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Middle Cambrian to Permian subduction-related accretionary orogenesis of Northern Xinjiang, NW China: Implications for the tectonic evolution of central Asia

Wenjiao Xiao [a,*], Chunming Han [a], Chao Yuan [b], Min Sun [c], Shoufa Lin [d], Hanlin Chen [e], Zilong Li [e], Jiliang Li [a], Shu Sun [a]

[a] State Key Laboratory of Lithospheric Evolution, Institute of Geology and Geophysics, Chinese Academy of Sciences, P.O. Box 9825, Beijing 100029, China
[b] Guangzhou Institute of Geochemistry, Chinese Academy of Sciences, Guangzhou 510640, Guangdong, China
[c] Department of Earth Sciences, The University of Hong Kong, Hong Kong, China
[d] Department of Earth Sciences, University of Waterloo, 200 University Avenue West, Waterloo, Ont., Canada
[e] Faculty of Sciences, Zhejiang University, Hangzhou 310027, Zhejiang, China

Abstract

Middle-Cambrian to Permian subduction-related records are widely distributed in Northern Xinjiang which can be grouped into the Chinese Altay–East Junggar–Eastern Tien Shan, West Junggar, Yili, and Tarim domains. By integrating paleogeographic and geological data, we suppose that the Chinese Altay–East Junggar–Eastern Tien Shan domain was more closely located to Siberia, while the West Junggar and Yili domains occupied an intermediate position near the Kazakhstan block in the early Paleozoic Paleoasian Ocean. Distribution of Andean-type magmatic arcs, island arcs, accretionary wedges, ophiolitic slices, and/or microcontinents shows an archipelago paleogeography forming a huge accretionary active margin sequences. The Tarim domain was on the opposite side of the early Paleozoic Paleoasian Ocean remaining passive margin. These tectonic units drifted northwards and approached the southern active margin of the Siberian craton in the late Paleozoic, leading to termination of the Paleoasian Ocean and formation of a complicated orogenic collage between Siberian craton and the Tarim block between the end-Permian and Triassic. These multiple accretion processes significantly contributed to the lateral growth of central Asia.

Keywords: Northern Xinjiang; Altaids; Intra-oceanic subduction; Ophiolite; Accretion; Central Asia

1. Introduction

The Altaids is one of the biggest accretionary orogens that grew southward in general from Siberia (Fig. 1), encompassing a huge areas of Kazakhstan, Russia, Mongolia, China and their surroundings (Şengör et al., 1993; Mossakovsky et al., 1994; Şengör and Natal'in, 1996; Jahn et al., 2000; Dobretsov, 2003; Dobretsov et al., 2004; Seltmann et al., 2003; Xiao et al., 2003; Yakubchuk, 2004). However, there is a strong debate about the mechanism of the accretionary growth as to whether there was a long-lived, single subduction system (Şengör et al., 1993; Şengör and Natal'in, 1996), a collage of various terranes with multiple subduction systems (Coleman, 1989, 1994; Mossakovsky et al., 1994; Buslov et al., 2001, 2003; Windley et al., 2002; Badarch et al., 2002), or huge chains of double arc-backarc pairs (Yakubchuk, 2002, 2004). The final phase of the various geological entities or terranes amalgamated is in controversial and the final closure time of the Paleoasian Ocean is not clear (e.g., early to middle Paleozoic, He et al., 1994; Han et al., 1997; or late Paleozoic, Filippova et al., 2001; Li et al., 2003; Xiao et al., 2004a,b, 2006b; Yakubchuk, 2004). Northern Xinjiang

* Corresponding author. Tel.: +86 10 8299 8524; fax: +86 10 6201 0846.
E-mail address: wj-xiao@mail.igcas.ac.cn (W. Xiao).

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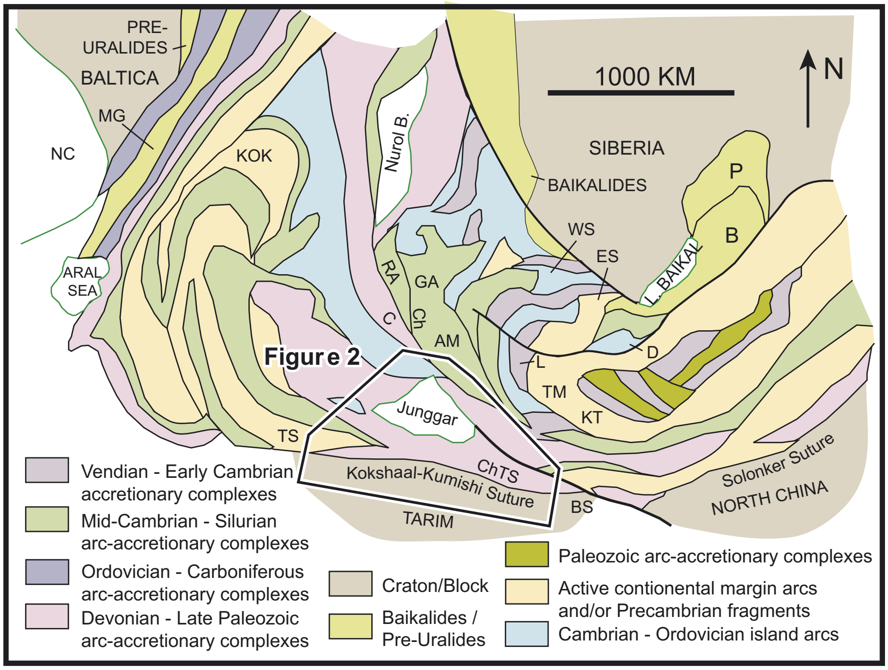

