Final Subduction Processes of the Paleo-Asian Ocean in the Alxa Tectonic Belt (NW China): Constraints From Field and Chronological Data of Permian Arc-Related Volcano-Sedimentary Rocks

Dongfang Song1,2,3, Wenjiao Xiao1,2,4,5, Alan S. Collins3, Stijn Glorie3, Chunming Han1,2,4,5, and Yongchen Li1,2

1State Key Laboratory of Lithospheric Evolution, Institute of Geology and Geophysics, Chinese Academy of Sciences, Beijing, China, 2Institutions of Earth Sciences, Chinese Academy of Sciences, Beijing, China, 3Centre for Tectonics Resources and Exploration (TRaX), Department of Earth Sciences, The University of Adelaide, Adelaide, SA, Australia, 4CAS Centre for Excellence in Tibetan Plateau Earth Sciences, Chinese Academy of Sciences, Beijing, China, 5Xinjiang Research Centre for Mineral Resources, Xinjiang Institute of Ecology and Geography, Chinese Academy of Sciences, Urumqi, China

Abstract The timing of final subduction and closure of the Paleo-Asian Ocean (PAO) is controversial. Located in a key position within the southern Central Asian Orogenic Belt, the Alxa Tectonic Belt (ATB) provides a crucial window to evaluate the final subduction processes of the PAO. This study presents field and geochronological data for Permian volcano-sedimentary rocks from the southwestern ATB. Field observations revealed a syntectonic unconformity between the Middle and Upper Permian strata. Detrital zircon U-Pb analyses show a major peak at ~273 Ma and a subordinate peak at ~440 Ma for the Middle Permian sample. The Upper Permian samples show consistently unimodal age spectra with single peaks at ~261 and ~263 Ma, respectively. The Permian zircons from the analyzed samples yield predominately positive εHf(t) values, indicating major juvenile magmatic processes mixed with limited recycled Precambrian basement. The diagnostic zircon U-Pb-Hf isotopic characteristics and ubiquitous intermediate and felsic volcanic detritus in these rocks indicate rapid sedimentation sourced from a proximal magmatic terrane in a suprasubduction zone environment. The Paleozoic zircon U-Pb age peaks from this study are comparable to those for the Permian arc-related sediments along the Solonker Suture Zone, thus linking the Alxa active margin with the northern margin of the North China Craton during Middle-Late Permian times. Our study thus provides key constraints for the final subduction processes of the PAO, documented within the ATB, before the terminal amalgamation of the southern Central Asian Orogenic Belt.

1. Introduction

The Central Asian Orogenic Belt (CAOB circa 1.0 Ga–250 Ma, or Altaids circa 600–250 Ma), located between the Karakum, Tarim and North China cratons to the south and the Baltic and Siberian cratons to the north, constitutes a major tectonic domain of the Asian continent (Figure 1; e.g., Jahn et al., 2000; Safonova et al., 2017; Şengör et al., 1993; Xiao, Windley, Huang, et al., 2009; Xiao, Windley, Yuan, et al., 2009). The CAOB is one of the largest and most complex Phanerozoic accretionary systems in the world with a long evolutionary history from circa 1000 Ma to circa 250 Ma and has long been the focus of many international studies due to its importance for understanding continental growth, geodynamics, and metallogeny (e.g., Fu et al., 2016; Schulmann & Paterson, 2011; Şengör & Natal’in, 1996; Wilhem et al., 2012; Windley et al., 2007; Xiao et al., 2015; Xu et al., 2013). Different models have been proposed for deciphering the formation mechanism and tectonic evolutionary history of the CAOB, which can be summarized into two end-member models: (1) single-arc accretion model (Şengör et al., 1993; Şengör & Natal’in, 1996), and (2) multiple subduction-accretion model (e.g., Safonova et al., 2017; Windley et al., 2007; Xiao, Windley, Yuan, et al., 2009; Xiao et al., 2013). Despite the existence of different opinions on the specific mechanism for the formation of the CAOB, there has been broad consensus that the CAOB was formed through successive accretion of magmatic arcs, arc-flanking basins, subduction-accretion complexes, ophiolites, seamounts, and continental fragments, along with large-scale strike-slip faulting and orocline bending during the continuous subduction and final closure of the Paleo-Asian Ocean (PAO; Charvet et al., 2007; Mossakovskiy et al., 1993; Şengör & Natal’in, 1996; Wakita et al., 2013; Windley et al., 2007; Xiao, Windley, Yuan, et al., 2009; Xiao, Huang, et al., 2010).
It is widely considered that the growth of the CAOB generally migrated southward (present-day coordinates). Thus, the southernmost segment of the CAOB (Figure 1), extending from the Tianshan Orogenic Belt in the west through the Beishan and Alxa tectonic belts in the middle to the Inner Mongolian Orogenic Belt in the east, has long been considered as the location that records the final subduction history of the PAO and the terminal amalgamation of the CAOB (e.g., Han et al., 2011; Q. Liu, Zhao, Han, Eizenhofer, Zhu, Hou, & Zhang, 2017; Şengör et al., 1993; Xiao et al., 2003, 2013). A large number of publications have been focusing on the tectonic evolution of the western and eastern segments of the southern CAOB (e.g., Charvet et al., 2007; Eizenhöfer et al., 2014; Han et al., 2011; Jepson et al., 2018; Jian et al., 2008, 2010; Y. J. Li et al., 2010, Y. L. Li et al., 2016; Song et al., 2015; B. Wang et al., 2011; Xiao, Windley, Yuan, et al., 2009; Xiao, Huang, et al., 2010), while relatively little attention has been given to the Alxa area in the middle part of the southernmost CAOB (Figure 2; Feng et al., 2013; Q. Liu et al., 2016; Q. Liu, Zhao, Han, Eizenhofer, Zhu, Hou, & Zhang, 2017; Q. Liu, Zhao, Han, Eizenhofer, Zhu, Hou, Zhang, & Wang, 2017). This makes the Alxa area one of the least understood tectonic belts within the CAOB. Moreover, it is still highly ambiguous how the western CAOB connects to the eastern CAOB during the Late Paleozoic.

In the Tianshan Orogenic Belt, the South Tianshan Suture Zone (South Tianshan accretionary complex), composed of turbidites, ophiolitic mélanges, and (ultra) high-pressure metamorphic rocks, is regarded as the location where the Central Tianshan arc amalgamated with the northern margin of the Tarim Craton (Figure 1). Different views on the timing of the final accretion-collision process of the South Tianshan Suture Zone exist, which can be summarized into Late Devonian–Early Carboniferous (e.g., Charvet et al., 2007), Late Carboniferous (e.g., Gao et al., 2011; Han et al., 2011; B. Wang et al., 2011), and Late Permian–Early Triassic (e.g., Jepson et al., 2018; Xiao et al., 2013; L. F. Zhang et al., 2007). In the eastern segment of the CAOB, the Solonker Suture Zone has been considered as the place where the eastern branch of the PAO closed in a manner of accretionary wedge-wedge collision, although the timing and specific geodynamic processes for the final formation of the Solonker Suture Zone is highly debatable (e.g., Jian et al., 2008; Xiao et al., 2003; Xu et al., 2013). The divergent double subduction of the PAO since Cambrian generated the Southern Orogen, which developed on the northern margin of the North China Craton (NCC). The Northern Orogen was built on the southern margin of the Uliastai microcontinent (Jian et al., 2010).
During the Permian, tectonic activity continued with subduction, arc formation, and ridge-trench interaction along the Southern Orogen, and the final closure of the PAO in the Late Permian led to the formation of the Solonker Suture Zone (Jian et al., 2010; Xiao et al., 2003). Recent detailed geochronological and geochemical study on Permian arc-related sediments further constrained the final closure of the PAO along the Solonker Suture Zone to be Late Permian–Early Triassic (Eizenhöfer et al., 2014).

The Alxa area is located in a key tectonic position linking the Tianshan and Beishan orogenic belts to the west with the Solonker Suture Zone to the east (Figure 1). It is usually termed the Alxa Block in the literature since Precambrian metamorphic basement rocks sporadically distribute across this region (Figure 2; Bureau of Geology and Mineral Resources of Nei Mongol Autonomous Region, BGMRNM, 1991). However, the outcrops in the Alxa area are mostly Paleozoic intrusions and volcano-sedimentary rocks, as well as some ultramafic rocks including thrust-imbricated ophiolitic mélanges (Figure 2; e.g., Feng et al., 2013; Zheng et al., 2014); therefore, we use the term Alxa Tectonic Belt (ATB) in this study to fully incorporate the complicated evolutionary history of the Alxa area, particularly during the Paleozoic (Song et al., 2018). Despite its importance in understanding the accretionary processes of the southern CAOB, the Late Paleozoic geography and tectonic evolutionary history of major tectonic units in the ATB have not been satisfactorily resolved. In particular, there are controversies on the tectonic setting for the ATB during the Late Carboniferous–Permian. For example, Dan, Li, Wang, Tang, et al. (2014) proposed that the oceanic subduction in the ATB ceased before Late Carboniferous and the large-scale Permian intrusions distributed in this region represent a silicic large igneous province induced by the Permian Tarim mantle plume. Alternatively, Dang et al. (2011) and Jiang, Li, et al. (2011) proposed a model of intraplate rifting in a postorogenic setting to interpret the Late Carboniferous to Permian volcanism and sedimentation in this area. Furthermore, continuous subduction and accretion processes have also been proposed to exist in the ATB during the Late Carboniferous (e.g., X. J. Shi et al., 2014), or until Late Permian–Early Triassic (Feng et al., 2013; Lin et al., 2014; Xiao et al., 2015). Based on the geochemical and geochronological studies on Late Paleozoic granitoids, Q. Liu, Zhao, Han, Eizenhofer, Zhu, Hou, and Zhang (2017) and Q. Liu, Zhao, Han, Eizenhofer, Zhu, Hou, Zhang, and Wang (2017) proposed that the PAO was closed at ~280–265 Ma in the ATB. However, Shi et al. (2016) suggests that the Permian volcanic-sedimentary rocks in the ATB was formed in an incipient continental rift setting after the final closure of the PAO and before the Middle Devonian. Moreover, there is still little consensus on
the location of the southernmost CAOB and the boundary between the subduction-dominated CAOB and the pericratonic basement in the Alxa area (J. J. Zhang, Wang, et al., 2015). These on-going debates call for more detailed investigation and an extensive study of the Permian tectonic processes across the ATB.

Subduction-accretionary complexes form as the direct result of oceanic plate subduction and are considered to be one of the most important terranes in accretionary orogenic belts (Şengör & Natal'in, 1996). However, many subduction zones may have no records of typical accretionary complexes where subduction erosion develops, as exemplified by modern subduction zones along the Pacific Ocean (Closs & Shreve, 1988). Alternatively, the recognition of active margin components such as subduction-related volcanic-sedimentary successions eroded from magmatic arcs and then deposited in arc-related basins provide the essential constraints on the subduction-accretion history of a consumed ocean. This work evaluates the timing of final subduction events of the PAO in the ATB by integrated field geological and LA-(MC)-ICP-MS zircon U-Pb-Hf isotopic studies on the Permian volcano-sedimentary rocks in the southwestern segment of the ATB. These new data not only provide valuable information for when, where, and how the PAO finally closed in the ATB but also enhance our understanding of the paleogeography during the Permian along the southern CAOB.

2. Regional Tectonics

The ATB is separated from the Early Paleozoic North Qilian Orogenic Belt by the Longshoushan Fault (or the Hexi Corridor) to the south and from the NCC by a series of NE-SW trending faults (i.e., Langshan Fault) to the east (Figure 2). The western part of the ATB is largely buried by Cenozoic sediments of the Badain Jaran Desert, while the northern part of the ATB connects to the southern Mongolian accretionary system, a part of the CAOB (Lamb & Badarch, 1997).

The ATB is largely covered by Cenozoic sediments, which to some extent hinders our understanding of the tectonic history of this region. The geology of the ATB includes the Precambrian basement and Phanerozoic magmatic-sedimentary rocks and ultramafic-mafic rocks, which possibly represent fragments of ophiolites (Feng et al., 2013). Previously, studies have largely focused on the tectonic affinity of the Precambrian basement, which is exposed mainly along the eastern and southwestern margins of the ATB (Figure 2; Dan, Li, Wang, Wang, et al., 2014; J. X. Zhang et al., 2013). The Precambrian rocks in the ATB have long been considered as Neoproterozoic to Early Paleoproterozoic in age and represent the western extension of the NCC, either a part of the Yinshan Block or the Khondalite Belt (Geng et al., 2007; J. X. Zhang et al., 2013; Zhao & Cawood, 2012). However, the discovery of Neoproterozoic magmatism in the ATB and comparable detrital zircon age spectra to the South China Craton spurred some authors to propose that the Precambrian basement of the ATB was independent from the NCC (e.g., Dan, Li, Wang, Wang, et al., 2014; J. Zhang, Zhang, et al., 2015). Despite of these debates, the basement rocks are regarded to have been extensively overprinted by Permian tectonothermal events related to the orogenic processes of the CAOB as revealed by muscovite 40Ar–39Ar and zircon U-Pb dating on metamorphic and deformed rocks (Geng & Zhou, 2012).

