The early Paleozoic tectonic evolution of the Russian Altai: Implications from geochemical and detrital zircon U–Pb and Hf isotopic studies of meta-sedimentary complexes in the Charysh–Terekta–Ulagan–Sayan suture zone

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ABSTRACT

The Charysh–Terekta–Ulagan–Sayan suture zone was regarded as a tectonic boundary separating two distinct subduction–accretion systems in the Central Asian Orogenic Belt (CAOB). In the north, magmatic arcs, such as the Gorny Altai terrane, formed in the southwestern periphery of the Siberian continent, whereas in the south, arc–prism systems, such as the Altai–Mongolian terrane, formed around the so-called Kazakhstan–Baikal composite continent with Gondwana affinity. When did these two systems amalgamate and whether the metamorphic complexes in the suture zone represent Precambrian micro-continental slivers are critical for our understanding of the accretionary orogenesis and crustal growth rate in the CAOB. A combined geochemical and detrital zircon U–Pb–Hf isotopic study was conducted on the meta-sedimentary rocks from the Ulagan (also referred to Bashkaus) and Teletsk Complexes in the suture zone. The results indicate that the protoliths of these rocks were dominated by immature sediments deposited in a time period between 500 and 420 Ma. Thus, Precambrian micro-continental slivers may not exist in the suture zone and even in the whole Altai Orogen.

The meta-sedimentary rocks from the Ulagan Complex yield geochemical compositions between those of common intermediate and felsic igneous rocks, implying that these kinds of rocks possibly served as dominant sources. Detrital zircons from this complex consist of a major population of ca. 620–500 Ma, a subordinate one of ca. 931–671 Ma and rare grains of ca. 2899–1428 Ma. This age spectrum is compatible with the magmatic records of the western Mongolia. We propose that the Ulagan Complex possibly represents part of a subduction–accretion complex built upon an active continental margin of the western Mongolia in the early Paleozoic. The remarkable similarities in source nature, provenance, and depositional setting to the early Paleozoic meta-sedimentary rocks from the northern Altai–Mongolian terrane imply that the Ulagan Complex was possibly fragmented from this terrane. The meta-sedimentary rocks from the Teletsk Complex show similar detrital zircon populations but contain higher proportions of mafic sediments and have more depleted whole-rock Nd isotopic compositions. Our data suggest that the detritus mostly came from the same source as that for the Ulagan Complex but those from the Gorny Altai terrane also contributed. This implies that the Gorny Altai and Altai–Mongolian terranes possibly amalgamated prior to the early Devonian rather than in the middle Devonian to early Carboniferous as previously thought. Thus, the widespread Devonian to early Carboniferous magmatism within these two terranes was possibly generated in a similar tectonic setting. Moreover, the dominant Neoproterozoic to early Paleozoic detrital zircons from the Teletsk Complex yield largely varied $\epsilon_{\text{Hf}}(t)$ values of -23.8 to 12.4 , indicating that crustal growth and reworking are both important in the accretionary orogenesis.

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1. Introduction

The Central Asian Orogenic Belt (CAOB) was developed from the latest Mesoproterozoic to late Paleozoic or early Mesozoic (e.g., Zonenshain

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et al., 1990; Khain et al., 2003; Xiao et al., 2003; Windley et al., 2007; Xiao et al., 2009; I. Safonova et al., 2011; Wilhem et al., 2012) and it covers a vast area among the Siberian, East European, Tarim, and North China continents (Fig. 1a, inset). This orogenic belt was formed by prolonged and complicated amalgamation of diverse island arcs, accretionary complexes, and minor micro-continental blocks/slivers (e.g., Berzin et al., 1994; Didenko et al., 1994; Yolkina et al., 1994; Badarch et al., 2002; Buslov et al., 2002; Xiao et al., 2010; Levashova et al., 2011), signifying substantial crustal growth in the Phanerozoic (e.g., Jahn et al., 2000; B. Jahn et al., 2001; B.-M. Jahn et al., 2001; Kovalenko et al., 2004).

Precambrian rocks have been identified within some micro-continental blocks/slivers in the CAOB, such as the Tuva–Mongolian terrane (e.g., Salnikova et al., 2001 and references therein; Badarch et al., 2002; Kozakov et al., 2005, 2007; Demoux et al., 2009a), the Central Tianshan belt (e.g., Yang et al., 2008; Lei et al., 2013; X.S. Wang et al., 2014; He et al., 2015), the Tarbagatai block (Kozakov et al., 2011), and the Baga Bogd massif (Demoux et al., 2009b). The substantial amounts of Precambrian detrital zircons in the widespread sedimentary sequences (e.g., Long et al., 2007; Kelty et al., 2008; Sun et al., 2008; Jiang et al., 2010; Long et al., 2010; Jiang et al., 2011; Rojas-Agramonte et al., 2011; Jiang et al., 2012; Ma et al., 2012; Y. Wang et al., 2014; Chen et al., 2015a) suggest that these Precambrian tectonic units possibly served as backbones, surrounding which fore-/back-arc basins and accretionary prisms formed (e.g., Jiang et al., 2011; Chen et al., 2015a). An important feature of these micro-continental blocks/slivers is the occurrence of high-grade metamorphic rocks that usually have Proterozoic or even older whole-rock Nd model ages (e.g., Hu et al., 2000; Badarch et al., 2002). Accordingly, tectonic units with such characteristics within the CAOB were mostly assumed to have been formed in the Precambrian (e.g., He et al., 1990; Hu et al., 2000; Badarch et al., 2002; Wang et al., 2006, 2009). However, recent high-precision zircon U–Pb geochronological data demonstrate that this interpretation can be misleading in some cases. For instance, some previously regarded Precambrian continental blocks with high-grade gneisses, such as the Central Block of the Chinese Altai and the Tsel terrane in western Mongolia, have been proven to be actually formed in the early Paleozoic (Long et al., 2007; Sun et al., 2008; Jiang et al., 2010; Long et al., 2010; Jiang et al., 2011, 2012; Y. Wang et al., 2014). Therefore, it is imperative to re-evaluate the distribution, size, and origin of the Precambrian

continental fragments, which is crucial to understand the geodynamic evolution and crustal growth rate of the CAOB.

The Russian Altai, situated to the southwestern margin of the Siberian continent (Fig. 1a), is a key area documenting the accretionary orogenesis in the northwestern CAOB (e.g., Yolkina et al., 1994; Buslov et al., 2001, 2002, 2004a, 2004b; Ota et al., 2007; Glorie et al., 2011; Kruk et al., 2011; Wilhem et al., 2012; Chen et al., 2014, 2015a, 2015b). Two separated tectonic units, namely, the Gorny Altai and Altai–Mongolian terranes, amalgamated along the Charysh–Terekta–Ulagan–Sayan (CTUS) suture zone (e.g., Buslov et al., 1993, 2001, 2004a, 2004b; Dobretsov and Buslov, 2007). A series of variably sized metamorphic units consisting of greenschist- to amphibolite-facies rocks, such as the Ulagan (also referred to Bashkaus), Teletsk, and Uimon Complexes, are identified within this suture zone (Fig. 1b; Daukeev et al., 2008; Glorie et al., 2011; Kruk et al., 2011). Controversies exist on the origin and tectonic nature of these complexes, i.e. whether they are Precambrian micro-continental slivers (e.g., Ota et al., 2007; Daukeev et al., 2008) or represent Paleozoic collisional units (e.g., Buslov et al., 1993, 2001; Safonova, 2014 and references therein). Timing of amalgamation between the Gorny Altai and Altai–Mongolian terranes is another issue of debate. Some researchers thought that the CTUS suture zone was formed in the middle Devonian to early Carboniferous (e.g., Buslov et al., 2001, 2004a, 2004b; Glorie et al., 2011), while others proposed that the amalgamation possibly occurred prior to the early Devonian (Filippova et al., 2001; Windley et al., 2007; Chen et al., 2015b). Samples of greenschist- to amphibolite-facies metamorphosed sedimentary sequences from the Ulagan and Teletsk Complexes in the CTUS suture zone were collected (Fig. 2). An integrated whole-rock geochemical and detrital zircon U–Pb–Hf isotopic study was conducted to provide firm constraints on their age, provenance, and depositional setting, which shed light on the abovementioned scientific issues.