Fig. 1. Simplified tectonic map of the Central Asian Orogenic Belt. AM, Altai-Mongolia block; B, Barguzin; BS, Beishan; C, Chara suture; Ch, Charysh suture; ChTS, Chinese Tien Shan; D, Dzhida; ES, East Sayan; GA, Gorny Altai; K, Keketuohai; Kok, Kokchetav; KT, Khantaishir; H, Halatongke; L, Lake (Ozernaya); MG, Magnitogorsk; NC, North Caspian basin; P, Patom; RA, Rudny Altai; SG, South Gobi microcontinent; TM, Tuva Mongol massif; TS, Tien Shan; WS, West Sayan. Modified after Şengör et al. (1993) and Windley et al. (2007). The Northern Xinjiang region is outlined.

occupies in the southern part (Fig. 1) of the Altaids. Its almost complete geological records and excellent exposure of ophiolites, magmatic arcs, and accretionary wedges have made it an ideal natural laboratory to address this puzzle, in particular, to unravel the final subduction and accretion processes through the Paleozoic (Coleman, 1989; Windley et al., 1990; Allen et al., 1993; Yin and Nie, 1996; Jahn et al., 2000; Jahn, 2001; Xiao et al., 2004a,b). Despite its important significance, nevertheless, nearly all published English syntheses on the Altaids were constructed without qualified, updated data from Northern Xinjiang. On the other hand, there is no agreement about the tectonics of Northern Xinjiang. For instance, the final amalgamation time was regarded either as early–middle Devonian (Wang et al., 1990; Han et al., 1997), late Devonian–early Carboniferous (Gao et al., 1995; Windley et al., 1990; Allen et al., 1993), or Permian (Sun et al., 1991; Li et al., 2005; Xiao et al., 2006a,b). The major debate centres on the time, nature and tectonic setting of the various tectonostratigraphic units. Therefore, the systematic definition of the various tectonic entities of Northern Xinjiang should be of a key significance to better understanding of the final stage of tectonics in central Asia.

As several Chinese national key projects and international joint programs were launched on the metallogeny and tectonics of Northern Xinjiang, huge quantities of data have been accumulated. The most important breakthrough is that many geological bodies, such as arcs, accretionary prisms, and ophiolitic fragments, have been dated by high-resolution SHRIMP zircon dating and/or paleontological method. Therefore new data on the various geological entities should be summarized and their tectonic settings needs be revised and reinterpreted. Also, many results and progress reports were published in Chinese, and there is an urgent need to synthesize the geology of Northern Xinjiang in English. This paper presents a new version of tectonic subdivision of Northern Xinjiang, and based on those data and observations we provide a new tectonic model and reconstruction for Northern Xinjiang in the framework of the southern Altaids.

2. Methodology

Tectonic facies analysis (Hsü, 1994) provides a large-scale view on relationships between orogens and plate tectonics, while terrane methodology (Coney et al., 1980; Nokleberg et al., 2000, 2005) emphasizes a detailed tectonic philosophy for orogen anatomy. In accretionary orogens like Cordilleran, Andean, and Mongolian mountain ranges, the recognition of terranes is useful for understanding the complicated amalgamation history (Nokleberg et al., 2000, 2005; Badarch et al., 2002), if combined with detailed structural, tectonic, and paleontological data (Dewey et al., 1988; Şengör, 1990; Robertson, 1994; Guo, 2000, 2001). Therefore we will use paleontological and paleomagnetic data as important constraints to define first-order tectonic domains, and in that framework we define the second-order tectonic units using tectonic analysis combined with detailed structural, petrologic, geochemical, geochronological and stratigraphic data.

3. Regional geology and previous tectonic views

Northern Xinjiang is a vast area occupied by a desert of the Junggar Basin surrounded by mountain ranges (Figs. 2 and 3). The Chinese Altay is the northerly distributed, NW-trending mountain range, and the Tien Shan is the southerly distributed, approximately E–W-trending mountain range with high peaks of several thousand meters. To the north of the Chinese Altay are the mountain ranges of Kazakhstan, Russia, and Mongolia. To the south of the Tien Shan is the Tarim Basin. Those small mountain ranges located to the east and west of the Junggar Basin are called "East Junggar" and "West Junggar", respectively. They both are in fault contact with the Chinese Altay to the north along the Erqis fault, and with the Tien Shan to the south along the Tien Shan ophiolitic mélanges (see the ophiolitic fragments along the Tien Shan south of the Junggar Basin in Figs. 2 and 3).

The structural lines in Northern Xinjiang are mainly parallel to the mountain ranges, and the major tectonic elements are mainly NW- or E–W-trending, but those in West Junggar are NE-trending. Tectonics of Northern Xinjiang was studied by various groups of geologists in general (Feng et al., 1989; Xiao and Tang, 1991; Xiao et al., 1994; He et al., 1994; Pirajno et al., 1997; Liu, 2000, 2002). However, the distribution of oceanic and continental domains and the final suture zone between Siberia and Tarim is controversial. One school of researchers recognised the Siberian (Chinese Altay), Kazakhstan–Junggar (Junggar Basin basement, East and West Junggar), and the Tarim plates, separating by two major sutures along the Erqis fault and Tien Shan Mountains (Li, 1980; Li et al., 1982; He et al., 1994, 2001, 2004). The Erqis suture that extends roughly along the Erqis fault actually is a much complicated structural belt composed of many different shear zones (Shu et al., 2002; Laurent-Charvet et al., 2003; Windley et al., 2002) (Fig. 3). Another school of researchers regarded some other ophiolites in the Junggar, such as the Armantai or Kelameili ophiolites as suture zone separating the Siberia to the north and the Junggar or Tarim plate to the south (Li, 1980; Li et al., 1982; Ma et al., 1997).

