wedge in the Mongolian Altai

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Abstract Neoproterozoic to early Paleozoic accretionary processes of the Central Asian Orogenic Belt have been evaluated so far mainly using the geology of ophiolites and/or magmatic arcs. Thus, the knowledge of the nature and evolution of associated sedimentary prisms remains fragmentary. We carried out an integrated geological, geochemical, and zircon U-Pb geochronological study on a giant Ordovician metasedimentary succession of the Mongolian Altai Mountains. This succession is characterized by dominant terrigenous components mixed with volcanogenic material. It is chemically immature, compositionally analogous to graywacke, and marked by significant input of felsic to intermediate arc components, pointing to an active continental margin depositional setting. Detrital zircon U-Pb ages suggest a source dominated by products of early Paleozoic magmatism prevailing during the Cambrian-Ordovician and culminating at circa 500 Ma. We propose that the Ordovician succession forms an “Altai sedimentary wedge,” the evolution of which can be linked to the geodynamics of the margins of the Mongolian Precambrian Zavhan-Baydrag blocks. This involved subduction reversal from southward subduction of a passive continental margin (Early Cambrian) to the development of the “Ikh-Mongol Magmatic Arc System” and the giant Altai sedimentary wedge above a north dipping subduction zone (Late Cambrian-Ordovician). Such a dynamic process resembles the tectonic evolution of the peri-Pacific accretionary Terra Australis Orogen. A new model reconciling the Baikalian metamorphic belt along the southern Siberian Craton with peri-Pacific Altai accretionary systems fringing the Mongolian microcontinents is proposed to explain the Cambro-Ordovician geodynamic evolution of the Mongolian collage system.

1. Introduction

Long-lasting, continuous Pacific-type subduction has brought together diverse oceanic lithospheric segments scrapped off the subducting plate in areas named accretionary orogenic belts (Cawood et al., 2009). Significant tectonic scraping and/or sedimentary additions filling the trench with bedded cherts, deep marine “red clays,” and turbiditic sediments that are characterized by heterogeneous input from both upper plate continental crust and active magmatic arcs may form giant sedimentary wedges covering large surfaces of the world oceans (Kusky et al., 2013; Listizin, 1972). Sedimentary wedges therefore represent key structures of accretionary systems that may provide pivotal information on their geodynamic reconstructions.

The Central Asian Orogenic Belt (CAOB) represents the largest known Phanerozoic accretionary orogenic system on Earth, which covers about one third of the Asian continent and records a long-lived oceanic subduction (Şengör et al., 1993; Windley et al., 2007). Its oceanic evolution was terminated when the newly formed and accreted crust was squeezed between the northward moving North China and Tarim Cratons and the southward moving Siberian Craton in late Paleozoic to early Mesozoic times (Xiao et al., 2003). However, the dynamics of Proterozoic to early Paleozoic oceanic domains (collectively known as the

Paleo-Asian Ocean, PAO) (Zonenshain et al., 1990) that were responsible for the formation of the future CAOB has not been satisfactorily constrained.

Up to date, such an evolution has mainly been investigated by using geology of ophiolites and/or magmatic arcs. Khain et al. (2002) and Kuzmichev and Larionov (2013) documented circa 1.0 Ga ophiolite and island arc system in eastern Sayan of southern Siberia, suggesting that the current southern margin of the Siberian Craton faced an open ocean before 1.0 Ga. However, most ophiolites thrust over Precambrian continental blocks of the CAOB are Neoproterozoic-early Paleozoic (Buchan et al., 2002; Jian et al., 2010; Khain et al., 2003; Kovach et al., 2005; Kuzmichev et al., 2005), suggesting the existence of a Neoproterozoic-early Paleozoic PAO (Mossakovsky et al., 1993; Zonenshain et al., 1990). The evolution of the PAO remains uncertain; by some authors it has been considered as a typical interior Iapetus-Rheic type ocean, which was formed in between Siberia and Gondwana after the breakup of Rodinia (e.g., Zonenshain, 1990; Dobretsov & Buslov, 2007; Wilhem et al., 2012). In contrast, Şengör et al. (1993, 2014) suggested that the main elements of the CAOB can be interpreted as a single Pacific-type oceanic arc system, termed the Kipchak-Tuva-Mongol arc, which evolved from the Early Cambrian (circa 542 Ma) to the Late Permian (250 Ma). In this model, Precambrian crustal fragments were interpreted as rifted margins of Siberia (e.g., Barguzin block), only reattached to their host continent during late Proterozoic or Late Cambrian along the Baikalian metamorphic belt (Donskaya et al., 2000; Gladkochub et al., 2008, Figure 1). Other authors found most of these crustal fragments to be of peri-Gondwana affinity on the basis of similarities with the north China, Tarim, and Amur continents (Dobretsov & Buslov, 2007; Jiang et al., 2011; Levashova et al., 2010; Mossakovsky et al., 1993; Rojas-Agramonte et al., 2011). Alternatively, many authors have interpreted the PAO as a long-lived (from 1.0 Ga to 250 Ma) archipelago ocean similar to the modern southwest Pacific (e.g., Kröner et al., 2007; Windley et al., 2007). The poorly constrained origins of ophiolite units and paleogeographic uncertainties for many major tectonic elements have hindered our understanding of Neoproterozoic-early Paleozoic accretionary processes in the PAO. It has been demonstrated that the characterization of sedimentary accretionary systems can provide an important input into the definition of subduction polarity as well as timing the onset and duration of upper plate erosion (e.g., Kuzmichev et al., 2007). However, details regarding the nature and evolution of many sedimentary prisms are missing.

The Neoproterozoic-early Paleozoic Mongolian part of the CAOB extends from Zavhan-Baydrag blocks in the east to Mongolian Altai Mountains in the west (Figure 1). Here are preserved contrasting lithological units, such as Precambrian continental blocks, passive margins, ophiolites, high-pressure units, island and continental arcs, and accretionary wedges (Badarch et al., 2002; Kröner et al., 2010). These tectonic elements make it one of the key areas for reconstructing the Neoproterozoic-early Paleozoic geodynamics of the CAOB. In the current contribution, we present whole-rock geochemical data, zircon U-Pb ages, and Hf isotopic signatures for the pericontinental sedimentary succession along the Mongolian tract of an approximately 2,000 km sedimentary succession from Russia to southern Mongolia, in order to constrain the nature and provenance of this succession. These data are then integrated with existing geological information in order to decipher oceanic subduction processes giving rise to the Mongolian part of the CAOB. Our results show that the studied succession forms an "Altai sedimentary wedge" that together with the contemporary "Ikh-Mongol" arc system (Janoušek et al., 2017), represents a > 1,800 km long subduction-related structure ("Altai accretionary system") along the margin of Mongolian continental blocks. Such an accretionary system probably shared the early Paleozoic Pacific oceanic accretion with the Terra Australis Orogen (TAO) of NE Gondwana. This peri-Pacific accretionary system is contrasted with the Late Cambrian kinzigite belt in the eastern, Chinese part of the CAOB, and the contemporaneous Baikalian orogeny developed along the southern margin of the Siberian continent. The coexistence of these two so dissimilar but coeval geodynamic regimes allows us to propose a new model for the evolution of the Mongolian collage system in the Cambrian-Ordovician times.

2. Geological Framework

2.1. Regional Geological Background

The CAOB features various lithological elements of Archean to Mesozoic ages such as Precambrian continental blocks, ophiolites, accretionary prisms, magmatic arcs, and back arcs (Figure 1). Şengör et al. (1993) subdivided this giant orogenic system into 26 first-order independent orogenic components such as the Altai-Sayan, Mongol-Okhotsk, Kazakhstania, Tianshan, and Uralian. Wilhem et al. (2012) even increased the

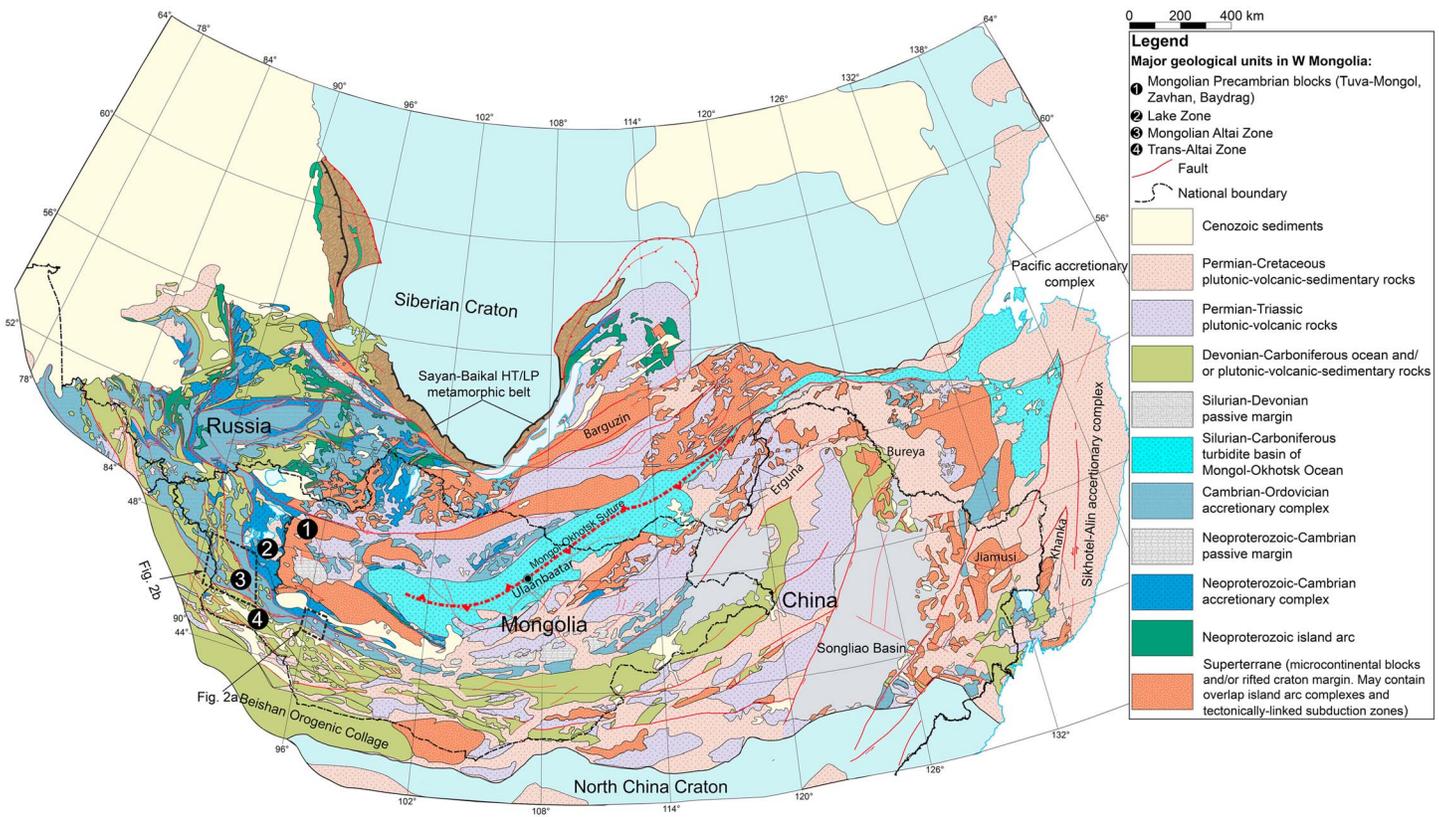


Figure 1. Simplified geological map of the central CAOB (modified from Parfenov et al., 2003). Positions of major units in western Mongolia and the studied areas are also indicated.

number of such key regions into 107 zones. In contrast, Xiao et al. (2015) proposed a three-part subdivision of the entire CAOB, that is, the Mongolian collage system in the north, the Tarim-north China collage system in the south, and the Kazakhstan collage system in the west. In the present study, we focus on diverse crustal components extending from the southern Siberian margin to the China-Mongolia border. We generally adopt the approach of Xiao et al. (2015) and consider the studied area as a part of the Mongolian orogenic collage system (Figure 1). This is in line with the definition of Lehmann et al. (2010), who proposed that the crustal components in the current Mongolian collage system could represent a coherent accretionary system. Its geological features are briefly described below.

Geologically, the Mongolian collage system is in tectonic contact with the northerly Siberian Craton, marked by the circa 500 Ma Sayan-Baikal high-temperature/low-pressure (HT/LP) metamorphic belt (Donskaya et al., 2000; Gladkochub et al., 2008, Figure 1), and from the southerly North China Craton it is separated by the Late Permian-Early Triassic Solonker suture zone (Eizenhöfer et al., 2014; Xiao et al., 2003). Its eastern limit is less clearly defined, but the development of the Sikhote-Alin accretionary complex in NE China and Russian Far East is generally taken as marking the onset of tectonism of the Pacific subduction regime (Jahn et al., 2015; Wilde, 2015). In the Mongolian collage system, Precambrian blocks (microcontinents and/or superterranes with presumed cratonic basement) of either Siberian or Gondwanan affinities are widely distributed in western Mongolia (e.g., Zavhan-Baydrag), the vast area along the southern margin of Siberia (e.g., Barguzin), and in NE China (e.g., Jiamusi) (Figure 1). These blocks were thought to have acted as important tectonic nuclei around which younger arcs formed and associated subduction complexes accreted. Broadly speaking, Neoproterozoic-early Paleozoic arcs and accretionary complexes associated with many Precambrian blocks formed tectonic provinces in the north, while oceanic tectonic domains of predominantly Silurian-Carboniferous ages associated with limited continental fragments evolved in the south (Figure 1).

