Paleozoic accretionary orogenesis in the Paleo-Asian Ocean: Insights from detrital zircons from Silurian to Carboniferous strata at the northwestern margin of the Tarim Craton

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\section*{Abstract}
A detrital zircon U-Pb and Lu-Hf isotopic study was carried out in the Middle Silurian to Late Carboniferous sedimentary strata of the northwestern Tarim Craton in order to understand accretionary processes in the southern part of the Central Asian Orogenic Belt. Detrital zircons from these strata yielded U-Pb ages clustering around 2.8–2.3 Ga, 2.0–1.7 Ga, 1.3–0.9 Ga, 880–600 Ma, and 500–400 Ma, with age populations and Hf isotopic signatures matching those of magmatic rocks in the Tarim Craton and the Central Tianshan Block. Abundant 500–400 Ma detrital zircons most likely reflect deposition in a retroarc foreland basin inboard of an Andean-type magmatic arc to the north, supporting the northern Tarim-Central Tianshan connection during early Paleozoic time. The absence of 380–310 Ma zircon population in the Carboniferous siliciclastic rocks suggests that the Central Tianshan Block may have been separated from the Tarim Craton in the Early Devonian, caused by the interarc/back-arc opening of the South Tianshan Ocean. We propose an accretionary orogenic model switching from advancing to retreating mode during Paleozoic time in the southwestern part of the Paleo-Asian Ocean. This transition most likely occurred coevally with the rifting of Southeast Asian blocks from the northeastern margin of Gondwana.

\section*{1. Introduction}
Accretionary orogenesis has been shown to be important in deciphering geological processes at convergent margins, such as subduction and accretion of tectonic domains, crustal growth, and evolution of supercontinents [e.g., Xiao et al., 2003; Jahn, 2004; Cawood and Buchan, 2007; Cawood et al., 2009]. However, recognition of different types of fossil accretionary orogens (e.g., advancing and retreating) is not straightforward, and the mechanism of formation and duration of the orogenesis are frequently unclear [Cawood et al., 2009; Xiao and Santosh, 2014]. The Central Asian Orogenic Belt (Figure 1a), or Altaids, represents a typical accretionary orogen preserving a long-term and complicated record (Neoproterozoic-Mesozoic) of accretion and collision processes in the Paleo-Asian Ocean realm [Şengör et al., 1993; Khain et al., 2003; Windley et al., 2007]. Despite the numerous studies on the accretionary history of this belt [e.g., Jahn, 2004; Wilhem et al., 2012; Kröner et al., 2014; Rojas-Agramonte et al., 2014; Safonova and Santosh, 2014], the tectonic evolution remains controversial, especially close to the southern margin along the Tianshan-Solonker Suture Zone (Figure 1a) [Xiao et al., 2003, 2010, 2013; Shu et al., 2004; Rojas-Agramonte et al., 2011; Eizenhöfer et al., 2014]. The South Tianshan Orogenic Belt (Figure 1b) records the development and closure of one of the southernmost branches of the Paleo-Asian Ocean, termed South Tianshan Ocean. Arguments remain concerning the time of opening and the subduction polarity of the ocean, despite the large amount of research on its preclosure history [e.g., Windley et al., 1990; Gao et al., 1998; Charvet et al., 2011; Han et al., 2011; Wang et al., 2011; Lin et al., 2013; Xiao et al., 2013].

Early studies suggested that the South Tianshan Ocean was long lived and separated the northern blocks from the Tarim Craton [Windley et al., 1990; Allen et al., 1992]. Recent data, however, support an Early Precambrian connection between the Tarim Craton and the Central Tianshan Block prior to the opening of the South Tianshan Ocean [Shu et al., 2002; Glorie et al., 2011; Ma et al., 2012b; Kröner et al., 2013; Rojas-Agramonte et al., 2014]. Nevertheless, a consensus has not been reached regarding the opening of the ocean basin, with inferred ages ranging from the Neoproterozoic to the Middle Devonian [Gao et al., 1998; Shu et al., 2002; Wang et al., 2008; Charvet et al., 2011; Lin et al., 2013; Ge et al., 2014]. The subsequent consumption of the South Tianshan Ocean has long been considered as a result of northward subduction of the oceanic lithosphere beneath...
the Central Tianshan Block [Windley et al., 1990; Allen et al., 1992; Gao et al., 2009; Han et al., 2011; Xiao et al., 2013; Xiao and Santosh, 2014]. However, structural analyses in the South Tianshan region and newly discovered Silurian arc-related magmatism in the northeastern Tarim margin have led some authors to argue for a southward or bidirectional polarity of the subduction beneath the northern Tarim margin [Lin et al., 2009, 2013; Charvet et al., 2011; Wang et al., 2011; Ge et al., 2012; Ma et al., 2014]. This work attempts to address the controversy by studying the provenance of detrital zircons from Paleozoic strata in the northwestern part of the Tarim Craton (Figure 1b). We aim to constrain the early stage tectonic evolution of the South Tianshan Ocean and the interaction between adjacent blocks in a context of an evolving Paleo-Asian Ocean regime.