Even in the Kazakhstan and Junggar areas there are many ophiolites of different ages (Coleman, 1989; Feng et al., 1989; Filippova et al., 2001; Buslov et al., 2001; Bykadorov et al., 2003). Major sutures in the Tien Shan are more complicated and composed of numerous ophiolitic mélanges (Windley et al., 1990; Xiao et al., 2004a,b) (Figs. 2 and 3). Obviously, there are far more sutures than just the two major ones as previously thought. Some researchers have applied the terranes methodology to analyzing the geology of Northern Xinjiang or its part areas (e.g. Coleman, 1989; Allen et al., 1993; Feng et al., 1989; Shu et al., 2002; Buckman and Aitchison, 2004).

Therefore there were many different kinds of oceanic basins or even big oceans that were active in the geological history of this part of central Asia. Nevertheless, it is not clear where there the major ocean was, which once separated the Siberian and Tarim blocks, and fragments of which became the major suture after closure of these ocean basins. Also it is not clear when the subduction-related growth ended and the whole Northern Xinjiang area developed into a post-accretionary stage.

4. Middle Cambrian to Permian subduction-related records

4.1. Chinese Altay: Middle Cambrian to early Permian

The Chinese Altay consists of volcanic and plutonic rocks with ophiolites, high-grade gneiss and schist. The

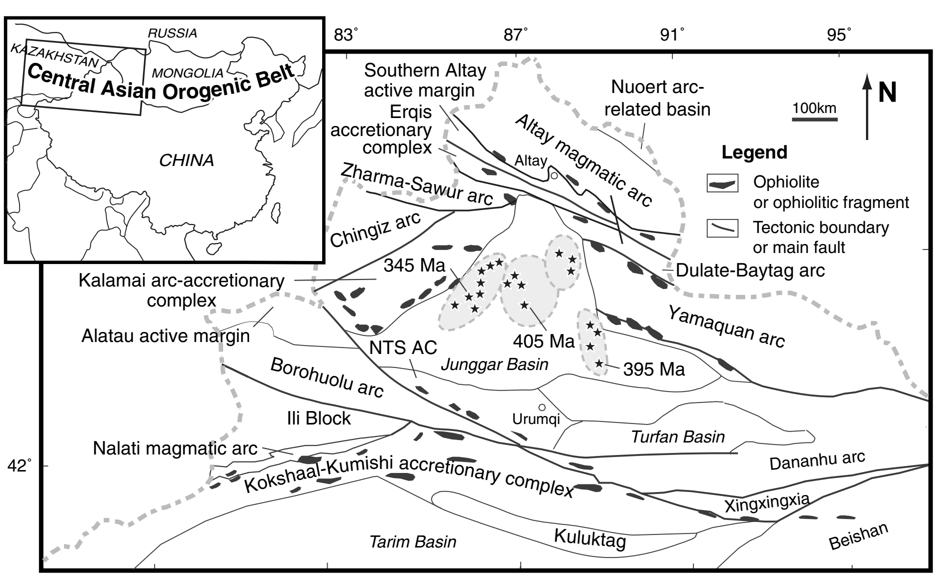

Fig. 2. Tectonic map of Northern Xinjiang showing the major arcs and ophiolites (after Xiao et al., 2004a,b; ; Han et al., 2006a,b). Borehole positions for the northern Junggar Basin are shown as starts within gray areas (Wang et al., 2002; Zheng et al.. 2007b).

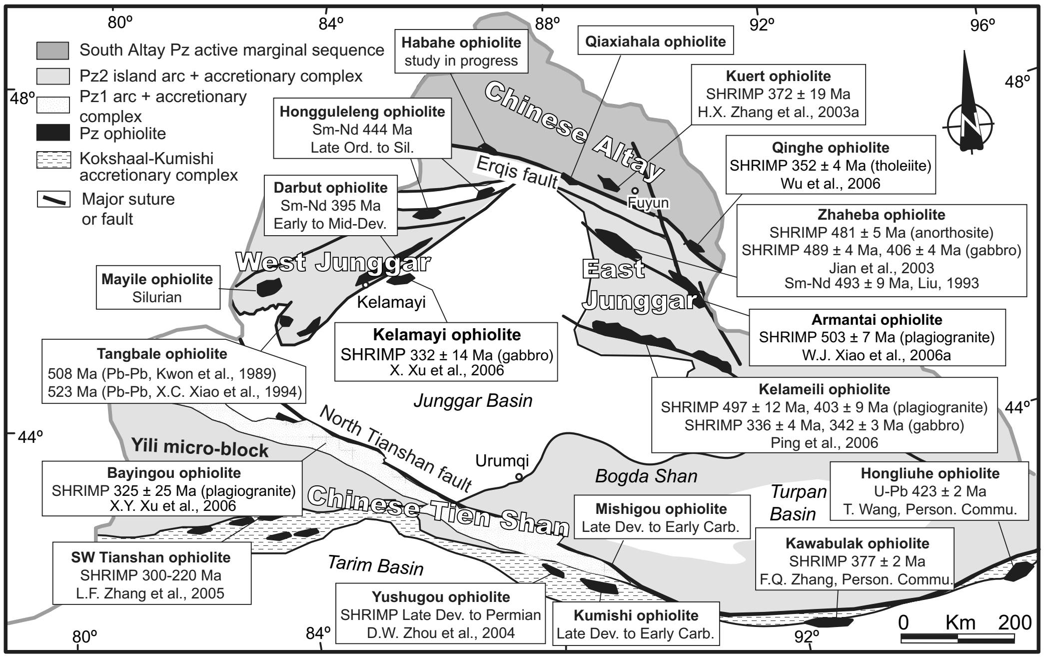

Fig. 3. Tectonic map of Northern Xinjiang showing the major ophiolitic mélanges and their ages (after Xiao et al., 2004a,b).