2. Geological setting

The term Russian Altai refers to the part of the Altai Orogen in Russia. It consists of the Gorny Altai terrane in the north, northern segment of the Altai–Mongolian terrane in the south, and the CTUS suture zone between them (Fig. 1).

Fig. 1. (a) The general tectonic framework of the northwestern Central Asian Orogenic Belt (CAOB, modified after Buslov (2011), Glorie et al. (2011) and Cai et al. (2014)). The figure inset shows the location of the CAOB. (b) The simplified geological units in the Russian Altai, with emphasize on the complexes within the Charysh–Terekta–Ulagan–Sayan (CTUS) suture zone (modified after Smirnova et al. (2002), Theunissen et al. (2002), De Grave et al. (2009), Glorie et al. (2011), and Kuibida et al. (2014)). The voluminous granitoid intrusions are also shown. Erehta and Ulagan Complexes in (b) are also referred to Chulcha and Bashkaus Complexes, respectively. Abbreviations: SC, Siberian continent; TC, Tarim continent; NCC, North China continent; GA, Gorny Altai terrane; AM, Altai–Mongolian terrane; WS, West Sayan terrane; TM, Tuva–Mongolian terrane; B, Barguzin; O, Ordovician; D, Devonian.

Fig. 2. Geological map showing major geological units in the southeastern Russian Altai (modified after Buslov et al. (1993) and Glorie et al. (2011)). The Ulagan Complex is also referred to Bashkaus Complex.

It is widely accepted that the triangle-shaped Gorny Altai terrane represents part of a subduction–accretion system (i.e., the Kuznetsk–Altai intra-oceanic arc) close to the southwestern margin of the Siberian continent in the late Neoproterozoic to early Ordovician (present coordinate; Buslov et al., 2001, 2002; Safonova et al., 2004; Ota et al., 2007; Utsunomiya et al., 2009; Kruk et al., 2010; Glorie et al., 2011; Kruk et al., 2011; Safonova et al., 2011a; Buslov et al., 2013; Safonova and Santosh, 2014). The magmatic rocks of the island arc are mainly distributed in the eastern side of this terrane, including tholeiitic–boninitic volcanic rocks (possibly late Neoproterozoic to early Cambrian) and a few ca. 540–480 Ma granitoid plutons (Buslov et al., 2002; Kruk et al., 2007; Ota et al., 2007; Kruk et al., 2010; Glorie et al., 2011 and references therein). Closely associated are the accretionary complexes consisting of ophiolitic mélangé, oceanic crustal relicts with both MORB and OIB geochemical affinities, and olistostromes (Ota et al., 2002; Safonova et al., 2004; Ota et al., 2007; Safonova et al., 2011a; Safonova and Santosh, 2014). Cambrian to early Ordovician fore-arc sedimentary sequences crop out mainly in the western side of the Gorny Altai terrane, and they contain detrital zircons with ages predominantly of ca. 540–470 Ma and to a much lesser extent of ca. 640–550 Ma (Buslov et al., 2013; Chen et al., 2015b). The subduction–accretion assemblages were covered by Ordovician to early Devonian passive margin sedimentary sequences (Buslov et al., 1993, 2013; Safonova, 2014), which were intruded by extensive Devonian to early Carboniferous and minor Permian–Triassic granitoids (Rotarash et al., 1982; Glorie et al., 2011; Kruk et al., 2011; Cai et al., 2014; Kruk, 2015).

The Altai–Mongolian terrane, stretching from the southern Russian Altai, through northwestern China (i.e., the Chinese Altai) to western Mongolia (i.e., the Mongolian Altai), is bounded by the CTUS suture zone in the north (Fig. 1a), the North-Eastern fault in the west, and the Irtysh fault in the south. This terrane is dominated by thick terrigenous sedimentary sequences consisting of quartz-feldspar and polymictic sandstones, siliceous and phyllitic shales, and slates (Buslov et al., 2001; Safonova, 2014). In the southern Russian Altai, these sequences are thought to be middle Cambrian to early Ordovician, and they were covered by Ordovician to early Silurian grey marine sedimentary sequences and Devonian volcanoclastic rocks (Buslov et al., 2001;

Daukeev et al., 2008). In the southeastern Russian Altai, the terrigenous sequences (i.e., turbidite in Fig. 2) were controversially thought to be Cambrian (Daukeev et al., 2008) or late Precambrian (Safonova, 2014 and references therein). However, recent detrital zircon dating shows that they were actually deposited in the late Cambrian to early Ordovician (Gusev and Shokalsky, 2010; Chen et al., 2014 and references therein). Voluminous plutonic rocks intruded the terrigenous sedimentary sequences (e.g., Wang et al., 2006; Yuan et al., 2007; Daukeev et al., 2008; Sun et al., 2008, 2009; Wang et al., 2009; Cai et al., 2011a, 2011b; Kruk et al., 2011; Cai et al., 2012; Kruk, 2015) and the magmatism culminated in the Devonian (Fig. 2; Daukeev et al., 2008; Cai et al., 2011c). Minor late Paleozoic to Mesozoic plutons with A-type granite affinities are sparsely distributed (Tong et al., 2014; T. Wang et al., 2014).

The CTUS suture zone is V-shaped and extends from the Russian Altai, through the West Sayan terrane, and possibly to the Baikal region (i.e., the Ol'khon zone; Fig. 1; Buslov et al., 2013). It was regarded as a tectonic boundary separating two distinct subduction–accretion systems (e.g., Buslov, 2011). To the north, as represented by the Gorny Altai terrane, magmatic arcs formed in the southwestern periphery (present coordinate) of the Siberian continent without involvement of Precambrian micro-continents. In contrast, to the south, island arc formed around the so-called Kazakhstan–Baikal composite continent comprising assumed micro-continents (e.g., the Barguzin and Tuva–Mongolian terranes; Fig. 1a) with Gondwana affinity (Buslov, 2011 and references therein; Buslov et al., 2013). It was proposed that this composite continent was separated by an open ocean from the Siberian continent in the late Cambrian to early Ordovician (e.g., Buslov, 2011). This ocean was considered to be closed in a diachronous pattern, which initiated in the southeastern margin of the Siberian continent (i.e., the Baikal region) with formation of the Ol'khon zone in the Ordovician (Dobretsov and Buslov, 2007; Buslov, 2011; Buslov et al., 2013 and references therein), and completed by the collision between the Gorny Altai and Altai–Mongolian terranes in the middle Devonian to early Carboniferous (e.g., Buslov et al., 2001, 2004a, 2004b; Glorie et al., 2011). Fragments of early Paleozoic island arc rocks, oceanic crustal relicts, turbidites, and high-pressure metamorphic rocks are