There are three major fault belts across the ATB, which are termed, from south to north, the Quagan Qulu Fault (also called the Badain Jaran Fault), the Engger Us Fault, and the Yagan Fault (Figure 2). These faults divide the ATB into four tectonic zones, from south to north, they are the Nuru-Langshan, Shalazhashan, Zhusileng-Hangwula, and Yagan tectonic zones (Figure 2; T. Y. Wang et al., 1994; T. R. Wu & He, 1993; T. R. Wu et al., 1998). Along the Quagan Qulu Fault an ophiolitic mélangé is exposed, which is composed of tectonic blocks of lenticular and striped ultramafic rocks, gabbro, chert, and rare basalt in a matrix consisting mainly of tuff, siltstone, sandstone, and mudstone (T. R. Wu & He, 1993; Zheng et al., 2014). The gabbro from this mélangé was dated at ~275 Ma by SHRIMP zircon U-Pb (Zheng et al., 2014). This ophiolite was regarded to represent remnants of a back-arc basin that formed as a result of southward subduction of the PAO beneath the northern margin of the NCC (Zheng et al., 2014). The Engger Us Fault is the major fault trending ENE in this area, and possibly extends eastward into the Mongolia (T. R. Wu & He, 1993). Along the Engger Us Fault, there are also occurrences of ophiolitic mélanges, which are composed of ultramafic rock, basalt, gabbro, and chert in a matrix composed of siltstone, greywacke, sandstone, and tuff. Here the ophiolite mélanges are highly deformed with mainly northward facing imbricated thrust deformation (Zheng et al., 2014). The Engger Us Fault is generally considered as a major suture zone separating the CAOB to the north from the NCC to the south (T. R. Wu & He, 1993; Zheng et al., 2014).
The Nuru-Langshan Tectonic Zone marks the transition region between the ATB and the western part of the NCC (Figure 2). This tectonic zone is mainly composed of Precambrian metamorphic basement, Late Paleozoic-Mesozoic granitoids, and minor mafic-ultramafic rocks. The metamorphic rocks were mapped as the Alxa Group (BGMRNM, 1991) with ages ranging widely from Paleoproterozoic to Neoproterozoic (Dan et al., 2012; Hu et al., 2014). Large volumes of granitoids intruding into the metamorphic rocks have ages ranging from Late Silurian to Middle-Late Triassic (Z. Z. Wang et al., 2015), with most of them clustering in a relatively short period (circa 290–270 Ma, Dan, Li, Wang, Tang, et al., 2014; Dan et al., 2015; Geng & Zhou, 2012; Q. Liu, Zhao, Han, Eizenhofer, Zhu, Hou, Zhang, & Wang, 2017; Zhang et al., 2016). In the northern part of the Nuru-Langshan Tectonic Zone, ultramafic-mafic rocks occur, hosted in Precambrian gneisses in the Bijiertai, Honggueryulin, and Diebusige areas. Gabbros from the Bijiertai and Diebusige areas were dated at 274 ± 3 Ma and 262 ± 5 Ma, respectively, using LA-ICP-MS zircon U-Pb method (Feng et al., 2013).

The Shalazhashan Tectonic Zone is situated between the Quagan Qulu Fault to the south and the Engger Us Fault to the north. In contrast to the Nuru-Langshan Zone, this zone is composed mainly of Phanerozoic rocks including Early Paleozoic to Mesozoic granites, Late Paleozoic ultramafic-mafic rocks, Carboniferous-Permian volcanic-sedimentary rocks, and minor Precambrian basement rocks (Figure 2). The Early Paleozoic to Carboniferous granites have been largely considered as being products of subduction of the PAO, while the Middle-Late Permian and Mesozoic granites were regarded to be formed in a post-collisional setting (e.g., X. J. Shi et al., 2014; Wang et al., 1994). The Carboniferous–Permian strata are composed of volcanoclastic rocks and sedimentary rocks, which were either considered as formed in a subduction setting (T. Y. Wang et al., 1994), or post-collisional setting (G. Z. Shi et al., 2016). The western part of this zone is entirely covered by the Cenozoic sediments of the Badain Jaran Desert.

The Zhusileng-Hangwula Tectonic Zone, bounded by the Yagan Fault to the north and the Engger Us Fault to the south, extends eastward to the Mongolia and disappears under the Badain Jaran Desert to the west (Figure 2). This zone contains Neoproterozoic to Mesozoic rocks. The Neoproterozoic strata are mainly composed of marble, metasandstone, siliceous slate, quartzite, phylite, and metarhyolite (BGMRNM, 1991). During the Early Paleozoic, this area received continuous sedimentation of clastic rocks accompanied by carbonate rocks with abundant Dalmanites fossils, which was regarded as an Early Paleozoic passive continental margin (T. R. Wu & He, 1993). The Late Paleozoic strata are widely exposed in this zone, which are dominated by Permian deep-sea flysch and submarine volcanic rocks. These strata are overlain unconformably by Upper Triassic and Cretaceous continental clastic sediments (BGMRNM, 1991).

The Yagan Tectonic Zone, separated from the Zhusileng-Hangwula Tectonic Zone to the south by the Yagan Fault, extends to the Beishan in the west and to the southern Mongolia to the east and north (Figure 2). Few Neoproterozoic metasedimentary rocks including metasandstone, marble, and limestone expose to the northeast of Ejin Banner. Early Paleozoic rocks are mainly Middle Ordovician volcanic rocks including basalt and rhyolite, with subordinate phyllite and shale. Late Paleozoic strata include Devonian rhyolitic and andesitic tuff and lava, and thick Permian volcanic-clastic rocks such as dacite, rhyolite, and greywacke, conglomerate, limestone, and mudstone (BGMRNM, 1991).

The Beishan Orogenic Belt (BOB) lies west to the ATB. There are four ophiolitic mélanges in the BOB, including, from south to north, the Liyuan mélange, the Hongliuhe-Xichangjing mélange, the Shibanjing-Xiaohuangshan mélange, and the Hongshishan mélange. These mélanges divide the BOB into five arcs, named the Shibanshan arc, Huanushan arc, Mazongshan arc, Heiyingshan arc, and Que’ershans arc (Xiao, Mao, et al., 2010). It is possible that the Liyuan mélange connects to the Quagan Qulu mélange in the ATB, as both of them were formed in Early Permian times (Mao et al., 2012; Xiao, Mao, et al., 2010; Zheng et al., 2014). However, the detailed relationship between the tectonic units of the BOB and the tectonic zones in the ATB is ambiguous because the junction between the BOB and ATB is covered by the Badain Jaran Desert where no outcrop is available.

3. Geology of the Southwestern ATB

The southwestern segment of the ATB is a NW–SE trending belt starting from Dingxin Town in the NW through Alxa Youqi to Jinchang City in the SE, where it connects with the NE–SW trending Nuru-Langshan Tectonic Zone (Figure 2). This area is separated from the Early Paleozoic Qilian Orogenic Belt to the
southwest by the Hexi Corridor, and to the northeast it disappears under the Badain Jaran Desert. The lithotectonic units of the southwestern ATB have a similar macroscopic strike with that of the southern BOB (Figure 2); however, the relationship between these two tectonic belts is unknown.

The rocks exposed along the southwestern ATB include Precambrian middle- to high-grade gneisses and low-grade metasedimentary sequences, Paleozoic granites, Carboniferous–Permian volcanic-sedimentary rocks as well as minor Mesozoic intrusions and continental clastic rocks (Figure 2). The oldest rocks in this belt are granitic gneisses (TTG gneisses; tonalite-trondhjemite-granodiorite) from the Beidashan area in the SE end of this belt, which were dated at circa 2.5 Ga by SHRIMP zircon U-Pb (J. X. Zhang et al., 2013). Paleoproterozoic ages (circa 2.33–2.05 Ga) were reported for the middle- to high-grade gneisses and metasedimentary rocks exposed along the Longshoushan (Gong et al., 2016). Neoproterozoic metasedimentary rocks consisting of marble, quartzite, metasandstone, and schist are mainly exposed in the Longshoushan and Gaotai areas (BGMRNM, 1991; Song et al., 2017). The Early Paleozoic granites mainly occur along the Beidashan, southeast of Alxa Youqi (Figure 2), and were dated at ~415–450 Ma by LA-ICP-MS U-Pb on zircons (Q. Liu et al., 2016). The Late Paleozoic granitoids were mainly emplaced during Late Carboniferous to Middle Permian (BGMRNM 1991; Q. Liu, Zhao, Han, Eizenhöfer, Zhu, Hou, Zhang, & Wang, 2017; our unpublished data), although some Early Devonian granites (~397–411 Ma) were also reported in the Beidashan area (Zhou et al., 2016). In Tebai area to the southeast of the study area (Figures 2 and 3), some Late Paleozoic mafic-ultramafic rocks can be found, composed of gabbro, serpentinitized peridotite, and amphibolite (Anonymous, 1978; BGMRNM, 1991). The Carboniferous–Permian strata are mainly distributed in the central part of the southwestern ATB (Figure 2), which are composed dominantly of volcanoclastic rocks, conglomerates, greywackes, and tuffaceous sandstones, with minor volcanic lavas and argillaceous limestones (Figures 3 and 4). The Mesozoic granites only crop out in the NW end of the southwestern ATB, where they intrude into granitic gneisses with Mesoproterozoic protolith age and Late Paleozoic metamorphic age (Figure 2; Song et al., 2017). The Mesozoic strata are mainly Cretaceous terrigenous clastic rocks, which distribute widely in the southwestern ATB. Minor Jurassic coal-bearing sandstone and conglomerate are also present in this area.

In previous studies, the southwestern ATB has not been discussed in detail and the tectonic history of this belt is highly ambiguous. Traditionally, this belt is simply regarded as a part of the Precambrian Alxa Block.
with Early Paleozoic passive margin or active margin development (e.g., Song et al., 2014; Xiao, Windley, Yong, et al., 2009). However, the Late Paleozoic volcano-sedimentary rocks have not been systematically studied in available publications. There has been no consensus on the tectonic relationship between the southwestern ATB and other tectonic zones in the ATB. To better understand the tectonic origin of Late

| Stratigraphy  | stratigraphic column | lithology description |
|--------------|----------------------|-----------------------|
| Permian      |                      | 4th rock member: grey-green fine sandstone, greywacke and coarse sandstone |
|              |                      | 3rd rock member: grey, purple coarse sandstone and conglomerate with minor volcanic breccia |
|              |                      | 2nd rock member: yellowish-green and grey-purple calcareous sandstone interlaid with minor argillaceous limestone and rhyolite and tuff |
|              |                      | 1st rock member: purple sandstone and conglomerate interlaid with rhyolite |
| Jushitan Formation | P_J         | 4th rock member: claret-colored rhyolitic lava, breccia lava interlaid with sandstone and conglomerate |
|              |                      | 3rd rock member: claret-colored sandstone interlaid with minor tuff sandstone and argillaceous limestone in the upper part; yellowish-brown sandstone in the lower part |
|              |                      | 2nd rock member: grey-green sandstone interlaid with conglomerate |
|              |                      | 1st rock member: grey-green calcareous siltstone, sandstone interlaid with coarse sandstone and argillaceous limestone, brachiopod and coral fossils present |
| Carboniferous|                      | Upper part: grey-green, purple intermediate-acid (minor mafic) lava, volcanic breccia interlaid with conglomerate and sandstone |
| Ganquan Group | C_Jgn       | Lower part: purple, grey conglomerate and sandstone with plant fossil |
| Precambrian  |                      | grey quartzite, slate, marble, sericite metasandstone, phylite |

Figure 4. Stratigraphic column of the Permian strata and its underlying strata in the southwestern Alxa. The Permian strata are consisting of conglomerate, sandstone, limestone, volcanic, and volcaniclastic rocks. Modified from Anonymous (1978) and BGMRNM (1991), and based on our own observations.
Paleozoic magmatic-sedimentary events and to present an integrated tectonic-paleogeographic reconstruction for this area, this study focuses on the Permian volcanic-sedimentary successions.

4. Stratigraphy of the Permian Volcanic-Sedimentary Successions

The Permian volcanic-sedimentary strata in the southwestern ATB contain the “Lower Permian” Jushitan Formation (P1j) and Upper Permian strata with no specific formation name (Figure 3; Anonymous, 1978). The Lower Permian strata unconformably overlie the Upper Carboniferous Ganquan Group (Figure 4; Anonymous, 1978; BGMRNM, 1991). The nomenclatures and ages for these stratigraphy are mostly based on fossil records or regional stratigraphic correlation when fossils are not available (BGMRNM, 1991).

The Jushitan Formation in the study area has a total thickness of over 980 m and is divisible into four rock members from bottom to top (Figure 4; Anonymous, 1978). The first rock member consists of gray-green calcareous siltstone, sandstone with interlayers of coarse-grained sandstone and argillaceous limestone. Plant fossils, brachiopod (Spiriferella saranae, Hustedia grandicosta), and coral (Lophophyllidum multisepatum) fossils are present in this section. The second member consists of gray-green sandstone with conglomerate interlayers. The third rock member consists of sandstone with interlayers of minor tuffaceous sandstone and argillaceous limestone in the upper part, and yellowish-brown sandstone in the lower part. The fourth rock member consists of rhyolitic lava and breccia lava with interlayers of sandstone and conglomerate. According to the fossil records and regional geological data (Jiang, Chen, et al., 2011), the Lower Permian Jushitan Formation in the study area should be put into Middle Permian (Guadalupian) using the recently published Geological Time Scale (Cohen et al., 2013).