Chinese Altay was subdivided into several tectonic units or terranes (He et al., 1994; Windley et al., 2002; Zhang et al., 2003a; Xiao et al., 2004a). A detailed description on the lithology and structures of the Chinese Altay–East Junggar was presented in He et al. (1994), Windley et al. (2002), Li et al. (2003) and Xiao et al. (2004a).

Although different terranes in this region have been distinguished (Windley et al., 2002), all these terranes define an island arc/subduction zone with some southward younging (Rotarash et al., 1982). A rhyodacite dated at 505 ± 2 Ma was interpreted as the oldest arc volcanic rocks (Windley et al., 2002). Based on terrane analysis and zircon geochronology in the Chinese Altay region, Windley et al. (2002) concluded that the early Paleozoic Chinese Altay was a continental magmatic arc in the middle Cambrian to Ordovician. Chen et al. (2005) dated dacitic–rhyolitic rocks with a 405 ± 57 Ma Rb–Sr isochron age and an arc geochemical signature in the southwestern part of the Chinese Altay. Permian mafic granulite was found and its protolith is igneous genetic calc-alkalic basalt formed in an island arc setting (Chen et al., 2006a,b). Zheng et al. (2007a) have used CHIME (Chemical U–Th-total Pb isochron method) ages of monazite to date the metamorphism of the high-grade gneisses sampled from the central part of the Chinese Altay. They obtained Devonian and Permian ages which were interpreted as associated with orogeny in the Chinese Altay (Zheng et al., 2007a). Some gneisses along the southern part of the Chinese Altay, whose geochemistry shows island arc affinity, also yield Early Permian SHRIMP zircon ages of 281 ± 3 Ma, which was interpreted as a young phase of arc event (Hu et al., 2006).

Niu et al. (2006) presented petrographic and geochemical data on representative samples of the Devonian adakite, boninite, low-TiO_2 and high-TiO_2 basalt and associated rocks in the southern Altay areas. They pointed out that in the Devonian the juxtaposition of volcanic rocks of various origin even within a limited area, composed of the adakite and the boninite that are associated with high-TiO_2 and low-TiO_2 basalt and/or gabbro, respectively, is most likely produced by complex accretionary processes during the convergence in the Devonian–Carboniferous (Niu et al., 1999, 2006). Yuan et al. (2007) and Sun et al. (2006) have conducted LA-ICP-MS zircon U–Pb dating and whole rock analyses for major, trace element and Nd–Sr isotope compositions of granitic intrusions in the SW Chinese Altay. The results unravel that granitic intrusions were formed in an extensional forearc setting during the Devonian, Late Carboniferous, and Permian (Yuan et al., 2007). Recently Wang et al. (2006) undertook SHRIMP zircon U–Pb dating of six Paleozoic synorogenic plutons in the Chinese Altay Mountains, and found three Paleozoic granitic plutonic events at ca. 460, 408, and 375 Ma, related to an active margin. Therefore the Chinese Altay is mostly a Middle Cambrian to Early Permian magmatic arc or components of an active marginal sequence.

4.2. East Junggar: Middle Cambrian–Permian subduction-related records

The East Junggar is composed of several tectonic units. From the north to the south, the Dulate–Baytag arc and Yamaquan arc, shown on Fig. 2, are separated from each other by two ophiolitic belts (Armantai and Kelameili) (Li et al., 2003; Xiao et al., 2004a). The northerly Dulate–Baytag arc comprises boninite, Nb-enriched basalt, adakite, andesitic basalt, chert, and gabbro (XBGMR, 1993; Liu et al., 1993; He et al., 1994, 2001). Massive and pillowed basalt, Nb-enriched basalt (Zhang et al., 2003b,c, 2005; Yuan et al., 2007), boninite (Liu et al., 1993; He et al., 1994, 2001; Qin, 2000; Qin et al., 1999, 2002), and Lower Devonian adakite (Xu et al., 2001; Zhang et al., 2005), imbricated with Ordovician–Silurian radiolarian chert, Silurian–Devonian turbidite, and Devonian–Carboniferous arc volcanic rocks (Liang et al., 1999; Liu and Zhang, 1993), suggest an arc-forearc setting. A mature arc setting in the Carboniferous is indicated by presence of felsic tuff, pyroxene-bearing basalt, andesite and porphyry copper ore deposits. The Armantai ophiolite, extending NW–SE and farther east to the China–Mongolia border (Figs. 1 and 2), is composed of serpentinite, serpentinized peridotite, cumulative pyroxenite and gabbro, troctolite, rodingite, dolerite, basalt and chert. Field observations indicate that these components are mutually juxtaposed, and emplaced with Devonian–Carboniferous arc volcanic-sedimentary rocks. The oldest rocks are those ophiolitic fragments that yield middle to late Cambrian SHRIMP zircon ages (Jian et al., 2003; Ping et al., 2005; Xiao et al., 2006a).

The Kelameili ophiolite crops out mainly along the Kelaimeili fault. It consists of serpentinized peridotite, serpentinite, gabbro, rodingite and basalt, overlain by chert (Ma et al., 1997). The geochemistry of the ophiolite suggests a supra-subduction zone origin in a forearc setting (Wang et al., 2003). The chert yields Devonian and Carboniferous radiolaria (He et al., 2001; Ma et al., 1997). A number of isotopic dates on the ophiolite indicate an Early Paleozoic age for the ocean floor (Hu et al., 2000; Jian et al., 2003; Ping et al., 2005; Xiao et al., 2006a). These ophiolitic rocks are structurally imbricated with strongly deformed Devonian–Carboniferous arc volcanic rocks. Volcanic and associated pyroclastic rocks, and turbidites, ranging from Ordovician–Silurian to Devonian–lower Carboniferous in age, of possible forearc basin origin were also imbricated with ophiolites and volcano-clastic rocks (Xiao et al., 2004a).