2. Geological Background

The Tianshan orogenic collage lies adjacent to the northern margin of the Tarim Craton (Figure 1b) and extends east-west for ~2500 km across northwestern China, Kyrgyzstan, southern Kazakhstan, Tajikistan, and Uzbekistan. The orogenic collage is traditionally divided into the South, Central/Middle, and North Tianshan by major faults in China, Kyrgyzstan, and Kazakhstan and into the eastern and western Tianshan along ~90°E in China [Xiao et al., 2013]. The South Tianshan Belt extends continuously from northwestern China to southern Kyrgyzstan. The Central Tianshan in China was probably connected to the Kyrgyz Middle Tianshan taking into account their stratigraphic and magmatic similarities and their affinities to the Tarim Craton [Gao et al., 2009; Qian et al., 2009; Kröner et al., 2013; Rojas-Agramonte et al., 2014]. The North Tianshan in Kyrgyzstan possibly corresponds to the Yili Block in China. This study is mainly focused on the western part of the Tianshan orogenic collage since the eastern Tianshan possibly underwent different evolution during Paleozoic time (e.g., X. R. Zhang et al., Tectonic evolution from subduction to arc-continent collision of the Junggar ocean: Constraints from U-Pb dating and Hf isotopes of detrital zircons from the North Tianshan belt, NW China, Geological Society of America Bulletin, under review, 2015). We use the term “Central Tianshan Block” to refer to the Chinese Central Tianshan and Kyrgyz Middle Tianshan in Figure 1b.

The Tarim Craton is composed of Archean-Early Neoproterozoic basement and a Middle Neoproterozoic-Phanerozoic cover (Figure 2) [Lu et al., 2008; Zhao and Cawood, 2012; C. L. Zhang et al., 2013]. Outcrops only occur along the periphery of the craton due to desert sand cover. The basement rocks consist mainly of
medium-high-grade paragneisses and granitoid gneisses, as well as low-grade metasedimentary and volcanic rocks [C. L. Zhang et al., 2013]. The overlying Middle to Late Neoproterozoic cover consists of unmetamorphosed clastic and volcanic rocks, tills, and minor carbonates. The Paleozoic is characterized by thick Cambrian-Ordovician carbonate sequences, Silurian-Devonian siliciclastic sequences, and Carboniferous-Permian clastic-carbonate-volcanic sequences, which are separated by two regional unconformities (Figure 2). Magmatic events occurred in several major episodes from the Neoarchean to the Early Permian (Figure 2) [Lu et al., 2008; Long et al., 2010; Shu et al., 2011; C. L. Zhang et al., 2012]. Circa 2.0–1.8 Ga metamorphic events are widespread and have been suggested as a response to the assembly of the supercontinent Columbia [Zhao et al., 2002, 2004; Lu et al., 2008; C. L. Zhang et al., 2012; J. X. Zhang et al., 2013]. High-/ultrahigh-pressure (HP/UHP) metamorphism took place in southwestern Tarim (Altyn Tagh area) during early Paleozoic time (504–475 Ma) [Liu et al., 2012; Zhang et al., 2014].

**Figure 2.** Sketch stratigraphic columns and major events in the Tarim, South Tianshan, and Central Tianshan areas (summarized from C. L. Zhang et al. [2013], Shu et al. [2011], H. L. Wang et al. [2007], Konopelko et al. [2013], Shu et al. [2013], and Xiao et al. [2013]). See Table S3 (supporting information) for crystallization ages of felsic-intermediate magmatic rocks. E.D.-C. = Early Devonian to Carboniferous. Ar = Archean, Pt1 = Paleoproterozoic, Pt2 = Mesoproterozoic, Pt3 = Neoproterozoic, Cam = Cambrian, O = Ordovician, S = Silurian, D = Devonian, and C = Carboniferous.
The South Tianshan Orogenic Belt marks a Late Paleozoic-Early Mesozoic suture formed by the collision of the Tarim Craton with northern blocks [Xiao et al., 2013]. The main lithology of the South Tianshan Belt is composed of Silurian-Carboniferous marine sedimentary and volcanic rocks metamorphosed at low to medium grade, which are intensely folded and faulted along major thrusts (Figures 1b and 2). Many relics of ophiolite nappes are tectonically imbricated with the sedimentary and volcanic sequences and crop out discontinuously along the South Tianshan Belt (Figure 1b) [Wang et al., 2011, 2012; Jiang et al., 2014]. A HP/UHP belt, represented by blueschists, eclogites, and granulites, extends to near the northern boundary of the South Tianshan Belt (Figure 1b) [e.g., Gao and Klemd, 2003; L. F. Zhang et al., 2007; Hegner et al., 2010]. The peak HP/UHP metamorphism most likely occurred at 320–310 Ma according to recent radiometric dating [Klemd et al., 2011; Q. L. Li et al., 2011; Yang et al., 2013; L. F. Zhang et al., 2013].