The Upper Permian strata has a thickness of over 1,480 m and can also be divided into four rock members from bottom to top (Figure 4). The first rock member consists of purple sandstone and conglomerate with interlayers of rhyolite. The second member consists of yellowish-green and gray-purple calcareous sandstone with interlayers of minor argillaceous limestone and rhyolite. The third rock member consists of gray-purple coarse-grained sandstone and conglomerate with minor volcanic breccia. The top rock member is mainly composed of gray-green fine-grained sandstone, greywacke, and coarse sandstone.

5. Field Relationship and Sedimentary Characteristics

The Permian strata are generally in fault contact with the surrounding rock units, implying possible active tectonic activity during their sedimentation (Figure 3). The Middle Permian Jushitan Formation distributes more widely across the southwestern ATB compared to the Upper Permian strata (Figure 3). Field investigations revealed an angular unconformity relation between the Middle and Upper Permian strata. The unconformity contact is also clearly visible on Google Earth images (Figure 5). The Middle Permian Jushitan Formation below the unconformity surface shows tight folding structures with NE to ENE trending axial planes, while the Upper Permian strata only record gentle folding with a NE trending axial plane (Figures 5a and 5b). There is a basal conglomerate bed along the unconformity surface separating the Middle Permian pyroclastic rocks (tuffaceous sandstone) from the Upper Permian rhyolite (Figure 6). The unconformity plane dips to NNE with a dipping angle of ~43°. The gravels consisting of the basal conglomerate include purple to gray volcanic rocks such as porphyritic andesite, dacite, and rhyolite, and white quartz (Figure 6c). All the gravels display well-rounded shapes with long axial lengths from <1 cm to ~10 cm. The arrangement of the long axis for the gravels shows a preferred orientation apparently parallel to the unconformity surface, suggesting the influence of tectonic stresses during its formation. The pyroclastic rocks below this basal conglomerate layer show subvertical bedding as a result of strong folding, while the strata above the basal conglomerate is more horizontal (Figure 6b). Along the strike of the basal conglomerate, the unconformity plane pinches out both westward and eastward and the Middle and Upper Permian strata gradually become in transpressional fault contact between each other (Figure 5; Anonymous, 1978). This implies that the unconformity may be closely related to the transpressional deformation. The NW trending transpressional fault was cut by a later NE trending strike-slip fault (Anonymous, 1978).

In the Jushitan Formation, the gravels consisting of the conglomerates are dominated by volcanic rocks which are well rounded but poorly sorted, with diameters from several millimeters to >15 cm (Figure 7a). The pyroclastic rocks show parallel bedding similar to structures developed in volcaniclastic turbidites (Figure 7b). These sedimentary characteristics show that the Jushitan Formation was probably
deposited in a high-energy turbiditic environment, although a typical Bouma sequence has not been observed. The presence of both plant fossils and marine fossils such as brachiopods and corals suggest a neritic to littoral facies sedimentary environment for the Jushitan Formation (Anonymous, 1978; Jiang, Chen, et al., 2011).

In the lower part of the Upper Permian strata, the conglomerate clasts are dominated by intermediate-acidic volcanic rocks such as andesite, dacite, and rhyolite, showing porphyritic textures with plagioclase as the main phenocrysts (Figures 7c–7e). In addition, minor granite as well as fossil-bearing limestone gravels are also present in the conglomerate. The gravels are generally well rounded but poorly sorted, similar to that from the Jushitan Formation. The diameters of the gravels range from several millimeters to ~50 cm. The volcanic lithic sandstone (litharenite) are interbedded with conglomerate, and typical graded bedding are clearly observed in these rocks (Figure 7f). Granite gravels are more abundant in the conglomerate from the upper part of the Upper Permian strata. As indicated in Figure 8, the alternating sedimentation of sandstone, tuff, and conglomerate can be observed, suggesting the existence of strong synsedimentary igneous activities in the study area in the Late Permian. A ~50-cm-wide limestone layer is exposed within coarse-grained greywackes (Figure 9a), consistent with a marine sedimentary environment for the Upper Permian strata. Limestone pebbles with marine fossils can also be observed in the conglomerate from the Upper Permian strata. In addition, soft-sediment deformation structure such as ball-and-pillow structure was recognized in the sandstone (Figure 9b).

**Figure 5.** (a) Simplified geological map showing the distribution of the main lithologies and structures in the Permian strata in the study area. (b) Google Earth-based map showing the angular unconformity relation between the folded middle Permian Jushitan formation and the upper Permian strata. (c) Detailed cross section for the Carboniferous and Permian volcano-sedimentary rocks in the southwestern Alxa, legend similar to Figure 4.
In summary, field investigations confirm that the Permian strata form the southwestern ATB cover a large range of lithologies including conglomerate, greywacke, sandstone, limestone, volcanic lava, volcanic breccia, and tuff. The field characteristics of the volcanic-sedimentary successions indicate that both the Middle Permian and Upper Permian rocks were deposited in a high-energy environment where these sediments accumulated rapidly. During our field investigation, no cross-bedding was observed in the Permian volcanic-sedimentary rocks.

6. Sample Locations and Compositional Characteristics

In order to investigate the maximum depositional ages, provenances, and tectonic settings for the Permian volcanogenic sediments in the southwestern ATB, samples from both the Middle and Upper Permian strata were collected for zircon U-Pb and Lu-Hf isotopic analyses. The main petrographic features of the studied samples are described below.

Sample 15ALS28 is a purple sandstone collected from the Middle Permian Jushitan Formation below the angular unconformity (Figures 4 and 6b; Global Positioning System (GPS) coordinate: N39°38′21″, E101°02′50″). Under the microscope, three types of components can be distinguished: quartz (Q), feldspar (F), and lithic fragment (L). All the components show subangular shapes and form a grain-supported texture, indicating textural immaturity and thus short distance of transportation (Figure 10a). Quartz grains are mainly monocristalline and embayments are common, indicating a volcanic origin (Donaldson & Henderson, 1988).

Figure 6. Field photos showing the angular unconformity contact between the middle and upper Permian strata. See text for detailed description. (a) and (b) Contrasting geological attitudes for strata below and above the unconformity surface. (c) Basal conglomerate, the gravels are mainly volcanic and quartzose rocks, with subrounded texture. V = volcanic gravel, Q = quartzose gravel.

In summary, field investigations confirm that the Permian strata form the southwestern ATB cover a large range of lithologies including conglomerate, greywacke, sandstone, limestone, volcanic lava, volcanic breccia, and tuff. The field characteristics of the volcanic-sedimentary successions indicate that both the Middle Permian and Upper Permian rocks were deposited in a high-energy environment where these sediments accumulated rapidly. During our field investigation, no cross-bedding was observed in the Permian volcanic-sedimentary rocks.

6. Sample Locations and Compositional Characteristics

In order to investigate the maximum depositional ages, provenances, and tectonic settings for the Permian volcanogenic sediments in the southwestern ATB, samples from both the Middle and Upper Permian strata were collected for zircon U-Pb and Lu-Hf isotopic analyses. The main petrographic features of the studied samples are described below.

Sample 15ALS28 is a purple sandstone collected from the Middle Permian Jushitan Formation below the angular unconformity (Figures 4 and 6b; Global Positioning System (GPS) coordinate: N39°38′21″, E101°02′50″). Under the microscope, three types of components can be distinguished: quartz (Q), feldspar (F), and lithic fragment (L). All the components show subangular shapes and form a grain-supported texture, indicating textural immaturity and thus short distance of transportation (Figure 10a). Quartz grains are mainly monocristalline and embayments are common, indicating a volcanic origin (Donaldson & Henderson, 1988).
Feldspars contain both K-feldspar and plagioclase. The lithic fragments are mainly intermediate-acidic volcanic rocks such as andesites, dacites, and rhyolites with porphyritic textures (Figure 10a). Sample 15ALS17 is a purple, fine-grained conglomerate collected from the lower part of the Upper Permian strata (Figures 4 and 5; GPS coordinate: N39°37′27″, E101°05′57″). The clasts are dominated by lithic fragments with subordinate mineral crystals (Figure 10b). The lithic fragments are mainly andesitic to rhyolitic porphyries, and the crystal fragments are mainly monocrystalline quartzs and feldspars (Figure 10b). Compared to sandstones from the Jushitan Formation, sample 15ALS17 contains more lithic fragments than mineral crystals. The andesite clast contains phenocrysts of clinopyroxene and plagioclase (Figure 10e). Similar to sample 15ALS28, all the grains in sample 15ALS17 have angular to subangular shapes, suggesting a proximal source (Figure 10b). Sample 15ALS25 is a gray-green coarse-grained sandstone.

Figure 7. Field photos showing representative rocks from the Permian strata in the southwestern Alxa Tectonic Belt. (a) Conglomerate with dominated well-rounded rhyolite gravels (Jushitan Formation). (b) Parallel bedding within the tuffaceous sandstone (Jushitan Formation). (c–e) Conglomerate with well-rounded but poorly sorted andesitic, dacitic, and rhyolitic gravels, most of the gravels show porphyritic textures (Upper Permian strata). (f) Sandstone interbedded with conglomerate, graded bedding is indicated (Upper Permian strata).
collected from the upper part of the Upper Permian strata (Figures 4 and 5; GPS coordinate: N39°38'07″, E101°05'48″). The sandstone is covered by a conglomerate layer, which consists of both volcanic and granitic gravels. The inverse graded bedding indicates an overturned bedding in this location, as also pointed out in Anonymous (1978). Under the microscope, the sandstone is composed of lithic fragments of granite and volcanogenic-porphyry, as well as crystal fragments of quartz and feldspar (Figure 10c). The grain sizes range from <0.5 mm up to ~3 mm. All the clasts from this sample are angular in shape, similar to the other two samples described above. In order to investigate the provenance for the Upper Permian sediments, a rhyolitic porphyry clast (sample 15ALS19, GPS coordinate: N39°37'24″, E101°05'51″) from the conglomerate close to sample 15ALS17 was also collected for zircon U-Pb-Hf analyses. The phenocrysts in the rhyolitic porphyry are dominated by vericular quartz and K-feldspar crystals (Figure 10d).

The abundance of quartz grains, feldspar grains, and lithic fragments from five sedimentary samples were counted in thin sections under microscope following the Gazzi-Dickinson method proposed by Dickinson (1985) to determine the composition and provenance for the Permian strata. A minimum of 327 individual grains were counted on each thin section. The percentage amounts of quartz, feldspar, and lithic fragment from both the Middle and Upper Permian strata are plotted in the field of dissected to undissected arc on the Q-F-L diagram (Figure 10f; Dickinson, 1985).

7. Analytical Methods

More than 1,000 zircon grains were exacted from ~3 kg of rock by crushing and conventional heavy liquid and magnetic separation for each sample. About 300 grains were randomly handpicked and mounted on adhesive tape, set in epoxy resin, then polished to reveal internal zircon sections. Cathodoluminescence (CL) imaging was carried out using a Philips XL20 Scanning Electron Microscope equipped with a tungsten filament electron source and a Gatan CL detector attached for high-resolution imaging and spectroscopy at Adelaide Microscopy, within the University of Adelaide, in order to identify the zircon internal structures and choose target sites for U-Pb-Hf isotopic analyses.

In situ zircon U-Pb dating were carried out at Adelaide Microscopy, within the University of Adelaide. Zircons were ablated using an ASI Resolution laser with a spot size of 30 μm, repetition rate of 5 Hz, and intensity of ~8 J/cm². Isotopic data were acquired using an Agilent 7900 ICP-MS (Inductively Coupled Plasma-Mass

Figure 8. Outcrop showing the alternative distribution of sandstone, tuff, and conglomerate in the Upper Permian strata, showing intense synsedimentary igneous activity.
Spectrometry). Mass discrimination and elemental fractionation during laser ablation were corrected by calibration against the GEMOC GJ-1 zircon with thermal ionization mass spectrometry (TIMS) normalizing ages of $^{207}\text{Pb}/^{206}\text{Pb} = 607.7 \pm 4.3 \text{ Ma}$, $^{206}\text{Pb}/^{238}\text{U} = 600.7 \pm 1.1 \text{ Ma}$, and $^{207}\text{Pb}/^{235}\text{U} = 602.2 \pm 1.0 \text{ Ma}$ for U-Pb fractionation (Jackson et al., 2004). The Plešovice zircon internal standard (TIMS $^{206}\text{Pb}/^{238}\text{U}$ age = $337.13 \pm 0.37 \text{ Ma}$; Sláma et al., 2008) was used to assess the accuracy during the analysis of the unknowns. More detailed explanation on the analytical procedure can be found in Payne et al. (2006). Data reduction was performed using the Iolite extension for the Igor analytical software package (Paton et al., 2011). U-Pb concordia diagrams were made using Isoplot3 for Excel (Ludwig, 2003). Probability density and kernel distributions were created using DensityPlotter version 7.2 (Vermeesch, 2012).