The Mongolian collage system was originally characterized as fault-bounded lithologically contrasting units. In agreement with early models for the tectonic evolution of the CAOB (Mossakovsky et al., 1994; Zonenshain,

1973), it was thought to have experienced two distinct geodynamic events: (1) the Cambrian accretion of Neoproterozoic-early Paleozoic arc-related terranes and ophiolitic belts of the Lake Zone to Precambrian basement blocks in northern Mongolia and (2) thrusting, metamorphism, and magmatism affecting the southerly Cambrian-Ordovician Mongol Altai Zone and Silurian-Carboniferous Trans-Altai Zone in Devonian-Carboniferous times (e.g., Kröner et al., 2010; Lehmann et al., 2010). These differences were considered as a major argument for the distinction of an early Paleozoic domain (“Caledonian” in the Russian literature) and a late Paleozoic domain (“Hercynian” in the Russian literature) in northern and southern Mongolia, respectively (e.g., Mossakovsky et al., 1994; Zonenshain, 1973). These fault-bounded tectonic elements were thought to have had a specific structural, metamorphic, and magmatic evolution and have been juxtaposed by transcurrent faults. These ideas led Badarch et al. (2002) to define them into a range of suspect terranes. Such a terrane subdivision, however, is questionable, because various authors have documented that the proposed terrane boundaries are invalid and many specific “terranes” have strong mutual affinities (e.g., Guy et al., 2014; Lehmann et al., 2010). In this contribution we mainly focus on the Neoproterozoic to early Paleozoic geodynamic evolution of the Mongolian collage system, which involved several geological units mainly including Precambrian continental blocks, the Neoproterozoic-Cambrian ophiolitic Lake Zone, and Cambrian-Ordovician sedimentary succession of the Altai Zone in Mongolia (Figure 1).

The *Precambrian continental blocks* are named Tuva-Mongol (Gargan) in the north, Zavhan in the center, and Baydrag in the south. They were interpreted as remnants of a major Precambrian continent. They consist of Archean (2.9–1.8 Ga) to early Neoproterozoic gneisses (1.05–0.86 Ga) (Demoux et al., 2008; Kozakov et al., 2007; Kröner et al., 2001), rare Neoproterozoic (812 ± 18 Ma Rb-Sr age and 785 ± 11 Ma zircon U-Pb age) tonalitic plutons (Kuzmichev et al., 2001), and volcanic rocks with zircon U-Pb ages of 805–770 Ma (Bold et al., 2016; Levashova et al., 2010). These basement complexes are overlain by Neoproterozoic to Cambrian passive margin sedimentary succession consisting of pebbly sandstone, marble, quartzite, and diamictite (K-Ar muscovite age of 699 ± 35 Ma, Badarch et al., 2002) and limestones (Kröner et al., 2010; Lindsay et al., 1996).

The *Lake Zone* mainly consists of ophiolite fragments and accretionary prisms (Ruzhentsev & Burashnikov, 1995; Zonenshain & Kuzmin, 1978). The ophiolites show circa 570 Ma protolith ages, and their geochemical signatures suggest a forearc suprasubduction setting (Buchan et al., 2002; Jian et al., 2014; Khain et al., 2003; Kröner et al., 2001; Matsumoto & Tomurtogoo, 2003; Simonov et al., 2004). The structural development of the Lake Zone is characterized by the emplacement of ophiolitic complexes and island arc assemblages over the southern margin of the Precambrian Tuva-Mongol, Zavhan, and Baydrag blocks. The related phengite-bearing foliation in eclogite and high-pressure fabrics of the associated metapelites yielded $^{40}\text{Ar}/^{39}\text{Ar}$ cooling ages circa 540 Ma (Štípská et al., 2010).

The *Mongolian Altai Zone* was subdivided into two different fault-bounded terranes, the Khovd Terrane in the east and the Altai Terrane in the west (Badarch et al., 2002). However, many recent studies suggest that these terranes form a single lithotectonic unit on the basis of their similar lithological features (e.g., Lehmann et al., 2010). This unit is dominated by Late Cambrian and Ordovician schists, volcano-sedimentary succession, sandstones, siltstones, and intermediate to mafic volcanic rocks (Badarch et al., 2002; Safonova, 2009). The whole complex is irregularly covered by Silurian basalt, tuff, and siliciclastic sediments (Badarch et al., 2002). This thick succession, extending into China, Kazakhstan, and Russia for 2,000 km, was interpreted as a giant accretionary wedge (Xiao et al., 2009). Its Chinese and Russian Altai tracts have been the subjects of several studies, and the results suggest that the succession is composed of chemically immature detritus similar to graywacke (Chen et al., 2014; Jiang et al., 2012), for which significant volcanic input was proposed (e.g., Long et al., 2008).

Recent studies reveal the presence of Late Cambrian-Early Ordovician arc-type granitoid magmatism that affected both the southern border of the Precambrian continental blocks and the Lake Zone (Buriánek et al., 2017; Janoušek et al., 2017; Kozakov et al., 1999; Kröner et al., 2010; Soejono et al., 2016), forming a giant magmatic arc, named Ikh-Mongol arc system in western central Mongolia (Janoušek et al., 2017). Abundant granitoids dated as Silurian-Devonian intruded the Altai Zone mainly in the south (e.g., Wang et al., 2006; Yuan et al., 2007), coevally with the formation of migmatite-magmatite domes (Jiang et al., 2015). These were first thought to be derived from arc-related magmatic rocks (e.g., Wang et al., 2006) but were recently reinterpreted to have originated by anatexis of chemically primitive accreted detritus (e.g., Jiang et al., 2016).

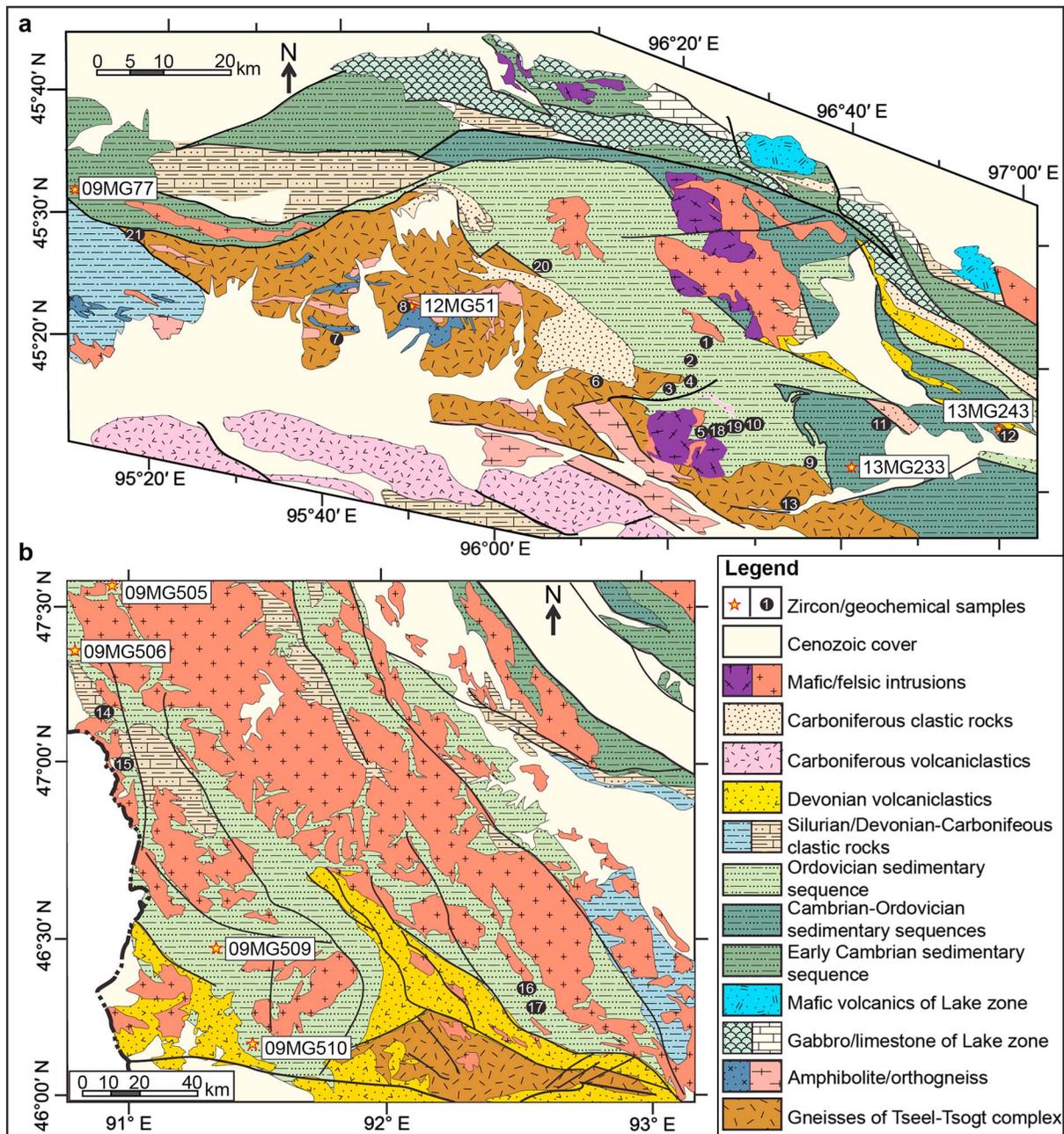


Figure 2. Geological map of the studied areas in SW Mongolia. Modified from Tomurtogoo (1998) and Hanžl et al. (2016). Sample locations are shown. Numbers in circles refer to samples in numerical order in Table S1. See Figure 1 for location of the figures.

2.2. Geology of the Study Area

The southern part of the Mongolian Altai principally consists of Cambrian-Ordovician volcano-metasedimentary turbiditic rocks and minor pillow basalts (Figure 1). This sequence was defined as the so-called Tugrug Formation which extends into the SE Chinese Altai where it is known as the Habahe Group (Long et al., 2008). The Tugrug formation and associated rocks are in tectonic contact with the Lake Zone in the NE and with a Devonian to Carboniferous volcano-sedimentary succession of the Trans-Altai Zone in the south (Figure 2). The Tugrug formation sequence rests on, or is juxtaposed to, a high-grade metamorphic unit that is well exposed along the southern slopes of the Altai Range. The high-grade unit was traditionally interpreted as a Precambrian continental sliver of uncertain origin (Badarch et al., 2002;

Tomurtogoo, 1998) and was named “Tseel Terrane” by Badarch et al. (2002). The dominant metamorphic rocks include high-grade paragneiss, granitic gneiss, schist with subordinate intercalations of amphibolite, gabbro bodies, and syntectonic granitoid intrusions (Badarch et al., 2002; Demoux, Kröner, Hegner, et al., 2009; Helo et al., 2006; Kozakov, 1986; Kozakov et al., 2002). Recent U-Pb zircon dating of both low-grade volcanoclastic metasedimentary rocks and high-grade paragneisses in the western part of the Tseel Terrane shows the same age patterns, implying a significant input of Late Cambrian-Early Ordovician (506–471 Ma) detritus (Jiang et al., 2012). These rocks exhibit mutually comparable geochemistry characterized by an arc-related signature with minor contributions of old crustal material (Helo et al., 2006; Jiang et al., 2012). Based on these data, the gneissic rocks were reinterpreted to be high-grade metamorphic equivalents of the northerly Ordovician sedimentary sequence (i.e., Tugrug formation) (Jiang et al., 2012). The Tugrug formation is overlain by low-grade pyroclastic rocks of presumed Silurian age, locally interlayered with thick carbonates, followed by thick Lower Devonian siliciclastic sediments, fossiliferous limestones, and interbedded felsic volcanic rocks (Markova, 1975). Sensitive high-resolution ion microprobe (SHRIMP) zircon U-Pb dating of two felsic volcanic samples yielded ages of 396 ± 3 and 397 ± 3 Ma (Demoux, Kröner, Hegner, et al., 2009), documenting Early Devonian volcanism in the region. Local accumulations of Lower Carboniferous siliciclastic sediments were interpreted as intramountain basins (Markova, 1975). Granitic intrusions crop out in many places and have predominant emplacement ages of 420–360 Ma with a subordinate age population ranging from 320 to 260 Ma (Burenjargal et al., 2014, 2016; Jiang et al., 2012; Kröner et al., 2010).