Fig. 3. Field occurrence (a–c) and petrographic observation (d–h) of representative meta-sedimentary rocks from the Ulagan and Teletsk Complexes in Russian Altai. (a) Greenschist-facies meta-sandstone from the Ulagan Complex. (b) Biotite gneiss from the Teletsk Complex, showing partial migmatization. (c) Epidote–hornblende gneiss from the Teletsk Complex is intruded by a ca. 420 Ma granitic dyke (unpublished data). (d) Sample HKAM069 from the Ulagan Complex is a greenschist-facies meta-sandstone with mineral assemblage mainly of quartz (Qz), chlorite (Chl), Fe–Ti oxides and to a less extent of plagioclase (Pl). (e) Sample HKAM077 from the Ulagan Complex is a greenschist-facies meta-siltstone and consists mainly of quartz and chlorite. (f) Sample HKAM059 is a biotite gneiss from Teletsk Complex. It is mainly composed of quartz, plagioclase, biotite (Bi), cordierite (Cord), and Fe–Ti oxides, and to a much less extent of muscovite (Mus). A lot of tiny Fe–Ti oxides and muscovite grains are included in the cordierite prophyroblast. The recrystallization of quartz forms banded structure. (g) Sample HKAM166 from the Teletsk Complex is a biotite schist with minerals predominantly of quartz and biotite. (h) Sample HKAM160 from the Teletsk Complex is an epidote–hornblende gneiss, composing mainly of quartz, plagioclase, hornblende (Hb), epidote (Ep), and less of Fe–Ti oxides. Banded structure is well developed as a result of recrystallization of quartz. The symbol “(–)” in the up right angles of figures c–h represent plane-polarized light.

distributed along the CTUS suture zone (Volkova et al., 2005; Volkova and Sklyarov, 2007; Buslov, 2011; Glorie et al., 2011; Volkova et al., 2011; Safonova et al., 2011b). The region was reactivated by the late Paleozoic strike-slip faults, forming a mosaic pattern (Fig. 2). Some metamorphic units occur within this suture zone, such as the Uimon, Teletsk, and Ulagan Complexes (Fig. 1b; Glorie et al., 2011). They are characterized by greenschist- to amphibolite-facies metamorphism (e.g., Ota et al., 2007; De Grave et al., 2009; Safonova, 2014) and some of them were reported to have Proterozoic whole-rock Nd model ages (Kruk et al., 2011 and references therein).

3. Sampling and petrography

3.1. The Ulagan Complex

The Ulagan Complex is about 40 km long and 30 km wide (Fig. 2). The exposed rocks are predominantly meta-sandstones with greenschist-facies metamorphism (Fig. 3a, d, e), which were intruded by Mesozoic granitoid plutons (Fig. 2; Cai et al., 2014). Nine representative samples were analyzed for whole-rock geochemical compositions and one sample (HKAM071) was selected for zircon separation (Appendix Table S1). Except for sample HKAM077 that is a meta-siltstone (Fig. 3e), others are all fine- to medium-grained meta-sandstones (Fig. 3d). Relict sedimentary textures, such as the relatively poor rounding and sorting, are preserved (Fig. 3d, e). Some rock samples show micro-folding (e.g., sample HKAM077; Fig. 3e). All the samples have similar mineral assemblages, consisting mainly of quartz and chlorite, with minor Fe–Ti oxides and plagioclase.

3.2. The Teletsk Complex

The Teletsk Complex is >200 km long and ca. 30 km wide and stretches in a north-to-south orientation (Fig. 1b). This unit forms a domal structure and is mainly composed of greenschist- to amphibolite-facies schists and gneisses (Dehandschutter et al., 2002; Smirnova et al., 2002; Ota et al., 2007 and references therein; De Grave et al., 2009), which were intruded by late Silurian to early Devonian granitic plutons (ca. 422–406 Ma; Glorie et al., 2011; Kruk et al., 2011 and references therein). Samples were collected from the southern part of this tectonic unit (Fig. 2; Appendix Table S1). Thirteen representative samples were analyzed for whole-rock geochemical compositions and sample CK-43 was selected for zircon separation. Biotite gneiss/schist (Fig. 3b, f, g) is the major rock type and can be further divided into two sub-groups. Samples G10-2, G10-3, HKAM058, and HKAM059 constitute the first sub-group and they have mineral assemblages of quartz, plagioclase, biotite, cordierite, Fe–Ti oxides, and muscovite (Fig. 3f; Appendix Table S1). Abundant tiny Fe–Ti oxides and some muscovite crystals are included in the cordierite porphyroblasts (Fig. 3f). Other biotite gneiss/schist samples, belonging to the second sub-group, are featured by absence of cordierite porphyroblasts but occasionally contain a few garnet grains. Samples HKAM160 and HKAM162 are epidote–hornblende gneisses, which are intercalated with the biotite gneisses/schists (Fig. 3c). These two samples are dominated by quartz, plagioclase, hornblende, and epidote (Fig. 3h). The hornblendes are mostly euhedral in morphology (Fig. 3h) and some of them form aggregates with a radiation pattern. The two epidote–hornblende gneisses are characterized by well-developed schistosity or gneissosity, with ribbons of polycrystalline quartz formed by recrystallization during metamorphism (Fig. 3h). Samples HKAM100 and HKAM101 were collected from the southeastern margin of the Teletsk Complex (Fig. 2). They are greenschist-facies meta-sandstones with mineral assemblages mainly of chlorite and quartz.

4. Analytical methods

4.1. Zircon separation and cathodoluminescence (CL) imaging

About 2–3 kg of each sample were crushed, and zircons were handpicked under a binocular microscope from the 40–80 mesh non-magnetic heavy mineral fractions. About 200 zircon grains were selected from each sample and mounted in an epoxy resin. Then these zircons were polished down to about half of their thickness. The carbon coating and subsequent cathodoluminescence (CL) imaging were carried out in the Department of Earth Sciences, the University of Hong Kong.

4.2. In situ zircon U–Pb and Hf-isotope analysis

In situ zircon U–Pb dating was conducted in the Department of Earth Sciences, the University of Hong Kong, applying a Nu Instruments MC-ICP-MS with a Resonetics Resolution M-50-HR Excimer Laser Ablation System. Analyses were performed with a beam of 30 μm in diameter and 6 Hz repetition rate, generating a signal intensity of 4 mV at mass ^{238}U for the standard zircon 91500. Typical ablation time is 40 s, resulting in pits of ca. 30–40 μm in depth. Masses ^{238}U , ^{232}Th , ^{208}Pb , ^{207}Pb , ^{206}Pb , ^{204}Pb were measured simultaneously in a static-collection mode. Zircons 91500 (1065.4 ± 0.3 Ma, Wiedenbeck et al., 1995) and GJ-1 (609 Ma, Jackson et al., 2004) were used as external standards and each was analyzed twice with every 10 analyses of unknown samples. The detailed operation conditions and procedures followed Xia et al. (2011). Off-line signal selection, quantitative calibration, and time-drift correction were processed by software ICPMSDataCal (Liu et al., 2010). Concordia diagrams and probability density plots were made by Isoplot/Ex_ver3 (Ludwig, 2003). The U–Pb dating results are presented in Appendix Table S2.