In situ zircon Lu-Hf isotopic analyses were performed using a Geolas 193 laser ablation system attached to a Neptune Multi-Collector ICP-MS at the State Key Laboratory of Lithospheric Evolution, Institute of Geology and Geophysics, Chinese Academy of Sciences. Details on instrumental conditions are illustrated in F. Y. Wu et al. (2006). Lu-Hf isotopic compositions were analyzed for zircons near the same sites where U-Pb analyses were carried out. A beam diameter of 65 μm, a repetition rate of 8 Hz and laser energy of 15 mJ/cm² were used during the analysis. Two reference zircon standards Mud Tank and Plešovice were analyzed to monitor the reliability and stability of the instrument. The measured $^{176}\text{Lu}/^{177}\text{Hf}$ ratios and the $^{176}\text{Lu}$ decay constant of $1.865 \times 10^{-11} \text{ year}^{-1}$ reported by Scherer et al. (2001) were used to calculate initial $^{176}\text{Hf}/^{177}\text{Hf}$ ratios. The chondritic values of $^{176}\text{Lu}/^{177}\text{Hf} = 0.0332$ and $^{176}\text{Hf}/^{177}\text{Hf} = 0.282772$ reported by Blichert-Toft and Albarède (1997) were used for the calculation of εHf(t) values. The depleted mantle line is defined by present-day $^{176}\text{Hf}/^{177}\text{Hf} = 0.28325$ and $^{176}\text{Lu}/^{177}\text{Hf} = 0.0384$ (Vervoort & Blichert-Toft, 1999). The $^{176}\text{Lu}/^{177}\text{Hf}$ ratio for average continental crust is 0.015 (Griffin et al., 2002).

8. Analytical Results

More than 110 zircon grains were randomly analyzed for each sedimentary sample for U-Pb dating, and a minimum of 81 zircons with concordant ages were further analyzed for Lu-Hf isotopic compositions. The U-Pb and Lu-Hf analytical results are available in the supporting information Tables S1 and S2, respectively. In this study, $^{206}\text{Pb}/^{238}\text{U}$ ages were used for zircons younger than 1 Ga, while $^{207}\text{Pb}/^{206}\text{Pb}$ ages were used for zircons older than 1 Ga. Ages with discordance ≤10% are considered to be near-concordant and those with discordance >10% are excluded for further discussion. Individual zircon ages in the following sections were reported with uncertainties at 2σ level.

8.1. Sample 15ALS28 (Jushitan Formation: Tuff Sandstone)

Zircons from sample 15ALS28 can be divided into two groups based on CL features. The majority of zircons are dark, luminescent in color, while a few zircon grains are bright. Both groups of zircons have sizes from ~60 to ~200 μm with aspect ratios from ~1:1 to ~3:1 (Figure 11a). They are mostly euhedral with oscillatory zoning, suggesting a magmatic origin. Among the 120 analyzed spots, 114 of them yielded concordant ages. Except for three spots yielding Th/U ratios <0.1, all the other grains show Th/U ratios ranging from 0.1 to 2.21, supporting their magmatic origins (Table S1). The concordant ages range widely from $267 \pm 4 \text{ Ma}$ to $2709 \pm 47 \text{ Ma}$ (Figure 12a, Table S1). The overwhelming majority of ages (~94% of all data) are Phanerozoic that cluster into two populations. The first population (~$267 \text{ Ma}$ to ~$312 \text{ Ma}$, ~71% of all data) yield a peak of ~273 Ma, and the second, smaller population (~408 Ma to ~464 Ma, ~21.9% of all data)
yield a peak of ~440 Ma (Figure 12b). Only seven of the analyzed grains yield Precambrian ages, of which two are Late Mesoproterozoic (1131 ± 55 Ma and 1173 ± 35 Ma), two are Late Paleoproterozoic (1626 ± 38 Ma and 1670 ± 57 Ma), one is Early Paleoproterozoic (2444 ± 32 Ma), and the other two are Neoarchean (2501 ± 33 Ma and 2709 ± 47 Ma). Two youngest grains yield nearly identical concordant ages of 267 ± 4 Ma and 267 ± 7 Ma, respectively (Table S1).

One hundred and thirteen zircon grains with concordant ages were analyzed for Lu-Hf isotopic compositions (Figure 13, Table S2). The Late Carboniferous–Middle Permian age population yield εHf(t) values ranging from −1.6 to +9.6, with mostly >0, and crustal model ages from 680 to 1146 Ma. The Late Ordovician–Devonian age

Figure 10. Photomicrographs and Q-F-L diagram showing the compositional characteristics of the rocks from the Permian strata. The sedimentary samples contain considerable amounts of lithic fragments. (a) Sandstone from the Jushitan Formation (15ALS28). (b) Fine-grained conglomerate from the Upper Permian strata (15ALS17). (c) Sandstone from the Upper Permian strata (15ALS25). (d) Rhyolitic porphyry clast (15ALS19) from the conglomerate in the Upper Permian strata, the quartz phenocryst display vesicular structure. (e) Andesite gravel from the Upper Permian conglomerate containing phenocrysts of clinopyroxene and plagioclase. (f) Quartz-feldspar-lithic fragment (Q-F-L) ternary provenance discrimination diagram of point counts for the Permian sedimentary rocks, provenance areas after Dickinson (1985). All the photos were taken under cross-polarized light using polarizing microscope. Q = quartz, F = feldspar, L = lithic fragment; Kf = K-feldspar; PI = plagioclase; Cpx = clinopyroxene.
population yield both positive and negative $\varepsilon_{Hf}(t)$ values ranging from $-10.3$ to $+6.4$, and crustal model ages from 876 to 1698 Ma. The Precambrian zircons have $\varepsilon_{Hf}(t)$ values from $-9.0$ to $+5.0$, with crustal model ages from 1517 to 3277 Ma.

8.2. Sample 15ALS17 (Upper Permian Strata: Fine-Grained Conglomerate)

Zircon grains from sample 15ALS17 are dark, luminescent with sizes ranging from $\sim50 \mu m$ to $\sim300 \mu m$ and axial ratios from $\sim1:1$ to $\sim6:1$ (Figure 11b). All the zircons are euhedral to subeuhedral, angular in shape, and oscillatory or sector zoning patterns are common, suggesting magmatic origins. The zircon morphology indicates short distance of transportation and a proximal source for the sediments. Among the 112 analyzed grains, 101 of them yielded concordant ages. All analyzed grains show a range of Th/U ratios from 0.21 to 1.16, consistent with their magmatic origins. Except for one analyzed Ediacaran zircon (611 ± 11 Ma), all the other 100 zircons are Late Paleozoic in age, within a relatively narrow range from 251 ± 5 Ma to 314 ± 8 Ma (Figure 12c, Table S1) and yielding a single age peak at $\sim261$ Ma (Figure 12d). The youngest concordant age is 251 ± 5 Ma, and the second youngest one is 252 ± 6 Ma (Table S1).

Eighty-one grains with concordant ages were analyzed for Lu-Hf isotopic compositions (Figure 13, Table S2). Except for two grains yielding negative $\varepsilon_{Hf}(t)$ values, all the other grains yield positive $\varepsilon_{Hf}(t)$ values from $+0.8$ to $+5.8$, and crustal model ages from 768 to 1085 Ma.

8.3. Sample 15ALS25 (Upper Permian Strata: Coarse-Grained Sandstone)

The majority of zircon grains from sample 15ALS25 are dark, luminescent, while several of them are bright. The zircons are euhedral to subeuhedral and angular in shape, with sizes from $\sim50 \mu m$ to $\sim150 \mu m$ and aspect ratios from $\sim1:1$ to $\sim3:1$ (Figure 11c). Most zircons display oscillatory or sector zoning, indicating magmatic origins. Similar to the previous samples, the zircon morphology from sample 15ALS25 also indicates short distance of transportation for the sediments. One hundred and twenty zircon grains were dated, and 103 of them yield concordant ages (Figure 12e, Table S1). All the analyzed spots yield relatively high Th/U ratios ranging from 0.23 to 1.12, supporting a magmatic origin. All the concordant analyses yield Late Paleozoic ages, except for one Precambrian zircon grain with a Neoproterozoic age of 884 ± 11 Ma (Figure 12e, Table S1). The Late Paleozoic ages form a relatively narrow range from $\sim256$ to $\sim290$ Ma, with a unimodal peak at $\sim263$ Ma (Figure 12f). The two youngest concordant zircons yield identical ages of 256 ± 5 Ma and 256 ± 4 Ma, respectively (Table S1).

Eighty-two grains were analyzed for Lu-Hf isotopic compositions (Figure 13, Table S2). The majority of the Permian zircons have positive $\varepsilon_{Hf}(t)$ values up to $+9.4$ and crustal model ages from 588 to 1046 Ma. One grain with Neoproterozoic age has $\varepsilon_{Hf}(t)$ value of $+3.1$ and crustal model age of 1410 Ma.

8.4. Sample 15ALS19 (Rhyolitic Porphyry Clast From Upper Permian Conglomerate)

Zircons from the rhyolitic porphyry gravel are $\sim30$–$150 \mu m$ in length with aspect ratios ranging from $\sim1:1$ to $\sim4:1$. The zircons can be

---

**Figure 11.** Representative CL images for zircons from the analyzed samples. The red and yellow circles are spots of U-Pb and Lu-Hf analyses, respectively. The red numbers are $^{206}\text{Pb}/^{238}\text{U}$ ages with 2σ uncertainty (in Ma), and the yellow numbers are $\varepsilon_{Hf}(t)$ values.
Figure 12. U-Pb concordia diagram (a, c, e, and g) and kernel density estimate plots (b, d, and f) for detrital zircon ages from the sedimentary rocks in this study. (a, b) Sample 15ALS28 from the Middle Permian Jushitan Formation. (c-f) Samples 15ALS17 and 15ALS25 from the upper Permian strata. (g, h) The rhyolitic porphyry clast (sample 15ALS19) from the Upper Permian conglomerate. The inserted diagrams in (b), (d) and (f) show the Phanerozoic detrital zircon U-Pb ages for each sedimentary sample. The red vertical arrow indicates approximate maximum depositional age based on the youngest single grain age of the sample. "N" stands the number of concordant ages for each sample. Data are plotted at the 2σ uncertainty level. Kernel density estimate plots are generated using DensityPlotter version 7.2 (Vermeesch, 2012).
classified into two groups based on their CL image characteristics (Figure 11d). The first group of zircons are dark, luminescent, while the second group are bright. Despite their difference in CL images, they yield similar U-Pb ages. Thirty-five of the 40 analyzed zircons yield concordant ages ranging from 262 ± 5 Ma to 281 ± 5 Ma, with Th/U ratios from 0.38 to 1.19 (Figure 12g, Table S1). Thirty-three ages yield a weighted mean $^{206}$Pb/$^{238}$U age of 267.5 ± 0.9 Ma (MSWD = 1.9, Figure 12h), representing the timing of rhyolitic volcanism.

All the 29 analyzed zircon grains have positive $\varepsilon_{Hf}(t)$ values from +3.2 to +8.3 and crustal model ages from 645 to 903 Ma (Figure 13, Table S2).

9. Discussion
9.1. Constraints on Depositional Ages and Timing of Unconformity

The depositional ages of the Permian volcanic-sedimentary successions in the study area are very important as they constrain the timing of deposition of the youngest marine strata in the study area and would give a possible maximum age for the termination of subduction processes of the PAO in the ATB. Prior to this study, there has been no isotopic age data reported for the Permian volcanic-sedimentary rocks from the southwestern ATB. The geological mapping loosely divided the Permian strata into Lower and Upper Permian based on fossils and regional stratigraphic correlations (Anonymous, 1978). However, fossils sometimes give a large range for the depositional age for a sedimentary succession, and in this case the detrital zircon U-Pb dating will be helpful to add further robust constraints on the maximum depositional age.

It can be demonstrated that the age of the youngest single detrital zircon grain within a sedimentary sample with 1σ error less than 10 Ma is a good estimate for the maximum depositional age when sufficient concordant ages are available and if the age is reproducible (Dickinson & Gehrels, 2009). In this study, more than 100 concordant ages have been obtained for each of the three volcano-sedimentary samples. The sedimentary characteristics and zircon morphology indicate that the volcanogenic sediments likely had a rapid, simple depositional path from a proximal source region (Figures 7, 10, and 11), and the detrital zircon U-Pb ages form concentrated unimodal distribution patterns (Figure 12). In such circumstance, the youngest single grain age is higher resolution than the other methods such as youngest numerical age peak proposed to evaluate the maximum depositional age of a sedimentary rock (Dickinson & Gehrels, 2009).

The youngest two detrital zircon grains from the Jushitan Formation (sample 15ALS28) yield $^{206}$Pb/$^{238}$U ages of 267 ± 4 Ma and 267 ± 7 Ma, respectively. These two ages are identical with each other within uncertainty. Therefore, this age (~267 Ma) is the best estimation for the maximum depositional age for the Jushitan Formation (Figure 12b). The age is consistent with the fossil records of this formation, which include H. grandicosta and L. multiseptatum (Anonymous, 1978). These fossils are broadly distributed in many Permian marine strata across Asia (fossilworks.org). Thus, the Jushitan Formation is most likely deposited in the Middle Permian (Guadalupian).

Figure 13. U-Pb age versus $\varepsilon_{Hf}(t)$ plot of concordant zircons from the Permian volcanic-sedimentary rocks from the southwestern Alxa in this study. CHUR = chondritic uniform reservoir. Data for the Precambrian basement rocks in the Alxa Tectonic Belt are from Dan, Li, Wang, Tang, et al. (2014), Gong et al. (2016), and J. X. Zhang et al. (2013).
Sample 15ALS17 from the Upper Permian strata yield the youngest single detrital zircon age of 251 ± 5 Ma (Figure 12d), overlapping at 1σ uncertainty with the next youngest grain age of 252 ± 6 Ma. Another sample also from the Upper Permian strata (sample 15ALS25) has two youngest zircon grains dated at 256 ± 4 Ma and 256 ± 5 Ma (Figure 12f), respectively. These ages are identical to the youngest single zircon age from sample 15ALS17 within uncertainty. We therefore use the age of 251 Ma as the best estimation for the maximum depositional age for the Upper Permian strata.