The Tugrug formation was affected by postdeposition deformation and metamorphism, resulting in the formation of superposed structures and polymetamorphic fabrics. The rocks of this formation show a penetrative flat greenschist-facies fabric (Hanžl et al., 2016), whereas its high-grade metamorphic equivalents were affected by upper amphibolite- to granulite-facies deformation, followed by exhumation of metamorphic and magmatic domes (Broussolle et al., 2015; Lehmann et al., 2010). The prominent tectonothermal event was thought to have taken place in the Middle-Late Devonian, based on U-Pb and Pb-Pb zircon ages of migmatitic gneisses and syntectonic granitoids ranging from circa 360 to 385 Ma (Bibikova et al., 1992; Hanžl et al., 2016; Kozakov et al., 2002; Kröner et al., 2010, 2007). Late Permian to Triassic steep lower greenschist-facies cleavage and folds overprinted the entire area and gave rise to numerous strike-slip or thrust faults that further fragmented the entire region into several small units (Lamb et al., 2008; Lehmann et al., 2010) (see also Figure 2).

3. Petrography, Sampling Strategy, and Analytical Methods

The thick terrigenous-volcanogenic clastic metasedimentary sequence dominating the vast area of the southern Mongolian Altai is the subject of this study (Figure 2). The dominant phase of the sequence is a terrigenous clastic sedimentary component, but a subordinate volcanogenic component is also present. The proportion of volcanic and tuffaceous sedimentary rocks varies at different localities, but interbeds of terrigenous and volcanogenic layers are always present (Figure 3a). The terrigenous layers mainly consist of quartz-feldspar and polymictic sandstones, siliceous and phyllitic shales, and slates (Buslov et al., 2001; Safonova, 2014). The volcanogenic layers are composed of pyroclastic and tuffaceous rocks with felsic to mafic compositions. The primary sedimentary structures have been almost obliterated by subsequent strong greenschist-facies deformation that produced a well-developed penetrative schistosity dipping steeply to the SW (Figure 3b). The high-grade rocks in the Tseel metamorphic complex are considered to be high-grade equivalents of the sedimentary sequence, mainly consisting of garnet-sillimanite-biotite paragneiss, amphibolite, and quartz- or mica-rich metapelite (e.g., Hanžl et al., 2016). The metapelitic layers are interlayered with mafic layers (commonly amphibolites) at many localities, and both show penetrative, steep foliations (Figure 3b).

In order to constrain its provenance, samples from this sequence were collected for petrological and geochemical studies, zircon U-Pb dating, and Hf-in-zircon isotopic analysis. Eight samples, including four terrigenous clastic metasedimentary (three sandstones and one schist) and four volcanogenic (mainly tuffaceous) lithologies, were collected for zircon U-Pb dating and Hf-in-zircon isotopic analysis. Seven of these, together with 15 terrigenous clastic sedimentary and eight volcanogenic (tuffaceous) samples, were used for additional geochemical studies. The terrigenous samples are composed of variable amounts of quartz and feldspar fragments, microcrystalline quartz and sericite, and minor amounts of clay minerals as

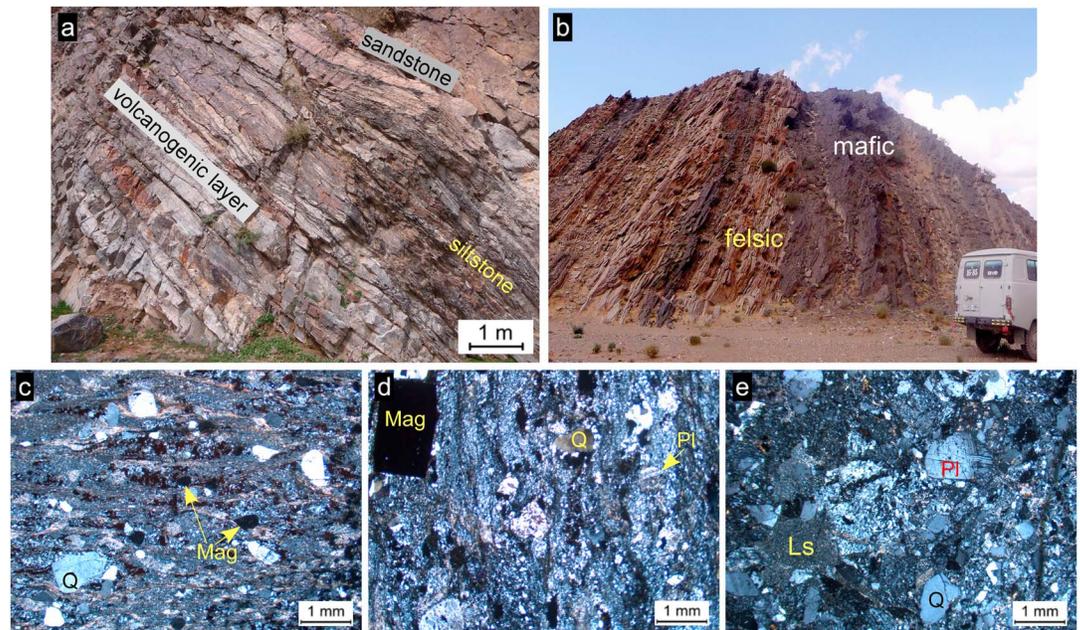


Figure 3. (a) Field photograph showing the Ordovician sedimentary succession characterized by interbeds of terrigenous and volcanogenic layers. (b) Field photograph showing metapelitic (“felsic”) interlayered with amphibolite (“mafic”) layers with penetrative steep foliations. Photomicrographs illustrating textural characteristics of (c, d) terrigenous and (e) volcanogenic samples. Abbreviations for minerals: Q, quartz; Pl, plagioclase; Mag, magnetite; Ls, lithic fragments.

well as magnetite grains (Figures 3c and 3d). The volcanogenic samples are mostly fine- to medium-grained, poorly sorted and contain either angular grains composed mainly of quartz and feldspar or lithic fragments (Figure 3e).

Major and trace element compositions for most samples were determined at Activation Laboratories Ltd. (ActLabs) in Ontario, Canada. Chemical analyses of a few samples were performed at the Guangzhou Institute of Geochemistry, Chinese Academy of Sciences (GIG-CAS). The geochemical data are presented in supporting information Table S1. For U-Pb zircon dating, samples 09MG77, 12MG51, 13MG233, and 13MG243 were analyzed by laser ablation multicollector inductively coupled plasma mass spectrometry (LA-MC-ICP-MS) in the Department of Earth Sciences, The University of Hong Kong (HKU), and zircons from samples 09MG505, 09MG506, 09MG509, and 09MG510 at the Beijing SHRIMP Center, Chinese Academy of Geological Sciences. The mass fractionation correction and isotopic results for the LA-MC-ICP-MS analyses were calculated by ICPMSDataCal (version 7.0, Liu et al., 2008). A common Pb correction was applied to all measured ratios using the interference and background-corrected ^{204}Pb signal intensity following the model of Andersen (2002). Corrections for common Pb for SHRIMP analyses were undertaken using the ^{204}Pb method, assuming that for low counts of ^{204}Pb , common Pb is mainly surface related (Kinny, 1986) and has the composition of Broken Hill lead. Data reduction followed the method of Nelson (1997), using the programs Prawn, WALEAD, and Plonk. The age calculations and concordia plots for both methods were done using ISOPLOT (version 3.0, Ludwig, 2003). Selected zircon grains were then analyzed for Lu-Hf isotopic compositions using LA-MC-ICP-MS at HKU. For each analysis, the ablation spot was placed either at the same position as a previous U-Pb spot or on the same zircon domain of the grain, based on cathodoluminescence (CL) images. The dating results and Hf isotopic data are listed in Table S2. Detailed information on sample preparation and analytical procedures is available in the supporting information Text S1.

4. Results

4.1. Geochemistry

The geochemical compositions of both terrigenous and volcanogenic samples vary widely as exemplified by their SiO_2 contents ranging from 44 to 77 wt % and 47 to 74 wt %, respectively (Table S1). Some samples have

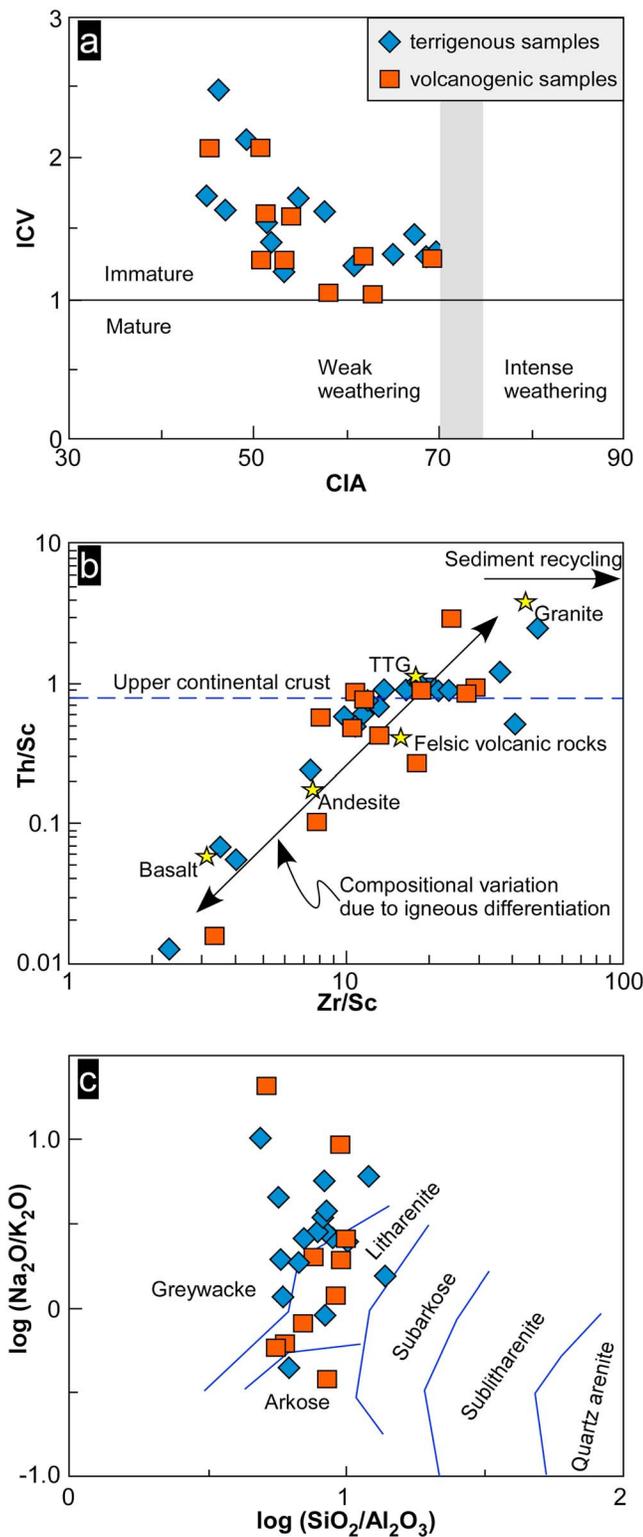


Figure 4. Geochemical characteristics of Ordovician sedimentary rocks from the Mongolian Altai. (a) CIA-ICV classification diagram after Nesbitt and Young (1984) and Cox et al. (1995). (b) Zr/Sc versus Th/Sc diagram after McLennan et al. (1993). (c) Classification diagram after Pettijohn et al. (1987), showing the graywacke-dominated nature of the analyzed samples.

relatively high and variable loss-on-ignition (LOI) values, probably implying postdiagenetic alteration. CaO and Na₂O are potentially the most mobile components among major elements. In order to minimize possible effects due to such alteration, we restrict our following discussions on major elements to samples with less than 5% LOI. In general, all related samples are characterized by a low chemical index of alteration [CIA = Al₂O₃/(Al₂O₃ + CaO_{silicate fraction} + Na₂O + K₂O) × 100, molar ratio] and a high index of compositional variability [ICV = (Fe₂O₃ + K₂O + Na₂O + CaO + MgO + TiO₂)/Al₂O₃, molar ratio], suggesting an immature source affected by weak chemical weathering (Figure 4a, Cox et al., 1995, Nesbitt & Young, 1982). This is also consistent with their commonly low Th/U ratios (<5), suggesting that preferential leaching of U, a potential indicator of alteration during metamorphism, was negligible.

The Th/Sc ratios vary significantly between sediments derived from different igneous rock types since Th is enriched in felsic relative to mafic rocks, but Sc shows the opposite behavior; moreover, this ratio is not affected by sedimentary recycling (Cullers, 1994). In contrast, the Zr/Sc ratio will increase considerably during sedimentary recycling due to the enrichment of zircon (McLennan, 1989). The studied samples reveal highly variable Th/Sc (0.01–3.4) and Zr/Sc (3.4–52.9) ratios. The good positive correlation in the Th/Sc versus Zr/Sc diagram (Figure 4b) suggests that geochemical variation was mainly due to the derivation from variable mafic to felsic (meta) igneous sources, while the sedimentary recycling was just a modifying influence. The SiO₂/Al₂O₃ ratios (molar) for all studied samples vary between 2.95 and 8.05, and Na₂O/K₂O ratios (molar) range from 0.24 to 92.76, and thus almost all samples classify as either graywacke or litharenite (Pettijohn et al., 1987) (Figure 4c). The chondrite-normalized rare earth element (REE) patterns of most samples, both terrigenous and volcanogenic, are mutually comparable (Figures 5a and 5c). They feature moderate light REE enrichment, relatively flat heavy REE segments, and weak to moderate negative Eu anomalies (Eu/Eu* = 0.8–0.6). A few samples show relatively flat REE patterns without obvious negative Eu anomalies, indicating insignificant REE fractionation. In the upper continental crust normalized multielement diagrams (Figures 5b and 5d), both terrigenous and volcanogenic samples have patterns resembling western Pacific trench sediments but show concentrations of large ion lithophile elements (e.g., Rb, Sr, Ba, Th, U, and Pb) and high field strength elements (HFSE) (e.g., Zr, Hf, Nb, and Ta) somewhat lower than the average post-Archean Australian shale (PAAS).