The Permian volcanic rocks in the area southeast of the Armantai ophiolite have been interpreted as products of subduction-related setting (Lin et al., 1997). Zhao et al. (2006a) also reported major elements, trace elements and isotopic data on the latest-Paleozoic volcanic rocks, which include early-Carboniferous andesite, early-Permian trachytoid and late-Permian basalt, sampled in the same area and adjacent to the area of Lin et al. (1997). They interpreted the enriched large ion lithophile elements (LILE) relative to high field strength elements (HFSE). They revealed strongly negative anomalies in Ta and Nb relative to rare earth elements (REE), enriched light rare earth elements (LREE) relative to heavy rare earth elements (HREE), a typical characteristics of subduction-related magmas (Zhao et al., 2006a).

Therefore, the East Junggar hosts subduction-accretionary terranes, produced mainly in middle Cambrian to Permian time, including remnants of island arc, subduction complexes, seamount and ophiolites (Xiao et al., 2004a).

4.3. West Junggar: Middle Cambrian–late Carboniferous intra-oceanic arc

The West Junggar region comprises various terranes of island arc subduction origin (Coleman, 1989; Feng et al., 1989; Windley et al., 1990; Xiao and Tang, 1991; Xiao et al., 1994; Zhang et al., 1993; Buckman and Aitchison, 2001, 2004). The terranes of the West Junggar domain are mostly allochthonous, which are partially due to the severe Mesozoic–Cenozoic tectonic overprint (Allen et al., 1989; Feng et al., 1989).

Another conspicuous character is that there are more ophiolitic terranes than in the East Junggar domain (Allen et al., 1989; Feng et al., 1989; Kwon et al., 1989; Zhang et al., 1993; Liang et al., 1999). The oldest rocks in the West Junggar are the ophiolitic fragments of 508 ± 60 Ma within the Tangbale ophiolite (Kwon et al., 1989; Feng et al., 1989). The youngest ophiolites are the newly found Keramay ophiolites in which gabbro samples yield SHRIMP zircon ages of 332 ± 14 Ma (Xu et al., 2006b). Therefore the whole ophiolitic and arc-related components have many different ages varying from Ordovician to Carboniferous, which are actually relicts of possible Ordovician–Silurian arc-related basins that acted as basement or substrata of Devonian–Carboniferous arc edifices or arc-related basins (Allen et al., 1989; Wang et al., 2003; Xiao et al., 2004a).

Based on regional geology, radiolarian fossils and isotopic dating, all terranes in the West Junggar were thought to amalgamate by the end of Carboniferous time (Allen et al., 1989; Buckman and Aitchison, 2004). Geological, chemical, and isotopic studies on Carboniferous granites in the West Junggar mountain ranges suggest that they are derived from partial melting of material of oceanic crust with no contribution from Precambrian basement (Coleman, 1989; Feng et al., 1989; Kwon et al., 1989; Carroll et al., 1990; Chen and Jahn, 2002, 2004; Chen and Arakawa, 2005).

4.4. Junggar Basin basement: a collage of arcs, accretionary complexes, and tapped oceanic crust

The Junggar Basin is located in the core of Northern Xinjiang area and was previously considered as the eastern part of the Kazakhstan–Junggar plate together with the Turpan basins in the Eastern Tien Shan (Zhang et al., 1984; He et al., 1994). There has been a controversial issue concerning the basement of the Junggar Basin, which is mostly covered by Mesozoic–Cenozoic sediments. Some researchers have thought that the Junggar Basin is underlain by a Precambrian continental block (Zhang et al., 1984; Wu, 1986; Li, 2006). Based on geological, geochemical, geochronological, and geophysical data, Hsü (1988, 1989), Carroll et al. (1990), Xiao and Tang (1991), Hu et al. (2000), and Chen and Jahn (2002, 2004) proposed that the basement of the Junggar Basin may be mostly composed of arcs and accretionary complexes or trapped oceanic crust. Some key evidence for these two contrasting opinions is mostly from the surrounding West and East Junggar mountain ranges. Recently, Wang et al. (2002) and Zheng et al. (2007b) have obtained borehole samples from the north and middle part of the Junggar Basin. They sampled the borehole at 493 m and 5341 m depth, and got rhyolite and alkali basalt (for borehole positions see Fig. 2). The U–Pb ages of these rocks yield 345 Ma and 395 Ma for the rhyolite and alkaline basalt, respectively (Wang et al., 2002; Zheng et al.. 2007b). Geochemical analysis indicates that the basaltic rock is Nb-enriched, a possible intraoceanic island arc without continent basement (Wang et al., 2002; Zheng et al.. 2007b).

Some of the authors (Yuan et al., 2007) have done some geochemical and isotopic analyses on Early Devonian Nb-enriched basalts in the area north of the Armantai ophiolite in the East Junggar area. Together with previous studies on the Nb-enriched basalt (Zhang et al., 2005) and granitoid (Chen and Jahn, 2002, 2004), we conclude that the Early Devonian Nb-enriched basalts, found in the Junggar Basin borehole and East Junggar, belong to either one or pieces of various intraoceanic arcs, thought of similar ages. Recent geological and geophysical investigations along boundary between the West Junggar and Junggar Basin show that the surface ophiolitic complex has a deep root both in the West Junggar and the adjacent basement of the Junggar Basin (Xu et al., 2006b). Coleman (1989) suggested that mafic basement materials might have accounted for strong magnetic anomalies within the Junggar Basin (Carroll et al., 1990). Combining all these data, we propose that large part of the Junggar block is a collage of arcs, accretionary complexes, and trapped oceanic crust in the Paleozoic.