The Central Tianshan Block is bounded by the Nikolaev Line-North Nalati Fault to the north and the Atbashy-Inylchek-South Nalati Fault to the south (Figure 1b). Its western counterpart is right laterally displaced by the Talas-Fergana strike-slip fault. The block preserves a Precambrian metamorphic basement consisting mainly of metasediments and orthogneisses (Figure 2) [Konopelko et al., 2013; Shu et al., 2013]. The overlying cover in the Kyrgyz part is represented by Middle to Late Neoproterozoic sandstones/diamictites and Cambrian-Ordovician shales, carbonates, cherts, and turbidites and is unconformably overlain by Middle Devonian-Late Carboniferous shallow-marine carbonate and siliciclastic rocks [Konopelko et al., 2013]. In the Chinese part, the sedimentary cover crops out sporadically, including Ordovician greenschists, sandstones, slates and limestones, Silurian volcano-siliciclastic rocks, and Carboniferous sandstones, siltstones, and shales [Shu et al., 2013]. Radiometric dating results have revealed several Precambrian magmatic events occurring from ~2.3 Ga to ~800 Ma (Figure 2) [Chen et al., 2009; Glorie et al., 2011; L. L. Long et al., 2011; Yu et al., 2011; Kröner et al., 2013]. Intensive magmatism occurred in the Paleozoic and can be divided into three major stages:

Figure 3. Geological map of the Wushi-Keping area (upper) and three cross sections (lower) showing sample locations (modified after Bureau of Geology and Mineral Resources of Xinjiang Uygur Autonomous Region [BGMRXUAR] [1965, 1966] and H. L. Wang et al. [2007]). Cam-O = Cambrian to Ordovician, S1 = Early Silurian, S2 = Middle Silurian, S3-D1 = Late Silurian to Early Devonian, C1 = Early Carboniferous, C2 = Late Carboniferous, and P1 = Early Permian. KPF = Keping Formation, TTF = Tataiertage Formation, YMF = Yimugantawu Formation, KZF = Keziertage Formation, BSF = Bashisuogong Formation, BGF = Biegentawu Formation, SGF = Suogedantawu Formation, and KKF = Kangkelin Formation.
490–390 Ma, 380–310 Ma (Figures 1b and 2), and 300–250 Ma [Alekseev et al., 2009; Gao et al., 2009; Glorie et al., 2011; Seltmann et al., 2011; De Grave et al., 2013; Ma et al., 2014].

3. Geology in the Kepingtage Area, Samples, and Analytical Methods

The most complete Paleozoic sedimentary record of the Tarim Craton is preserved in its northwestern margin—the Kepingtage area (Figure 1b). Near the Wushi-Keping area (Figure 3), the Paleozoic strata overall form a ~70 km wide gentle anticline with an ENE-WSW axis plunging to the WSW at a low angle. These strata were faulted along several thrusts probably activated during Cenozoic time due to the India-Asia collision [Allen et al., 1999]. The strata are well exposed, with dips typically ranging from ~20° to ~45°. The Cambrian and Ordovician strata are characterized by carbonate successions, unconformably overlain by Silurian to Early Devonian usually cross-bedded sandstones (Figures 4, 5a, and 5b). The sandstones are unconformably overlain by the Carboniferous and Permian strata, which are composed mainly of Carboniferous turbidite sequences and limestones (Figures 4 and 5c) and Permian clastic and basaltic volcanic rocks [Carroll et al., 2001].

We collected seven siliciclastic rock samples from the Silurian-Carboniferous strata along three sections for detrital zircon separation and U-Pb and Lu-Hf isotope analyses (Figures 3 and 4). The samples include three quartz arenites from the Middle Silurian to Early Devonian (Figures 5d and 5e) and one conglomerate and three quartz arenites from the Carboniferous (Figure 5f).

Zircon U-Pb and Lu-Hf isotopes were analyzed using the LA-(MC-)ICP-MS method at the Northwest University in China and at the University of Hong Kong, respectively. Detailed information on sample preparation and analytical procedures is available in the supporting information Text S1. For U-Pb dating, only one analysis was performed on each zircon grain. Selected grains were then analyzed for Lu-Hf isotopic compositions. For each grain, the Lu-Hf spot was placed either on the same position as a previous U-Pb spot or on the same zircon.
domain of the grain, based on CL images (Figure 6). We report here a total of 686 U-Pb and 265 Lu-Hf isotope analyses on detrital zircons from the seven samples.

4. Results

Detrital zircons from the seven samples show colors varying from colorless, light pink to rose and lengths between ~60 μm and ~250 μm (Table 1). Three types of zircon internal textures can be recognized according to CL images: clear oscillatory zoning (~71%, type 1), sector/irregular zoning (~7%, type 2), and homogeneous (~22%, type 3) (Figure 6 and Table 1). Most of the zircons are magmatic in origin, as indicated by their clear
oscillatory zoning and high Th/U ratios (mostly 0.2–1.6, Figure 7) [Corfu et al., 2003], although a few of them are probably metamorphic according to their core-rim structures and/or low Th/U ratios (<0.1) (Figure 7).

U-Pb and Lu-Hf isotopic data of analyzed detrital zircons are presented in Tables S1 and S2 (supporting information), respectively. Approximately 5.5% U-Pb analyses were excluded from the discussion because of their large signal variations and/or high age discordance (not between 90% and 110%). The three Middle Silurian to Early Devonian samples (LT22A, LT20A, and LT19A) yielded detrital zircon ages almost identical to the four Carboniferous samples (LT14A, LT13A, LT12A, and LT11A) (Figure 8). These ages range from ~413 Ma to ~346 Ma and cluster around five main populations on a normalized probability plot: 2.8–2.3 Ga, 2.0–1.7 Ga, 1.30–0.90 Ga, 0.84–0.60 Ga, and 0.50–0.40 Ga (Figures 8c–8i). The youngest age component for each sample was calculated using both the weighted mean $^{206}\text{Pb}/^{238}\text{U}$ age method and the Isoplot-embedded “Unmix Ages” routine method [Ludwig, 2003]. The two methods yielded consistent youngest age components ranging from 414 ± 9 Ma to 456 ± 5 Ma (Table 1).