4.2. Zircon Internal Structures and Ages

Zircons from *terrigenous clastic samples* exhibit similar morphological and internal structures. The populations are dominated by clear, euhedral, and stubby to long-prismatic crystals, some with variably corroded surfaces. These zircon grains mainly range from 100 to 200 μm in length and generally display simple oscillatory zoning in CL images (Figure 6), implying igneous growth. In addition, several zircons are subhedral and show thin metamorphic overgrowth (Figure 6). In this case, most of these zircon cores display complicated internal structures, that is, fragmented or rounded cores surrounded by weakly zoned low-luminescent rims (Figure 6). The cores are always characterized by

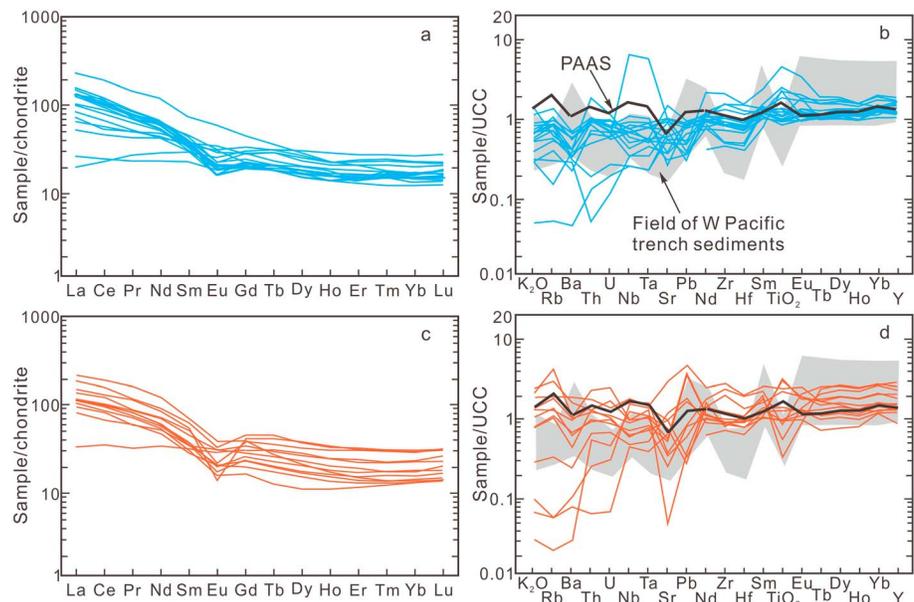


Figure 5. Chondrite-normalized REE and upper continental crust (UCC) normalized trace element patterns for (a, b) terrigenous and (c, d) volcanogenic samples. Normalizing values are from Sun and McDonough (1989) and Taylor and McLennan (1985), respectively. Literature data for Pacific-type trench sediments of Plank and Langmuir (1998) and the average post-Archean Australian shale (PAAS) of Taylor and McLennan (1985) are shown for comparison.

nebulous zoning, and some are replaced by very dull domains that reveal hardly any internal structures. Still, in some cases oscillatory zoning can be recognized (Figure 6). In summary, the observed variability in internal structures of zircons suggests highly variable but mostly igneous protoliths.

An important strategy in provenance analysis is to ensure that the analyzed grains are representative of the entire detrital zircon population, which invokes the concept of statistical adequacy (see summary in Fedo et al., 2003). The number of analyses required for a given level of confidence has been expressed by the standard binomial probability formula of Dodson et al. (1988). Based on the equation of Dodson et al. (1988), in

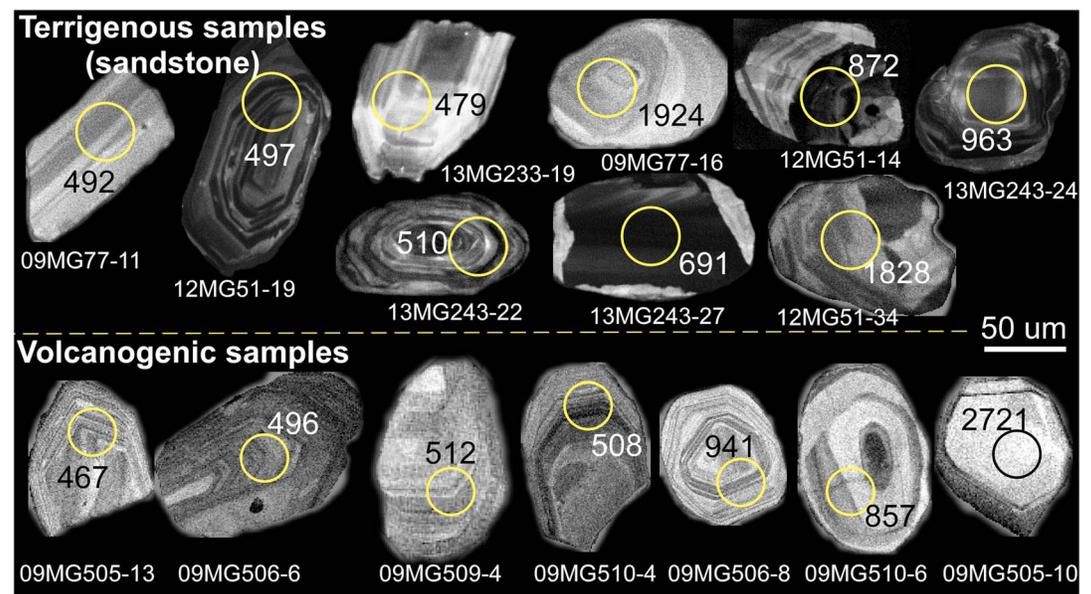


Figure 6. Representative CL images of zircons from samples of terrigenous-volcanogenic sedimentary succession of the Mongolian Altai. Analytical positions and ages (Ma) are labeled, and analysis numbers as in Table S2 are also indicated.

order to reduce the probability of missing a provenance component comprising 5% of the entire age population to 5%, at least 59 randomly selected grains need to be measured. This is in line with the conclusion of Andersen (2005), who suggested that 60 analyses per sample are sufficient to identify on a 95% confidence level, a single age component representing more than 5% of the entire age population. It has also been outlined by Vermeesch (2004) that 117 analyses are required to identify at a 95% confidence level every age component comprising more than 5% of the total sample. In the current study, a minimum of 84 grains were analyzed for each sample (except for sample 13MG233), and the total number of concordant analyses is 302; therefore, the probability of missing out a single age population occurring in the source region statistically tends to 0 (see Andersen, 2005).

Analysis of the most oscillatory-zoned grains yielded ages clustering around 494, 513, 470, and 503 Ma, for samples 09MG77, 12MG51, 13MG233, and 13MG243, respectively (Figure 7). Only a few (<10%) grains also yielded Neoproterozoic ages (Figure 7). Dating zircon cores with complicated structures, however, usually provided relatively old $^{207}\text{Pb}/^{206}\text{Pb}$ ages varying from Neoproterozoic to Neoproterozoic to Neoproterozoic (0.7–2.7 Ga). For example, one rounded grain in sample 09MG77 has a rounded core surrounded by two low-luminescent layers, and analysis of the core provided a concordant age of 1.92 Ga (Figure 6). The U and Th contents for all analyses vary irrespective to the ages, in accord with a multisource origin. Still, almost all analyses (>98%) have Th/U ratios >0.1, and more than 92% have Th/U ratios ranging from 0.2 to 1, irrespective of their ages or growth characteristics.

Zircons from *volcanogenic samples* are predominantly euhedral, stubby, and prismatic. Only a few grains are subhedral with slightly rounded terminations (Figure 6). Their length varies between 80 and 200 μm , and most exhibit clear igneous-related oscillatory zoning without inherited cores in the CL images (Figure 6). Some zircons display rims in CL images, suggesting a relatively complicated crystallization history (Figure 6). SHRIMP analyses were restricted to zircons characterized by well-developed igneous zoning. Most analyses yielded concordant early Paleozoic ages (540–460 Ma, Figure 6) with minor older results at 600–1,000 Ma, corresponding to Th/U ratios mainly varying from 0.2 to 0.9, irrespective of ages (Figure 6). Simple age populations were obtained for samples 09MG505, 09MG506, 09MG509, and 09MG510, with weighted mean $^{206}\text{Pb}/^{238}\text{U}$ ages of 465 ± 4 , 495 ± 4 , 511 ± 4 , and 509 ± 6 Ma, respectively (Figure 8). An inherited core of a single rounded grain in sample 09MG505 gave a concordant Neoproterozoic $^{207}\text{Pb}/^{206}\text{Pb}$ age of $2,721 \pm 8$ Ma (Figure 6).

4.3. Hf-in-Zircon Isotopic Compositions

For the terrigenous metasedimentary samples, Hf isotopic analyses were performed on selected large zircon grains mainly from the dominant Neoproterozoic-early Paleozoic population. Forty-three, 29, 15, and 34 grains from samples 09MG77, 12MG51, 13MG233, and 13MG143, respectively, were analyzed. Hafnium isotopic compositions of zircons from these four samples exhibit very similar characteristics, and all have large variations in $^{176}\text{Hf}/^{177}\text{Hf}$ ratios, irrespective of their ages. The corresponding $\varepsilon_{\text{Hf}}(t)$ values are plotted in Figure 9a. The early Paleozoic (460–540 Ma) zircons have initial ε_{Hf} values in a range of -19 to $+15$, and Neoproterozoic zircons range from -27 to $+10$. Correspondingly, the early Paleozoic zircons have T_{DM}^{C} model ages ranging from 0.6 to 2.3 Ga and the Neoproterozoic zircons yielded T_{DM}^{C} model ages from 0.9 to 2.8 Ga. The sparse pre-Neoproterozoic zircons have initial ε_{Hf} values between -13 and $+14$ (Figure 9a) and T_{DM}^{C} model ages between 1.4 and 3.1 Ga.

For the volcanogenic samples, Hf-in-zircon isotopic analyses were only performed on the dominant early Paleozoic population. The isotopic analyses yielded large variations in the $^{176}\text{Hf}/^{177}\text{Hf}$ ratios, corresponding to initial ε_{Hf} values of -15 to $+12$ (Figure 9b). These analyses yielded T_{DM}^{C} model ages from 0.6 to 2.0 Ga, similar to those of the major zircon population in the terrigenous clastic metasedimentary samples.

5. Discussion

5.1. Depositional Setting

The Ordovician Tugrug formation forms the bulk of the Mongolian Altai and has been the subject of considerable stratigraphic and paleontological research since the 1970s (Markova, 1975). However, its depositional environment and potential provenance has not been satisfactorily resolved. The ubiquitous presence of clastic sedimentary components in this sequence led Zonenshain et al. (1990) to consider it to