Sample 15ALS28 is from the strata directly below the angular unconformity and the fault plane, while samples 15ALS17 and 15ALS25 are from the strata above the unconformity and the fault plane (Figure 5). The timing of the unconformity and the transpressional fault within the Permian strata is thus constrained to be between ~267 Ma and ~251 Ma, that is, Middle to Late Permian, implying a syndepositional tectonic activity for the Permian volcanogenic sedimentation.

9.2. Sedimentary Environment, Provenance, and Tectonic Setting for the Permian Volcano-Sedimentary Rocks

The Permian strata from the southwestern ATB show a diversity in lithology including siltstone, sandstone, greywacke, conglomerate, tuffaceous sandstone, limestone, volcanic lava, and volcanic breccia (Figure 4). All the volcano-sedimentary rocks in this study contain considerable amounts of lithic fragments (Figures 7 and 10), suggesting low compositional maturity. The conglomerates from both the Middle and Upper Permian strata show poorly sorted characteristics, indicating short distance of transportation and proximal source areas. The gravels constituting the conglomerates are mainly intermediate-felsic volcanic rocks such as andesite, dacite, and rhyolite. Many of the conglomerate clasts show porphyritic textures with phenocrysts dominated by columnar feldspars (Figures 7c and 7d). No mafic gravels or lithic fragments have been found in the conglomerates and sandstones. All these rocks show grain-supported fabrics with low matrix content. The field and microscopic features, thus, indicate that the sedimentary rocks were formed shortly after the volcanic activity and sourced from a proximal terrane.

The presence of marine fossils such as brachiopods and corals indicates that the Middle Permian Jushitan Formation in the study area was deposited in a marine sedimentary environment. Regionally, the Jushitan Formation has been considered to be deposited in a littoral-neritic facies environment (Jiang, Chen, et al., 2011). The presence of limestone layers within the Upper Permian strata may indicate a similar sedimentary environment. The sedimentary structures such as parallel bedding, graded bedding, and ball-and-pillow structures imply a high-energy depositional environment. The well-rounded, but poorly sorted gravels in the conglomerate also suggest a high-energy, fast sediment accumulation scenario. The sediments were probably supplied from a rapidly uplifting source area. This is also consistent with the presence of the syntectonic angular unconformity between the Middle and Upper Permian strata as described above (Figures 5 and 6). These observations indicate that significant active tectonic movements took place, contemporaneous with intense volcanism and sedimentation processes. The alternating deposits of sandstone, conglomerate, and tuff furthermore indicate that the sedimentation took place simultaneously with the volcanic activity (Figure 8). Taking all these findings together, the Permian sediments were most likely sourced from a proximal active magmatic process and deposited in a continental slope environment.

At subduction zones, strong subduction tectonic erosion is likely to occur (Clift et al., 2005) and these tectonic processes may erase field evidence for volcanic arcs, making it difficult to reconstruct the subduction history of a consumed ocean. However, it is possible to rebuild the magmatism and subduction history if the eroded arc materials were preserved in the arc-flanking basins, and the sedimentary record is a valid representation of the magmatic record (Hawkesworth et al., 2010). Therefore, detrital zircon U-Pb-Hf analyses are a powerful tool for unraveling the sedimentary provenance and magmatic events in the source areas (Gehrels, 2014).

In this study, all the sedimentary samples are dominated by Paleozoic detrital zircon ages and only a few Precambrian ages were obtained (Figures 12a–12f), and no Precambrian age has been detected for the rhyolitic porphyry clast (Figures 12g and 12h). Therefore, the sedimentary samples were mainly sourced from Paleozoic magmatic processes with rare Precambrian basement. A large population of zircons from sample 15ALS28 fall in the range of Late Carboniferous to Middle Permian (~312–267 Ma), with a prominent peak at ~273 Ma (Figure 12b), indicating intense Permian magmatism in the source area. A smaller population of Late Ordovician to Early Devonian ages with a peak at ~440 Ma indicate subordinate Early to Middle
Paleozoic magmatic sources (Figure 12b). As stated above, the Permian sedimentary rocks are mainly sourced from proximal volcanic rocks dominated by andesite, dacite, and rhyolite. The Permian age population thus represent the timing of intermediate-felsic volcanism in the proximal source area in the ATB. There is an obvious age gap between ~315 Ma and ~400 Ma, indicating weak or even cessation of Middle Devonian to Early Carboniferous magmatism (magmatic lull) in the ATB. This is consistent with regional data that few magmatic events of this time interval exist in the Nuru-Langshan and Shalazhashan tectonic zones in the ATB (Dan, Li, Wang, Tang, et al., 2014). The Late Ordovician to Early Devonian magmatic events (~408–464 Ma) recorded in sample 15ALS28 are consistent with the Early-Middle Paleozoic granitic magmatism (~408 Ma and ~415–450 Ma) reported in the Beidashan area in the southeast end of the southwestern Alxa (Figure 2), which was interpreted as the product of southward subduction of the PAO (Q. Liu et al., 2016; Zhou et al., 2016). This observation indicates that the Early-Middle Paleozoic plutons could have been eroded and supplied detritus to the Middle Permian sedimentary rocks. The seven Precambrian grains dated in our study fall into a wide age range from Late Mesoproterozoic to Neoarchean (Figures 12a and 12b) and are consistent with zircon ages from the Alxa Precambrian basement gneisses and related metasedimentary rocks (Song et al., 2017; J. X. Zhang et al., 2013).

Samples 15ALS17 and 15ALS25 from the Upper Permian strata yield consistent detrital zircon U-Pb age distributions (Figures 12d and 12f), indicating similar provenances. Both samples display unimodal age distributions in a narrow range from ~251 to ~300 Ma (>95% of them between ~251 and ~280 Ma), with single age peaks at ~261 Ma and ~263 Ma, respectively (Figures 12d and 12f). These age data are indicative of intense Middle-Late Permian magmatism in the source area. Magmatic events of this age peak have not been reported from the southwestern Alxa so far, although a recent study by Q. Liu, Zhao, Han, Eizenhöfer, Zhu, Hou, Zhang, and Wang (2017) reported ~269 and ~281 Ma granitoids for the southwestern Alxa. These granitoids are systematically older than the age peaks of ~261 and ~263 Ma for the volcanic-sedimentary rocks in this study and could thus not be the major source, if any. Alternatively, several Middle–Late Permian mafic and granitic intrusions were reported for the Nuru-Langshan and Shalazhashan tectonic zones to the northeast of the study area (Dan, Li, Wang, Tang, et al., 2014; Feng et al., 2013; Z. B. Liu & Zhang, 2014; X. J. Shi et al., 2014), which could have provided detritus to the Upper Permian strata in the southwestern ATB. However, the abundance of ~251–270 Ma zircon grains and ubiquitous intermediate-felsic porphyritic clasts in samples 15ALS17 and 15ALS25 probably imply a distinct Middle-Late Permian volcanic activity in the southwestern ATB. This is further supported by the rhyolitic porphyry clast from a conglomerate from the Upper Permian strata, which yield an age of 267.5 ± 0.9 Ma (Figures 12g and 12h). The presence of only one Precambrian zircon grain in both samples 15ALS17 and 15ALS25 indicates that these sedimentary rocks were deposited shortly after the Middle–Late Permian magmatic activity, preventing mixing with distal pre-existing crustal sources during sedimentation.

In general, the Permian volcanic-sedimentary rocks in this study yield a prominent Middle Permian (~266 Ma) and a subordinate Early Silurian (~440 Ma) age peak (Figure 14a). The Early Silurian age peak is consistent with age records in other parts of the southern CAOB, including southern Beishan Orogenic Belt (Figure 14c, peaking at ~428 Ma) and southern Mongolia accretionary system (Figure 14d, peaking at ~441 Ma). The ~266 Ma age peak, however, is significantly younger than the Late Paleozoic peaks for the southern Beishan (~282 Ma) and southern Mongolia (~305 Ma). Permian strata from the southern Mongolia mainly yield Carboniferous and older (>300 Ma) ages with very low abundances of Permian zircon (e.g., Heumann et al., 2012), which is different from the Permian strata from the southwestern ATB with large amounts of Middle–Late Permian zircons. Moreover, the Late Devonian to Early Carboniferous age population with peaks of ~362 Ma and ~321 Ma for the southern Mongolia Permian strata (Figure 14d) were not detected in this study. The Late Paleozoic magmatism in the southern Beishan is dominated by early Permian granites and mafic rocks (e.g., Mao et al., 2012; W. Zhang et al., 2015). Although a few Middle–Late Permian intrusions have also been reported in the southern Beishan (Figure 14c), they are characterized by negative ϵHf(t) values (W. Zhang et al., 2015), contrasting to the Middle–Late Permian detrital zircons with predominantly positive ϵHf(t) values in the southwestern Alxa (Figure 13). These observations indicate that neither the Beishan nor the southern Mongolia could be the major source areas for the Permian strata in the southwestern ATB.

A compilation of published zircon ages on magmatic rocks (mainly intrusions) from the ATB shows two main age populations: ~240–330 Ma and ~390–500 Ma, with a prominent peak at ~272 Ma and two subordinate peaks at ~413 and ~446 Ma (Figure 14b). Our data from the Permian strata thus show comparable age
distribution patterns with the zircons from magmatic rocks in the ATB (Figures 14a and 14b), although the Permian peak of this study is slightly younger than that from the intrusive rocks. Therefore, the source area for the Permian volcano-sedimentary rocks in the southwestern ATB is likely local, where magmatic activity was quickly followed by rapid sedimentation.

Sediment provenance can be indicative of the tectonic settings into which the sediments were deposited (e.g., Cawood et al., 2012). Convergent plate margins are characterized by intense magmatism and...
sedimentation; therefore, sedimentary basins related to convergent plate margin processes (e.g., forearc, trench, intraarc, and backarc basins) contain large amounts of zircons that have crystallization ages quite close to the depositional ages of the rocks (Dickinson & Gehrels, 2009). Contrarily, sedimentary rocks in collisional and extensional settings tend to contain greater proportions of zircons with older ages reflecting the history of the preexisting basement (Cawood et al., 2012). According to the method proposed by Cawood et al. (2012), convergent settings have CA-DA (crystallization age minus depositional age) less than 100 Ma in the youngest 30% of zircons. In this study, 72% of the zircons from sample 15ALS28 have CA-DA < 100 Ma, and 99% of zircons from samples 15ALS17 and 15ALS25 have CA-DA < 100 Ma. The overall detrital zircon U-Pb age distribution of the three volcano-sedimentary samples in the study area thus show typical convergent tectonic setting, indicating a basin within or near an active arc system during the Middle to Late Permian in the southwestern ATB. The scarcity of Precambrian zircon grains in these samples is consistent with a local arc source (Figure 12). This is supported by the high proportion of porphyritic clasts and lithic fragments in the conglomerates and sandstones, most of which are andesite and dacite in composition with typical columnar plagioclase phenocrysts (Figures 7 and 10). These rock fragments along with rhyolite interlayers form a typical assemblage of continental margin arc-type volcanic rocks distributed along the margins of the current Pacific Ocean (Best, 2003). This is further supported by the Q-F-L diagram for the sedimentary rocks from both the Middle and Upper Permian strata, indicating sources from a dissected to undissected arc system (Figure 10f; Dickinson, 1985). The Permian zircons from this study have positive to slightly negative εHf(t) values (Figure 13). These zircon Hf isotopic patterns can be interpreted as the result of mixing of mostly Permian new crust with minor recycled Precambrian crust. The large number of zircons with positive εHf(t) values suggest the dominant role of juvenile magma process in the southwestern ATB, contrasting to the limited Precambrian basement as also indicated by the few Precambrian detrital zircons for the Permian strata (Figure 14). This characteristic is consistent with arc magmatic processes revealed by sedimentary records in other parts of the southern CAOB (e.g., Meng et al., 2010; Song et al., 2016) and the Cordillera orogenic system (e.g., Beranek et al., 2016; Mišković & Schaltegger, 2009). All these data in this study thus point to an arc-related setting in a convergent plate margin for the Permian volcanic-sedimentary rocks in the southwestern ATB.

In summary, the Middle–Late Permian marine sedimentary successions in the southwestern ATB are characterized by rapid lateral changes in lithofacies including clastic, volcanic, and volcanoclastic rocks (Figure 4). These sediments were probably rapidly deposited in a continental slope environment related to a convergent plate margin, which is similar in structural style and composition to conglomerates and sandstones that widely develop in the Cordillera arc-related basins on the eastern Pacific subduction zone (e.g., Bassett & Busby, 2005; Dickie & Hein, 1995). The provenances of the volcanic-sedimentary rocks in the southwestern ATB were mostly sourced from a Permian tectonically active arc massif dominated by intermediate to felsic volcanics and subordinate plutons, mixed with minor Precambrian basement of the ATB.