4.5. Tien Shan and Yili: Ordovician–Permian subduction-related records

The Tien Shan can be basically subdivided into eastern and western parts (Eastern and Western Tien Shan which were used to described the parts east to and west to Urumqi, respectively), including the Yili block, which is characterised by a broad occurrence of pre-Cambrian continental basement, and Paleozoic Kokshaal–Kumishi and North Tien Shan accretionary complexes. The Northern and Southern Tien Shan are mainly composed of tectonic mélanges (Windley et al., 1990; Gao et al., 1995, 1998; Xu et al., 2006b), while the Central Tien Shan is complicated and mostly composed of high-grade metamorphic rocks and a broad variety of deeper marine and shallower marine deposits, ranging in age from Sinian to late Carboniferous. The Yili block has Precambrian basement and cover similar to those in Kazakhstan block; Paleo-Proterozoic basement rocks were found on which middle and late Proterozoic clastic rocks and carbonates occur. Therefore it was regarded as a continental slice or microcontinent (XBGMR, 1993; Xiao and Tang, 1991; He et al., 1994, 2001, 2004; Chen et al., 1999; Xiao et al., 2004b).

The eastern part is more complicated than the western part of the Tien Shan. In the eastern part of the Tien Shan, South to the Kelameili fault, the Dananhu arc and the Xiaopu-Bogda intra-arc basin crop out along the northern and southern edges of the Turpan Basin of Cenozoic age (Xiao et al., 2004b).

The oldest rocks are Lower Ordovician metamorphosed clastics, volcaniclastics, tholeiites and andesites. The overlying Upper Ordovician is mainly composed of slightly metamorphosed clastics, volcanics and minor marble. These rocks belong to a series of Ordovician to Permian island arc, created by south-dipping subduction of the Kelameili oceanic floor because there were an arc edifice located to the north and accretionary complex and ophiolitic fragments to the south (Ma et al., 1997; Xiao et al., 2004a,b, 2006b).

The Ordovician to Devonian–Carboniferous volcanic and pyroclastics rocks make up the Dananhu arc. Devonian–Carboniferous tholeiitic basalt and calc-alkaline andesite were interpreted to be volcanic rocks of an island arc (Yang et al., 1996, 2000). In fault contact with the Dananhu arc to the north, large amount of marine lava and pyroclastics rocks occur and form coherent strata in the southern part, and mélanges and broken formations in the northern part (Yang et al., 1996; Xiao et al., 2004b). The coherent strata include several Lower to Mid-Carboniferous several formations, which are composed of mainly volcano-sedimentary rocks. Geochemistry of tholeiitic rocks in these formations suggests an island arc origin (Yang et al., 1996). Ophiolitic slices including serpentinite, pillowed basalt, meta-gabbro, meta-basalt, meta-diabase, meta-plagiogranite, quartz keratophyre, and chert have been structurally juxtaposed against graywacke, phyllite, sericite schist, and meta-tuff in the southern part of the Dananhu arc (Xiao et al., 2004b). Yang et al. (1998) reported Devonian to Carboniferous radiolaria, and Li et al. (2003) discovered possible Late Silurian to Early Carboniferous radiolaria in chert. They form an accretionary complex located to the south of the arc system.

Along the southern part of the Dananhu arc ultramafic-mafic complexes occur as zoned bodies whose geochemical data suggest oceanic tholeiite and MORB affinity (Zhou et al., 2001). They were interpreted as the Alaska-type zoned ultramafic complexes (Xiao et al., 2004b). A U–Pb zircon age of 280 Ma (Qin, 2000; Qin et al., 2002) and SHRIMP zircon ages of 269.2 ± 3.2 Ma and 277.0 ± 1.6 Ma (Li et al., 2003) confirm that the ultramafic–mafic complex mainly formed in the Permian (Ji et al., 1999, 2000), which was simultaneous with the eruption of early Permian basic lavas and the intrusion of granitic plutons in the area. The Early Permian age and spatial association with arc-accretion complexes occur in the southern part of the Dananhu arc suggest that these rocks represent a final pulse of the arc in the eastern part of the Tien Shan.

There are considerable mineral deposits in this accretionary complex (Qin, 2000; Qin et al., 2002; Rui et al., 2002; Zhou et al., 2004; Han et al., 2006a,b; Zhang et al., 2004, 2006). The N–S distribution of porphyry gold-copper, orogenic-type gold, and epithermal gold is similar to that in Alaska (Goldfarb, 1997), where NE-dipping subduction of the Pacific ocean has produced a progressive sequence from orogenic gold to porphyry gold-copper deposits. Therefore the distribution of mineral deposits also supports the interpretation that the subduction polarity in the Chinese Eastern Tien Shan might have been mainly to the north.

In the Tien Shan collage, there are some high-grade metamorphic rocks occurring as knockers or slices in the Yili and Xingxingxia area. In the Xingxingxia area there are Paleozoic calc-alkaline-type basaltic andesite, volcanoclastics, minor I-type granite and granodiorite, with Precambrian basement rocks in amphibolite facies. The Precambrian basement of this arc consists of gneiss, quartz schist, migmatite, and marble, with U–Pb and Sm–Nd ages that range from 1400 to 1800 Ma (Chen et al., 1999; Hu et al., 2000). However, Carboniferous fossils have been discovered in the rocks, which were formerly considered as Proterozoic rocks, which were regarded as remnants of volcanic arc because of their calc-alkaline geochemistry (Fang, 1994; Zhou et al., 2001). They are imbricated with deformed volcanics, clastics, limestone, and ultramafic rocks (Fang, 1994). Therefore the central part of the Tien Shan could have been interpreted as an arc that lasted to the Carboniferous.