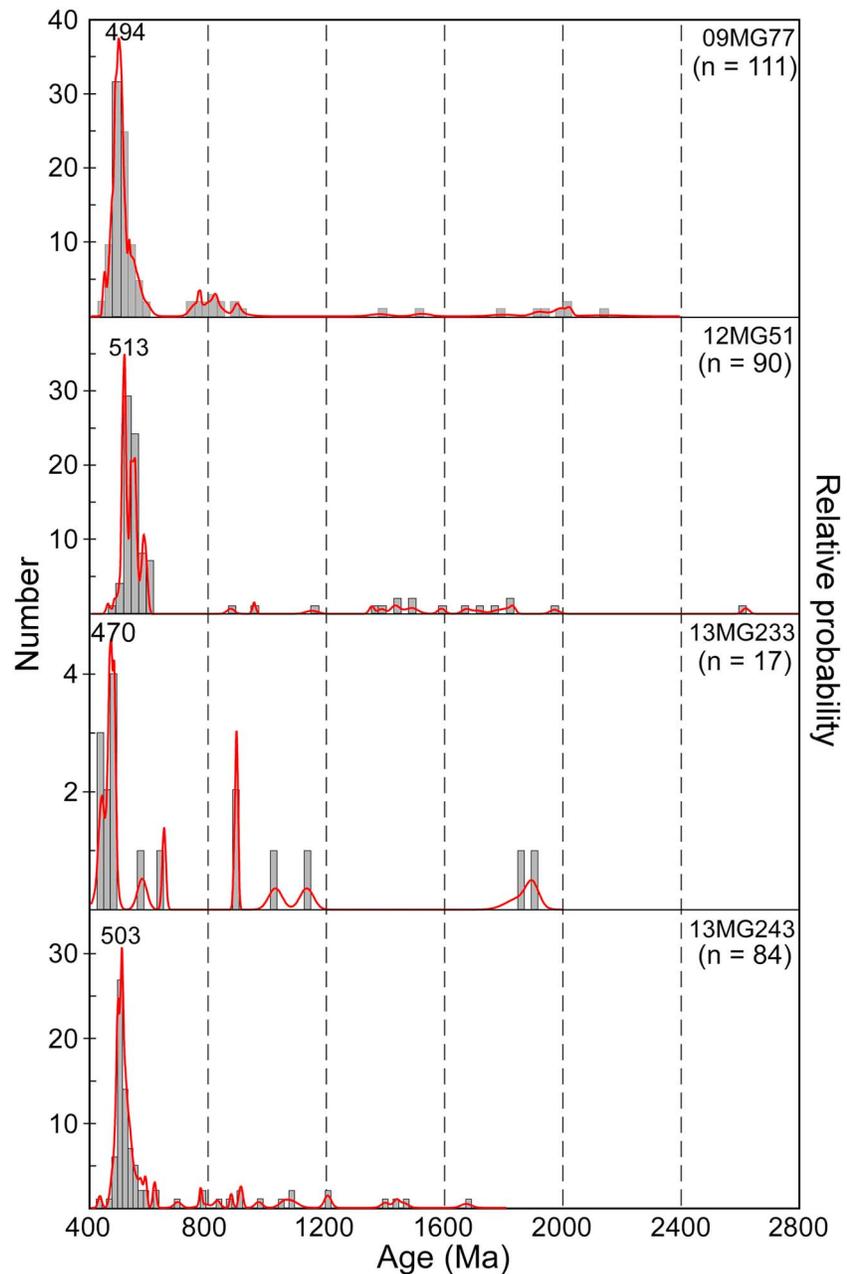


Figure 7. Relative probability plots for detrital zircon ages of terrigenous clastic sedimentary samples from the Ordovician succession. $^{206}\text{Pb}/^{238}\text{U}$ and $^{207}\text{Pb}/^{206}\text{Pb}$ ages are used for zircons younger and older than 1.0 Ga, respectively. Only analyses less than 10% discordant are considered in the plots to achieve the best possible age resolution (disc % = $\text{abs}(100 - 100 \times (^{206}\text{Pb}/^{238}\text{U age}) / (^{207}\text{Pb}/^{206}\text{Pb age}))$), Gehrels (2012)). Determination of age peaks was done by ISOPLOT.

be of passive continental margin affinity. In contrast, the identification of volcanogenic components caused other authors to argue that the sequence was deposited in an arc-related tectonic setting (Mossakovsky & Dergunov, 1985). The lithologies investigated in this study exhibit a notable presence of terrigenous and volcanogenic sedimentary layers but lack of pure pelitic, quartzitic, or calcareous layers. Such a lithological composition does not support a passive margin setting but generally correlates with a rapid transport-deposition cycle, likely pointing to turbiditic deposition. The immature sedimentary features characterized by euhedral feldspar and zircon crystal shapes (Figures 3 and 6) also suggest short transport and fast deposition. Some sedimentary layers are relatively rich in mafic minerals (such as hornblende and chlorite),

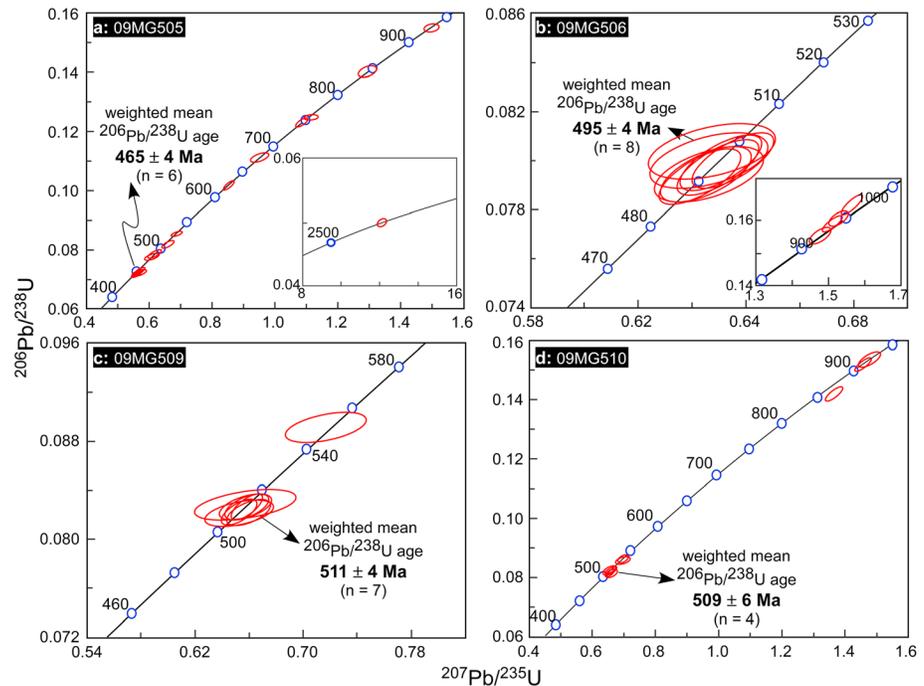


Figure 8. U-Pb concordia diagrams for zircons from volcanogenic rocks of the Ordovician succession in the Mongolian Altai.

and most of our studied samples reveal relatively high contents of MgO and Cr, again in contrast with typical passive continental margin sediments but more likely supporting a volcanic-related origin. This is consistent with the fact that the sediments are chemically immature and compositionally resembling graywacke (Figure 4c).

Modern studies revealed that the provenance and depositional setting of sediments can be inferred from their whole-rock geochemistry (e.g., Bhatia & Crook, 1986; Long et al., 2008; MacLean & Barrett, 1993; Taylor & McLennan, 1985). In order to minimize possible effects of late remobilization, we restrict our discussion to the fluid-immobile REE, high field strength elements (HFSE, e.g., Zr, Nb, Ta, Y, and Ti) and transition elements such as Cr, Co, and Sc, which are little affected during the metamorphism and therefore largely reflect the chemistry of their source (MacLean & Barrett, 1993; Münker et al., 2004; Taylor & McLennan, 1985). In general, the HFSE and REE are more enriched in felsic than mafic minerals. In contrast, in the basaltic melt compatible transition metals such as Sc and Co exhibit the opposite behavior (McLennan et al., 2003). Therefore, detritus originated from a mafic source would theoretically have higher Co/Th and lower La/Sc ratios compared to that of felsic origin. In the current work, the studied detrital samples have high to moderate Co/Th ratios and low to moderate La/Sc ratios, suggesting a mixture, in various proportions, of

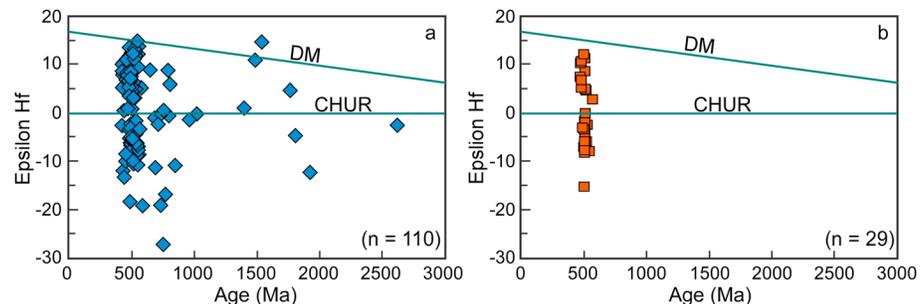


Figure 9. Diagrams of $\epsilon_{\text{Hf}}(t)$ values versus crystallizing ages for zircons from (a) terrigenous and (b) volcanogenic samples of the Ordovician succession. Age data with discordance larger than 10% are excluded.

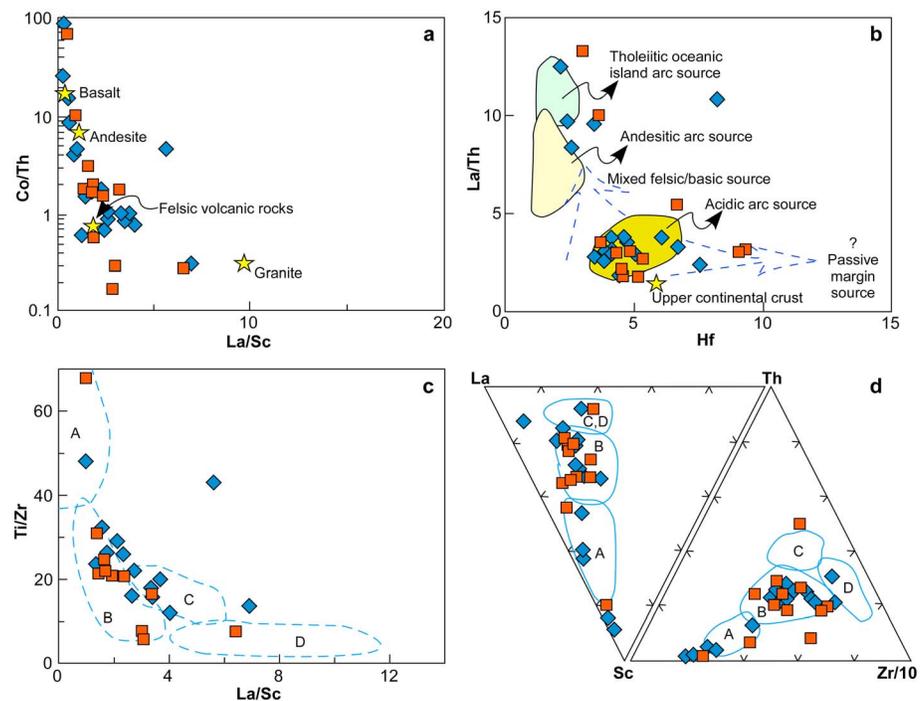


Figure 10. Source rock and tectonic setting discrimination diagrams for the Ordovician sedimentary succession from the Mongolian Altai. (a) La/Sc versus Co/Th diagram (after Condie et al., 1992; Gu et al., 2002; McLennan et al., 1984), showing derivation mainly from mixed felsic-intermediate volcanic source. (b) Hf versus La/Th diagram (after Floyd & Leveridge, 1987), indicating predominantly felsic sources. (c) La/Sc versus Ti/Zr diagram (after Bhatia & Crook, 1986), suggesting a continental arc and active continental margin setting. (d) Triangular trace element plots (after Bhatia & Crook, 1986) suggesting a continental island arc/active continental margin affinity. A = oceanic island arc; B = continental island arc; C = active continental margin; D = passive margin.

felsic and mafic volcanic components (Figure 10a). This is supported by the discrimination diagram of Floyd and Leveridge (1987), in which the studied samples mainly plot within the acidic arc source field with minor contribution from andesitic and/or tholeiitic island arc, while only sparse samples show passive margin sedimentary affinities (Figure 10b).

Discrimination diagrams of Bhatia and Crook (1986) are widely used in the discussion of tectonic setting for the sediments, based on the different behavior of elements during various geological processes. When considering the diagram of La/Sc versus Ti/Zr and the ternary plots involving La, Th, Sc, and Zr (Figures 10c and 10d), nearly 60% of our data are chemically similar to sediments deposited in an active continental arc (corresponding to a source region dominated by felsic volcanic rocks, Bhatia & Crook, 1986). Subordinate groups of data are comparable to those occurring on oceanic island arcs (a source dominated by mafic volcanic rocks) and active continental margin (a source region dominated by granitoid gneisses), and only one analysis falls in the field of a passive margin setting. It is important to realize that the four broad settings are “end-members,” and the sedimentary basins, in particular those in a suprasubduction systems, have changed tectonic regimes during their evolution due to plate movements. This may, at least in part, explain the spread of our data. In any case, the observed chemistry argues against the deposition on a passive margin but is in line with the concept that the studied sedimentary succession represents accretionary wedge sediments that were derived from source regions of arc-related (both continental and oceanic island arcs) and active continental margin affinities (Xiao et al., 2009).

Taken together, our samples are chemically immature and compositionally similar to graywacke. This detritus was characterized by a significant contribution of felsic to intermediate volcanic components into the sedimentary basin, which may have developed at an active continental margin. The studied rocks resemble immature Pacific trench sediments but differ from mature shales (Figure 5b). Moreover, also the variable zircon $\varepsilon_{\text{Hf}}(t)$ values suggest an addition of juvenile material combined with reworking of old crust in the source region (Figure 9), implying an environment similar to that of an active continental margin.

5.2. Potential Provenance

Zircons from the studied sedimentary sequence record a long geological history of the source region(s) from the Neoproterozoic to early Paleozoic (Figures 6–9). The dominance of circa 540–460 Ma zircons suggests that early Paleozoic magmatic rocks prevailed in the source area. The subordinate Neoproterozoic and rare pre-Neoproterozoic grains also reveal the presence of Precambrian continental crust in the source region (Figure 7). It is noteworthy that the main early Paleozoic zircon population shows mostly euhedral shapes and displays oscillatory zoning, whereas the Precambrian zircons are generally rounded with complicated magmatic-metamorphic internal structures (Figure 6). Combined with the geochemical signature, these features suggest that the detritus for the studied Ordovician sedimentary succession was mainly derived from both the nearby early Paleozoic arc-proximal sources and perhaps more distant, but certainly more mature, Precambrian continental sources.