The Hf isotope results of detrital zircons from the three Middle Silurian-Early Devonian samples also roughly overlap with those of two selected Carboniferous samples (LT12A and LT11A), with $\varepsilon_{\text{Hf}}(t)$ values varying from −21.7 to +11.3 (Figure 9).

5. Discussion

5.1. Detrital Zircon Provenance

Our results indicate similar zircon morphology and Th/U ratios, comparable U-Pb age distributions, and overlapping Hf isotope between the Middle Silurian-Early Devonian samples (Figures 8 and 9). These features suggest that the Carboniferous rocks probably represent recycled materials sourced from the three Middle Silurian-Early Devonian samples (LT22A, LT20A, and LT19A), with ages ranging from 413 Ma to 346 Ma. The youngest age component for each sample was calculated using both the weighted mean $^{206}\text{Pb}/^{238}\text{U}$ age method and the Isoplot-embedded “Unmix Ages” routine method [Ludwig, 2003]. The two methods yielded consistent youngest age components ranging from 414 ± 9 Ma to 456 ± 5 Ma (Table 1).

Table 1. Summary of Sample Location, Detrital Zircon Morphology, and Analytical Information$^a$

<table>
<thead>
<tr>
<th>Sample</th>
<th>Age</th>
<th>GPS Location</th>
<th>Length (µm)</th>
<th>Aspect Ratio</th>
<th>Roun.-Ellip. Grains$^a$</th>
<th>Eu.-Sub. Grains$^a$</th>
<th>Oscillatory Zoning</th>
<th>Sector/Irregular Zoning</th>
<th>Homogeneous</th>
<th>No. of Valid (All) U-Pb Analyses</th>
<th>No. of Lu-Hf Analyses</th>
<th>Youngest Age Component ± 2σ (No. of Spots, MSWD)</th>
</tr>
</thead>
<tbody>
<tr>
<td>LT11A</td>
<td>C2</td>
<td>41°6′20″N, 79°16′39″E</td>
<td>80–250</td>
<td>1.0–2.6</td>
<td>74%</td>
<td>16%</td>
<td>70%</td>
<td>6%</td>
<td>24%</td>
<td>97 (100)</td>
<td>50</td>
<td>431 ± 6 Ma (4, 1.7)$^b$</td>
</tr>
<tr>
<td>LT12A</td>
<td>C2</td>
<td>41°7′54″N, 79°16′34″E</td>
<td>80–220</td>
<td>1.0–2.5</td>
<td>86%</td>
<td>5%</td>
<td>67%</td>
<td>8%</td>
<td>25%</td>
<td>97 (101)</td>
<td>63</td>
<td>449 ± 6 Ma (5, 1.5)$^b$</td>
</tr>
<tr>
<td>LT13A</td>
<td>C2</td>
<td>41°8′23″N, 79°16′45″E</td>
<td>60–160</td>
<td>1.0–2.5</td>
<td>82%</td>
<td>5%</td>
<td>76%</td>
<td>6%</td>
<td>18%</td>
<td>93 (100)</td>
<td>0</td>
<td>414 ± 9 Ma (2, 0.01)$^b$</td>
</tr>
<tr>
<td>LT14A</td>
<td>C1</td>
<td>41°9′39″N, 79°16′41″E</td>
<td>60–140</td>
<td>1.0–2.7</td>
<td>74%</td>
<td>4%</td>
<td>77%</td>
<td>7%</td>
<td>16%</td>
<td>88 (93)</td>
<td>0</td>
<td>416 ± 10 Ma (1)</td>
</tr>
<tr>
<td>LT19A</td>
<td>S2  D1</td>
<td>40°3′51″N, 78°49′55″E</td>
<td>70–190</td>
<td>1.0–2.5</td>
<td>43%</td>
<td>29%</td>
<td>76%</td>
<td>9%</td>
<td>15%</td>
<td>93 (106)</td>
<td>54</td>
<td>421 ± 5 Ma (5, 1.3)$^b$, 420 ± 7 Ma $^c$</td>
</tr>
<tr>
<td>LT20A</td>
<td>S2  D1</td>
<td>40°3′36″N, 78°50′0″E</td>
<td>100–220</td>
<td>1.0–2.5</td>
<td>71%</td>
<td>10%</td>
<td>73%</td>
<td>9%</td>
<td>18%</td>
<td>92 (94)</td>
<td>52</td>
<td>456 ± 5 Ma (6, 1.7)$^b$</td>
</tr>
<tr>
<td>LT22A</td>
<td>S2</td>
<td>40°4′41″N, 79°50′11″E</td>
<td>90–230</td>
<td>1.0–3.0</td>
<td>61%</td>
<td>25%</td>
<td>60%</td>
<td>1%</td>
<td>39%</td>
<td>88 (92)</td>
<td>46</td>
<td>428 ± 4 Ma (11, 1.3)$^b$, 427 ± 5 Ma $^c$</td>
</tr>
</tbody>
</table>

$^a$ Roun./Ellip. = rounded and ellipsoidal. Eu./Sub. = euhedral and subhedral.

