Paleozoic magmatism and metamorphism in the Central Tianshan block revealed by U–Pb and Lu–Hf isotope studies of detrital zircons from the South Tianshan belt, NW China
Paleozoic magmatism and metamorphism in the Central Tianshan block revealed by U–Pb and Lu–Hf isotope studies of detrital zircons from the South Tianshan belt, NW China

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Abstract
As a major Precambrian microcontinent in the southernmost Central Asian Orogenic Belt (CAOB), the Central Tianshan block (CTS) in the Chinese Tianshan is essential for understanding the final assembly of the southern CAOB. It experienced multistage Paleozoic magmatism and metamorphism, but the detailed processes are still controversial and far from being completely understood. This paper reports coupled U–Pb and Lu–Hf isotopic data of detrital zircons from late Paleozoic (meta-)sedimentary strata in the South Tianshan belt, which can provide new insight into deciphering the Paleozoic evolution of the eastern segment of the CTS block. Characterized by typical oscillatory zoning and high Th/U ratios (>0.2), detrital zircons in the Permian sedimentary samples yield dominant age populations at ca. 505–490 Ma, 475–440 Ma, 430–400 Ma and 340–250 Ma, pinpointing the development of four episodes of magmatism in the eastern CTS block. Particularly, Ordovician–Silurian (475–440 Ma) zircons, possessing low negative εHf(t) values, predominate in sedimentary strata in and surrounding the CTS block, indicating that the 475–440 Ma magmatic rocks probably constitute the main body of the CTS block. The origin of this (early Paleozoic) episode of magmatism was most likely related to the southward subduction of the Junggar Ocean beneath the CTS block. Carboniferous–Triassic (340–250 Ma) zircons have dominantly positive εHf(t) values, probably derived from the post-collisional juvenile rocks in the CTS block. Combined with previous studies, our data suggest that the single source terrane for the sampled strata was the CTS block, which had been a topographic high providing substantial detritus to the surrounding areas at least since the Early Permian. In the metasedimentary sample, detrital zircons mostly show partially/fully recrystallized internal textures and low Th/U ratios (<0.2), probably sourced from the amphibolite- to granulite-facies metamorphosed rocks in the eastern CTS block. The youngest zircons suggest that the sampled metasedimentary strata were Carboniferous (341–305 Ma) in age, rather than Neoproterozoic (or Early Sinian in Chinese literatures) as previously interpreted. Based on U–Pb–Hf isotopes and Ti-in-zircon thermometer of metamorphic zircons in this study, as well as previous investigations, we suggest that the eastern CTS block has experienced (a) a 400–370 Ma collisional event, related to the closure of the eastern segment of the South Tianshan Ocean, and (b) a 360–340 Ma extensional event, as a result of post-collisional mantle upwelling. Therefore, the final assembly of the Eastern Tianshan took place during Late Carboniferous time.

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1. Introduction
The Central Asian Orogenic Belt (CAOB) is sandwiched between the European and Siberian blocks to the north (present-day coordinates) and the Tarim and North China blocks to the south. It has a long-lived evolution ranging from Neoproterozoic to Paleozoic times, as evidenced by the multiple accretion of arcs, accretionary complexes, continents and microcontinents within the Paleo-Asian Ocean (Allen et al., 1993; Charvet et al., 2007, 2011; Chen et al., 2012; Eizenhöfer et al., 2014, 2015a, 2015b; Gao et al., 1998; Han et al., 2015; Jahn et al., 2006; Windley et al., 1990, 2007; Xiao et al., 2012, 2013; Zhu et al., 2015). The Central Tianshan block (CTS; Fig. 1), one of the southernmost Precambrian microcontinents in the CAOB, has provided insight into the tectonic architecture and accretion–collision processes of the southern CAOB (Hu, 1982; Hu et al., 1998, 2007; Ma et al., 2014; Shi et al., 2014; Xiao et al., 2004). In the last decade, extensive studies were carried out in...
Fig. 1. Simplified geological map of the Eastern Tianshan showing sample locations, modified after BGMRXUAR (2007). The age data of granitoids in the northern Beishan (black triangles) are cited from Li et al. (2011b), Mao et al. (2010b), Zhao et al. (2007) and references therein. NTS—North Tianshan belt, CTS—Central Tianshan block, STS—South Tianshan belt.
its western segment, especially focusing on its Precambrian origin and Phanerozoic magmatism, metamorphism and mineral deposits (BGMRXUAR, 1993; Charvet et al., 2007, 2011; Gao et al., 1998; Ma et al., 2012a,b, 2014). However, due to limited investigations, the magmatic and metamorphic histories of the eastern segment (Xingxingxia area) still remain unclear, leading to ambiguous interpretations with respect to the subduction and closure of the relevant (South Tianshan and Junggar) oceans. For example, Windley et al. (1990) suggested that the Paleozoic intrusions in the CTS block were formed predominantly by the northward subduction of the South Tianshan Ocean beneath the CTS block, whereas Charvet et al. (2011) and Wang et al. (2011a) argued for their formation by the southward subduction of the Junggar Ocean. Moreover, He et al. (2012, 2014) found 380–320 Ma (zircon–rims ages) high-grade paragneisses and orthogneisses in the eastern CTS block, most likely marking the closure of the eastern segment of the South Tianshan Ocean. However, Ma et al. (2014) proposed that the ocean remained open in the Early Carboniferous based on the presence of ca. 340 Ma volcanic arc granitoids in the CTS block. Generally, these previous studies, based on single or several certain-aged magmatic/metamorphic rocks, are not sufficient to decipher the Paleozoic magmatic and metamorphic events in the CTS block, which are vital to the understanding of the accretionary and collisional processes and especially final assembly of the southern CAOB.

Detrital zircon studies of (meta-)sedimentary rocks, combined with in-situ Hf isotope analysis, are an ideal tool to provide provenance information of (meta-)sedimentary rocks, insight into regional crustal growth and overview over magmatism/metamorphism by receiving detrital zircons derived from different–aged magmatic/metamorphic rocks from a large area (Andersen, 2005; Cawood et al., 1999, 2012; Wang et al., 2013). In addition, Ti-in-zircon thermometry can place unique constraints on zircon crystallization temperatures, shedding light on origin of the studied zircons (Trail et al., 2007; Watson et al., 2006). In this study we conducted U–Pb–Hf isotopic analysis on detrital zircons, in combination with Ti-in-zircon crystallization temperatures of metamorphic grains, in (meta-)sedimentary strata from the South Tianshan belt, which can provide rigorous new constraints on the Paleozoic evolution of the eastern CTS block and the closure of the eastern South Tianshan Ocean.