In situ Hf-isotope compositions of zircons were analyzed on a Neptune Plus MC-ICP-MS equipped with a RESOLUTION M-50 laser-ablation system at Guangzhou Institute of Geochemistry, Chinese Academy of Sciences, Guangzhou, following the procedures described by Wu et al. (2006). The ablation beam is 45 μm in diameter and 8 Hz in repetition rate, which is equivalent to about 80 mJ per pulse. Helium was used as carrier gas with a small flow of nitrogen to improve the signal sensitivity. Each measurement includes 30 s gas blank collection and 30 s laser ablation. The interferences of ^{176}Yb and ^{176}Lu on ^{176}Hf were corrected by measuring ^{173}Yb and ^{175}Lu . Data were normalized to $^{179}\text{Hf}/^{177}\text{Hf}$ of 0.7325, using exponential correction for mass bias. We adopt Penglai zircon as external standard (Li et al., 2010), which was analyzed twice with every 10 analyses of unknown samples. The ^{176}Lu decay constant of $1.865 \times 10^{-11} \text{ year}^{-1}$ (Scherer et al., 2001), as well as chondritic $^{176}\text{Hf}/^{177}\text{Hf}$ ratio of 0.282772 ± 29 and $^{176}\text{Lu}/^{177}\text{Hf}$ ratio of 0.0332 ± 2 (Blichert-Toft and Albarède, 1997), were used to calculate the initial $^{176}\text{Hf}/^{177}\text{Hf}$ ratios and $\square_{\text{Hf}}(t)$ values. Furthermore, the Hf isotopic compositions of the depleted mantle (DM; $^{176}\text{Lu}/^{177}\text{Hf} = 0.0384$; $^{176}\text{Hf}/^{177}\text{Hf} = 0.283250$) and average continental crust (CC; $^{176}\text{Lu}/^{177}\text{Hf} = 0.015$; $f_{\text{Lu}/\text{Hf}} = -0.55$) (Griffin et al., 2000, 2002) were adopted in calculating two-stage Hf model ages (T_{DM2}). The zircon Hf-isotope data are presented in the Appendix Table S3.

4.3. Whole-rock major-, trace-element, and Nd isotopic analysis

Whole-rock major-element compositions were measured on a Philips PW2400 wavelength-dispersive X-ray fluorescence spectrometry on fused glass beads with samples to $\text{Li}_2\text{B}_4\text{O}_7$ flux ratios of 1:10 in the Department of Earth Sciences, the University of Hong Kong.

Whole-rock trace-element and Nd isotopic analyses were carried out at Guangzhou Institute of Geochemistry, Chinese Academy of Sciences. For trace-element analysis, about 50 mg powders for each sample were digested by a mixture of HF + HNO_3 mixture in high-pressure Teflon bombs. Pure Rh solution was applied as internal standard in monitoring signal drift. The prepared solutions were measured

on a Perkin-Elmer Sciex ELAN 6000 ICP-MS. Standard samples BHVO-2, G-2, and GSP-2 were utilized for calibrating unknown samples. The analytical precision for most trace elements is better than 3%. For Nd-isotope analysis, rare earth elements were firstly separated by cation exchange columns, and element Nd was further separated by HDEHP-coated Kef columns. Nd-isotope compositions were then measured on a Micromass Isoprobe multi-collector ICP-MS (Li et al., 2003). The measured $^{143}\text{Nd}/^{144}\text{Nd}$ ratios were normalized to $^{146}\text{Nd}/^{144}\text{Nd} = 0.7219$. The reported $^{143}\text{Nd}/^{144}\text{Nd}$ ratios of unknown samples were adjusted to the Shin Etsu JNdi-1 standard $^{143}\text{Nd}/^{144}\text{Nd} = 0.512110$.

The whole-rock major- and trace-element, and Nd-isotope compositions of the studied samples are presented in Appendix Tables S4, S5, and S6, respectively.

5. Results

5.1. Zircon U–Pb and Hf-isotope compositions

5.1.1. Sample HKAM071

This sample was collected from the Ulagan Complex. Sixty representative detrital zircons are featured by oscillatory zoning (Fig. 4a, b) and yield high Th/U ratios from 0.10 to 1.49 (Appendix Table S2), suggesting a magmatic origin. Most analyses show concordance (by comparison of $^{206}\text{Pb}/^{238}\text{U}$ and $^{206}\text{Pb}/^{207}\text{Pb}$ ages) higher than 90% and have $^{206}\text{Pb}/^{238}\text{U}$ ages mainly clustering at ca. 620–500 Ma and less at ca. 931–671 Ma with peaks at ca. 522 and 851 Ma (Figs. 4b, 5a), respectively. These zircons mostly have euhedral to subhedral prismatic morphology with length/width ratios of ca. 1.2–2.0. Other concordant zircons show sub-rounded to rounded shapes and have scattered $^{207}\text{Pb}/^{206}\text{Pb}$ ages varying from 2899 to 1428 Ma (Fig. 5a).

5.1.2. Sample CK-43

This sample was collected from the Teletsk Complex. Sixty-seven representative zircon grains were analyzed. They are featured by high Th/U ratios varying from 0.12 to 1.88 (Appendix Table S2) and well oscillatory zoning (Fig. 4c, d), indicating their magmatic origin. Thirty-seven zircon analyses yield concordance higher than 90%. Two sub-rounded to rounded zircon grains (CK43-53, -54) have $^{207}\text{Pb}/^{206}\text{Pb}$ ages of 2039–2021 Ma (Appendix Table S2; Fig. 4c). Others are euhedral to subhedral crystals with prismatic morphology and have length/width ratios mainly of 1.5–3.0. They have $^{206}\text{Pb}/^{238}\text{U}$ ages mainly clustering at ca. 937–766 Ma and 563–472 Ma, with most prominent peaks at ca. 786 and 516 Ma (Figs. 4d, 5b), respectively. Thirty representative zircons from these two dominant populations were selected for Hf-isotope analysis (Fig. 6; Appendix Table S3). They yield varied $\square_{\text{Hf}}(t)$ values ranging from –23.8 to 12.4. Correspondingly, the two-stage Hf model ages ($T_{\text{DM}2}$) vary from 3175 to 688 Ma.

5.2. Major- and trace- element compositions

Samples from the Ulagan and Teletsk Complexes have varied SiO_2 contents (52.4–66.4 wt.% and 55.9–67.1 wt.%, respectively; Appendix Table S4), which are relatively well correlated with TiO_2 , Al_2O_3 , Fe_2O_3 , and MgO contents, but poorly correlated with CaO (not shown), K_2O and Na_2O contents (Fig. 7a–f). This is possibly due to the mobility of calcium, potassium, and sodium during weathering of source rocks, diagenesis, and metamorphism.

All samples from the Ulagan and Teletsk Complexes show sub-parallel rare earth elements (REEs) patterns in the chondrite-normalized diagrams (Fig. 8a, c). The two complexes have narrow ranges of total REEs contents (ΣREEs) varying from 97.1 to 169 ppm (except for the sample HKAM068 with ΣREEs of 256 ppm) and from 109 to 169 ppm, respectively (Appendix Table S5), which are comparable with those of

Fig. 4. U–Pb concordia plots of detrital zircons from the investigated meta-sedimentary rocks.