Several fault-bounded mafic granulite blocks have been identified along the Kokshaal–Kumishi accretionary complex in the eastern part of the Tien Shan (Shu et al., 2002). Zhou et al. (2004) reported the youngest metamorphic age of Permian. Crossite-bearing schist blocks were found within the volcanic rocks and graywacke and phengite schist blocks also have been found along the eastern part of the Tien Shan (Ma et al., 1997; Gao et al., 1995; Shu et al., 2002; Liu and Qian, 2003). Liu and Qian (2003) reported 345 Ma for phengite from these high-pressure rocks, although no details presented. Late Devonian to Early Carboniferous ophiolites are imbricated with volcanic and volcaniclastic rocks, and with blueschist and eclogite (Gao et al., 1998; Xiao and Tang, 1991; Xiao et al., 1994). The ^{40}Ar–^{39}Ar date of 350.89 ± 1.96 Ma for glaucophane from the Changawuzi high-pressure metamorphic belt south of the Nalati magmatic arc in the western part of the Tien Shan near the Chinese-Kyrgyzstan border provides a key age for the northward subduction of the southern Tien Shan oceanic crust (Xiao and Tang, 1991; Xiao et al., 1994). Liu and Qian (2003) reported blueschist and eclogite with ^{40}Ar–^{39}Ar age of 360.7 ± 1.6 Ma. Zhang et al. (2005, 2007) summarized Permian and Early Triassic ages for the ultra-high-pressure metamorphic rocks along the southern Tien Shan. Carboniferous adakitic and Nb-enriched rocks in the Tien Shan and Carboniferous–Permian adakitic rocks in Northern Xinjiang (Wang et al., 2007; Zhao et al., 2006b), discovery of Early Carboniferous and late Permian (?) radiolarian fossils (Liu, 2001; Li et al., 2005) and the Permian–Triassic ultrahigh-pressure rocks (Zhang et al., 2007) in this ophiolitic mélanges, and the unconformity separating the Upper Permian below from Middle to Upper Triassic above (Fig. 4) all indicate that the final tectonic accretion might have taken place between the latest Permian and the Triassic.

5. North Tarim

Bounded by the Southern Tien Shan mélange or the Kokshaal–Kumishi accretionary complex in the north, the Tarim block is located in the southernmost part of the Northern Xinjiang. All the tectonic units to the north are truncated by the Kokshaal–Kumishi accretionary complex. The Tarim block has a variably deformed and metamorphosed basement of Archaean–Proterozoic to Early Paleozoic sediments (XBGMR, 1993; Hu et al., 2000; Bykadorov et al., 2003). The basement is characteristic by Archaean high-grade tonalite–trondhjemite–granodiorite gneiss and amphibolite and Proterozoic granitic gneiss, which have model ages (TDM) ranging from 3.2 to 2.2 Ga (Hu et al., 2000). It has been interpreted mainly as a cratonal block although some deferent ideas exist (Hsü, 1988, 1989). The late Paleozoic magmatism along the northern part of the Tarim block was thought as reflection of arc or subduction (Chen et al., 1999), but the ages of

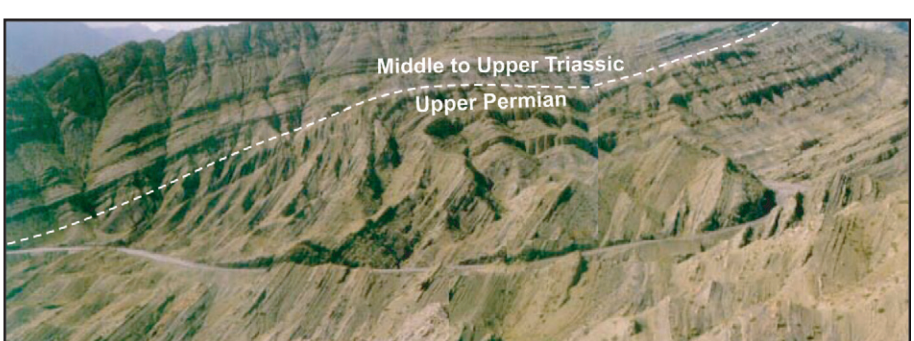

Fig. 4. Field photo of the unconformity in between the Upper Permian turbidites and the Middle to Upper Triassic redbeds. Note the folded, steep beddings of the Upper Permian. Looking SW. Aiweigou, about 106 km south of Urumqi.

these intrusions are not precisely constrained and their tectonic setting is still controversial. Some of these intrusions intruded either in part of the Kokshaal–Kumishi accretionary complex or part of the rifted slices (Xiao et al., 2004b; Li et al., 2003). The southern part of the Tarim block was mainly active during the Paleozoic (Xiao et al., 2002a,b, 2005), while a north-facing passive margin was previously proposed along the northern margin of the Tarim block in the Paleozoic (Windley et al., 1990; Graham et al., 1990, 1993; Allen et al., 1993).