$^b$ The youngest age was calculated by weighted mean of several youngest $^{206}\text{Pb}/^{238}\text{U}$ apparent ages which resulted in reasonable MSWDs (<2).

$^c$ The youngest age was calculated using Unmix Ages routine in Isoplot program [Ludwig, 2003] for ages between 410 and 460 Ma by assuming two mixed components.
from the Silurian-Devonian sedimentary successions due to weathering and reworking. This is also consistent with the inference based on previous stratigraphic investigations [Carroll et al., 2001]. Therefore, only the provenance of Silurian-Early Devonian sediments is discussed below.

A significant number of Early Precambrian ages, clustering at 2.8–2.3 Ga and 2.1–1.7 Ga, have been detected in the three Middle Silurian-Early Devonian samples (Figures 8g–8i). The two age populations are consistent with the two early stage magmatic episodes in the Tarim Craton, with one at 2.8–2.3 Ga and the other at 2.0–1.75 Ga (Figures 2 and 8b). Relevant rocks are represented by widespread granitoid gneisses preserved in the cratonic basement [Lu et al., 2008; Long et al., 2010, 2012; Lei et al., 2012; C. L. Zhang et al., 2012; J. X. Zhang et al., 2013]. Detrital zircons in these clusters are typically well rounded or ellipsoidal with pitted surfaces, implying multiple episodes of recycling and/or long-distance transport. In addition, the $\varepsilon_{\text{Hf}}(t)$ values and $T_{DM2}$ ages of these zircons are also consistent with those of the Early Precambrian magmatic rocks (Figure 9). Therefore, the 2.8–2.3 and 2.1–1.7 Ga detrital zircons from Middle Silurian to Early Devonian rocks were probably derived from the basement of the Tarim Craton.

Grenville-age detrital zircons (circa 1300–900 Ma) are abundant in the Middle Silurian-Early Devonian samples (Figures 8g–8i). However, contemporaneous magmatic events are absent in the study area (northwestern Tarim) and are scarce in other parts of the Tarim Craton (minor in northeastern Tarim [Shu et al., 2011]) except for the southwestern part—the Altyn Tagh area. Recent radiometric dating in the Altyn Tagh area has revealed intense granitic magmatism occurring in the period of 1040–900 Ma [C. Wang et al., 2013; Yu et al., 2013; Long et al., 2014]. These events likely corresponded to the “Tarimian Orogeny” that resulted in the assembly of the Tarim cratonic basement [e.g., Lu et al., 2008]. Since the younger portion of our 1300–900 Ma detrital zircons shares similar crystallization ages and relatively juvenile $\varepsilon_{\text{Hf}}(t)$ values with zircons from these Grenville-age granitoids (Figures 8 and 9),

![Figure 7. Th/U ratios versus U-Pb ages of three types of detrital zircons (see Figure 6).](image_url)
we suggest that a large proportion of these detrital zircons were eroded and transported from the Altyn Tagh area. This is consistent with the commonly well rounded shapes of these zircons, possibly indicative of long-distance transportation.

A large number of detrital zircons in the Middle Silurian-Early Devonian samples have ages spanning ~880–600 Ma and can roughly be divided into two intervals at 880–720 Ma and 680–600 Ma (Figures 8g–8i). These two intervals are largely coeval with the Middle to Late Neoproterozoic magmatic events occurring mainly in the northern Tarim Craton, represented by diverse magmatic rocks with radiometric ages at 840–720 Ma and 670–610 Ma (Figure 8b) [e.g., C. L. Zhang et al., 2007; Xu et al., 2009; X. P. Long et al., 2011; Shu et al., 2011; Ge et al., 2014]. Therefore, the 880–600 Ma detrital zircons in this study are likely of local origin from the northern part of the Tarim Craton.

The 500–400 Ma detrital zircons form the most prominent age peaks for our samples (Figures 8c–8i). This age interval is consistent with intense magmatic events occurring during 460–390 Ma in the northern (mainly northeastern) Tarim Craton (Figures 8b and 10) [Ge et al., 2012, 2014; Huang et al., 2013; Lin et al., 2013; Z. Y. Zhao et al., 2014] and during 490–390 Ma in the Central Tianshan Block (Figures 8a and 10) [Gao et al., 2009; Dong et al., 2011; Glorie et al., 2011; L. L. Long et al., 2011; Zhu, 2011; Ma et al., 2014]. Related magmatic rocks are dominated by granitoids, with some felsic volcanic rocks and minor diorites and ignimbrites. The 500–400 Ma detrital zircons in this study are mostly euhedral to subhedral with clear oscillatory zoning (Figure 6), high Th/U ratios (Figure 7), and large length/width ratios up to 3.5, indicating magmatic grains likely derived from near-source regions. Also, these zircons have a large spread of εHf(t) values (−17 to +12), largely overlapping with those of the early Paleozoic magmatic rocks (εHf(t) mostly between −23 and +13) in the Central Tianshan and the northern Tarim (Figure 9). Moreover, detailed work,
including point counting of sandstones and cross-bed measurements, on Middle Silurian-Early Devonian strata indicates a recycled orogenic provenance and SSW-W directed paleocurrents (Figure 4) [Carroll et al., 2001]. From the above evidence, it is believed that the 500–400 Ma detrital zircons were derived from the magmatic rocks in the northern Tarim Craton and the Central Tianshan Block.