Fig. 5. Histogram diagrams showing the age patterns of detrital zircons (concordance $\geq 90\%$) from samples HKAM071 and CK-43. Detrital zircon records of the early Paleozoic (meta-)sedimentary rocks from the Altai-Mongolian terrane (modified after Chen et al. (2015a)) and Gorny Altai terrane (data source: Chen et al., 2015b), as well as magmatic records from the western Mongolia (modified after Chen et al. (2015a)), are shown for comparison.

the upper continental crust (UCC, Rudnick and Gao, 2003) and Post Archean Australian Shale (PAAS, Taylor and McLennan, 1985). Both groups of samples are characterized by moderate to strong enrichment of light rare earth elements (LREEs) and relatively flat heavy rare earth elements (HREEs) patterns. Samples from the Ulagan Complex show $(La/Yb)_N$ ratios (subscript N refers to chondrite-normalized values) of 6.16–10.7 and $(Gd/Yb)_N$ ratios of 1.57–2.15, and those from the Teletsk Complex have such ratios of 4.86–8.87 and 1.32–2.08, respectively (Appendix Table S5). Samples from the Ulagan and Teletsk Complexes are all characterized by moderate to strong negative Eu anomalies and

have δEu values of 0.63–0.73 and 0.61–0.83, respectively. In contrast, there are no Ce anomalies, and δCe values are near 1.0.

In the UCC-normalized spider diagram (Fig. 8b, d), the two groups of samples have contents of large ion lithosphere elements (LILEs, e.g., Rb, Ba, K, Pb, and Sr) and high field strength elements (HFSEs, e.g., Nb, Ta, Zr, and Hf) mostly lower than, but compatible elements (e.g., Sm, Eu, Tb, Dy, Yb, Lu, and Y) contents overlapping with, those of the PAAS (Fig. 8b, d). Slightly distinct from the samples from the Teletsk Complex, those from the Ulagan Complex mostly show stronger depletion in Pb and Sr (Fig. 8b, d). Moreover, the Th contents of samples from the Ulagan Complex are slightly higher than those of samples from the Teletsk Complex (Appendix Table S5). In general, both groups of samples have largely overlapped Ni, Cr, Sc, V, and Co contents (Appendix Table S5). However, the average Sc, V, and Co abundances of samples from the Ulagan Complex are 16.5, 117, and 22.9 ppm, respectively, which are slightly lower than those of samples from the Teletsk Complex (average Sc = 20.9 ppm, V = 141 ppm, and Co = 26.9 ppm; Appendix Table S5). In contrast, the average Ni abundances of samples from the Ulagan Complex (average = 114 ppm) are slightly higher than those from the Teletsk Complex (average = 70.6 ppm).

5.3. Nd-isotope compositions

Five representative samples from the Ulagan Complex have $^{147}Sm/^{144}Nd$ ratios from 0.1190 to 0.1326, and $\epsilon_{Nd}(420\text{ Ma})$ values ranging from -5.2 to -6.3 (Fig. 9; Appendix Table S6). Their two-stage Nd model ages (T_{DM2}) are 1.67–1.58 Ga. The four selected samples from the Teletsk Complex yield comparable $^{147}Sm/^{144}Nd$ ratios of 0.1245–0.1348 but much higher $\epsilon_{Nd}(420\text{ Ma})$ values (-1.4 to 0.6) and lower T_{DM2} values (1.28–1.12 Ga).

6. Discussions

6.1. Protolith and timing of deposition

Samples from the Ulagan Complex all retain relict sedimentary textures, such as poor rounding/sorting and fine- to medium-grained sizes (Fig. 3d, e). These rocks are characterized by relatively low Al_2O_3 contents of 12.5–17.6 wt.% and Al_2O_3/SiO_2 ratios of 0.19–0.31 (Appendix Table S4), indicating that they were originally metamorphosed from sedimentary rocks with low contents of clay minerals. This may imply relatively weak chemical weathering in the source area (e.g., Nesbitt and Young, 1982; Fedo et al., 1995), which is further evidenced by the preservation of detrital plagioclase grains in our samples (Fig. 3d, e). Except for the two samples HKAM100 and HKAM101 showing mineral assemblages and textures indistinguishable from the above-mentioned low-grade rocks, other samples from the Teletsk Complex are mostly amphibolite-facies biotite schists/gneisses and have lost their primary mineral assemblages and textures. These higher-grade rocks are characterized by high abundance of mica and quartz with varied Al_2O_3 contents. The high- Al_2O_3 samples (G10-2, G10-3, HKAM058, and HKAM059; Appendix Table S4) generally contain aluminum-rich cordierite porphyroblasts (Fig. 3f). The elevated Al_2O_3 contents of 19.6–20.8 wt.% and Al_2O_3/SiO_2 ratios of 0.35–0.40 (Appendix Table S4) indicate that the protoliths of these rocks were possibly enriched in clay minerals, which in turn suggests relatively high degree of weathering in the source area. In contrast, other biotite schists/gneisses are featured by lower Al_2O_3 contents of 12.6–17.2 wt.% and Al_2O_3/SiO_2 ratios of 0.20–0.33 (Appendix Table S4), implying that clay minerals contributed less in the formation of their protoliths possibly as a result of lower degree of weathering. Samples HKAM160 and HKAM162 are epidote-hornblende gneisses, distinctive from other samples from the Teletsk Complex by higher CaO and lower Al_2O_3 contents (Appendix Table S4). This is consistent with the absence of aluminum-rich minerals (e.g., muscovite, cordierite, and garnet) but high proportion of calcium-rich epidotes (Fig. 3h). These two samples are all enriched in

Fig. 6. Hf-isotope compositions of the detrital zircons from the sample CK-43 (Teletsk Complex).

quartz, despite of relatively high proportion of hornblende and epidote, indicating that they are paragneisses possibly metamorphosed from calcareous sedimentary or volcanoclastic rocks.

The Ulagan and Teletsk Complexes were traditionally regarded as Meso- to Neoproterozoic continental slivers incorporated within the CTUS suture zone (Dehandschutter et al., 2002; Smirnova et al., 2002; Ota et al., 2007; Daukeev et al., 2008; De Grave et al., 2009), but some recent researchers consider them as parts of Paleozoic collisional units (e.g., Buslov et al., 2001; Safonova, 2014 and references therein). Due to the paucity of reliable geochronological data, the ages of these two complexes have not been well constrained. The meta-sedimentary rocks from the Ulagan and the Teletsk Complexes contain youngest detrital zircons with concordant $^{206}\text{Pb}/^{238}\text{U}$ ages of ca. 500 Ma and ca. 472 Ma, respectively (Appendix Table S2). This indicates that they were deposited not prior to late Cambrian and early Ordovician, respectively. Furthermore, the intrusion of ca. 422–406 Ma granitoid plutons (Glorie et al., 2011; Kruk et al., 2011) and ca. 420 Ma granitic dykes (Fig. 3c) indicates that the investigated meta-sedimentary sequences from the Teletsk Complex deposited before the early Devonian. Our results rule out the Precambrian origin for the Ulagan and Teletsk Complexes. Therefore, Precambrian micro-continental slivers may not be involved in the CTUS suture zone. Because the oldest rocks from the Gorny Altai terrane are the late Neoproterozoic to early Ordovician magmatic arc suite (e.g., Buslov et al., 2002; Ota et al., 2007; Chen et al., 2015b) and the previously regarded Precambrian basement rocks within the Altai–Mongolian terrane have been proven to be formed in the early Paleozoic (Long et al., 2007; Sun et al., 2008; Gusev and Shokalsky, 2010; Jiang et al., 2010; Long et al., 2010; Jiang et al., 2011, 2012; Chen et al., 2014 and references therein; Y. Wang et al., 2014), all the available data do not support the existence of Precambrian continental slivers in the whole Altai Orogen.