2. Geological background

2.1. Chinese Tianshan

The ca. 400-km-wide Chinese Tianshan orogenic belt is located between the Tarim block to the south and the Junggar blocks to the north, occupying a key position in the southern CAOB (Allen et al., 1993; Gao et al., 1995, 1998, 2009, 2011; Hu et al., 2000; Ma et al., 1993, 1997; Xiao et al., 2004, 2009, 2012, 2013). Tectonically, the Chinese Tianshan is subdivided into the North Tianshan belt (NTS), Yili and Central Tianshan blocks and South Tianshan belt (STS), separated by the Weiyi–Shaquanzi fault (Fault 1 in Fig. 1) in the north and the Kumishi–Xingxingxia fault (Faults 2 and 3 in Fig. 1) in the south, respectively (Shu et al., 1999, 2004; Windley et al., 1990; Xiao et al., 2004). The Kumishi–Xingxingxia dextral strike–slip fault was active during 298–280 Ma (muscovite and biotite 40Ar/39Ar plateau ages) in the Mānqiao area (Cai et al., 2012). The Hongliuhe–Niujianzi Fault (Fault 4 in Fig. 2) can be considered as the boundary between the CTS and Beishan blocks, according to the spatial distribution of the reported ophiolites.

Across the entire Chinese Tianshan orogenic belt at least three sub-oceans of the Paleo–Asian Ocean were identified, including from south to north (a) the South Tianshan Ocean between the Tarim and CTS blocks, (b) the Paleo–Tianshan Ocean (Central Tianshan Ocean) between the Yili and CTS blocks and (c) the Junggar Ocean between the Yili–CTS and Junggar blocks, predominantly based on distributions of ophiolitic mélanges, high-pressure metamorphic rocks or arc–related granitoids (Charvet et al., 2011; Gao et al., 2011; Ma et al., 1993, 1997; Wang et al., 2011a; Xiao et al., 2004). Geographically, the Chinese Tianshan can be further subdivided into the western and eastern segments roughly along a transect between the cities of Urumqi and Korla, with the Yili block entirely located in the Western Tianshan.

This study is mainly focused on the tectonic evolution of the Eastern Tianshan, a thorough review of which has been provided by Xiao et al. (2004).

2.2. North Tianshan (NTS) belt

The NTS belt, where Paleozoic magmatic and imbricated Carboniferous to Jurassic sedimentary rocks are well-developed, is composed mainly of a series of island arcs (e.g., Harlik, Bogda, Dananhu and Yamsansu), the formation of which was related to the southward subduction of the Junggar Ocean beneath the Eastern Tianshan (BGMRXUAR, 1993; Ma et al., 1993, 1997; Xiao et al., 2004). Paleozoic magmatism and ophiolitic mélanges in the NTS belt, such as ca. 545 Ma rift-related mafic–ultramafic rocks (Xu et al., 2006a) and ca. 325 Ma plagiogranites (Xu et al., 2006b), pinpoint a Cambrian to Carboniferous evolution of the Junggar Ocean. The final closure of the Junggar Ocean was most likely at some time before ca. 295 Ma (Chen et al., 2011) or at ca. 300 Ma (our unpublished data), although Xiao et al. (2009) argued for a Permian to Triassic termination.

2.3. Central Tianshan (CTS) block

The CTS block is composed predominantly of Precambrian basement and Paleozoic rocks (BGMRXUAR, 1993; Hu et al., 2000; Shu et al., 2004; Xiao, 1992; Xiao et al., 2004). The Precambrian basement, much of which has undergone high-greenschist to amphibolite facies metamorphism (Hu, 1982; Hu et al., 1998; Liu et al., 2004; Xiao et al., 2004), is covered by or in fault contact with Ordovician–Silurian strata, which are in turn unconformably overlain by Carboniferous–Permian volcano-clastic rocks (BGMRXUAR, 1993; Xia et al., 2004). Exposed in the Xingxingxia, Weiyi, Alatage and Balunai areas, the basement rocks were previously assumed to be Paleoproterozoic to Neoproterozoic in age based on several isotopic isochron or zircon U–Pb intercept ages, such as whole-rock Rb–Sr isochron ages of 1829 ± 143 Ma, 913.8 ± 4.5 Ma, 724.0 ± 8.1 Ma and 696.6 ± 5.7 Ma for granitic gneisses (Gu et al., 1990; Hu et al., 1997) and a Rb–Sr isochron age of 927 Ma for a gneissic granite (Zhang et al., 2005).

Early Paleozoic to early Mesozoic plutons are found throughout the CTS block (Dong et al., 2011; Gu et al., 2006; Hu et al., 2007; Ma et al., 2014; Shi et al., 2007, 2014; Wang et al., 2011b; Wu et al., 2006a; Yang et al., 2006, 2012; Zhang et al., 2007). The formation of these plutons was attributed to the southward subduction of the Junggar Ocean (Hu et al., 2007; Ma et al., 1997, 2013b; Zhou et al., 2001b; Zhu and Song, 2006), the northward subduction of the South Tianshan Ocean (Allen et al., 1993; Dong et al., 2011; Gao et al., 1998; Gu et al., 2006; Windley et al., 1990; Xiao et al., 2004; Zhou et al., 2001a), or the regional (post-)collisional events (Dong et al., 2011; Ma et al., 2013a; Shi et al., 2014).

2.4. South Tianshan (STS) belt

The STS belt, characterized by well-preserved ophiolitic mélanges in the Heiyingshan, Kulehu, Yushugou, Kumishi, Wuwamen, Hongliuhe, Niujianzi and Tonghuashan areas, was formed by the development of the South Tianshan Ocean between the CTS and Tarim blocks (BGMRXUAR, 1993; Gao et al., 1998; Wang et al., 2011a; Xiao et al., 2004). Based on synthetic geological and geochemical studies, Dong et al. (2005) and Wang et al. (2011a) concluded that the Wuwamen and Heiyingshan ophiolites formed in a back-arc setting. However, the exact opening and closure times and subduction polarity of this ocean are still controversial. Up to now, most well-constrained ophiolites in the STS belt are Silurian to Devonian in age. For example, Yang et al.