In summary, our results show that the Carboniferous sediments in northwestern Tarim are recycled materials mainly from the Silurian-Devonian strata. The Precambrian detrital zircons from the Middle Silurian to Early Devonian rocks were primarily derived from the Tarim Craton, whereas the early Paleozoic detrital zircons probably came from the early Paleozoic magmatic rocks in northern Tarim and the Central Tianshan.

5.2. Constraint on Depositional Ages

Because the ages of the Carboniferous strata are supported by fossil assemblages [Drafting Group for the Regional Stratigraphic Table of Xinjiang Uygur Autonomous Region, 1981; Carroll et al., 1995; Jia et al., 2004], we only discuss the depositional ages of the poorly constrained Keziertage and Yimugantawu formations. Owing to the scarcity of fossils, the depositional age of the Keziertage Formation is uncertain and has been presumed to be the Early to Middle Silurian [Zhao et al., 2009], the Late Silurian [Wang et al., 2002], or the Late Silurian to Middle Devonian [Zhang and Xi, 1997]. Limited fossils found in the Yimugantawu Formation also led different authors to argue for different depositional ages: Middle Silurian [Liu, 1995; Zhang and Wang, 1995; Zhang and Xi, 1997] or latest Early Silurian [Wang et al., 1998; Sansom et al., 2005].

Previous studies have demonstrated that the youngest detrital zircon age component approximates the age of deposition if continuous sedimentation in a basin has a source region with continuous magmatism [Dickinson and Gehrels, 2009; Wu et al., 2010]. It is the case with our samples because we have shown that the early Paleozoic detrital zircons in the northwestern Tarim margin were transported from the northern magmatic arc that was continuously active during 490–390 Ma. The five youngest detrital zircons from the Keziertage Formation (sample LT19A) yielded a mean $^{206}Pb/^{238}U$ age of 421 ± 5 Ma (mean square weighted deviate (MSWD) = 1.3) (Table 1). This age thus can be treated as the depositional age, indicating that the Keziertage Formation likely formed in the Late Silurian to Early Devonian. For the same reason, the Yimugantawu Formation was probably deposited in the Middle Silurian, as indicated by the mean age of 428 ± 4 Ma (MSWD = 1.3) for 11 youngest analyses (Table 1).

5.3. Tectonic Implications

5.3.1. Tarim-Central Tianshan Connection During Early Paleozoic Time

The South Tianshan Ocean was formerly assumed to be a long-lived, wide ocean separating the Tarim Craton to the south and independent blocks to the north (Central Tianshan and Yili Blocks) [Windley et al., 1990; Allen et al., 1992]. However, recent investigations have revealed comparable age patterns, both for xenocrystic zircons from basement rocks and for detrital zircons from Neoproterozoic to early Paleozoic sedimentary rocks, between the Tarim Craton and the Central Tianshan Block [Glorie et al., 2011; Ma et al., 2012a, 2012b; Jian et al., 2013; Kröner et al., 2013; Rojas-Agramonte et al., 2014]. These similarities suggest that there was a connection between the two tectonic units, which were later separated by the opening of the South Tianshan Ocean [Shu et al., 2002; Wang et al., 2008, 2011; Gao et al., 2009; Charvet et al., 2011].

However, controversy remains about the timing of their separation due to opening of the South Tianshan Ocean, with age estimates ranging from Cambrian to Middle Devonian [Shu et al., 2002; Wang et al., 2008; Gao et al., 2009; Charvet et al., 2011; Lin et al., 2013]. More recently, a Neoproterozoic separation model has been proposed based on geochemical and geochronological studies on granitoids in the northeastern Tarim Craton [Ge et al., 2014].

Our results indicate that the significant population of 500–400 Ma detrital zircons from the Middle Silurian to Early Devonian sandstones was most likely derived from the 490–390 Ma magmatic rocks in the northern Tarim margin and the Central Tianshan Block (Figure 10). These magmatic rocks are dominantly calc-alkaline in composition and have been considered to be arc related [Gao et al., 2009; Dong et al., 2011; Zhu, 2011; Lin et al., 2013; Ge et al., 2014; Ma et al., 2014; Z. Y. Zhao et al., 2014]. Some authors interpret these rocks to be a result of divergent, double-sided subduction (both southward and northward) of the South Tianshan Ocean, implying a separation of the Tarim and the Central Tianshan before the Ordovician [Ge et al., 2012; Lin et al., 2013; Ma et al., 2014]. However, the magmatic rocks in these two regions share similar characteristics such as crystallization-age patterns (Figures 8a and 8b), zircon $ε_{Hf}(t)$ values (Figure 9) and geochemical
compositions. It is more likely that these magmatic rocks in the Central Tianshan and the northern Tarim were joined together in a broad magmatic arc (more than 200 km wide, Figure 10) during early Paleozoic time, prior to the opening of the South Tianshan Ocean. As discussed below, this interpretation is more consistent not only with our detrital zircon ages but also with other events. According to a compiled data set of detrital zircon ages from the northern Tarim and the Central Tianshan, the population of Grenville-age detrital zircons is nearly absent in Neoproterozoic strata but increase significantly in Silurian-Devonian strata (Figure 11). This is the same trend for the northern Tarim and the Central Tianshan, also suggesting that they were likely together in the Silurian and received these Grenville-age detritus from the Altyn Tagh area. Moreover, this connection is supported by the similarity of Ordovician-Silurian conodont and brachiopod species found in the Central Tianshan, South Tianshan, and Tarim regions [Rong et al., 1995; Z. H. Wang et al., 2007].