Indeed, neighboring Neoproterozoic-early Paleozoic arc-related complexes of the Lake Zone and its adjacent Zavhan and Baydrag blocks may have provided an important contribution to the studied Ordovician sedimentary basin. It is well documented that the Mongolian Precambrian blocks underwent multiple magmatic and metamorphic events dated at 2.8 Ga to 0.9 Ga (Bold et al., 2016; Buriánek et al., 2017; Demoux, Kröner, Badarch, et al., 2009; Kozakov et al., 2007; Kröner et al., 2001). The widely reported Neoproterozoic magmatic rocks correlated with subsequent magmatic event yielded ages of 750–610 Ma (Dijkstra et al., 2006; Kuzmichev et al., 2001; Levashova et al., 2010; Osozawa et al., 2008; Sal'nikova et al., 2001). In addition, the Lake Zone is characterized by the presence of ophiolitic sequences and oceanic arcs dated mainly between 600 and 570 Ma (Jian et al., 2014; Kovach et al., 2011; Kröner et al., 2014). These age data are comparable with the subordinate Precambrian zircon population in the present study.

More importantly, both the Precambrian blocks and the Lake Zone were intruded by numerous subduction-related granitoids (e.g., Kröner et al., 2010; Rudnev et al., 2012; Soejono et al., 2016) of a giant, >1,800 km long Cambrian Ikh-Mongol arc system (Janoušek et al., 2017). These rocks and their eruptive equivalents yielded formation ages between 460 and 520 Ma with a peak around 510 Ma (see summary in Janoušek et al., 2017; Glorie et al., 2011; Jiang et al., 2011; Rudnev et al., 2012), exactly matching the predominant zircon population in the studied sedimentary succession.

It is worth emphasizing again that the Cambrian-Ordovician sedimentary succession dominates vast areas of the Russian, Chinese, and Mongolian Altai. Recently published geochemical data on these successions from the Russian and Chinese Altai suggest that they both have affinities to an active continental margin depositional setting (Chen et al., 2016, 2014; Long et al., 2008, 2010; Sun et al., 2008), very similar to our findings for their Mongolian equivalents. The published detrital zircon age patterns also characterized a prominent early Paleozoic peak with a subordinate Neoproterozoic one (Chen, Sun, Buslov, et al., 2015; Chen, Sun, Cai, et al., 2015; Gibson et al., 2013; Jiang et al., 2011; Kovach et al., 2013; Long et al., 2007; Sun et al., 2008). For further comparison, detrital zircon age and related Hf isotopic data were compiled from literature on these three regions as shown in Figure 11. It is shown that all detrital zircons give consistently the same age patterns and do not show noticeable differences in their Hf isotopic variation with time. Even more interestingly, it appears that they characterize a sharp Cambrian-Ordovician and wide early Neoproterozoic “Grenvillian” age peaks (Figure 11). Such an age pattern fits the Neoproterozoic-early Paleozoic rocks in the Lake Zone and its adjacent Precambrian blocks (Figure 12). This observation may suggest that the Precambrian continental blocks in central western Mongolia and the Lake Zone could have contributed significantly to their southerly sedimentary basin that constituted the basement of future Russian, Chinese, and Mongolian Altai.

5.3. Early Paleozoic Geodynamic Evolution of the Mongolian Collage System

The fault-bounded lithologically contrasting units in the studied region were thought to have experienced distinct and independent geodynamic evolutions (Badarch et al., 2002). However, the correlation between the zircon age spectra and geochemical signatures of the studied sedimentary succession and the rocks in adjacent Precambrian blocks and the Lake Zone strongly indicate a possible genetic link.

It was recently shown that part of the Baydrag basement became tectonically interdigitated with high-pressure metamorphic rocks during NE directed (in recent coordinates) thrusting of Neoproterozoic ophiolites over its passive margin at circa 540 Ma (Lehmann et al., 2010; Štípská et al., 2010). These ophiolites were interpreted as being derived from Neoproterozoic marginal basins, oceanic arcs, and accretionary wedges

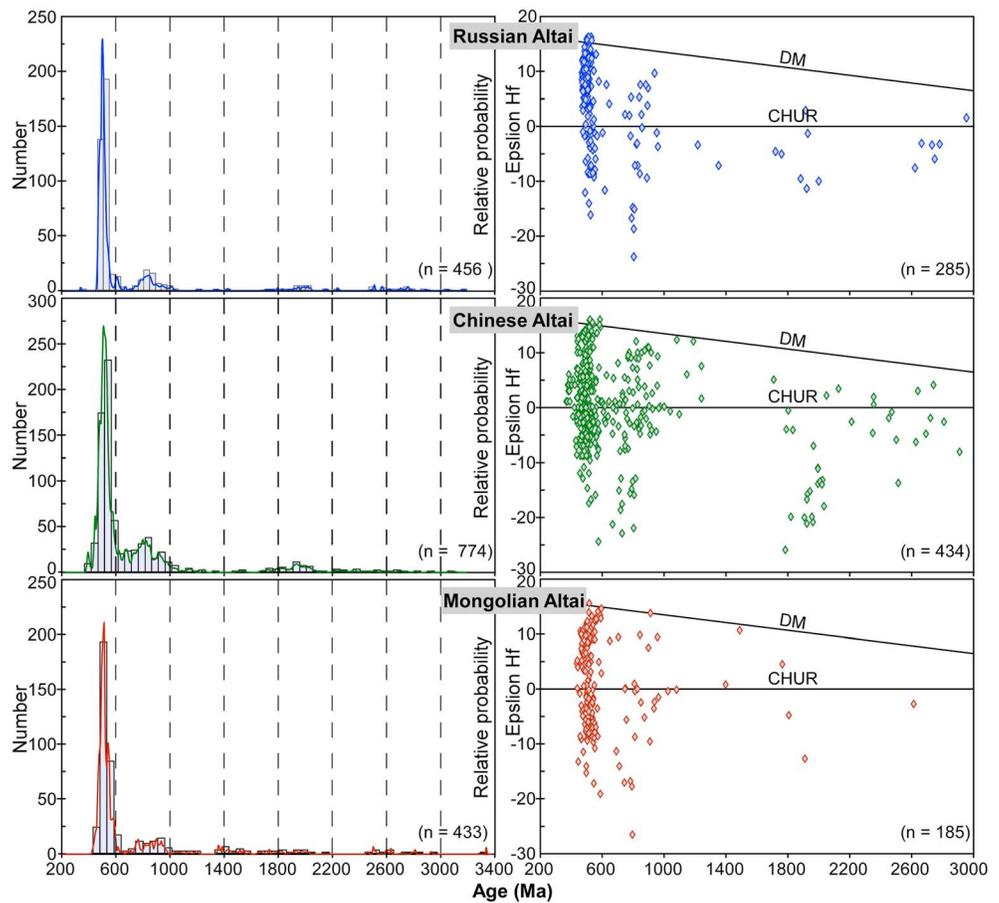


Figure 11. Age distribution and the Hf isotope pattern for igneous-related detrital zircons in Cambrian-Ordovician meta-sedimentary succession of the Russian Altai (data from Chen, Sun, Buslov, et al., 2015; Chen et al., 2016; Chen, Sun, Cai, et al., 2015), the Chinese Altai (data from Long et al., 2007, 2010; Sun et al., 2008; Jiang et al., 2011; Wang et al., 2014), and the Mongolian Altai (data from this study and previous works Jiang et al., 2012). $^{206}\text{Pb}/^{238}\text{U}$ ages are used for the grains younger than 1.0 Ga, and $^{207}\text{Pb}/^{206}\text{Pb}$ ages are used for the grains older than 1.0 Ga. We rely only on analyses that are less than 10% discordant.

soon before (Buriánek et al., 2017; Khain et al., 2003). Such a configuration implies a Neoproterozoic tectonic regime driven by a SW dipping subduction. On the other hand, the emplacement of the Cambrian Ikh-Mongol magmatic arc and the development of a Cambrian-Ordovician turbidite basin showing a generally southward younging (e.g., Tomurtogoo, 1998) favor NE dipping early Paleozoic subduction beneath the Precambrian continental blocks (Buriánek et al., 2017; Janoušek et al., 2017). In other words, we infer a reversal of the subduction system from SW to NE dipping during the early Paleozoic in the present coordinates.

Combined with the available geological data, we tentatively propose a revised Neoproterozoic to early Paleozoic geodynamic scenario of the Mongolian collage system. We agree with previous authors (e.g., Lehmann et al., 2010; Štípská et al., 2010) that the tectonic evolution was initially governed by south and/or SW subduction of a passive margin along the Precambrian continental blocks. Such a process probably caused the closure and obduction of young (Neoproterozoic) marginal oceanic basins associated with the high-pressure metapelites and eclogites at 540 Ma (Štípská et al., 2010). It may also account for the extinction of the Neoproterozoic island arc system and the formation of an accretionary complex, that is, the Lake Zone along the western margin of the Mongolian continental blocks (Kuzmichev, 2015, see also Figure 13).

During the Late Cambrian, a new NE and/or east dipping subduction system developed along the SW and west margins of the Mongolian Precambrian blocks giving rise to the generation of widespread arc magmatism (with maximum activity at circa 510 Ma) variously intruding the Precambrian basement and the accreted

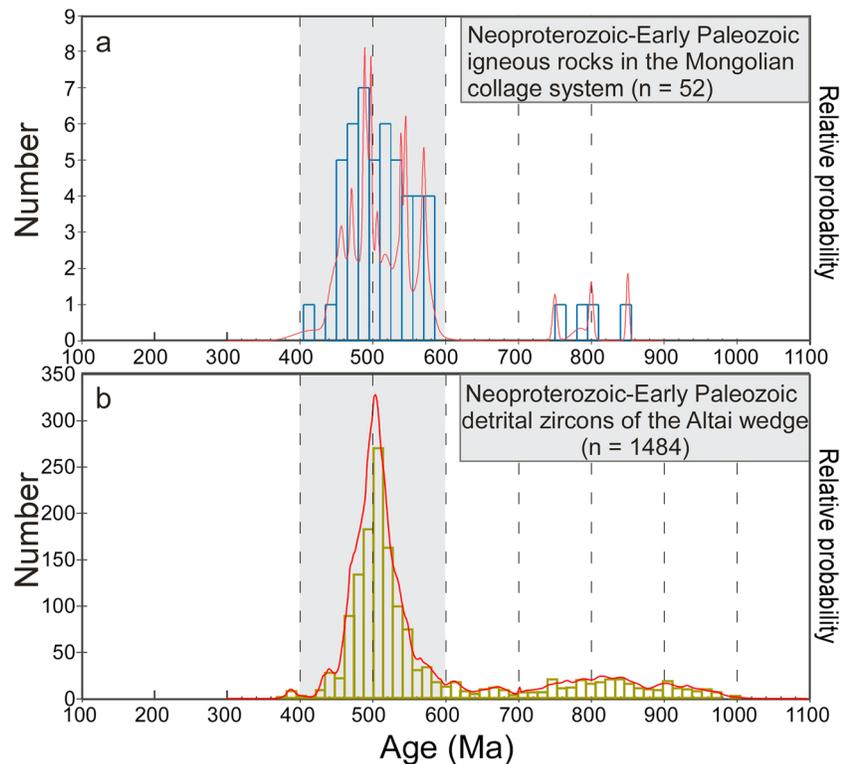


Figure 12. (a) Histogram of formation ages for Neoproterozoic-early Paleozoic (meta)igneous rocks from the Mongolian collage system (Xiao et al., 2015). Data are from Jiang et al. (2011, and references therein). (b) Histogram of ages for igneous-related Neoproterozoic-early Paleozoic detrital zircons from the Ordovician sedimentary succession of the Altai. Data sources are the same as in Figure 11.

Lake Zone (e.g., Izokh et al., 2011; Mongush et al., 2011; Rudnev et al., 2006, 2008, 2009, 2012; Yarmolyuk et al., 2011), exemplified by the Ikh-Mongol arc system (see Janoušek et al., 2017 Figure 14). We propose that formation of this giant arc was connected with the development of an equally giant turbidite basin to the south or west (Figure 13). During the Ordovician, subduction-related magmatism gradually ceased as Ordovician zircons are much less common compared to the prominent circa 510 Ma population (Figures 7 and 12), probably implying continuous retreat of the subduction system (Soejono et al., 2016). Subduction rollback would thus account for the formation of a giant accretionary sedimentary wedge constituting the bulk of the Mongolian and Chinese Altai from Late Cambrian to Late Ordovician times.

5.4. Peri-Pacific Accretionary History of Mongolian Collage System Compared to Terra Australis Orogen

The evolution of the CAOB was considered to have been associated with the formation of the Paleo-Asian Ocean, which was originally thought to be an extension of the internal Iapetus and Rheic oceans between the old continental blocks of Baltica and Siberia in the north and Tarim, Kazakhstan, and north China in the south (Dobretsov et al., 2003; Khain et al., 2003; Zonenshain et al., 1990). Closure of such ocean should theoretically lead to the collision of intervening continental blocks to make the CAOB a typical “internal” orogenic system. On the contrary, it has been increasingly noted that the PAO had evolved as a long-lived archipelago ocean similar to modern southwest Pacific (e.g., Didenko et al., 1994; Kröner et al., 2010; Windley et al., 2007). Nevertheless, no details regarding the paleogeographic positions of the PAO as well as several major tectonic elements involved into the formation of the CAOB were given.