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(2011) found 439.3 ± 1.8 Ma plagiogranites and 435.1 ± 2.8 Ma anorthosites in the Kumishi region; Tian et al. (2014) reported 444.3 ± 1.9 Ma plagiogranites and 435.0 ± 1.9 Ma gabbros in the Niujuanzi ophiolitic mélangé; Long et al. (2006) discovered 425 ± 8 Ma pillowed basalts in the Kulehu ophiolitic mélange; and Huang et al. (2011) documented 406.5 ± 5.0 Ma plagiogranites in the Tonghuashan ophiolites. One gabbro in the Hongliuhe ophiolites was assumed to be formed at 516.2 ± 7.1 Ma (Zhang and Guo, 2008). However, the reported zircons show a large variation in age (530–457 Ma), thus they are more likely to be inherited zircons, given that a nearby gabbro was dated by Yu et al. (2006) to be 425.5 ± 2.3 Ma in age. Collectively, most previous dating results of the ophiolitic rocks suggest that the South Tianshan Ocean was probably opened during Early Silurian time and lasted at least to the Early Devonian.

A northward subduction of the South Tianshan Ocean was suggested based on the presence of arc-related granitoids in the CTS block (Allen et al., 1993; Dong et al., 2011; Gao et al., 1998; Gu et al., 2006; Windley et al., 1990, 2004; Zhou et al., 2001a). In contrast, a southward subduction beneath the Tarim block was also proposed on the basis of detailed kinematic investigations in the NTS and STS belts (Charvet et al., 2007, 2011; Gao et al., 2011; Wang et al., 2011a, 2011b; Windley et al., 2007) and the discovery of ca. 420 Ma continental arc granitoids on the northern margin of the Tarim block (Ge et al., 2012). Therefore, a double-sided subduction model for the South Tianshan Ocean has been brought forward as well (Ge et al., 2012; Ma et al., 2014).

The retrograde metamorphic ages of eclogites in the high-pressure/low-temperature metamorphic belt in the Western Tianshan are commonly referred to mark the Late Carboniferous closure of the western South Tianshan Ocean (Gao and Klemd, 2003; Klemd et al., 2011). However, the closure time of the eastern South Tianshan Ocean is still poorly constrained, as evidenced by highly variable reported metamorphic ages ranging from ca. 405 Ma to ca. 320 Ma (Cai et al., 1996; He et al., 2012, 2014; Li et al., 2004; Liu and Qian, 2003; Wang et al., 2003; Zhang and Wu, 1985; Zhou et al., 2004).

2.5. Beishan block

Along the northern margin of the Beishan block, a large volume of granitoid intrusions aged between 440 Ma and 390 Ma have been documented. North of the Liuyuan area, Zhao et al. (2007) reported 436 ± 9 Ma granites, 423 ± 8 Ma granodiorites and 397 ± 7 Ma monzogranites, suggesting a post-collisional tectonic setting for their formation. However, most of their samples show arc-related geochemical affinities, which can be regarded as evidence supporting the southward subduction of the South Tianshan Ocean. Moreover, Mao et al.
Conglomerate sandstone and mudstone, section with sample 13XX2A from the main body and sample 13XX2C. Both samples were collected, several meters separated, from the middle shore and epicontinental marine environments (BGMRXUAR, 1993) and oil-bearing shale interlayers, which were probably deposited in gneiss and biotite.

3. Sampling and analytical methods

3.1. Sampling

Three representative samples (one muscovite–quartz schist and two siltstones) were collected to the south of the town of Xingxingxia in the STS belt. Sample locations are depicted in Fig. 2 and a stratigraphic column of the working area (BGMRGR, 1966; BGMRXUAR, 2007) is illustrated in Fig. 3. Representative photomicrographs are shown in Fig. 4.

Samples 13XX2A and 13XX2C (41°39'–24.7"N, 95°13'–21.4"E) were collected from the Zhesi Group on outcrops near the Jingwozi mine (Fig. 2). The Zhesi Group, interpreted to be Early Permian in age by BGMRXUAR (1993), can be further divided into three sections (Fig. 3): (a) a lower section that comprises fine-grained siltstone and limestone-bearing siltstone, (b) a middle section that is composed mainly of fine-to coarse-grained feldspar–quartz sandstone with interlayers of conglomerate, siltstone, shale, and limestone, interpreted to have formed in an alluvial fan environment, and (c) an upper section, consisting dominantly of migmatic gneiss, migmatisite, garnet-bearing biotite–feldspar gneiss and biotite–muscovite–quartz schist with mudstone, siltstone and oil-bearing shale interlayers, which were probably deposited in shore and epicontinental marine environments (BGMRXUAR, 1993). Both samples were collected, several meters separated, from the middle section with sample 13XX2A from the main body and sample 13XX2C from a lower reddish interlayer (Fig. 3). Sample 13XX2A is a gray-greenish siltstone (Fig. 4a), composed mainly of fine-grained quartz (40–50%), biotite and muscovite (40–50%) and minor plagioclase. Sample 13XX2C is a purple-colored siltstone (Fig. 4b), containing fine-grained quartz (40–50%), biotite and muscovite (30–40%) and scattered magnetite within a silt–clay matrix.

Sample 13XX3A (41°42'–20.7"N, 95°11'–12.7"E) is a low-grade meta-morphosed schist (Fig. 4c, d) that is composed of quartz (50–60%), muscovite (30%), microcline (5%) and minor hornblende. The sample was collected from the previously-assumed Neoproterozoic (or Early Sinian in Chinese literatures) strata (BGMRXUAR, 1993), which consist of muscovite–quartz schist, hornblende–plagioclase schist and chlorite–quartz schist with marble and lephtite interlayers. In the thin section, quartz and muscovite show well-preserved orientation. The preservation of coarse-grained microcline, hornblende and plagioclase probably reflects a proximal depositional environment.

3.2. Analytical methods

Zircon grains were separated using standard density and magnetic techniques at Hebei Geology and Resource Bureau, Langfang, China, and then were hand-picked under a binocular microscope without particular choice for shape, color, size or aspect ratio before embedded in epoxy resin. Then, the randomly selected zircons were polished to about half section prior to cathodoluminescence (CL) imaging using a Mono CL3+ (Gatan, USA) system at the Guangzhou Institute of Geochemistry, Chinese Academy of Sciences (Guangzhou, China). Using a laser ablation inductively coupled plasma mass spectrometry (LA-ICPMS) system, U–Pb and trace-element analyses for zircons in the sedimentary samples (13XX2A and 13XX2C) and those in the metasedimentary sample (13XX3A) were conducted at Guangzhou.