9.3. Implications for the Final Subduction Processes of the PAO in the ATB

The timing of final subduction of the PAO and the terminal amalgamation of the CAOB is an ongoing debated issue among the geological society. Different times ranging from Late Devonian to End Permian–Middle Triassic have been proposed for the termination of the accretionary processes of the southern CAOB (e.g., Eizenhöfer et al., 2015; Gao et al., 2011; Han et al., 2011; Windley et al., 2007; Xiao et al., 2003; Xiao, Windley, Huang, et al., 2009; Xu et al., 2013). The reasons for these controversies may lie on different criteria that were used to evaluate the timing of final amalgamation of an accretionary orogen. Unlike the continent-continent collisional orogens, where continental deep subduction commonly takes place after the oceanic crust has completely been consumed, accretionary orogenic belts are generally characterized by a “soft collision” between accretionary wedges and/or arc massifs (e.g., Şengör & Natal’In, 1996; Xiao et al., 2003). This kind of terrane accretion will result in the absence of typical geological phenomena such as molasse-filled foredeeps and high-pressure metamorphism, which are commonly present in collisional orogens (Şengör et al., 1993).

When and where the PAO finally disappeared in the ATB remains controversial. Some researchers consider the Late Carboniferous–Early Permian Amushan Formation as a benchmark for the termination of orogenic process in the Alxa area, based on the intraplate geochemical affinity for the basic rocks from this formation (e.g., Dan, Li, Wang, Tang, et al., 2014; Dang et al., 2011; Jiang, Li, et al., 2011). These authors argue for a Late
Carboniferous–Permian intracontinental rifting or mantle plume environment in a postcollisional tectonic setting for the ATB. However, as described by Dang et al. (2011), the Permian strata in the NE part of the ATB are mainly composed of marine volcanic-sedimentary rocks deposited in neritic shelf facies consistent with the presence of Middle Permian pillow basalts. Zhao et al. (2010) also pointed out that the rock association and sedimentary characteristics of Carboniferous–Permian strata in the ATB show intense volcanism in a submarine continental slope environment with sedimentary facies ranging from neritic facies, fan delta facies to braided delta facies. Both the Amushan Formation and other Carboniferous–Permian strata in the ATB contain abundant intermediate volcanic rocks such as andesite, dacite, and basaltic andesite (Dang et al., 2011; Jiang, Li, et al., 2011). These rock associations are inconsistent with a continental rifting setting where volcanism with typical bimodal compositions would be expected (e.g., Corti, 2009). They are furthermore incompatible with a mantle plume setting where continental flood basalts are predominant (Ernst & Buchan, 2003) but are similar to volcanic arc assemblages formed in subduction zone settings (Stern, 2002). Moreover, the presence of ~305 Ma oceanic subduction-related adakitic magmatism in the Shalazhashan Tectonic Zone clearly suggests that the PAO had not closed by the Late Carboniferous in the ATB (X. J. Shi et al., 2014). Recent geochemical and geochronological studies on the Engger Us and Quagan Qulu ophiolitic mélanges suggested the presence of a late Paleozoic subduction system including a trench, arc, and backarc basin in the Alxa area, and the final closure of the PAO might have taken place after Early Permian (Zheng et al., 2014).

Our study on the Permian strata from the southwestern ATB clearly indicates that the Middle–Late Permian volcanogenic sediments were probably deposited in a high-energy continental slope environment within an active arc setting, based on filed observations, compositional characteristics, detrital zircon U-Pb age distributions, and Hf isotopic compositions as discussed above. The Middle–Late Permian intense synsedimentary magmatic activity was the direct product of southward subduction of the PAO. Therefore, this arc-related basin in the southwestern ATB forms the southernmost subduction-generated component associated with the consumption of the PAO in the ATB. This is consistent with a recent geochemical and geochronological study, which dated granitoids from the southwestern ATB that were generated in a subduction setting to ~281–268 Ma (Q. Liu, Zhao, Han, Eizenhöfer, Zhu, Hou, Zhang, & Wang, 2017). The Middle-Late Permian subduction process is supported by the ~262 Ma Diebusige ultramafic-mafic rocks from the Nuru-Langshan Tectonic Zone, which show island arc modified transitional middle ocean ridge basalt geochemical signatures and were regarded to be the products of south-dipping subduction of the PAO associated with a slab window caused by ridge subduction before the final closure of the PAO (Feng et al., 2013). This is further evidenced by the ~266–250 Ma I-type, calc-alkaline intrusions in the Shalazhashan Tectonic Belt, which were interpreted as arc-related plutons formed in an active continental margin (Z. B. Liu & Zhang, 2014; Ran et al., 2012; X. J. Shi et al., 2014). G. Z. Shi et al. (2016) proposed an incipient rifting tectonic setting for the ATB based on the absence of Late Permian chaotic subduction-accretionary complexes and high-pressure metamorphism in the Engger Us and Quagan Qulu areas. However, convergent plate margins are highly diverse in the preservation of accretionary prisms, and the absence of accretionary complex could not be used as a diagnostic evidence for the cessation of oceanic plate subduction. Presently, over 50% of the global subduction systems are now tectonically erosive in nature and scarce or even no accretionary complex is essentially in existence in these erosive margins (Clift et al., 2005; Clift & Vannucchi, 2004). Current nonacccretionary subduction systems are widely distributed on the Earth, such as the NE Japan, Izu-Mariana, Costa Rica, Peru, North Chile, Tonga, and South Sandwich subduction zones (Clift & Vannucchi, 2004; Stern, 2011). In fact, in many subduction environments where accretionary prisms are developed, fault-bounded packets of well-bedded, coherent sediments are much more extensively developed than bodies of chaotically mixed mélanges (Clooś & Shreve, 1988). In the Engger Us area, the radiolarian chert, tuffaceous rocks, and fine-grained turbidites indicate a deep water setting from Early Permian (circa 299 Ma) to early Late Permian (circa 255 Ma) in the Alxa area (Xie et al., 2014). This provides compelling evidence for a considerable oceanic basin that was still in existence until the Late Permian within the Alxa area, consistent with the associated Middle–Late Permian sedimentation in the southwestern ATB in this study. In the Quagan Qulu area, Permian sandstones show geochemical affinities to both continental island arcs and active continental margins, and a dacite lava yields a zircon U-Pb age of ~254 Ma (G. Z. Shi et al., 2016), favoring a Late Paleozoic subduction scenario in the ATB. Furthermore, the Nuergong batholith from the Nuru-Langshan Tectonic Zone, consisting of monzogranites and gabbros with crystallization ages of ~276–270 Ma, contain considerable hydrated minerals such as amphibolite and biotite and shows clear calc-alkaline arc signatures, compatible with an
oceanic subduction setting (J. J. Zhang et al., 2016). The field geological, geochemical, and geochronological studies on the Permian porphyries, dolerites, and gabbros favor an active continental margin until the Late Permian in the Langshan area in the northeastern part of the ATB (Lin et al., 2014). In summary, a convergent tectonic environment related to the final subduction process of the PAO is inferred across the ATB during the Middle-Late Permian, based on available field, sedimentary, geochemical, and geochronological evidence. The Permian active margin can be traced from the southwestern ATB all through to the Nuru-Langshan Tectonic Zone, forming the southernmost segment of the CAOB in the Alxa area (Figure 15).

In the study area, there is no evidence for Triassic sedimentation, and the Late Permian volcano-sedimentary rocks may therefore mark the youngest subduction-related component in the southwestern ATB. Triassic sedimentary rocks are rare across the whole ATB, and minor Triassic terrestrial sedimentation only occurs in the Zhusileng-Hangwula and Yagan tectonic zones in the northern ATB, where Late Triassic gypsum-bearing sediments unconformably overlay Late Permian marine strata (Figure 2). This may indicate that after the final subduction process of the PAO in the Late Permian, the Alxa area had probably been uplifted to undergo denudation since Triassic (S. Li et al., 2014; Song et al., 2018).

9.4. Tracing a Permian Subduction-Accretion Margin Along the Southern CAOB

The southern segment of the CAOB extends from the Tianshan Orogenic Belt in the west, through the Beishan and Alxa tectonic belts in the middle, to the Sonlonker Suture Zone in the east, forming a huge accretion-collision system on the northern edge of the Karakum, Tarim and North China cratons (Figure 1). The tectonic evolutionary history of these orogenic belts during the Permian is crucial for our understanding of the final architecture of the CAOB and the paleogeography of the Asian continent. The timing of final subduction of the PAO and terminal amalgamation of the CAOB can be evaluated by the comprehensive analysis of data from arc-related marine strata, ophiolites, accretionary complexes, and subduction-/collision-related magmatism, metamorphism, and structural deformation. Available data point to a complicated convergent tectonic setting including oceanic subduction and terrane amalgamation across the southern margin of the PAO during the Permian (Eizenhöfer & Zhao, 2017; Windley et al., 2007; Xiao et al., 2015).
In the Chinese Tianshan and its adjacent regions, Permian subduction and accretionary processes are evidenced by regional sedimentary, structural, magmatic, and metamorphic events. A comprehensive analysis of the sedimentary facies and erosion history of Permian strata from the Turpan-Hami Basin indicates that the tectonic evolution and changing of sedimentary facies recorded the accretionary orogeny associated with subduction of the PAO, and the timing of final closure process of the Ocean was constrained to be Middle Permian (Jiang et al., 2015). The ages of radiolarians fossils preserved in the South Tianshan accretionary complex range from Devonian to Permian, with the youngest ones being Late Permian in age (Li et al., 2010), suggesting abyssal deposits still existing during the Late Permian. Triassic high-pressure metamorphism in the South Tianshan accretionary complex (Zhang et al., 2007), Permian–Triassic thrusting deformation along major faults in the Chinese Altay (Briggs et al., 2009), and Middle Permian (~266 Ma) N–S compressional deformation of the Turfan Basin (Yang et al., 2009) suggest complicated transpressional orogenic processes during Permian–Triassic. Furthermore, a recent study along the structural contact between the Tianshan and Pamirs in Tajikistan reveals consistent apatite U-Pb deformation ages of ~251 Ma (Jepson et al., 2018). In the Gobi-Tianshan in southern Mongolia, an intrusive complex dominated by voluminous intermediate hydrated magmatism typical of a continental margin arc was dated at 295–290 Ma and interpreted as the product of the subduction of the PAO (Economos et al., 2012). Although more detailed, multiple-disciplinary investigations are required, the available data from various studies support a complicated convergent margin environment during Permian in the Chinese Tianshan and its adjacent areas (Xiao et al., 2008, 2013, and references therein).

In the Beishan Orogenic Belt, Permian oceanic components and subduction-related rocks and structures are widely distributed. In the Hongshishan area in the northernmost Beishan near the China-Mongolia international border, a highly deformed ophiolitic mélangé consisting of marine sedimentary rocks, limestones, pelagic cherts, ultramafic, and mafic rocks including pillow basalts was regarded to be formed in Late Carboniferous–Early Permian times based on isotopic dating and biostratigraphic data (Xiao, Mao, et al., 2010). Alaskan-type, zoned mafic-ultramafic complexes with arc-related geochemical signatures intruded the southwestern Beishan during the Early Permian (Ao et al., 2010). A Permian–Triassic terminal accretion process was evidenced by the kilometer-scale complicated megafold interference patterns developed in the Permian Hongyanjing intrarc basin successions in the central segment of Beishan (Tian et al., 2013). A Carboniferous–Permian forearc ophiolite composed of pillow and massive basalts, gabbros, and serpentinites imbricated with Permian tuffaceous sediments and limestone is present in the Liuyuan area in the southern Beishan (Mao et al., 2012). Further evidence for the Permian active margin includes the well-preserved Permian turbidites in the southernmost Beishan, which consist mainly of marine volcanoclastic arenites and greywackes (Guo et al., 2012), similar in composition to what we have observed in the southwestern ATB for this study. Moreover, the diagnostic zircon U-Pb-Hf isotopic compositions and imbricated fold-thrust deformation style of the Permian metagreywacke in the southern Beishan also demonstrate a subduction-accretion setting during the Permian (Song et al., 2016). This is furthermore supported by the Permian magmatic records revealed by zircon age compilation (Figure 14c).

Farther east, the Solonker Suture Zone has long been considered to mark the location of the final disappearance of the PAO in the eastern segment of the CAOB (Jian et al., 2010; Şengör et al., 1993; Xiao et al., 2003). Extensive studies along the Solonker Suture Zone suggest a complicated arc-trench system in this area during the Permian. Arc-related volcanic and intrusive rocks with calc-alkaline signatures are widely distributed both north and south of the Solonker Suture Zone (Y. L. Li et al., 2016; Zhang et al., 2009). A continental arc was considered to be existing from ~400 to 275 Ma along the northern margin of the NCC based on detrital zircon U-Pb study of Carboniferous and Permian sedimentary rocks (Cope et al., 2005). Based on detailed geochemical and geochronological studies on ophiolites and associated magmatic rocks, Jian et al. (2010) proposed a Permian intraoceanic arc-trench system incorporation of ridge subduction along the Solonker Suture Zone during the Early–Middle Permian. The protolith of the Shuangjing schist in the Linxi area is a volcanic-sedimentary rock series deposited in an arc-forearc basin during the Late Carboniferous to Middle Permian south dipping subduction of the PAO (Li et al., 2011). Middle Permian marine turbidite and flysch are widely distributed across the Solonker Suture Zone, which transited to terrestrial sediments in the Late Permian (Li et al., 2014; Shen et al., 2006; Wang et al., 2009). Magmatic rocks related to terminal collision along the Solonker-Xar Moron suture zone were regarded to be formed in the Early–Middle Triassic (S. Li et al., 2016, 2017). A comprehensive analysis of field and published data suggest an accretionary wedge-wedge collision.