Therefore, we suggest that the Central Tianshan Block was connected to the northern Tarim margin to form a broad continental arc during Ordovician-Silurian time. The present-day northern part of the Tarim Craton was likely located in a retroarc foreland basin inboard of the arc (Figure 12b). This arc may have resulted from the southward subduction of the Terskey Oceanic lithosphere (namely, Turkestan 1 Ocean in Wilhem et al. [2012]).

5.3.2. Early Devonian Interarc/Back-Arc Opening of the South Tianshan Ocean

It has been well documented that 380–310 Ma felsic magmatism was widespread in the Central Tianshan Block (Figure 10) [e.g., L. L. Long et al., 2011; X. Y. Xu et al., 2013; Ma et al., 2014]. In contrast, our results indicate that the Early and Late Carboniferous samples in the northwestern Tarim Craton did not receive any detrital zircon grains younger than ~400 Ma. Cross bedding in Carboniferous strata has suggested prevailing northward paleocurrents (Figure 4) [Carroll et al., 1995]. The most likely interpretation is that the Central Tianshan Block was separated from the Tarim Craton by the back-arc opening of the South Tianshan Ocean, which obstructed the transport of detritus (Figure 12c). This event probably happened in the Early Devonian, corresponding to the cessation of magmatism at ~390 Ma on the northern margin of the Tarim Craton (Figure 8b) and to the regional unconformity at the top of the Silurian to Early Devonian siliciclastic sequence (Figure 4). The magmatic quiescent period in the northern Tarim lasted to ~300 Ma and was coeval with the development of thick Devonian-Carboniferous carbonate and turbidite sequences now preserved in the region of the northern Tarim and the South Tianshan Belt [Allen et al., 1992; Gao et al., 1998; Xiao et al., 2013]. This evidence, together with our detrital zircon results from Carboniferous rocks, suggests a passive continental environment along the northern Tarim margin in Devonian-Carboniferous time. During this period, the South Tianshan oceanic lithosphere was likely subducted northward because intense calc-alkaline magmatism resumed in the Central Tianshan Block since ~370 Ma (Figures 8a, 10, and 12d).
The Early Devonian opening of the South Tianshan Ocean is also supported by the age of radiolarian cherts and ophiolitic relics preserved in the South Tianshan Orogenic Belt. Recent investigations have indicated that these radiolarian cherts were deposited in the period between Early Devonian and Carboniferous [Wu and Li, 2013], such as at the sites of Ouxidaban [Li et al., 2007], Mandaleke [Han et al., 2011], and Heiyingshan [Shu et al., 2007] in the Chinese South Tianshan and at Atbashi [Alekseev et al., 2007] in the Kyrgyz South Tianshan. Recent radiometric dating of ophiolites in the South Tianshan Belt has yielded formation ages ranging from ~423 Ma to ~310 Ma (Figure 10). Although older ages (439–435 Ma) of the Yushugou mélange were reported [Yang et al., 2011], whether this unit belongs to true ophiolite or peridotites related to mantle diapirism is still controversial [Jian et al., 2013]. Yang et al. [2005] obtained two oldest ages of 590 ± 11 Ma and 600 ± 15 Ma for the Dalubayi ophiolite using the single-grain zircon Pb-Pb evaporation method. However, the reliability of the two ages is unknown since the original data and the details of the method were not provided. In addition, recent interpretations of seismic data in the middle and northern Tarim have revealed Ordovician to Middle Silurian compressional structures and Late Silurian to Carboniferous extensional structures [Li et al., 2014]. This is consistent with our suggestion of the Late Silurian lithospheric extension and the Early Devonian back-arc opening of the South Tianshan Ocean.

5.3.3. Tectonic Model and Implications

A new tectonic model is proposed here to reinterpret and reconcile available geological observations and analytical data in the Tarim, South Tianshan, and Central Tianshan regions (Figure 12). During Cambrian time the Central Tianshan Block was connected to the northern Tarim Craton to form a passive continental margin along the northern part of a proto-Tarim Craton, facing northward to the Terskey Ocean, a southern part of the Paleo-Asian Ocean (Figure 12a). Possibly since the Early Ordovician (~480 Ma), the northern margin of the proto-Tarim Craton progressively changed to a broad active continental arc (Figure 12b), reflected by large volumes of 490–390 Ma calc-alkaline magmatic rocks in the northern Tarim and Central Tianshan region. The broad arc most likely resulted from
the relatively low angle southward subduction of the Terskey oceanic lithosphere. It is possible that subduction initiation was induced by the continental collision occurring along the southeastern margin (Altyn Tagh area) of the Tarim Craton, where HP/UHP metamorphism has been constrained at 504–475 Ma [Zhang et al., 1999, 2004, 2005, 2014; Liu et al., 2009, 2012; Cao et al., 2013]. The northward force of the collision may have pushed the Tarim Craton to advance toward the Terskey oceanic lithosphere and resulted in a shallow-dipping angle of oceanic subduction and a broad magmatic arc under a compressional tectonic regime. This scenario resembles the formation of the Andes arc [Husson et al., 2008; Cawood et al., 2009]. This process can also account for the sudden increase of Grenville-age detrital zircons in Silurian-Devonian sediments, compared to Neoproterozoic rocks, in the study area (Figure 11). During Early to Middle Silurian time, a retroarc foreland basin developed inboard of the continental arc along the Kepingtage-Kuche-Kuluketage area (Figure 12b), due to lithospheric flexure caused by topographic loading of the magmatic arc and related thrust sheets [DeCelles and Giles, 1996]. The basin mainly received sediments from the northern magmatic arc with involvement of the Tarim basement rocks, as suggested by our detrital zircon studies.