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Fig. 3. Stratigraphic column in the study area, modified after BGMRGR (1966) and BGMRXUAR (2007). Ptk—Proterozoic Kawabulake Group, other abbreviations are the same as those in Fig. 2.
Institute of Geochemistry, Chinese Academy of Sciences (Guangzhou) and at Northwest University (Xi’an), respectively. Detailed analytical procedures have been described by Li et al. (2011a) and Liu et al. (2008), respectively. Detrital zircons embedded in epoxy resin were analyzed one by one with laser ablation spots of 33 μm in diameter. When core-rim textures were present, mostly only the cores were measured because of limited rim width. The isotopic ratios were calculated using GLITTER 4.0 (Griffin et al., 2008), and common Pb was corrected according to Andersen (2002). Weighted mean age calculation and concordia and probability density diagrams were produced using Isoplot (v. 3.0) (Ludwig, 2003). The concordant 206Pb/238U ages were preferred for <1000 Ma zircons and the 207Pb/206Pb ages for >1000 Ma zircons. All analyses on the U–Pb concordia plots were quoted at a 1σ uncertainty level with weighted mean age uncertainties at a 95% confidence level.

Using a Neptune Plasma multi-collector ICPMS coupled with a 193 nm COMPex Pro laser ablation system, Lu–Hf isotopic analysis was performed on concordant zircons (<10% discordance), targeting the pits generated during the U–Pb analysis, at Institute of Geology and Geophysics, Chinese Academy of Sciences (Beijing, China). Laser ablation spot sizes were 60 μm, and the ablation rate was 8 Hz with typical ablation time of 26 s. Detailed analytical procedures and isobaric interference corrections have been documented by Wu et al. (2006b). To calculate initial 176Hf/177Hf ratios and εHf(t) values, the 176Lu decay constant of 1.865 × 10−13 yr−1 (Scherer et al., 2001) and the chondritic values of 176Hf/177Hf = 0.282772 and 176Lu/177Hf = 0.0352 (Blichert-Toft and Albarede, 1997) were adopted. To assist discussion, single-stage model age (TDM) and two-stage crustal model ages (TDM) were calculated for each zircon using values of 176Hf/177Hf = 0.28325 and 176Lu/177Hf = 0.0384 (Griffin et al., 2004) and assuming that their parental magmas were produced from an average continental crust with 176Lu/177Hf ratio of 0.015 (Griffin et al., 2002). Mud Tank and Gj-1 zircons were analyzed to monitor instrument reliability and stability.

Our measurements of 176Hf/177Hf values on Mud Tank and Gj-1 zircons were 0.282516 ± 0.000003 (2σ) and 0.282033 ± 0.000004 (2σ), respectively, comparable within errors with the published values of 0.282504 ± 0.000022 for Mud Tank (Woodhead and Hergt, 2005) and 0.282015 ± 0.000019 for Gj-1 (Elhlou et al., 2006).

4. Results

Representative CL images of analyzed zircons coupled with U–Pb ages and εHf(t) values, as well as typical Th/U ratios, are shown in Fig. 5. U–Pb data of detrital zircons are illustrated in Fig. 6 and shown in Supplementary Table S1. Th/U ratios and Ti-in-zircon apparent temperatures of zircons in sample 13XX3A are presented in Fig. 7 and Supplementary Table S2. Zircon Lu–Hf isotopic data are shown in Supplementary Table S3 and displayed in Fig. 8. We present the graphic blips/peaks in detail in Fig. 6 for better comparison among the samples in this study and with detrital zircon profiles from the adjacent regions (Fig. 9). The merged blips/peaks were used to represent the major zircon age populations.

4.1. CL images and Th/U ratios of zircons

Most zircon grains from samples 13XX2A and 13XX2C are euhedral to subhedral with lengths of 50–200 μm and aspect ratios of 1–5. CL images of these zircons show well-developed oscillatory zoning. Their U and Th concentrations range from 49 ppm to 1770 ppm (13XX2A) and from 28 ppm to 1416 ppm (13XX2C), respectively, comparable within errors with the published values of 0.282504 ± 0.000022 for Mud Tank (Woodhead and Hergt, 2005) and 0.282015 ± 0.000019 for Gj-1 (Elhlou et al., 2006).

Fig. 4. Representative photomicrographs of the samples. The yellowish polarization color of quartz grains in (d) are caused by a large thickness of the thin section. Q—Quartz; Mus—Muscovite, Hbl—Hornblende, Mc—Microcline. (For interpretation of the references to color in this figure legend, the reader is referred to the web version of this article.)
4.2. Zircon U–Pb ages and Lu–Hf isotopes

A total of 354 zircon grains were selected for U–Pb analysis, among which 318 are concordant (≤10% discordance) yielding ages from 2574 Ma to 250 Ma. 231 concordant zircon grains were conducted for Lu–Hf isotopic analysis with four of them (13XX3A-23, 13XX3A-24, 13XX3A-98 and 13XX3A-101) neglected due to unusually high instrument drift. Only the concordant analyses were considered in depositional age and provenance interpretations.

4.2.1. Sample 13XX2A

In total, 102 zircons were analyzed with 99 of them yielding concordant ages ranging from 2314 Ma to 250 Ma (Fig. 6a). On the probability density distribution plot, the concordant results show major age peaks at ca. 1500–1320 Ma, 960–890 Ma, 464 Ma, 449–498 Ma, 340 Ma, 305 Ma and 265 Ma. Smaller peaks at ca. 2310 Ma, 2040 Ma, 1120 Ma, 805 Ma, 650 Ma, 510 Ma and 396 Ma are also detected (Fig. 6b).

Lu–Hf analysis was carried out on 51 zircon grains. Their εHf(t) ratios vary from 0.000118 to 0.003236 with initial 176Hf/177Hf ratios from 0.280759 to 0.283034, corresponding to εHf(t) values of −10.5 to +16.6. TDM model ages of 2894 Ma to 316 Ma and TDM model ages of 3285 Ma to 350 Ma are also detected (Fig. 6b). Particularly, 360–250 Ma zircons...
possess predominantly positive $\varepsilon_{Hf}(t)$ values with some plotted near the depleted mantle line.

### 4.2.2. Sample 13XX2C

Among the 126 analyses, 123 are concordant, showing ages from 2542 Ma to 382 Ma with peaks at ca. 1840–1610 Ma, 1250–1020 Ma, 550–500 Ma, 493 Ma, 469 Ma, 448 Ma, 428 Ma, 416 Ma and 393 Ma (Fig. 6c, d). A few Precambrian ages at ca. 2540 Ma, 2130 Ma, 950–930 Ma and 840–660 Ma were also detected. It should be noted that one zircon in this sample presents core–rim texture with a core age of 423 ± 11 Ma (13XX2C-07) and a rim age of 382 ± 11 Ma (13XX2C-08), the latter of which was probably related to a later tectonothermal event.