In the Chinese Tianshan and its adjacent regions, Permian subduction and accretionary processes are evidenced by regional sedimentary, structural, magmatic, and metamorphic events. A comprehensive analysis of the sedimentary facies and erosion history of Permian strata from the Turpan-Hami Basin indicates that the tectonic evolution and changing of sedimentary facies recorded the accretionary orogeny associated with subduction of the PAO, and the timing of final closure process of the Ocean was constrained to be Middle Permian (Jiang et al., 2015). The ages of radiolarians fossils preserved in the South Tianshan accretionary complex range from Devonian to Permian, with the youngest ones being Late Permian in age (Li et al., 2010), suggesting abyssal deposits still existing during the Late Permian. Triassic high-pressure metamorphism in the South Tianshan accretionary complex (Zhang et al., 2007), Permian–Triassic thrusting deformation along major faults in the Chinese Altay (Briggs et al., 2009), and Middle Permian (~266 Ma) N–S compressional deformation of the Turfan Basin (Yang et al., 2009) suggest complicated transpressional orogenic processes during Permian–Triassic. Furthermore, a recent study along the structural contact between the Tianshan and Pamirs in Tajikistan reveals consistent apatite U-Pb deformation ages of ~251 Ma (Jepson et al., 2018). In the Gobi-Tianshan in southern Mongolia, an intrusive complex dominated by voluminous intermediate hydrated magmatism typical of a continental margin arc was dated at 295–290 Ma and interpreted as the product of the subduction of the PAO (Economos et al., 2012). Although more detailed, multiple-disciplinary investigations are required, the available data from various studies support a complicated convergent margin environment during Permian in the Chinese Tianshan and its adjacent areas (Xiao et al., 2008, 2013, and references therein).

In the Beishan Orogenic Belt, Permian oceanic components and subduction-related rocks and structures are widely distributed. In the Hongshishan area in the northernmost Beishan near the China-Mongolia international border, a highly deformed ophiolitic mélangé consisting of marine sedimentary rocks, limestones, pelagic cherts, ultramafic, and mafic rocks including pillow basalts was regarded to be formed in Late Carboniferous–Early Permian times based on isotopic dating and biostratigraphic data (Xiao, Mao, et al., 2010). Alaskan-type, zoned mafic-ultramafic complexes with arc-related geochemical signatures intruded the southwestern Beishan during the Early Permian (Ao et al., 2010). A Permian–Triassic terminal accretion process was evidenced by the kilometer-scale complicated megafold interference patterns developed in the Permian Hongyanjing intrarc basin successions in the central segment of Beishan (Tian et al., 2013). A Carboniferous–Permian forearc ophiolite composed of pillow and massive basalts, gabbros, and serpentinites imbricated with Permian tuffaceous sediments and limestone is present in the Liuyuan area in the southern Beishan (Mao et al., 2012). Further evidence for the Permian active margin includes the well-preserved Permian turbidites in the southernmost Beishan, which consist mainly of marine volcanoclastic arenites and greywackes (Guo et al., 2012), similar in composition to what we have observed in the southwestern ATB for this study. Moreover, the diagnostic zircon U-Pb-Hf isotopic compositions and imbricated fold-thrust deformation style of the Permian metagreywacke in the southern Beishan also demonstrate a subduction-accretion setting during the Permian (Song et al., 2016). This is furthermore supported by the Permian magmatic records revealed by zircon age compilation (Figure 14c).

Farther east, the Solonker Suture Zone has long been considered to mark the location of the final disappearance of the PAO in the eastern segment of the CAOB (Jian et al., 2010; Şengör et al., 1993; Xiao et al., 2003). Extensive studies along the Solonker Suture Zone suggest a complicated arc-trench system in this area during the Permian. Arc-related volcanic and intrusive rocks with calc-alkaline signatures are widely distributed both north and south of the Solonker Suture Zone (Y. L. Li et al., 2016; Zhang et al., 2009). A continental arc was considered to be existing from ~400 to 275 Ma along the northern margin of the NCC based on detrital zircon U-Pb study of Carboniferous and Permian sedimentary rocks (Cope et al., 2005). Based on detailed geochemical and geochronological studies on ophiolites and associated magmatic rocks, Jian et al. (2010) proposed a Permian intraoceanic arc-trench system incorporation of ridge subduction along the Solonker Suture Zone during the Early–Middle Permian. The protolith of the Shuangjing schist in the Linxi area is a volcanic-sedimentary rock series deposited in an arc-forearc basin during the Late Carboniferous to Middle Permian south dipping subduction of the PAO (Li et al., 2011). Middle Permian marine turbidite and flysch are widely distributed across the Solonker Suture Zone, which transited to terrestrial sediments in the Late Permian (Li et al., 2014; Shen et al., 2006; Wang et al., 2009). Magmatic rocks related to terminal collision along the Solonker-Xar Moron suture zone were regarded to be formed in the Early–Middle Triassic (S. Li et al., 2016, 2017). A comprehensive analysis of field and published data suggest an accretionary wedge-wedge collision.
leading to the formation of the Solonker Suture Zone at the end of the Permian (Xiao et al., 2003). The spatial and temporal distribution of ophiolites and concurrent igneous activities along the Xing’an-Inner Mongolian accretionary belt favor a bilateral subduction of the PAO toward the NCC and Mongolian Microcontinent, with final collision at ~230–220 Ma (Song et al., 2015). Recent detailed field, compositional and detrital zircon U-Pb studies on the Middle-Late Permian volcanic-sedimentary rocks from the Huanggangliang and Linxi formations show immaturity in composition and intense syndepositional tectonic activity, suggesting that these rocks were formed in an active arc system (Eizenhöfer et al., 2014). Geochronological and Hf isotopic studies on detrital zircons in Paleozoic strata across the Solonker Suture Zone revealed a complicated subduction scenario from Late Ordovician to Late Permian, with final collision between the northern and southern accretionary orogens at the end of the Early Triassic (Eizenhöfer et al., 2015; Eizenhöfer & Zhao, 2017). In addition, the overall detrital zircon age distribution patterns (particularly the Paleozoic age population) from the Permian sedimentary rocks along the Solonker Suture Zone show significant similarities to that from the southwestern ATB in this study (Figure 16). Both of them display a major Middle Permian age peak (~269 Ma and ~266 Ma, respectively), a subordinate Early Silurian peak (~436 Ma and ~440 Ma, respectively), and an obvious age gap (magmatic lull) between ~310 Ma and ~380 Ma (Figure 16). These facts indicate that the southwestern ATB underwent a similar tectonic-magmatic history as the Solonker region during the Paleozoic, particularly during the Permian time. The Permian zircons in the Permian arc sediments along the Solonker Suture Zone are considered to be derived from the Southern Accretionary Orogen as a result of southward subduction of the PAO beneath the northern margin of the NCC (Eizenhöfer et al., 2014). These data suggest that the Alxa area and the northern margin of the NCC can be associated with the same south dipping subduction zone during the Permian. A synthesized data of Early Paleozoic magmatism also suggests that the 460–400 Ma magmatic arc in the Alxa area represents the western extension of the Early Paleozoic arc belt developed on the northern margin of the NCC (Liu et al., 2016). This is also supported by the similar Early Silurian age peaks in the Permian sediments between Alxa and Solonker (Figure 16). The different Precambrian age spectra, however, may reflect the different nature of Precambrian basement between the NCC and the Alxa ribbon continent (Song et al., 2017).

In summary, during the Permian, the southern margin of the PAO was still under subduction and generated a huge along-strike magmatic arc and arc-related basin system that can be traced from the Tianshan in the west to the Beishan and Alxa in the middle and to Solonker in the east. The Middle–Late Permian arc-related volcanic-sedimentary rocks in the southwestern ATB links the western and eastern segment of this long active continental margin. This archipelago-type complicated subduction and amalgamation scenario show similarities to the present southwest Pacific subduction-accretion system (e.g., Windley et al., 2007; Xiao et al., 2015).

10. Conclusions

The Permian volcano-sedimentary rocks from the southwestern ATB contain diverse lithologies including conglomerate, greywacke, sandstone, limestone, volcanic lava, volcanic breccia, and tuff. The conglomerates are generally composed of well-rounded but poorly sorted gravels dominated by porphyritic rocks such as andesite, dacite, and rhyolite. Graded bedding and pillow-and-ball structures are developed in the sedimentary rocks. These sediments were sourced from a proximal provenance and deposited rapidly in a high-energy continental slope environment. Detrital zircon U-Pb dating combined with previous biostratigraphic studies refine the maximum depositional ages of the Permian strata to the Middle Permian.

Figure 16. Comparison of detrital zircon U-Pb age spectra between southwestern Alxa Permian strata (this study) and Permian arc-related basin strata along the Solonker Suture Zone (Eizenhöfer et al., 2014). Noting the Permian strata from the southwestern Alxa and Solonker Suture Zone showing comparable Permian age peaks.
Acknowledgments
We are grateful to Benjamin Wade and Aoife McFadden from the Adelaide Microscopy for help during zircon CL imaging and LA-ICP-MS U-Pb dating. Staff from the MC-ICP-MS Laboratory at the Institute of Geology and Geophysics, Chinese Academy of Sciences were very helpful during the Lu-Hf isotope analysis. Data are available in the supporting information for this manuscript. We thank journal Editor Nathan A. Niemi for handling our manuscript. Constructive and detailed comments by an Associated Editor and two journal reviewers Timothy Kusky and an anonymous reviewer led to significant improvements on the earlier version of the manuscript, which are very much appreciated. This study has been financially supported by the National Key R&D Program of China (2017YFC0601206), the National Natural Science Foundation of China (41672219, 41730210, 41402196, and 41230207), Key Research Program of Frontier Sciences of the Chinese Academy of Sciences (grant QYZDJ-SSW-SYS012), and the China Postdoctoral Science Foundation project (2015T80133). D. F. S. was funded by the China Scholarship Council (CSC 201504910051) during his stay at the University of Adelaide, which is greatly acknowledged. A. C. and S. G. were supported by an Australian Research Council Discovery Project (DP150101730). This study forms TRaX record 400. This is a contribution to IGCP 662.