It has been suggested that the Mongolian Precambrian continental blocks were adjacent to southern Siberia prior to circa 500 Ma (Dobretsov et al., 2003; Kozakov et al., 2005; Kravchinsky et al., 2001; Kravchinsky et al., 2010). It is also noteworthy that the present southern Siberia margin originally faced northward to an external Panthalassa Ocean during the Cambrian (e.g., Cocks & Torsvik, 2007; Şengör et al., 2014). Overlapping in time

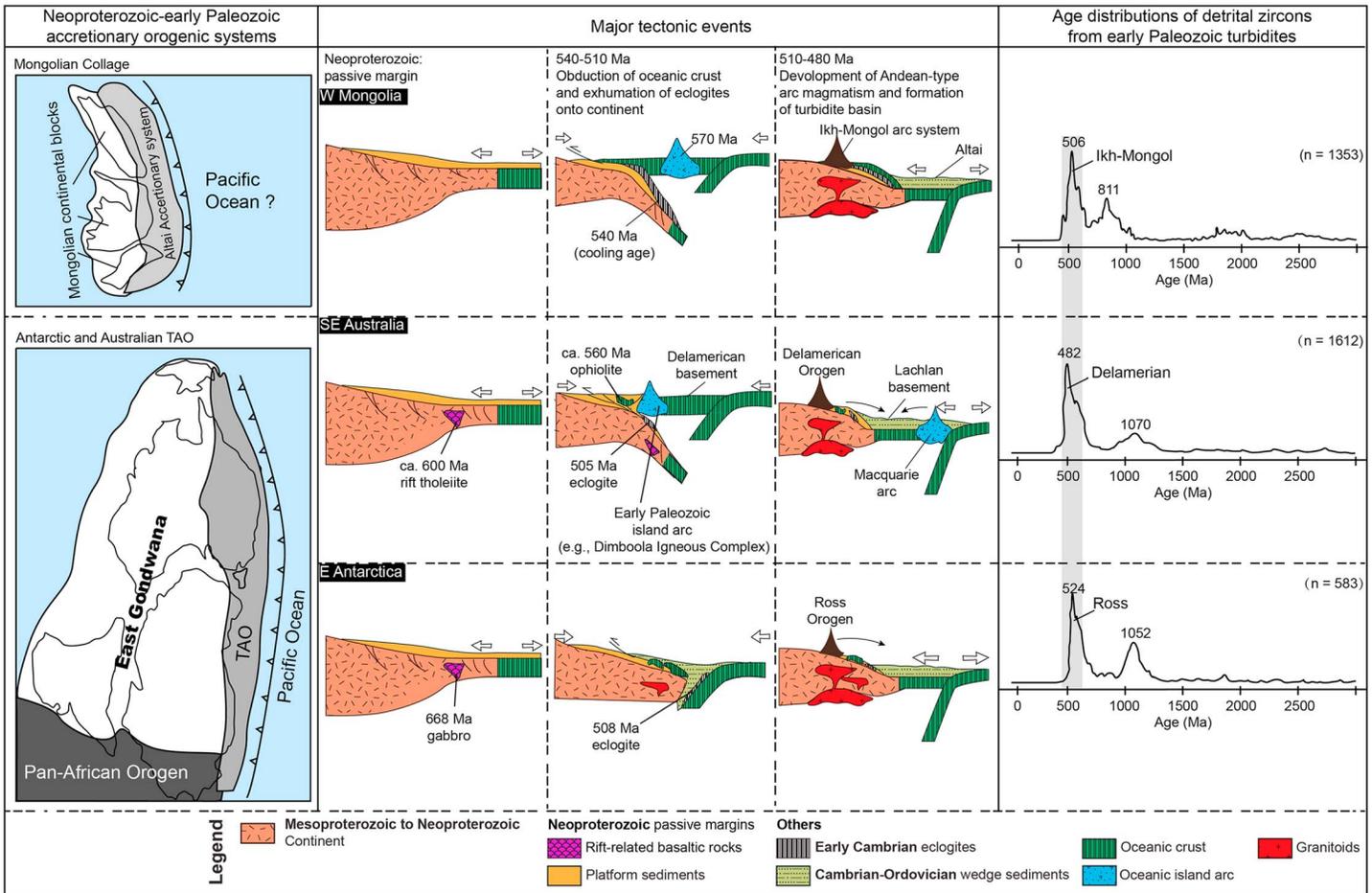


Figure 13. Architecture and main tectonic cycles of the accretionary system of the Mongolian collage system compared with that of the TAO. See text for detailed explanation. Detrital age patterns of zircons from early Paleozoic sedimentary successions within these two systems are also presented for comparison. For Mongolian data sources, see Figure 11b. Data for the SE Australian TAO are from Ireland et al. (1998), Fergusson and Fanning (2002), Fergusson et al. (2005, 2007, 2013), Squire et al. (2006), and Glen et al. (2011), and data for East Antarctica are from Goodge et al. (2002, 2004).

with the Neoproterozoic-early Paleozoic accretionary evolution of the Mongolian collage system was the evolution of the exterior Paleo-Pacific Ocean, which is best exemplified by the Terra Australis Orogen (TAO) (Cawood, 2005).

The Zavhan-Baydrag and adjacent units show many comparable features with the TAO, in particular concerning the following three major aspects (Figure 13): (1) A rifted passive margin sequence developed in the TAO at circa 600 Ma (Crawford et al., 2003; Direen & Crawford, 2003) when the southwestern Mongolian Precambrian blocks were characterized by the development of Ediacaran epicontinental basins and rifted passive margins (Bold et al., 2016; Khain et al., 2003; Kuzmichev, 2015). This was followed by thrusting of island arc fragments over the Australian passive margin at circa 520 Ma (Foster et al., 2005), almost simultaneous with the emplacement of high-pressure rocks and Neoproterozoic ophiolites on the margin of the Baydrag continent (Štípská et al., 2010); (2) Continuously advancing Pacific subduction was responsible for the Delamerian orogenic phase in the TAO and widespread Andean-type arc magmatism culminating at 505–495 Ma (Cawood & Buchan, 2007), coeval with the main orogenic cycle and active margin magmatism at 520–490 Ma in Mongolia (Buriánek et al., 2017; Janoušek et al., 2017); (3) Pacific plate rollback at 508–460 Ma produced a > 1,000 km wide back-arc basin in the Australian sector that became the basement for the Lachlan turbidites (Foster & Gray, 2000), again contemporaneous with the formation of the giant turbidite basin in the Mongolian and Chinese Altai. We compared detrital zircon age patterns of the Mongolian Ordovician turbiditic sediments with those of the Antarctic and Australian sectors of the TAO (Figure 13). It appears that these patterns are surprisingly consistent, showing early Neoproterozoic

(Grenvillian) age peaks followed by massive influx of early Paleozoic zircons, fingerprinting the active margin magmatism in both regions. This may suggest that the Mongolian Altai experienced a similar period of subduction rollback associated with the formation of a giant turbiditic basin of Lachlan type.

Taken together, the Mongolian collage system shows similarities with the TAO that developed along NE Gondwana and Paleo-Pacific Ocean boundaries, marked by almost coeval Neoproterozoic to Ordovician tectonic events. It appears that these events were connected with compressional and extensional settings that can be linked to the advancing and retreating subduction modes of the Pacific accretionary system (Cawood & Buchan, 2007). It was shown by Cawood and Buchan (2007) that the collisional orogeny between amalgamating continental bodies during the assembly of Gondwana was synchronous with subduction initiation within the accretionary TAO located along the margin of the supercontinent. Marginal accretionary orogens during supercontinent amalgamation were therefore considered to be driven by transitory coupling across the Pacific-Gondwana plate boundary, reflecting plate readjustments involving a temporary phase of increased relative convergence across the plate boundary (Cawood & Buchan, 2007). In the current case, we suggest that a change in global configuration of Gondwana and Pacific plate dynamics resulting in the formation of the TAO may therefore be applicable to the evolution of outboard margins of the Mongolian continental blocks as well.

It is worth mentioning that Neoproterozoic accretionary systems also coevally developed in two other main orogenic domains of the CAOB, collectively known as the Kazakhstan and Tarim-north China collage systems (Xiao et al., 2015). The former evolved as a single composite arc that was bent to form the Kazakhstan orocline in the west, and the latter was united and sutured by the Beishan Orogen in the south (Xiao et al., 2015). The Neoproterozoic to early Paleozoic geodynamics of the Kazakhstan collage system is characterized by progressive collision of several independent arc systems to form the Kokchetav-North Tianshan arc (Windley et al., 2007), whereas the Tarim-north China collage system mainly records the convergence between the Tarim Craton and the Dunhuang block (Xiao et al., 2015). The lithostratigraphic features of their basements and surrounding oceanic components are contrasted with the Mongolian collage system as summarized in several previous papers (Wilhem et al., 2012; Windley et al., 2007; Xiao et al., 2015) and may reflect their specific geodynamic evolution in the frame of the entire CAOB. Recent paleomagnetic data as well as the distributions of floral and faunal provinces both indicate that the Mongolian collage system was located far from the above two collages, before the Silurian, at least (see detailed explanations in Xiao et al., 2015). Considering that the Siberian and Mongolian collage systems underwent large-scale clockwise rotations of circa 50° from the Cambrian to the Late Permian-Early Triassic (Cocks & Torsvik, 2007; Domeier & Torsvik, 2014), the Siberian Craton and the Mongolian collage system were proposed to have not joined the CAOB until the Late Permian to Early Triassic (e.g., Xiao et al., 2015).

In conclusion, the Neoproterozoic-early Paleozoic geodynamic evolution of the Mongolian collage system shows similarities with the TAO rather than the Kazakhstan and Tarim-north China collage systems. This thus allows us to propose that the early Paleozoic evolution of both the Mongolian collage system and the TAO may have shared the same peri-Pacific oceanic accretion-subduction evolution.

5.5. Cambro-Ordovician Geodynamics of the Mongolian Collage System and Southern Siberia

We now integrate our data with the available geological information for southern Siberia, the Mongol-Okhotsk ocean basin, and the Mongolian collage system in order to discuss the general Cambro-Ordovician geodynamic evolution of the region.

We firstly focus on the geodynamic evolution of southern Siberia. Precambrian continental blocks are currently distributed in the vast area along the south margin of Siberia and northern Mongolia and NE China. Although derivation of those blocks from either Siberia or Gondwana has been the subject of much controversy, there seems a consensus that the continental blocks were already attached and/or adjacent to the southerly Siberia mainland in most Cambrian paleogeographic reconstructions (e.g., Kravchinsky et al., 2010; Kröner et al., 2017; Levashova et al., 2010). Such a proposition is supported by the findings that late Proterozoic sedimentary basins of the southern Siberian margin began receiving detritus from the Mongolian collage system, as exemplified by a progressively increasing contribution of Neoproterozoic zircons in the youngest Proterozoic formations (the Oselok Group and Ushakovka formation) in southern Siberia (e.g., Chumakov et al., 2011; Gladkochub et al., 2013; Letnikova et al., 2013; Powerman et al., 2015), similar to those found in the Neoproterozoic sedimentary successions of Mongolian blocks (e.g., Bold et al.,