6.2. Evaluation of sedimentary sorting

Mineralogical differentiation by sedimentary sorting possibly occurs during transport of sediments (Garcia et al., 1994; Nesbitt et al., 1996; Jian et al., 2013 and references therein). In general, quartz (and feldspar) would be concentrated in coarse-grained sediments and thus lower the $\text{Al}_2\text{O}_3/\text{SiO}_2$ ratios. Instead, phyllosilicates (e.g., chlorite) and clay minerals (e.g., gibbsite and smectite) would be enriched in relatively fine-grained sediments and thus elevate their $\text{Al}_2\text{O}_3/\text{SiO}_2$ ratios (Jian et al., 2013). In addition, REEs contents of coarse-grained sediments would be generally lower than those of the fine-grained ones as a result of the dilution by high contents of quartz (Jian et al., 2013; Chen et al., 2014). The samples from the Ulagan Complex are almost all fine- to medium-grained meta-sandstones and have high proportion of chlorite (Fig. 3d, e), indicating that their protoliths underwent insignificant sedimentary sorting (McLennan et al., 1993). This can be further testified by their $\text{Al}_2\text{O}_3/\text{SiO}_2$ ratios (0.19–0.31) and total REEs contents

(mostly 97.1–169 ppm) comparable with those of the PAAS and UCC (Appendix Tables S4, S5; Fig. 8a) (Taylor and McLennan, 1985; Rudnick and Gao, 2003). The samples from the Teletsk Complex mostly underwent higher-grade metamorphism and lost the primary textures. Protoliths of samples G10-2, G10-3, HKAM058, and HKAM059 were possibly enriched in clay minerals as reflected by their high $\text{Al}_2\text{O}_3/\text{SiO}_2$ ratios and occurrence of cordierite porphyroblasts (see discussion in Section 6.1). However, other samples from the Teletsk Complex possess $\text{Al}_2\text{O}_3/\text{SiO}_2$ ratios (0.20–0.33) and total REEs contents (109–146 ppm) comparable with those from the Ulagan Complex and therefore may have similar protoliths. The varied protoliths of samples from the Teletsk Complex imply that some degree of sedimentary sorting possibly occurred. Accessory minerals, such as zircon and monazite, would be accumulated by sedimentary sorting due to their high density and resistance to decomposition, resulting in diagnostic geochemical characteristics (Cullers, 1988; McLennan et al., 1993). Except for sample HKAM068 with high contents of Zr, Hf, and REEs, other samples from the Ulagan and Teletsk Complexes show contents of these elements comparable with those of the UCC and PAAS (Appendix Table S5; Figs. 7g, 8), precluding substantial enrichment of zircon. The low $(\text{Gd}/\text{Yb})_N$ ratios (mostly < 2.0; Appendix Table S5; Fig. 7h) further imply that monazite, a mineral featured by very high $(\text{Gd}/\text{Yb})_N$ ratio (McLennan et al., 1993), was not accumulated.

6.3. Tectonic affinity of the Ulagan Complex

6.3.1. Source nature

Samples from the Ulagan Complex contain relatively high proportion of mafic minerals, such as chlorite (Fig. 3d–e), and accordingly possess high Fe_2O_3 and MgO contents (Appendix Table S4). They have $\text{SiO}_2/\text{Al}_2\text{O}_3$ ratios of 3.23–5.31 (average = 4.49; Appendix Table S4) comparable with those of fresh igneous rocks (3–5; Roser et al., 1996 and references therein). Meanwhile, these rocks yield ICV values (1.35–1.91; the Index of Compositional Variability, $(\text{Fe}_2\text{O}_3 + \text{K}_2\text{O} + \text{Na}_2\text{O} + \text{CaO} + \text{MgO} + \text{TiO}_2)/\text{Al}_2\text{O}_3$, molar ratio; Cox et al., 1995) higher than that of the PAAS (0.89; McLennan et al., 1993) but partially overlapping with that of the UCC (1.36; Rudnick and Gao, 2003). These features indicate that the protoliths of these meta-sedimentary rocks possibly represent chemically immature sediments that were directly eroded from igneous rocks nearby.

In general, there is a positive correlation between SiO_2 contents and $\text{Al}_2\text{O}_3/\text{TiO}_2$ ratios for common igneous rocks (Hayashi et al., 1997). Similarly, the total REEs contents increase with growing SiO_2 contents from mafic to felsic igneous rocks (Cullers et al., 1997, and references therein). The meta-sedimentary rocks from the Ulagan Complex show $\text{Al}_2\text{O}_3/\text{TiO}_2$ ratios (15.6–22.0; Appendix Table S4) overlapping with those of intermediate magmatic rocks (8–21; Hayashi et al., 1997), but lower than the average compositions of the felsic volcanic rocks (ca. 40–55; Condie, 1993). Likewise, their total REEs contents are mostly

Fig. 7. Binary plots showing the compositional variation of the investigated meta-sedimentary rocks. Data of the upper continental crust (UCC) and post-Archean Australian average shale (PAAS) are from [Taylor and McLennan \(1985\)](#) and [Rudnick and Gao \(2003\)](#), respectively.

97.1–169 ppm (Appendix Table S4), which are higher than those of typical basaltic rocks but close to those of andesitic to felsic ones ([Kelemen et al., 2003](#); [Kemp and Hawkesworth, 2003](#)). All these data, together with the moderate to strong negative Eu anomalies (Appendix Table S5), suggest that the protoliths of the investigated meta-

sedimentary rocks were derived mainly from intermediate to felsic magmatic suites. In contrast to transition elements, such as Sc, V, and Co, which would be generally enriched in mafic minerals (e.g., olivine and pyroxene), HFSEs (e.g., Th, Zr, Hf, and Ti) are preferentially incorporated in evolved intermediate to felsic magmas ([Feng and Kerrich, 1990](#);

Fig. 8. Chondrite-normalized rare earth elements (REEs) patterns and upper continental crust-normalized spider diagrams of the meta-sedimentary rocks from the Ulagan and Teletsk Complexes in Russian Altai. Data of the chondrite and upper continental crust (UCC) are from Sun and McDonough (1989) and Rudnick and Gao (2003), respectively. Symbols are same as in Fig. 7.

McLennan and Taylor, 1991; Cullers et al., 1997). As a result, the Th/Sc, Zr/Sc, and La/Sc ratios would increase while the Co/Th ratio would decrease significantly as magma evolves toward more felsic compositions (Fig. 10a, b; Condie, 1993). For instance, the average Co/Th ratio of the Paleozoic felsic volcanic rocks can be as low as 0.56, but this value can increase significantly to 14.6 (about twenty-six times larger) for the Paleozoic basaltic rocks (Condie, 1993). Therefore, ratios between transitional elements (e.g., Co and Sc) and HFSEs (e.g., Th and Ti) are possibly more sensitive in discriminating the source rocks, due to their pronounced variation among various types of magmas (Fig. 10a, b).

The meta-sedimentary rocks from the Ulagan Complex show these ratios almost exclusively between the average Paleozoic andesites and felsic volcanic rocks (Fig. 10a, b), implying mixtures of these two types of rocks as dominant sediment sources. The relatively high Cr and Ni contents of these meta-sedimentary rocks (Appendix Table S5) further indicate that some mafic igneous rocks were possibly involved in their protoliths (e.g., Gao et al., 1999; Singh and Rajamani, 2001). Importantly, the meta-sedimentary rocks show Ti/Zr, La/Sc, La/Th, Th/Sc, Th/Zr, and Sc/Zr ratios quite similar to those sediments from typical continental arc settings (Fig. 10c, d; Bhatia and Crook, 1986), therefore favoring such kind of depositional environment. This is in line with the aforementioned source nature, as well as the textural and geochemical data showing that their protoliths underwent relatively weak weathering and poor sorting (see discussion in Sections 6.1 and 6.2).