References
Anonymous (1978). Geological map of the Nuerhai Region, China (in Chinese), scale 1:200,000. The Third Geological Team of the Gansu Bureau of Geology.
Ao, S. J., Xiao, W. J., Han, C. M., Mao, Q. G., & Zhang, J. E. (2010). Geochemistry and geochemistry of Early Permian mafic-ultramafic complexes in the Beishan area, Xinjiang, NW China: Implications for late Paleozoic tectonic evolution of the southern Altai. Gondwana Research, 18(2–3), 466–478. https://doi.org/10.1016/j.gr.2010.11.004
Bassett, K. N., & Busby, C. J. (2005). Tectonic setting of the glance conglomerate along the Sawmill Canyon fault zone, southern Arizona: A sequence analysis of an intra-arc strike-slip basin. Geological Society of America Special Papers, 393, 377–400. https://doi.org/10.1130/0-8137-2393-0.377
Beranek, L. P., Link, P. K., & Fanning, C. M. (2016). Detrital zircon record of mid-Paleozoic convergent margin activity in the northern U.S. Rocky Mountains: Implications for earlier orogeny and early evolution of the North American Cordillera. Lithosphere, 8, 533–550. https://doi.org/10.1130/L557.1
Best, M. G. (2003). Igneous and metamorphic petrology (2nd ed., p. 729). Malden: Blackwell Science Ltd.
Bilcher-Toff, J., & Albarède, F. (1997). The Lu-Hf isotope geochemistry of chondrites and the evolution of the mantle-crust system. Earth and Planetary Science Letters, 148, 243–258. https://doi.org/10.1016/S0012-821X(97)00040-X
Briggs, S. M., Yin, A., Manning, C. E., Chen, Z. L., & Wang, X. F. (2009). Tectonic development of the southern Chinese Altai range as determined by structural geology, thermobarometry, 40Ar/ 39Ar thermochronology, and Th/Pb ion-microprobe monazite geochronology. Geological Society of America Bulletin, 121(9-10), 1381–1393. https://doi.org/10.1130/B26385.1
Cawood, P. A., Hawkesworth, C. J., & Dhuime, B. (2012). Detrital zircon record and tectonic setting. Geology, 40(10), 875–878. https://doi.org/10.1130/G32945.1
Charvet, J., Shu, L. S., & Laurent-Charvet, S. (2007). Paleozoic structural and geodynamic evolution of eastern Tianshan (NW China): Welding of the Tarim and Junggar plates. Episodes, 30(3), 162–186.
Clift, P., & Vannucchi, P. (2004). Controls on tectonic accretion versus erosion in subduction zones: Implications for the origin and recycling of the continental crust. Reviews of Geophysics, 42, RG2001. https://doi.org/10.1029/2003RG000127
Clift, P. D., Pavlis, T., DeBari, S. M., Draut, A. E., Rixon, M., & Kelemen, P. B. (2005). Subduction erosion of the Jurassic Talkeetna-bonanza arc and the Messosic accretionary tectonics of western North America. Geology, 33(11), 881. https://doi.org/10.1130/G21822.1
Cloos, M., & Shreve, R. L. (1988b). Subduction-channel model of prism accretion, melange formation, sediment subduction, and subduction erosion at convergent plate margins: 1. Background and description. Pure and Applied Geophysics, 128(3), 455–500.
Cohen, K., Finney, S., Gibbard, P., & Fan, J. X. (2013). The ICS international chronostratigraphic chart. Episodes, 36(3), 199–204.
Cope, T., Ritts, B. D., Darby, B. J., Fildani, A., & Graham, S. A. (2005). Late Paleozoic sedimentation on the northern margin of the North China block: Implications for regional tectonics and climate change. International Geology Review, 47(3), 270–296. https://doi.org/10.1080/00206814.2004.10861370
Corti, G. (2009). Continental rift evolution: From rift initiation to incipient break-up in the Main Ethiopian Rift, East Africa. Earth-Science Reviews, 96(1–2), 1–53. https://doi.org/10.1016/j.earscirev.2009.06.005
Dan, W., Li, X. H., Guo, J., Liu, Y., & Wang, X. C. (2012). Paleoprotocorrosion evolution of the eastern Alxa block, westmost North China: Evidence from in situ zircon U-Pb dating and Hf-O isotopes. Gondwana Research, 21(4), 838–864. https://doi.org/10.1016/j.gr.2011.09.004
Dan, W., Li, X. H., Wang, Q., Tang, G. J., & Liu, Y. (2014). An Early Permian (ca. 280 Ma) silicic igneous province in the Alxa block, NW China: A magmatic flare-up triggered by a mantle-plume? Lithos, 204, 144–158. https://doi.org/10.1016/j.lithos.2014.01.018
Dan, W., Li, X. H., Wang, Q., Wang, X. C., & Liu, Y. (2014). Neoprotocorrosion S-type granites in the Alxa block, westmost North China and tectonic implications: In situ zircon U-Pb-Hf-O isotopic and geochronological constraints. American Journal of Science, 314(1), 110–153. https://doi.org/10.2475/01.2014.04
Dan, W., Wang, Q., Wang, X. C., Liu, Y., Wyman, D. A., & Liu, Y. S. (2015). Overlapping Sr-Nd-Hf-O isotopic compositions in Permian mafic enclaves and host granitoids in Alxa block, NW China: Evidence for crust-mantle interaction and implications for the generation of silicic igneous provinces. Lithos, 230, 133–145. https://doi.org/10.1016/j.lithos.2015.05.016
Song, D. F., Glorie, S., Xiao, W. J., Collins, A. S., Gillespie, J., Jepson, G., & Li, Y. C. (2018). Tectono-thermal evolution of the southwestern Alxa Tectonic Belt, NW China: Constrained by apatite U-Pb and fission track thermochronology. Tectonophysics, 722, 577–594. https://doi.org/10.1016/j.tecto.2017.11.029
Song, D. F., Xiao, W. J., Collins, A. S., Glorie, S., Han, C. M., & Li, Y. C. (2017). New chronological constraints on the tectonic affinity of the Alxa block, NW China. Precambrian Research, 299, 230–243. https://doi.org/10.1016/j.precamres.2017.07.015
Song, D. F., Xiao, W. J., Windley, B. F., Han, C. M., & Yang, L. (2016). Metamorphic complexes in accretionary orogens: Insights from the Beishan collage, southern central Asian Orogenic Belt. Tectonophysics, 688, 135–147. https://doi.org/10.1016/j.tecto.2016.09.012
Song, S. G., Niu, Y. L., Su, L., Zhang, C. G., & Zhang, L. F. (2014). Continental orogenesis from ocean subduction, continent collision/subduction, to ocean collapse, and oxygen recycling: The example of the North Qaidam UHPM belt, NW China. Earth-Science Reviews, 129, 59–84. https://doi.org/10.1016/j.earscirev.2013.11.010
Song, S. G., Wang, M. M., Xu, X., Wang, C., Niu, Y. L., Allen, M. B., & Su, L. (2015). Ophiolites in the Xing’an-Inner Mongolia accretionary belt of the CAOB: Implications for two cycles of seafloor spreading and accretionary orogenic events. Tectonics, 34, 2221–2248. https://doi.org/10.1002/2015TC003948
Stern, C. R. (2011). Subduction erosion: Rates, mechanisms, and its role in arc magmatism and the evolution of the continental crust and mantle. Gondwana Research, 20, 384–398. https://doi.org/10.1016/j.gr.2011.03.006
Stern, R. J. (2002). Subduction zones. Reviews of Geophysics, 40(4), 1012. https://doi.org/10.1029/2001RG000108
Tian, Z. H., Xiao, W. J., Han, C. M., Zhang, J. E., & Song, D. F. (2013). Mega-fold interference patterns in the Beishan orogen (NW China) created by change in plate configuration during Permo-Triassic termination of the Altaiids. Journal of Structural Geology, 32, 119–135. https://doi.org/10.1016/j.jsg.2013.03.016
Vermeesch, P. (2012). On the visualisation of detrital age distributions. Chemical Geology, 312–313, 190–194. https://doi.org/10.1016/j.chemgeo.2012.04.021
Vervoort, J. D., & Blechert-Toft, J. (1999). Evolution of the depleted mantle: Hf isotope evidence from juvenile rocks through time. Geochimica et Cosmochimica Acta, 63, 533–556. https://doi.org/10.1016/S0016-7037(98)00274-9
Wakita, K., Puebler, M., & Windley, B. F. (2013). Tectonic processes, from rifting to collision via subduction, in SE Asia and the western Pacific: A key to understand the architecture of the central Asian Orogenic Belt. Lithosphere, 5(3), 265–276. https://doi.org/10.1130/L3.4.1
Wang, B., Shu, L. S., Faure, M., Jahn, B. M., Cluzel, D., Charvet, J., et al. (2011). Paleozoic tectonics of the southern Chinese Tianshan: Insights from structural, chronological and geochemical studies of the Heiyingshan ophiolitic melange (NW China). Tectonophysics, 497(1–4), 85–104. https://doi.org/10.1016/j.tecto.2010.11.004
Wang, C. W., Sun, Y. W., Li, N., Zhao, G. W., & Ma, X. Q. (2009). Tectonic implications of Late Paleozoic stratigraphic distribution in Northeast China and adjacent region. Science in China Series D: Earth Sciences, 52(5), 619–626. https://doi.org/10.1007/s11430-009-0062-7
Windley, B. F., Alexeev, D., Xiao, W. J., Han, C. M., Yuan, C., Lin, S. F., et al. (2013). Paleozoic multiple accretionary and collisional tectonics of the Chinese Tianshan orogenic collage, southern central Asian Orogenic Belt. Acta Geologica Sinica (English Edition), 6(4), 373–385.
Wu, T. R., & He, G. Q. (1993). Tectonic units and their fundamental characteristics on the northern margin of the Alxa block. Acta Geologica Sinica (English Edition), 4(3), 256–263.
Xiao, W. J., Han, C. M., Yuan, C., Sun, M., Lin, S. F., Chen, H. L., et al. (2008). Middle Cambrian to Permian subduction-related accretionary orogenesis of Northern Xinjiang, NW China: Implications for the tectonic evolution of Central Asia. Journal of Asian Earth Sciences, 32, 102–117. https://doi.org/10.1016/j.jaes.2007.10.008
Xiao, W. J., Huang, B. C., Han, C. M., Sun, S., & Li, J. L. (2010). A review of the western part of the Altaiids: A key to understanding the architecture of accretionary orogenes. Gondwana Research, 18(2–3), 253–273. https://doi.org/10.1016/j.gr.2010.01.007
Xiao, W. J., Mao, Q. Q., Windley, B. F., Han, C. M., Qu, J. F., Zhang, J. E., et al. (2010). Paleozoic multiple accretionary and collisional processes of the Beishan orogenic collage. American Journal of Science, 310(10), 1553–1594. https://doi.org/10.2475/10.2010.12
Xiao, W. J., Windley, B. F., Allen, M. B., & Han, C. M. (2013). Paleozoic multiple accretionary and collisional tectonics of the Chinese Tianshan orogenic collage. Gondwana Research, 23(4), 1316–1341. https://doi.org/10.1016/j.gr.2012.01.012
Xiao, W. J., Windley, B. F., Hao, J., & Zhai, M. G. (2009). Accretion leading to collision and the Permian Solonker suture, Inner Mongolia, China: Termination of the central Asian orogenic belt. Tectonics, 22(6), 1069. https://doi.org/10.1029/2002TC001484
Xiao, W. J., Windley, B. F., Huang, B. C., Han, C. M., Yuan, C., Chen, H. L., et al. (2009). End-Permian to mid-Triassic termination of the accretionary processes of the southern Altaiids: Implications for the geodynamic evolution, Phanerozoic continental growth, and metallogeny of Central Asia. International Journal of Earth Sciences, 98(6), 1189–1217. https://doi.org/10.1007/s00531-008-0407-2
Xiao, W. J., Windley, B. F., Sun, S., Li, J. L., Huang, B. C., Han, C. M., et al. (2015). A tale of amalgamation of three Permio-Triassic collage Systems in Central Asia: Oroclines, sutures, and terminal accretion. Annual Review of Earth and Planetary Sciences, 43(1), 477–507. https://doi.org/10.1146/annurev-earth-060614-105254
Xiao, W. J., Windley, B. F., Yong, Y., Yan, Z., Yuan, C., Liu, C. Z., & Li, J. L. (2009). Early Paleozoic to Devonian multiple-accretionary model for the Qilian Shan, NW China. Journal of Asian Earth Sciences, 35(3–4), 323–333. https://doi.org/10.1016/j.jaes.2008.10.001
Xiao, W. J., Windley, B. F., Yuan, C., Sun, S., Han, C. M., Lin, S. F., et al. (2009). Paleozoic multiple subduction-accretion processes of the southern Altaiids. American Journal of Science, 309(3), 221–270. https://doi.org/10.2475/ajs.2009.03.032
Xie, L., Yin, H. Q., Zhou, H. R., & Zhang, W. J. (2014). Permian radiolarians from the Engeewusu suture zone in Alashan area, Inner Mongolia and its geological significance (in Chinese with English abstract). Geological Bulletin of China, 33, 691–697.
Xu, B., Charvet, J., Chen, Y., Zhao, P., & Shi, G. Z. (2013). Middle Paleozoic convergent orogenic belts in western Inner Mongolia (China): Framework, kinematics, geochronology and implications for tectonic evolution of the Central Asian Orogenic Belt. Gondwana Research, 23(4), 1342–1364. https://doi.org/10.1016/j.gr.2012.05.015
Yang, T. N., Li, J. Y., Wang, Y., & Dang, Y. X. (2009). Late Early Permian (266 ma) N-S compressional deformation of the Turfan basin, NW China: The cause of the change in basin pattern. International Journal of Earth Sciences, 98, 1311–1324. https://doi.org/10.1007/s00531-008-0396-y
Zhang, J., Zhang, Y. P., Xiao, W. X., Wang, Y. N., & Zhang, B. H. (2015). Linking the Alxa Terrane to the eastern Gondwana during the Early Paleozoic: Constraints from detrital zircon U–Pb ages and Cambrian sedimentary records. *Gondwana Research*, 28(3), 1168–1182. https://doi.org/10.1016/j.gr.2014.09.012

Zhang, J. J., Wang, T., Castro, A., Zhang, L., Shi, X. J., Tong, Y., et al. (2016). Multiple mixing and hybridization from magma source to final emplacement in the Permian Yamatu pluton, the northern Alxa block, China. *Journal of Petrology*, 57(5), 933–980. https://doi.org/10.1093/petrology/egw028

Zhang, J. J., Wang, T., Zhang, L., Tong, Y., Zhang, Z. C., Shi, X. J., et al. (2015). Tracking deep crust by zircon xenocrysts within igneous rocks from the northern Alxa, China: Constraints on the southern boundary of the central Asian Orogenic Belt. *Journal of Asian Earth Sciences*, 108, 150–169. https://doi.org/10.1016/j.jseaes.2015.04.019

Zhang, J. X., Gong, J. H., Yu, S. Y., Li, H. K., & Hou, K. J. (2013). Neoarchean–Paleoproterozoic multiple tectonothermal events in the western Alxa block, North China Craton and their geological implication: Evidence from zircon U–Pb ages and Hf isotopic composition. *Precambrian Research*, 235, 36–57. https://doi.org/10.1016/j.precamres.2013.05.002

Zhang, L. F., Ai, Y. L., Li, X., Rubatto, D., Song, B., Williams, S., et al. (2007). Triassic collision of western Tianshan orogenic belt, China: Evidence from SHRIMP U–Pb dating of zircon from HP/UHP eclogitic rocks. *Lithos*, 96(1–2), 266–280. https://doi.org/10.1016/j.lithos.2006.09.012

Zhao, G. C., & Cawood, P. A. (2012). Precambrian geology of China. *Precambrian Research*, 222, 13–54. https://doi.org/10.1016/j.precamres.2012.09.017

Zhao, X. M., Chen, D. C., & Deng, J. (2010). Depositional characteristic of Permo-Carboniferous system from Yingen-Ejinaqi and their surrounding areas, Inner Mongolia, China and its implications for petroleum (in Chinese with English abstract). *Acta Geologica Sinica*, 84(8), 1183–1194.

Zheng, R. G., Wu, T. R., Zhang, W., Xu, C., Meng, Q. P., & Zhang, Z. Y. (2014). Late Paleozoic subduction system in the northern margin of the Alxa block, Altaiids: Geochronological and geochemical evidences from ophiolites. *Gondwana Research*, 25(2), 842–858. https://doi.org/10.1016/j.gr.2013.05.011

Zhou, X. C., Zhang, H. F., Luo, B. J., Pan, F. B., Zhang, S. S., & Guo, L. (2016). Origin of high Sr/Y-type granitic magmatism in the southwestern of the Alxa block, Northwest China. *Lithos*, 256–257, 211–227. https://doi.org/10.1016/j.lithos.2016.04.021