Eighty nine zircon grains were analyzed for Lu–Hf isotope compositions, yielding $^{176}\text{Lu}/^{177}\text{Hf}$ ratios between 0.000325 and 0.002302 and initial $^{176}\text{Hf}/^{177}\text{Hf}$ ratios between 0.281345 and 0.282583. Therefore, their $\varepsilon_{Hf}(t)$ values show a wide range from $-10.5$ to $+9.2$ with TDM model ages from 2602 Ma to 948 Ma and crustal model ages (TDM) from 3002 Ma to 1185 Ma (Fig. 8c, d). Similar U–Pb ages and Hf model ages were observed in ca. 1.8 Ga and ca. 2.5 Ga zircons.

### 4.2.3. Sample 13XX3A

Among the 126 dated zircons, 96 grains possess concordant ages varying from 2574 Ma to 339 Ma. The discordant results were mostly related to influences from inherited cores. Of these, 18 analyses define a concordia line with an upper-intercept age of 2547 ± 30 Ma and a

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Fig. 6. Zircon U–Pb concordia diagrams (a, c and e) with weighted mean ages of the youngest zircons for calculating maximum depositional ages, and probability density distribution plots (b, d and f). N stands for the number of total analyses, and n for concordant ones only. 10% discordance was used as cut-off for concordant zircons. U–Pb ages are quoted in Ma and ellipses are drawn at a 1σ error level. MSWD—Mean Square of Weighted Deviates.
lower-intercept age of 327 ± 35 Ma (MSWD = 20), and another 11 results form a concordia curve with upper- and lower-intercept ages of 1828 ± 67 Ma and 317 ± 86 Ma (MSWD = 9.5), respectively. Paleozoic zircons are predominant with age peaks at ca. 508 Ma, 483 Ma, 448 Ma, 427 Ma, 399 Ma, 368 Ma, 357 Ma and 342 Ma, whereas Precambrian ones are rare, yielding ages of ca. 2570–2500 Ma and 1880–1740 Ma, which are most likely to be inherited zircons due to the limited number and euhedral to subhedral crystal shapes.

Eighty seven zircon grains were chosen for Lu–Hf analysis. Their $^{176}\text{Lu}/^{177}\text{Hf}$ ratios vary from 0.000459 to 0.002978 and initial $^{176}\text{Hf}/^{177}\text{Hf}$ ratios show a wide range from 0.281203 to 0.282229, corresponding to $\varepsilon_{\text{Hf}}(t)$ values of −16.1 to +10.5, $T_{\text{DM}}$ model ages of 2789 Ma to 1468 Ma and $T_{\text{DM}}$ model ages of 2955 Ma to 1789 Ma (Fig. 8e, f). Interestingly, zircons with ages of ca. 1.7–1.8 Ga and ca. 2.5 Ga have equivalent U–Pb ages and Hf model ages, as also observed in sample 13XX2C. Paleozoic zircons show dominantly low negative $\varepsilon_{\text{Hf}}(t)$ values of −16.1 to −8.6.

On the basis of zircon shape, internal textures (Fig. 5), U–Pb ages (Fig. 6f), Th/U ratios (Fig. 7) and Hf isotopic compositions (Fig. 8f), the concordant zircon grains can be categorized into three types. Type I: Metamorphic zircons. About 27% zircons show very low Th/U ratios (<0.1) without oscillatory zoning. Their ages spread from ca. 400 Ma to 340 Ma with peaks at 399 Ma, 368 Ma, 357 Ma and 342 Ma and uniform $\varepsilon_{\text{Hf}}(t)$ values between −15.4 and −13.7. Type II: Partially recrystallized zircons. Most zircons (ca. 60%) possess partially-preserved oscillatory zoning and low Th/U ratios (<0.2), much lower than those of typical igneous zircons. Their ages exhibit a wide range from 520 Ma to 410 Ma. Type III: Igneous zircon. About 13% zircon grains, including all Precambrian ones, are igneous in origin, as evidenced by their prismatic shapes, typical oscillatory zoning and relatively high Th/U ratios (>0.2). Contrary to those of type I zircons, $\varepsilon_{\text{Hf}}(t)$ values of type II and type III zircons vary within a large range from −16.1 to −8.6.

5. Discussion

5.1. Maximum depositional ages

Following the methods for defining maximum depositional ages of sedimentary strata by Dickinson and Gehrels (2009), we have obtained that (a) the youngest single-grain zircon age is 250 ± 6 Ma, (b) the youngest graphical age peak is at ca. 265 Ma (Fig. 6b), and (c) the mean age of the youngest grains with ages overlapping at 1 σ is 256 ± 4 Ma (Fig. 6a; N = 5) for sample 13XX2A from the Zhesi Group. We opt to take ca. 256 Ma (% in content) as the best estimate for the maximum depositional age of the sampled strata, because these estimates vary from the least to the most statistically robust from (a) to (c) (Dickinson and Gehrels, 2009). This result is slightly younger than the maximum depositional age of ca. 266 Ma for the Zhesi Group suggested by Chen et al. (2014) based on the youngest single-grain zircon age from two siltstones (615-1 and 615-2 in Fig. 2 with analyzed numbers of 64 and 70, respectively). However, a similar-aged peak at ca. 265 Ma (15% in content) is also identified in sample 13XX2A (Fig. 6b).

Therefore, our result (ca. 256 Ma) is more robust due to the larger number of zircon grains (N = 102) analyzed for one single sample, when it is more likely to detect low abundance zircon population (Andersen, 2005). Consequently, as evidenced by the abundant Middle to Late Permian zircons (24% in content) in sample 13XX2A, the strata we sampled were most likely deposited in the Late Permian. Thereby, the Zhesi Group should at least be Permian in age, rather than Early Permian as interpreted by BGMRXUAR (1993) or Middle Permian by Chen et al. (2014).

Sample 13XX2C was collected from a reddish interlayer, several meters stratigraphically beneath sample 13XX2A, also within the Permian Zhesi Group. Thus, this sample was most likely formed during Early to Late Permian times. However, the estimated ages are (a) 382 ± 11 Ma, (b) 393 Ma and (c) 386 ± 9 Ma for sample 13XX2C, quite
different from those of sample 13XX2A, which must be results of different sources and/or depositional environment and will be discussed below.