Fig. 9. Age versus epsilon Nd(420 Ma) for the meta-sedimentary rocks from the Ulagan and Teletsk Complexes. Data of the early Paleozoic (meta-)sedimentary rocks from the Gorny Altai terrane and northern Altai-Mongolian terrane are from Kruk et al. (2010), while those from the Chinese Altai are from Chen and Jahn (2002) and Long et al. (2012). Symbols are same as in Fig. 7.

6.3.2. Tectonic affinity of the Ulagan Complex

Age spectra of detrital zircons can provide additional clues on the provenance of sediments (e.g., Cawood et al., 2012), which in turn place constraints on the tectonic affinity of the sedimentary basins. Detrital zircons from sample HKAM071 of the Ulagan Complex show a prominent population of ca. 620–500 Ma, followed by a subordinate one of ca. 931–671 Ma (Fig. 5a). These zircons are mostly featured by euhedral to subhedral morphology, indicating that they were possibly sourced from a vicinity area, where extensive magmatism took place in the late Neoproterozoic to early Paleozoic. The remaining minor ca. 2899–1428 Ma zircon grains are dominated by rounded to sub-rounded shapes, implying that some detritus from Archean to Mesoproterozoic rocks in relatively far distance were also involved.

Close to the suture zone in the west is the Gorny Altai terrane, which is generally accepted as part of the Kuznetsk–Altai intra-oceanic subduction-accretion system (Buslov et al., 2001, 2002; Ota et al., 2002; Buslov et al., 2004a, 2004b; Ota et al., 2007; Buslov, 2011; Buslov et al., 2013). Detrital zircon studies showed that the magmatism of this island arc possibly lasted from ca. 640 to 470 Ma (Fig. 6e), with

Fig. 10. Geochemical discrimination diagrams showing the source nature and depositional setting of the meta-sedimentary rocks from the Ulagan and Teletsk Complexes in Russian Altai. (a) Zr/Sc–Th/Sc diagrams (after McLennan et al., 1993); (b) La/Sc–Co/Th diagram (after Gu et al., 2002). (c) La/Sc–Ti/Zr and (d) La–Th–Sc, Th–Sc–Zr/10 diagrams (after Bhatia and Crook (1986)). The average compositions of the Paleozoic basalt, andesite, granite, and felsic volcanic rocks are from Condie (1993). Data of the early Paleozoic meta-sedimentary rocks from the northern Altai–Mongolian terrane are from Kruk et al. (2010) and Chen et al. (2014); those of early Paleozoic (meta-)sedimentary rocks from the Gorny Altai terrane are from unpublished data. Abbreviations: OIA, oceanic island arc; ACM, active continental margin; CIA, continental island arc; PM, Passive margin. The red lines with dots show the mixing trends. Symbols are same as in Figs. 7 and 9.

most prominent activities at ca. 530–470 Ma (e.g., Buslov et al., 2013; Chen et al., 2015b). Moreover, these detrital zircons are almost exclusively featured by positive $\varepsilon_{\text{Hf}}(t)$ values, indicating juvenile source nature (Chen et al., 2015b). The island arc volcano-sedimentary rocks and fore-arc sediments possess depleted Nd isotopic compositions ($\varepsilon_{\text{Nd}}(420 \text{ Ma}) = 3.9\text{--}5.1$, $T_{\text{DM2}} = 0.75\text{--}0.85 \text{ Ga}$; recalculated from the data of Kruk et al. (2010)) (Figs. 9, 10). These geochemical features are remarkably different from those of the meta-sedimentary rocks from the Ulagan Complex ($\varepsilon_{\text{Nd}}(420 \text{ Ma}) = -6.3 \text{ to } -5.2$; $T_{\text{DM2}} = 1.58\text{--}1.67 \text{ Ga}$; Figs. 9, 10; Appendix Tables S5, S6). The above data suggest that sediments of the Ulagan Complex were unlikely to be derived from the Gorny Altai terrane.

To the south of the suture zone is the Altai–Mongolian terrane (Fig. 1a). Recent studies suggested that this terrane possibly represents an immense subduction–accretion complex built upon the active margin of the western Mongolia in the early Paleozoic (Long et al., 2007, 2008; Sun et al., 2008; Jiang et al., 2010; Long et al., 2010; Jiang et al., 2011; Long et al., 2012; Chen et al., 2014; Y. Wang et al., 2014; Chen et al., 2015a). The present western Mongolia consists of the following tectonic units westward: Tuva–Mongolian terrane, Lake terrane, Hovd or Khovd terrane, and Mongolian Altai (Badarch et al., 2002). The Tuva–Mongolian terrane has been proven to be a micro-continent, where the Precambrian basement includes ca. 2.83 Ga tonalite–trondhjemite gneiss and ca. 2.36–1.82 Ga granitic rocks (Kozakov, 1993; Kotov et al., 1995; Kozakov et al., 2001; Kröner et al., 2001 and references therein; Badarch et al., 2002; Demoux et al., 2009a). In the Neoproterozoic to early Paleozoic, the western margin of the Tuva–Mongolian terrane underwent multiple subduction–accretion processes. As a consequence, magmatic and (volcano-)sedimentary rocks were widely distributed in the Lake terrane, Hovd terrane, and Mongolian Altai (Fig. 1a; Badarch et al., 2002; Chen et al., 2015a). As

shown in Fig. 5, the magmatic records in western Mongolia (see summary in Chen et al., 2015a) broadly cover the detrital zircon populations from sample HKAM071 of the Ulagan Complex. Therefore, western Mongolia was likely sedimentary source for the investigated meta-sedimentary sequences. Of critical importance is that the meta-sedimentary sequences from the Ulagan Complex show remarkable similarities in source rock types, provenance, and depositional setting to the counterparts from the northern Altai–Mongolian terrane (Figs. 5, 9, 10; Kruk et al., 2011; Chen et al., 2014, 2015a). This suggests that these two tectonic units possibly belong to the same early Paleozoic subduction–accretion system situated upon the western Mongolia. We consider that the Ulagan Complex probably represents a detached fragment from the northern margin of the Altai–Mongolian terrane.

6.4. Origin of the Teletsk Complex and its tectonic implication

6.4.1. Source nature

The high- Al_2O_3 samples (G10-2, G10-3, HKAM058, HKAM059) are characterized by low $\text{SiO}_2/\text{Al}_2\text{O}_3$ ratios of 2.52–2.89 and ICV values of 1.18–1.39 (Appendix Table S4), suggesting that these rocks were possibly metamorphosed from pelitic (i.e., mature) sediments. Other samples from the Teletsk Complex yield higher $\text{SiO}_2/\text{Al}_2\text{O}_3$ ratios (3.04–5.13) and ICV values (1.48–2.04), implying that their protoliths possibly represent immature deposits without significant weathering and sorting. The moderate $\text{Al}_2\text{O}_3/\text{TiO}_2$ ratios of 15.1–21.7, total REEs contents of 109–169 ppm and moderate to strong negative Eu anomalies (Appendix Tables S4, S5) further indicate that intermediate-felsic magmatic rocks probably served as dominant sources for the protoliths, which is therefore similar to the case of the Ulagan Complex. Detrital zircons from sample CK-43 of the Teletsk Complex consist of major populations of ca. 563–472 Ma and ca. 937–766 Ma (Fig. 5b). This pattern is

Fig. 11. The Th/Sc versus epsilon Nd(420 Ma) diagram showing that the meta-sedimentary rocks from the Teletsk Complex can be formed by ca. 30–40% early Paleozoic sediments from the Gorny Altai terrane and ca. 60–70% counterparts from the Ulagan Complex (i.e., the northern margin of the Altai–Mongolian terrane). The average Th/Sc ratios of the early Paleozoic sediments from the Gorny Altai terrane are calculated from unpublished data, while their average Nd isotopic composition is calculated from data reported by Kruk et al. (2010). Symbols are same as in Fig. 7.

quite similar to that of detrital zircons from the Ulagan Complex. All these data suggest that the same source provided substantial detritus to both the Ulagan and Teletsk Complexes.