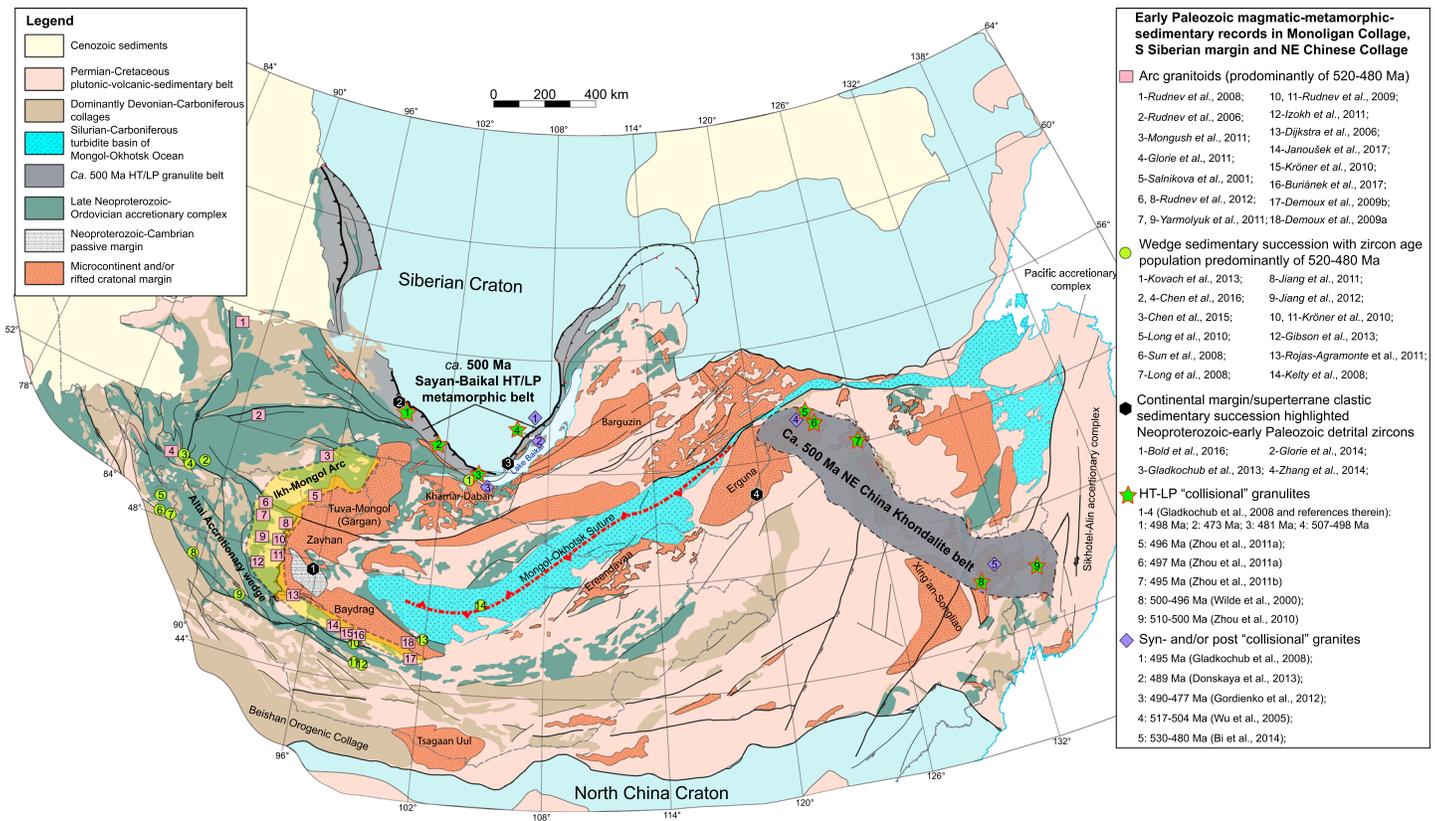


Figure 14. Simplified tectonic map of the eastern CAOB showing spatial distribution of major superterrane belts, circa 500 Ma HT/LP granulitic metamorphic belt along margins of Siberian Craton and the Khondalite belt in NE China as well as the Altai accretionary system including Cambro-Ordovician Ikh-Mongol magmatic arc system (highlighted) and Altai accretionary wedge. Published zircon U-Pb data related to the early Paleozoic magmatic-metamorphic records in the Mongolian collage system, south Siberian margin, and NE Chinese collage are also indicated.

2016; Zhang et al., 2014). It has also been documented that detritus derived from arc terranes of the Yenisey Ridge already contributed to Neoproterozoic sediments along the SW margin of Siberia (e.g., Glorie et al., 2014; Priyatkina et al., 2016). All this was previously interpreted as a result of progressive closure of oceanic basins between Siberia and exotic Mongolian blocks at the end of Proterozoic (Dobretsov & Buslov, 2007). The paroxysmal collisional event between Siberia and Mongolian blocks (such as Tuva-Mongol and Barguzin) was thought to have occurred during Middle-Late Cambrian as exemplified by the circa 500 Ma Sayan-Baikalian HT/LP granulite-facies metamorphic belt (Figure 14) (Donskaya et al., 2000), which is discontinuously rimming the southern border of the Siberian Craton (Figure 14) (Gladkochub et al., 2008). A similar granulite-facies belt dated at circa 500 Ma was recently described along the Erguna, Jiamusi, and Khanka Precambrian blocks in NE China, named the "NE China khondalite belt" (Figure 14) (Zhou, Wilde, Zhang, Zhao, et al., 2011b; Zhou et al., 2017; Zhou et al., 2010). Zhou and Wilde (2013) suggested that this "khondalite" metamorphic belt represents the northern continuation of the Baikalian collisional belt being later detached from Siberia during the opening of the Mongol-Okhotsk Ocean in Ordovician. Many so-called syncollisional and/or postcollisional granitoids dated at circa 500 Ma in the Baikalian khondalite belt (Figure 14) (e.g., Gordienko et al., 2012), seem to further support such high-temperature paroxysmal geodynamic scenario.

It should be mentioned that the circa 500 Ma HT/LP Sayan-Baikalian belt indeed experienced a Barrovian-type (circa 550–540 Ma) collisional metamorphism (Kozakov et al., 2006, 2008). A similar sequence of tectonometamorphic events has also been reported from several regions of the central part of the Mongolian collage system such as the Zavhan and Baydrag metamorphic footwall of the Dariv and Bayankhongor ophiolites and the Moron region of the Tuva-Mongolia Massif (Buriánek et al., 2017; Lehmann et al., 2010). In contrast to the previous interpretations, the Late Cambrian high-temperature metamorphism

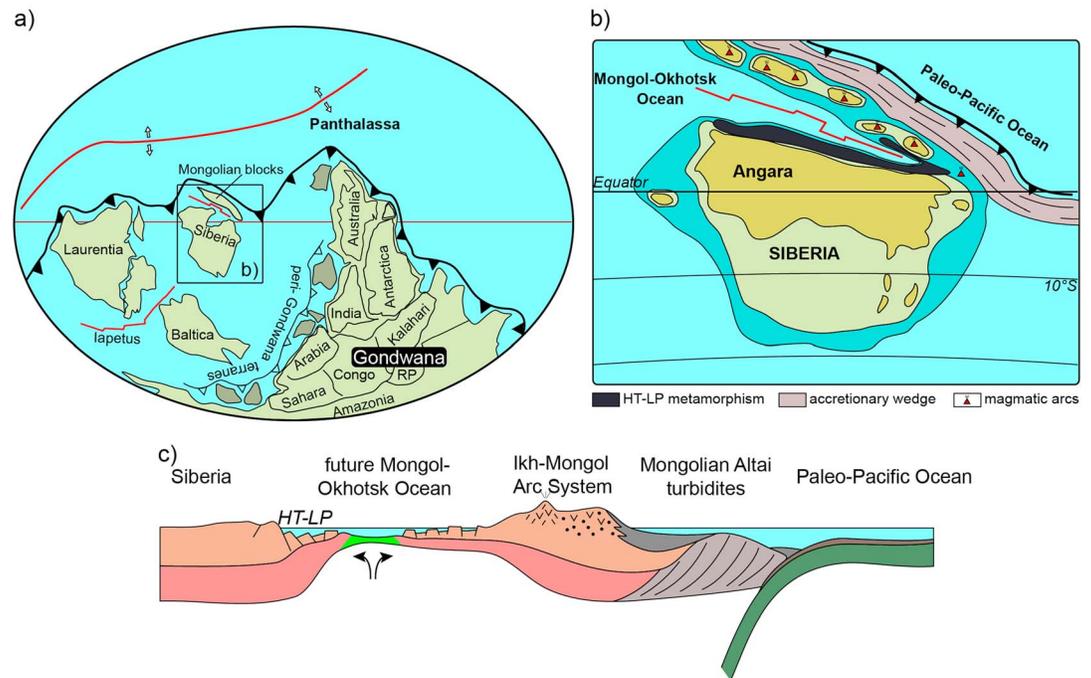


Figure 15. (a) Updated geodynamic scenario placing the Mongolian CAOB into a paleo-Pacific subduction system that extended from the TAO of NE Gondwana to Siberia. Global paleogeographic reconstructions in the Late Cambrian (circa 500 Ma) are modified from Scotese (2001). (b, c) Geodynamic model explaining the development of a typical HT/LP Baikalian granulitic metamorphic belt and a peri-Pacific Altai accretionary system, respectively. See text for details.

was interpreted to reflect persistent thermal activity of the lithospheric mantle along boundaries of the accreted blocks (Kozakov et al., 2008) or to have been associated with an extensional event (Lehmann et al., 2010). Apparently, two contrasting tectonometamorphic events affected all continental blocks forming the Mongolian collage system: (1) Barrovian-type metamorphism, perhaps related to a collisional amalgamation geodynamic environment (Thompson and England, 1984), and (2) Buchan-type metamorphism, commonly attributed to lithospheric extension (Thompson et al., 2001).

Simultaneously with the HT/LP event, the Cambrian-Ordovician sedimentary sequences of the northern part of the Hentey basin in Mongolia, that is, the core of future Mongol-Okhotsk Ocean (Figure 14), began receiving detritus of presumably both Siberia and Mongolian sources, from north and south (in recent coordinates), respectively (Kelty et al., 2008). This may imply the onset of the formation of the Mongol-Okhotsk Ocean in the Cambro-Ordovician. To the south, the development of the giant Ikh-Mongol arc system (Janoušek et al., 2017) and the Altai sedimentary wedge system (Figure 14) should be attributed to subduction-accretion during Cambro-Ordovician times.

On the basis of existing data and geodynamic interpretations, the Cambro-Ordovician geodynamic evolution of southern Siberia and the Mongolian collage system was governed by three contrasting regimes, represented by formation of HT/LP metamorphic belt in the north, onset of formation of the Mongol-Okhotsk Ocean in the center, and subduction-accretion in the south. To reconcile these three contrasting environments, we use the reconstruction of Scotese (2001) for the period at circa 500 Ma, in which the Mongolian continental blocks were adjacent to southern Siberian Craton and both of them faced the external Paleo-Pacific Ocean (Panthalassic) to the north (Figure 15a). As discussed above, the Altai accretionary system, represented by the Ikh-Mongol arc system and the Altai sedimentary wedge, may have developed during the subduction of the Paleo-Pacific oceanic plate beneath the Mongolian blocks since at least Cambrian. The question remains as to whether the HT/LP granulite-facies khondalite metamorphic belts between the Siberian Craton and the Barguzin, and Tuva-Mongol blocks (Gladkochub et al., 2010) are compatible with a collisional environment and do not reflect collapse of the Baikalian Orogen possibly related to the onset of Pacific subduction rollback and opening of Mongol-Okhotsk Ocean.

It has been generally accepted that the Tuva-Mongol, Khamar-Daban, and Barguzin continental blocks were accreted to the Siberian Craton at the end of the Neoproterozoic–Early Cambrian (Dobretsov & Buslov, 2007; Gladkochub et al., 2010). Such a process is compatible with the advancing cycle of Pacific oceanic plate and thrusting of ophiolites over the Zavhan and Baydrag continents from the south (Figures 13 and 15b). Here we propose that the entire system was subsequently stretched during the subduction rollback in Late Cambrian to Ordovician (Figures 13 and 15c) and could provide a feasible explanation for the coeval development of the circa 500 Ma HT/LP metamorphism in the region of Sayan-Baikal and NE China Khondalite belt, boundaries of the Tuva-Mongolia; Baydrag and Zavhan blocks as well as the Ikh-Mongol arc system and turbidite deposition in the region of the Mongolian Altai. We note that this early Paleozoic peri-Pacific accretionary system was rotated clockwise to the current position during late Paleozoic (Domeier & Torsvik, 2014) before being sandwiched between the Siberia and north China jaws.

6. Conclusions

Geological, geochemical, and geochronological data are combined to characterize the geodynamic evolution of the Mongolian collage system during the early Paleozoic and shed light on late Neoproterozoic–early Paleozoic accretionary processes of the CAO. The principal conclusions are the following:

1. Ordovician sedimentary successions in the Mongolian Altai represent a segment of a huge early Paleozoic accretionary sedimentary system that received detritus from Precambrian blocks, Neoproterozoic ophiolites, and, above all, an early Paleozoic magmatic arc system to the north.
2. The predominant arc-derived early Paleozoic zircon populations (540–460 Ma) combined with regional geological data suggest a reversal from SW dipping Early Cambrian subduction of passive margins of Mongolian Precambrian blocks to NE dipping subduction associated with the development of the Ikh-Mongol arc system during the Cambrian to Ordovician.
3. The Cambro-Ordovician geodynamics of the Mongolian collage system probably shared the same peri-Pacific oceanic accretion–subduction evolution with the Terra Australis Orogen. The seemingly contrasting but coeval geodynamic environments of the southern Siberian margin and the Mongolian collage system may be attributed to the subduction rollback of the Paleo-Pacific oceanic accretionary system in this time period.

Acknowledgments

This study was supported by the National Key Research and Development Program of China (2017YFC0601205), NSF China (41672056, 41190075, and 41273048), International Partnership Program of the Chinese Academy of Sciences (132744KYSB20160005), GIG-CAS 135 project Y234021001, and HKRGC grants (HKU705311P and HKU704712P). A postdoctoral fellowship from Charles University, a 100 Talents Program of the Chinese Academy of Sciences to Y. D. J., is also acknowledged. We appreciate financial support from the Czech Science Foundation (17-175405). This is contribution IS-2449 from GIG-CAS. Comments from journal reviewer Paul T. Robinson and two anonymous reviewers helped us to greatly improve the paper. The data used are listed in the references and supporting information.

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