Lithospheric extension in the arc/back-arc region probably happened in the Late Silurian to Early Devonian along the present-day South Tianshan Belt (Figure 12c), as indicated by the initiation of Late Silurian extensional structures in the northern Tarim [Li et al., 2014]. We suggest that the extension was possibly caused by the trench retreat due to slab rollback of the subducting Terskey oceanic lithosphere. Further extension caused the interarc/back-arc opening of the South Tianshan Ocean in the Early Devonian, leaving a remnant arc in the northeastern Tarim (Kuluketage area, Figure 12c). This process can be compared to the development of the Japan Sea [Tamaki, 1985], which also opened initially within a broad volcanic arc associated with shallow angle subduction of the Pacific slab. Polyphase granulite facies metamorphism from 396 Ma to 310 Ma was recorded in the Yushugou mafic granulites [Wang et al., 2003; Zhou et al., 2004; T. F. Li et al., 2011; Jian et al., 2013]. These events might be related to lithosphere extension during the opening of the South Tianshan Ocean and subsequent development of island arcs in the ocean basin [Kemp et al., 2007; Dhuime et al., 2009]. Our detrital zircon studies suggest that the South Tianshan Ocean probably still existed in the Late Carboniferous (Figure 12d) because the Early to Late Carboniferous siliciclastic rocks in the northeastern Tarim do not contain any 380–310 Ma detrital zircons, which should be ubiquitous in the Central Tianshan Block. This result does not support some previous studies advocating a closure time of the South Tianshan Ocean in Late Devonian to Early Carboniferous time [Windley et al., 1990; Lin et al., 2009; Charvet et al., 2011; Wang et al., 2011; X. Y. Xu et al., 2013].

Overall, our model suggests a tectonic transition from a compressional continental arc to extensional back-arc opening, which is consistent with the tectonic model switching from advancing to retreating accretionary orogenesis [Royden, 1993; Cawood et al., 2009]. This tectonic transition could be an important mechanism for the generation of arcs and terranes at early stages of the accretionary evolution of the Paleo-Asian Ocean, prior to the amalgamation of the Central Asian Orogenic Belt.

In a global context, the rifting of the Central Tianshan Block from the Tarim Craton was likely coincident with the separation of the Tarim Craton from the northeastern margin of Gondwana, as suggested by recent paleomagnetic and geological data [Fang et al., 1996; Zhan et al., 2007; Sun and Huang, 2009; Li et al., 2013; H. H. Wang et al., 2013; P. Zhao et al., 2014]. These data have suggested a long-term connection, lasting from the Neoproterozoic to the Middle Silurian, between Tarim and Australia and a separation during the Late Silurian to Early Devonian [e.g., P. Zhao et al., 2014]. Comprehensive paleontological comparisons have also suggested that Australia has early Paleozoic fauna and flora affinity with East and Southeast Asian blocks, such as Tarim, south China, and North China [Metcalf, 2013]. The separation of these blocks from the Australian margin of Gondwana likely occurred in the Middle Devonian in association with the opening of the Paleo-Tethys Ocean [Metcalf, 2013]. Therefore, the Early Devonian rifting of the Central Tianshan Block from the Tarim Craton and the later amalgamation probably witnessed a successive northward drift of East and Southeast Asian blocks from eastern Gondwana and a later accretion to Eurasia.

6. Conclusions

The following main conclusions can be drawn based on our detrital zircon studies in the northwestern Tarim Craton and on comparisons with recent literature data in adjacent regions.
1. The Middle Silurian to Early Devonian sandstones in the Kepingtage area yield detrital zircon U-Pb ages and HF isotopes comparable to those of magmatic rocks distributed in the Tarim Craton and the Central Tianshan Block. These sediments were most likely deposited in a retroarc foreland basin situated inboard of an Andean-type magmatic arc at the northern margin of the proto-Tarim Craton.

2. The Carboniferous samples from the Kepingtage area do not contain detrital zircons younger than ~400 Ma, implying a source from recycled autochthonous detritus. The Central Tianshan Block, which underwent intense granitic magmatism during 380–310 Ma, was likely separated from the Tarim Craton during Early Devonian by the interarc/back-arc opening of the South Tianshan Ocean. The ocean basin probably did not close until at least the early Late Carboniferous.

3. A tectonic switch from an advancing accretionary orogen to a retreating one likely occurred in the Tianshan and Tarim region during Late Silurian to Early Devonian time.

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