The mean age of the youngest grains with ages overlapping at 1σ is 341 ± 4 Ma for sample 13XX3A, which can be used to approximately constrain its maximum depositional age. In addition, ca. 305 Ma magmatic zircons, comprising a major component (ca. 10%) in sample 13XX2A, cannot be detected in sample 13XX3A, indicating that it was probably formed at some time before 305 Ma. Moreover, sample 13XX3A has experienced low-grade metamorphism, while the Permian samples 13XX2A and 13XX2C have not, implying that its deposition and metamorphism must have occurred before the formation of the Permian samples. Therefore, sample 13XX3A was most likely deposited and metamorphosed in the Carboniferous (341–305 Ma), indicating that the sampled strata must not be Neoproterozoic (or Early Sinian in Chinese literatures) in age as suggested by BGMRXUAR (1993).

5.2. Provenance

As mentioned above, the (meta-)sedimentary samples were probably deposited during Carboniferous to Permian times in the STS belt, when the eastern segment of the South Tianshan Ocean was already closed (He et al., 2012, 2014), or was about to close (Ma et al., 2014). Hence, the detritus could only be directly derived either from the CTS block in the north or from the southern margin of the Beishan block in the south (Fig. 1).

We rule out the northern Beishan as a source terrane for the following reasons. Firstly, 440–390 Ma detrital zircons are very rare (<3%) in sample 13XX2A, counterparts of which constitute the main body of the middle section of the Permian Zhesi Group (Fig. 3). However, the reported magmatic rocks along the northern margin of the Beishan block (Fig. 1), such as 436 ± 9 Ma granite, 423 ± 8 Ma granodiorite and 397 ± 7 Ma monzogranite (Zhao et al., 2007), 424 ± 4 Ma adakites (zircon $\varepsilon_{Hf}(t) = -0.8$ to +2.7; Mao et al., 2010b) and 397 ± 3 Ma K-
feldspar granite (zircon $\varepsilon_{Hf}(t) = -1.0$ to $+5.8$; Li et al., 2011b), were mostly formed during 440–390 Ma. Accordingly, if the northern Beishan or the Beishan block was a source terrane for the Permian Zhesi strata, 440–390 Ma magmatic zircons should at least be a dominant component, which is not the case in our samples. Secondly, $\varepsilon_{Hf}(t)$ values of 440–390 Ma zircons in this study range from $-16.1$ to $-0.7$ ($\text{mean} = -10.8$), significantly different from those ($-1.0$ to $+5.8$) of contemporaneous zircons in the northern Beishan (Li et al., 2011b; Mao et al., 2010b). Thirdly, 490–440 Ma and 390–340 Ma detrital zircons are important components in our samples 13XX2A (10% and 13%), 13XX2C (42%) and 13XX3A (42% and 23%), whereas such-aged magmatic/metamorphic rocks have barely been discovered in the northern Beishan. Similarly, the predominant 340–250 Ma zircons in sample 13XX2A (60%) cannot be sourced from the northern Beishan, where few coeval magmatism was found.

By contrast, Precambrian detrital zircons in this study correspond well with those previously reported Precambrian detrital zircons (Ma et al., 2012a,b) and magmatites (Gu et al., 1990; Hu et al., 1997; Lei et al., 2013; Liu et al., 2004), particularly the ca. 2.5–2.4 Ga juvenile rocks (Wang et al., 2014), in and surrounding the CTS block. More importantly, almost all Paleozoic zircons in our samples do have similar-aged magmatic counterparts in the CTS block, for example 475–474 Ma granodiorites (zircon $\varepsilon_{Hf}(t) = -12.9$ to $-6.0$; Ma et al., 2013b), 466.5 ± 9.8 Ma granitic gneisses (Hu et al., 2007), 458 ± 9 Ma gneissic granite (zircon $\varepsilon_{Hf}(t) = -13.1$ to $-6.9$; Shi et al., 2014), ca. 450 Ma granodiorites (zircon $\varepsilon_{Hf}(t) = -17.4$ to $-14.7$; Ma et al., 2014), 442 ± 7 Ma gabbro (zircon $\varepsilon_{Hf}(t) = -11.9$ to $-6.3$; Shi et al., 2014), 441.6 ± 3.8 Ma granites (Zhu and Song, 2006), 439.9 ± 2.2 Ma granites (zircon $\varepsilon_{Hf}(t) = -5.0$ to $-1.3$; Yang et al., 2012), 424.9 ± 5.8 Ma granodiorite (zircon $\varepsilon_{Hf}(t) = -8.1$ to $+0.4$; Lei et al., 2011) and 399 Ma (zircon $\varepsilon_{Hf}(t) = -3.7$ to $-0.8$) to 371–345 Ma (zircon $\varepsilon_{Hf}(t) = -2.4$ to $+7.6$) granodiorites (Ma et al., 2014), not to mention that they share identical Hf isotopic compositions. In addition, 380–320 Ma high-grade metamorphosed rocks (He et al., 2012, 2014) and late Paleozoic granites (BGMRFGR, 1966; BGMRXJUR, 2007) have been discovered in the Xingxingxia area, representing possible sources for the contemporary metamorphic/magmatic zircons in our samples. Moreover, age profiles and Hf isotopes of detrital zircons in this study are overall indistinguishable from those in the Early Permian strata from the NTS belt (Figs. 8 and 9; our unpublished data). A recent detrital zircon study of sedimentary rocks from the southern margin of the Junggar Basin has also revealed that the detrital zircons were derived dominantly from the southern Chinese Tianshan since the initiation of the basin in the Late Carboniferous (Yang et al., 2013). The above detrital zircon studies both strongly support that the CTS block had been a topographic high providing substantial detritus to the surrounding areas at least since the Early Permian. These lines of evidence suggest that the single source terrane for our sampled strata was the CTS block, rather than the Tarim block or the Bogda Arc as suggested by Chen et al. (2014).

Although sharing the same source terrane (the CTS block), each sample possesses a unique zircon age profile (Fig. 6). First, samples 13XX2C and 13XX3A have similar Paleozoic, but different Precambrian age components. This can be possibly related to the fact that Precambrian magmatic zircons in the Carboniferous sample 13XX3A are potentially inherited zircons in the source rocks because of their limited number...
and euhedral to subhedral crystal shapes, whereas Precambrian grains in the Permian sample 13XX2C are detrital zircons due to their large number and anhedral or rounded shapes. Thus, the detrital materials of sample 13XX3A were probably derived from the nearby Paleozoic magmatites, while those of sample 13XX2C were possibly sourced from both the Paleozoic magmatic and Precambrian basement rocks in the CTS block. Furthermore, their different Precambrian age components indicate that the Permian strata were not formed by simple recycling of the northern Carboniferous metasedimentary strata.