However, the samples from the Teletsk Complex show higher Co/Th (3.33–5.86), as well as lower Th/Sc (0.26–0.37) and Zr/Sc ratios (5.98–10.46) (Appendix Table S5; Fig. 10), indicating that a larger proportion of sediments from mafic igneous rocks was involved during the deposition. The more depleted ϵ_{Nd} (420 Ma) values (–1.4 to 0.6) and younger two-stage model ages (1.28–1.11 Ga; Appendix Table S6; Figs. 9, 11) further imply that these additional mafic sediments were dominated by juvenile isotopic compositions. Importantly, the sediments from the Gorny Altai terrane are characterized by high Co/Th and low Th/Sc and Zr/Sc ratios as a result of their dominant basaltic to andesitic source rocks (Fig. 10), and they have high ϵ_{Nd} (420 Ma) values (3.9–5.1) and young T_{DM2} ages (0.75–0.85 Ga; Fig. 9; recalculated from data of Kruk et al. (2010)). All these suggest that magmatic rocks from the Gorny Altai terrane possibly provided additional juvenile and mafic detritus to the meta-sedimentary rocks of the Teletsk Complex. In the diagrams of Th/Sc versus Zr/Sc, Co/Th versus La/Sc and Ti/Zr versus La/Sc, the meta-sediments from the Teletsk Complex plot well along the mixing arrays between the sediments from the Ulagan Complex and those from the Gorny Altai terrane (Fig. 10), therefore favoring a mixed origin. Further calculation suggests that the protoliths of the meta-sedimentary rocks from the Teletsk Complex were possibly formed by mixing of ca. 30–40% sediments from the Gorny Altai terrane and ca. 60–70% from the same source as for the meta-sedimentary rocks of the Ulagan Complex, i.e. part of the Altai–Mongolian terrane (Fig. 11). We note that the dominant Neoproterozoic to early Paleozoic detrital zircons are featured by largely varied $\chi_{\text{Hf}}(t)$ values of –23.8 to 12.4 (Fig. 6). This indicates that significant crustal growth and reworking occurred during the formation of the Altai Orogen.

6.4.2. Tectonic implication

The Gorny Altai terrane represents an intra-oceanic arc system in the Cambrian to early Ordovician (e.g., Buslov et al., 1993, 2002; Ota et al., 2002, 2007; Utsunomiya et al., 2009; Glorie et al., 2011; Safonova et al., 2011a), whereas the Altai–Mongolian terrane formed a continental arc-prism system in western Mongolia (e.g., Long et al., 2007, 2008, 2010; Jiang et al., 2011; Long et al., 2012; Chen et al., 2014, 2015a). The timing of amalgamation between these two subduction-accretion

systems has not been well constrained. Previous studies proposed that the Gorny Altai terrane obliquely collided with the Altai–Mongolian terrane in the middle Devonian to early Carboniferous along the CTUS suture zone (Fig. 1), coupled with strong strike-slip faulting (Buslov et al., 1993, 2004a, 2004b, 2013; Buslov, 2011; Glorie et al., 2011; Kruk et al., 2011; Safonova, 2014 and references therein). This interpretation was mainly based on the amphibole/mica K–Ar and $^{40}\text{Ar}/^{39}\text{Ar}$ ages (394–309 Ma) of metamorphic complexes within the CTUS suture zone (Buslov et al., 2001, 2003, 2004a, 2004b, 2013; Buslov, 2011). However, these geochronological data possibly record the timing of regional strike-slip faulting in the Russian Altai, and the collision may have initiated earlier, i.e. prior to the middle Devonian.

Our new data show that the protoliths of the meta-sedimentary rocks from the Teletsk Complex were deposited prior to ca. 420 Ma and the sediments possibly came from the Gorny Altai terrane and the sources for the early Paleozoic meta-sedimentary rocks from the Altai–Mongolian terrane. This implies that the two terranes possibly amalgamated before ca. 420 Ma (Fig. 12), different from the above-mentioned consideration of middle Devonian to early Carboniferous collision but favoring the proposed amalgamation before early Devonian in the paleogeographic reconstruction based on paleomagnetic data (Filippova et al., 2001; Windley et al., 2007). This timing constraint is also supported by our recent data of detrital zircons from the early Devonian sedimentary sequence of the Gorny Altai terrane, which show the input of Archean to Neoproterozoic detrital zircons from the Altai–Mongolian terrane (Chen et al., 2015b). Our results further

Prior to ca. 420 Ma

Fig. 12. A simplified tectonic model showing the meta-sedimentary rocks from the Teletsk Complex possibly consisted of sediments from the Gorny Altai terrane and those from the source of the Ulagan Complex (i.e., the northern margin of the Altai–Mongolian terrane) after the amalgamation of these two terranes, which occurred prior to ca. 420 Ma.

suggest that the widespread Devonian to early Carboniferous magmatism in both the Gorny Altai and Altai–Mongolian terranes (Buslov et al., 1993; Daukeev et al., 2008; Glorie et al., 2011; Kruk et al., 2011; Cai et al., 2011a, 2011b, 2012, 2014; Safonova, 2014 and references therein) was possibly generated in a coherent tectonic setting (Filippova et al., 2001; Windley et al., 2007).

7. Conclusions

The meta-sedimentary sequences in the CTUS suture zone deposited in a time period between 500 and 420 Ma, constrained by the youngest detrital zircons and the intruded granitoids. Available data do not support the existence of Precambrian micro-continental slivers in the suture zone and even in the whole Altai Orogen.

The detritus of meta-sedimentary sequences in the CTUS suture zone came from a provenance dominated by late Neoproterozoic to early Paleozoic igneous rocks. The protoliths of the meta-sedimentary sequences in the Ulagan Complex are mainly made up of immature sediments from nearby intermediate-felsic igneous sources. This complex possibly represents part of a subduction–accretion complex built upon an active continental margin of the western Mongolia in the early Paleozoic, and it was possibly fragmented from the northern margin of the Altai–Mongolian terrane.

The meta-sedimentary rocks in the Teletsk Complex show similar detrital zircon populations with those from the Ulagan Complex but have younger whole-rock two-stage Nd model ages. The protoliths of these meta-sedimentary rocks came from the same source as that for the counterparts from the Ulagan Complex, with addition of detritus from the Gorny Altai terrane. This implies that the Gorny Altai and Altai–Mongolian terranes were possibly amalgamated before the early Devonian, not middle Devonian to early Carboniferous as previously thought. Therefore, the two critical subduction–accretion systems of the CAO, one was developed in the southwestern periphery of the Siberian continent and the other was developed around continental blocks with Gondwana affinity, came together and the Paleo-Asian Ocean was significantly diminished before the early Devonian. This further implies that the widespread Devonian to early Carboniferous magmatism in the Altai Orogen was generated in the same tectonic environment. The largely varied zircon $\varepsilon_{\text{Hf}}(t)$ values (–23.8 to 12.4) for the Neoproterozoic to early Paleozoic detrital zircons suggest significant crustal growth and reworking during subduction–accretion processes.

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