Second, age profiles of the Permian samples 13XX2A (gray in color and younger) and 13XX2C (reddish in color and older) appear to be quite dissimilar (Fig. 6b, d), particularly with respect to the presence and absence of Precambrian (1.9–1.6 Ga and 1.5–1.3 Ga) zircons and the contents of Paleozoic (475–440 Ma and 340–250 Ma) ones. To the large number (102–126) of zircon grains analyzed for each sample in this study, zircon populations with contents as small as 2–3% (or 0.6–0.7%) can be statistically detected at a probability level of 95% (or 50%) (Andersen, 2005). Therefore, the differences in Precambrian age components are not caused by an insufficient number of analyses, but are more likely related to different depositional settings, receiving variable amounts of Precambrian material. This is further supported by the reappearance of 1.9–1.6 Ga zircons in the siltstones (615.1 and 615.2 in Fig. 2) that were collected a few kilometers west to sample 13XX2A in the Zhesi Group (Chen et al., 2014). The differences in the early to late Paleozoic portions may result from a sudden change in the depositional environment that was possibly related to the development of the Xingxingxia dextral strike–slip fault, the western part of which has been constrained to be active during 298–280 Ma (Cai et al., 2012). More importantly, the nearby early Paleozoic granites (Fig. 2) are considered to have formed during Ordovician–Silurian time (BMCRMGR, 2007) or during Caledonian Period (BMCRMGR, 1966) or at 444.5 ± 2.2 Ma (Mao et al., 2010a), and thus they are the most possible source rocks for the dominant ca. 448 Ma zircons in the older sample 13XX2C (Fig. 6d). Moreover, the late Paleozoic granites (Fig. 2) have been interpreted to be Carboniferous (BMCRMGR, 2007) or Middle Variscan (BMCRMGR, 1966) in age, and thus they can be considered as the most likely sources for the predominant 340–265 Ma detrital zircons in the younger sample 13XX2A (Fig. 6b). Accordingly, we propose that during the deposition of the older sample 13XX2C, the strata were possibly located in the east (e.g., the red dotted star in Fig. 2; just an assumption) and received abundant early Paleozoic material from the northern early Paleozoic intrusions, which in turn blocked out material from the late Paleozoic intrusions in the further north. Then, the Permian strata were moved by the Xingxingxia dextral strike–slip fault relatively westwards, predominantly receiving detritus from the late Paleozoic granites during the deposition of the younger sample 13XX2A. Although incomplete and unproven, this speculation is consistent with the progressive decreases of 475–440 Ma zircons from east to west from sample 13XX2C (34%) through sample 13XX2A (9%) to samples 615 (0%); Chen et al., 2014) and the increase of 340–250 Ma zircons from sample 13XX2C (0%) to sample 13XX2A (60%).

5.3. High-grade metamorphism recorded by detrital zircons in sample 13XX3A

Observed and thin section examination indicate that sample 13XX3A has experienced low-grade (probably greenschist-facies) metamorphism without the presence of high-grade metamorphic mineral or clue for retrograde reaction (Fig. 4c, d). However, most zircons in this sample possess partially- to fully-recrystallized textures and low Th/U ratios (<0.2), which cannot be explained by the low-grade metamorphism. Particularly, nearly all 400–340 Ma (type I) zircons in this sample possess metamorphic characteristics with age peaks at 399 Ma, 368 Ma, 357 Ma and 342 Ma, which are roughly comparable with the two lower-intercept ages (327 ± 35 Ma and 317 ± 86 Ma) of discordant zircons in this sample (Fig. 4e), and are consistent with the zircon-rim age of 382 ± 11 Ma (13XX2C-08), evidence for the existence of multistage high-grade metamorphic events in the CTS block. These metamorphic events are further supported by the discovery of 380–320 Ma amphibolite- to granulate-facies paragneisses and orthogneisses in the Xingxingxia area (He et al., 2012, 2014), in which early Paleozoic magmatic zircons show similar Th/U ratios and internal textures to those of type II zircons in sample 13XX3A.

Moreover, such-aged metamorphic rocks have been extensively reported in the CTS and STS, mostly interpreted to have formed during the closure of the South Tianshan Ocean and subsequent strike–slip movements. For example, Yang et al. (2011) found 405–396 Ma (metamorphic zircon ages) mylonites in the Kumish region and 396–387 Ma (metamorphic zircon ages) garnet gneisses in the Yushugou area. Moreover, basic granulites in the Yushugou ophiolitic mélanges yielded zircon mantle ages of 392–390 Ma and rim ages of 328 ± 12 Ma (Zhou et al., 2004), as well as amphibole 40Ar/39Ar plateau ages of 368–360 Ma (Wang et al., 2003). Similarly, Cai et al. (1996) discovered 370 ± 5 Ma highly-deformed quartz schist, and Li et al. (2004) reported 368 ± 1 Ma mylonitic quartzite in the Kulehu ophiolites.

Thereby, we suggest that the CTS block has possibly experienced multistage high-grade metamorphism during ca. 400–340 Ma. The uniform Hf isotopic compositions (εHf(t) = −15.4 to −13.7) of <400 Ma metamorphic zircons in sample 13XX3A suggest that these zircons were possibly formed in the presence of a relatively homogeneous melt, which was probably derived from partial anatexis of continental crust (Gerdes and Zeh, 2009), such as the granitic gneisses or metasedimentary rocks in the CTS block.

5.4. Paleozoic magmatism and metamorphism in CTS block

The discovery of 1.8–0.7 Ga basement rocks in the Xingxingxia area provides robust evidence for the Precambrian evolution of the eastern segment of the CTS block (Gu et al., 1990; Hu et al., 1997; Lei et al., 2013; Liu et al., 2004). However, the formation of Paleozoic magmatism and metamorphism and their relationship to the tectonic evolution of the South Tianshan and Junggar oceans remain ambiguous (Ma et al., 2014; Wang et al., 2011a; Windley et al., 1990). In this study, CTS-derived Paleozoic detrital zircons range in age from 520 Ma to 250 Ma, indicating a series of early to late Paleozoic magmatic events in the CTS block, formation of which were closely linked to the development of the South Tianshan and Junggar oceans. Moreover, metamorphic detrital zircons in sample 13XX3A provide evidence for late Paleozoic high-grade metamorphic events in the CTS block, probably related to the closure of the eastern South Tianshan Ocean. Therefore, coupled U–Pb and Hf isotopic analysis of these Paleozoic detrital zircons can provide systematic insight into understanding the Paleozoic evolution of the eastern CTS block and the respective oceans.

5.4.1. Paleozoic metamorphism

As aforementioned, metamorphic rocks in the CTS and STS exhibit a large range in metamorphic ages from ca. 405 Ma to ca. 320 Ma (He et al., 2012, 2014; Wang et al., 2003; Yang et al., 2011; Zhou et al., 2004), as also reflected in the ages of metamorphic zircons (type I) in sample 13XX3A. Are these metamorphic rocks/zircons all related to the closure of the eastern South Tianshan Ocean? In order to distinguish them, the Ti-in-zircon thermometer (Watson et al., 2006) was applied for zircons in sample 13XX3A. It is worth mentioning that the Ti-in-zircon thermometer by Ferry and Watson (2007) yielded roughly comparable or even higher zircon apparent temperatures after uncertainty correction for pressure, \( T_{app} \) and \( T_{app} \) using the peak metamorphic conditions (720–750 °C and 0.4–0.6 GPa) of the gneisses in the CTS block (He et al., 2014). Although a few results appear to be unreasonably high, probably related to cracks or inclusions within the analyzed zircons, most ~410 Ma zircons in sample 13XX3A seem to exhibit realistic crystallization temperatures varying from 600 °C to 900 °C with a mean
The 475–440 Ma episode: These CTS-derived early Paleozoic magmatic zircons are a predominant component in both the STS and NTS belts, indicating that 475–440 Ma magmatites must have constituted major parts of the CTS block. This agrees with the widely-spread similar-aged arc-related rocks throughout the CTS block (Hu et al., 2007; Ma et al., 2013b, 2014; Mao et al., 2010a; Shi et al., 2014; Yang et al., 2012) and the permanent dominance of such-aged detrital zircons in Paleozoic sedimentary strata in the CTS (Ma et al., 2012b), NTS (our unpublished data), STS (Xia et al., 2014) and even northern Tarim (Han et al., 2015). Highly-evolved Hf isotope signatures of these zircons (mean εHf(t) = −10) suggest magma formation primarily through melting of ancient continental crust, further matching those of zircons (εHf(t) = −12.9 to −6.0, εHf(t) = −13.1 to −6.9, εHf(t) = −17.4 to −14.7 and εHf(t) = −11.9 to −6.3) in contemporatory arc-related granitoids in the CTS block (Ma et al., 2013b, 2014; Shi et al., 2014; Yang et al., 2012). The generation of 475–440 Ma magmatites appears to be related to the southward subduction of the Junggar Ocean, rather than to the subduction of the South Tianshan Ocean, which had not opened during this time interval (445–440 Ma), as evidenced by the absence of respective zircons in the CTS belt (Huang et al., 2011; Long et al., 2006; Tian et al., 2014; Yang et al., 2011).

The 430–400 Ma episode: Such-aged detrital zircons in the NTS belt (8%), characterized by positive εHf(t) values (+3.7 to +7.9; Fig. 8d; our unpublished data), were derived from the NTS island arcs, which were probably formed during slab rollback of the Junggar Ocean. Whereas, 430–400 Ma zircons in the STS belt (12%) possess negative εHf(t) values (−16.1 to −0.7), comparable with those zircons in a nearby ca. 415 Ma volcanic arc granite (sample 13XX3C in Fig. 8f; our unpublished data) and those (−8.1 to −0.4) in the 424.9 ± 5.8 Ma Xingxingxia volcanic arc granodiorites (Lei et al., 2011). Thus, we speculate that the 430–400 Ma magmatic rocks along the southern margin of the CTS block were possibly formed by the northward subduction of the South Tianshan Ocean. However, this interpretation needs more investigations.

The 340–250 Ma episode: 340–250 Ma magmatic zircons represent a major population with dominantly positive εHf(t) values (−3.1 to +16.6 and mean = +4.6), indicating great contribution from mantle material with minor crustal contamination during their magma formation. Coeval juvenile rocks have been found in the CTS block, such as ca. 338 Ma granodiorites (εHf(t) = +0.7 to +5.9; Ma et al., 2014) and 290–270 Ma mafic–ultramafic intrusions (BGMXKUAR, 1993; Su et al., 2012, 2013). As the STS and CTS areas underwent postcollisional extension since 360 Ma, the formation of these juvenile rocks appears to be closely related to the regional post-collisional event, in which upwelling mantle material played a vital role. The Carboniferous volcanic arc granitoids in the CTS block reported by Ma et al. (2014) should be generated by the southward subduction of the Junggar Ocean, which was not closed until the Late Carboniferous (Xu et al., 2006b).

In summary, this study confirms that the eastern segment of the South Tianshan Ocean closed during Devonian time (ca. 400–370 Ma), which was prior to the closure of the western segment (320–310 Ma; Gao and Klemd, 2003; Klemd et al., 2011), indicating a diachronous scissor-like closure for the South Tianshan Ocean (Chen et al., 1999). Hence, the final assembly of the Eastern Tianshan took place during Late Carboniferous time by the closure of the Junggar Ocean.

6. Conclusions

Combined U–Pb and Lu–Hf isotopic analysis on detrital zircons from (meta-)sedimentary rocks in the South Tianshan belt and comprehensive comparisons with previous detrital zircon data from the North Tianshan belt have led us to draw the following conclusions:

(1) The 318 concordant U–Pb data of detrital zircons yield dominant Paleozoic and minor Precambrian ages, which were derived...
directly from the Central Tianshan block.

(2) Paleozoic zircons yield predominant age populations at ca. 505–490 Ma, 475–440 Ma, 430–400 Ma and 340–250 Ma, which are well consistent with the four major episodes of magmatism in the central Eastern Tianshan block. The 475–440 Ma highly-evolved zircons were most likely derived from the coeval arc-related magmatites that constitute the main body of the CTS block, the formation of which was probably related to the southwest subduction of the Junggar Ocean. The 340–250 Ma juvenile zircons were possibly sourced from regional post-collisional rocks in the CTS block.

(3) The youngest zircons in the metasedimentary sample from the south of the Xingxingxia suggest that the sampled strata were Carboniferous (341–305 Ma) in age, rather than Neoproterozoic (or Early Sinian in Chinese literature) as previously interpreted.

(4) U–Pb–Hf isotopic analysis combined with Ti-in-zircon thermometer of metamorphic zircons in the metasedimentary sample revealed a 400–370 Ma collisional event, related to the closure of the eastern segment of the South Tianshan Ocean, and a 360–340 Ma extensional event, possibly caused by post-collisional mantle upwelling.

(5) The final assembly of the Eastern Tianshan occurred in the Late Carboniferous.

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