6. New time-space framework

6.1. Major paleogeographic dividing boundary

It was proposed that the southern Altaids grew southward and this growth ended in the late Paleozoic (Şengör et al., 1993; Mossakovsky et al., 1994; Xiao et al., 2003, 2004a,b). Therefore, the late Paleozoic tectonic framework should be preserved more intact than any stages before. This is because in this huge accretionary orogen, large-scale strike-slip translation and oroclinal bending, which have been proposed to occur in the late Paleozoic (Levashova et al., 2003; Collins et al., 2003), would superimpose and rework the early and middle Paleozoic tectonic and paleogeographic marks. Like the Wallace Line in present day SE Asia and SW Pacific (Metcalfe, 2006) separating Eurasian faunas and floras to the northwest from Australasian faunas and floras to the southeast, an important biogeographic boundary has long been found along the Southern Tien Shan mountain range. It separates the Angaran floras, to the north, from the North China floras, to the south (Dewey et al., 1988) (Fig. 5). This nearly continuous, wide boundary zone that composed of mixed flora

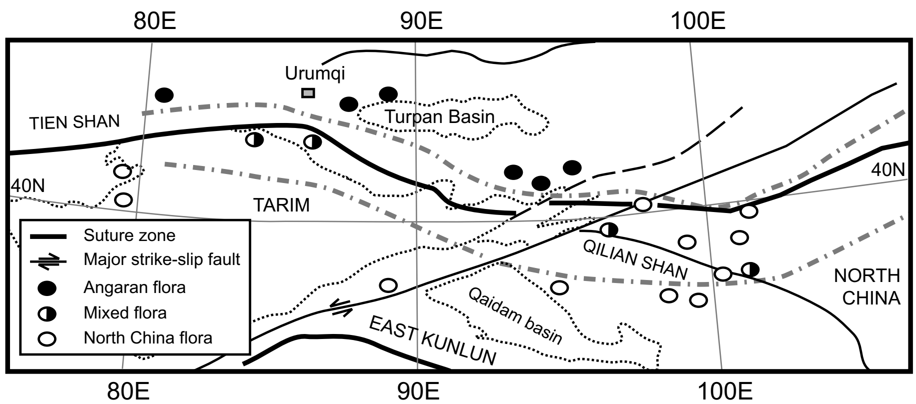

Fig. 5. Schematic tectonic map of Northern Xinjiang in late Paleozoic illustrating the separation of the Angaran flora from the Cathaysian flora along the southern Tien Shan (modified after Dewey et al., 1988).

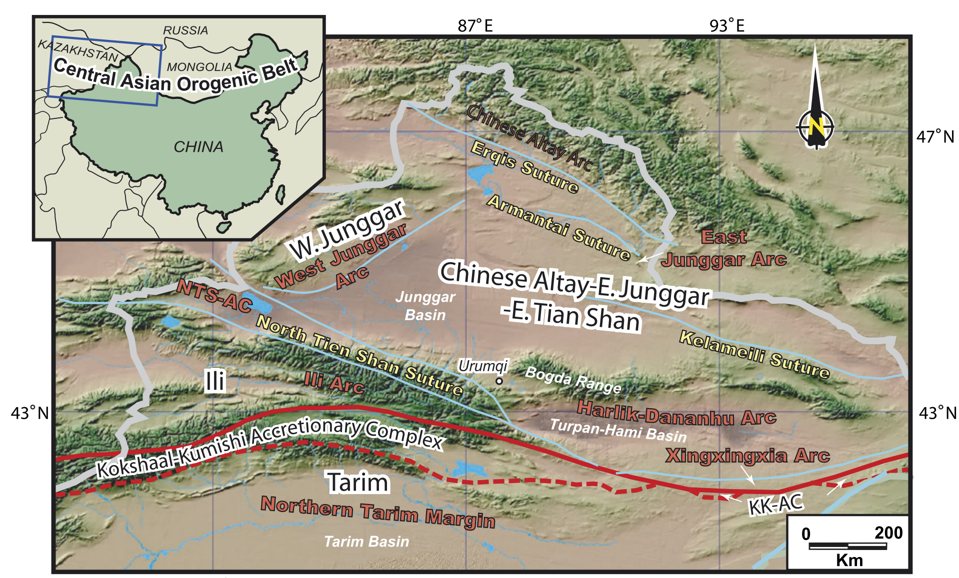

Fig. 6. Topographic map of Northern Xinjiang showing the tectonic domains (After Xiao et al., 2004a,b). Insert is a schematic map showing the special tectonic position of Northern Xinjiang in the southernmost part of the Central Asian Orogenic Belt or Altaids. KK-AC, Kokshaal–Kumishi accretionary complex. Bold line outlines the Kokshaal–Kumishi accretionary complex, dashed where proposed. Thin line denotes major faults or tectonic boundaries.

tells us that it corresponds to an important divide in the late Paleozoic.

6.2. New tectonic model

As it was shown above, the geology and tectonics of Northern Xinjiang is characterized by middle Cambrian to Permian subduction-related records, and composed of Paleozoic orogenic collages, including the Chinese Altay, East Junggar, West Junggar, and Tien Shan including the Yili block, which is conveniently used to describe the southernmost tectonic domain of the Altaids for it is connected with the Kazakhstan Paleozoic magmatic arc, occurring on the Precambrian rocks. Many ophiolites or ophiolitic mélanges were emplaced within these orogenic collages. The West Junggar has Paleozoic subduction-related records that may have at least lasted to late Carboniferous. In its western extension in the Balkhash and adjacent areas there are also some important late Paleozoic to Permian subduction-related records (Şengör et al., 1993; Şengör and Okurogullari, 1991; Buslov et al., 2001, 2003). The Chinese Altay, East Junggar, Eastern Tien Shan, and Yili all have early Paleozoic to Permian arc-related records. It is obvious that there are mostly subduction–accretionary domains in the north and a passive margin (Tarim) in the south (Fig. 6). The late Paleozoic accretionary complex (Kokshaal–Kumishi accretionary complex, see Xiao et al., 2004b) was a major tectonic boundary separating them (Fig. 6). The Kokshaal–Kumishi accretionary complex (Xiao et al., 2004b; cf. South Tien Shan suture in the literature) mainly occurs along the southern margin of the Yili–Central Tien Shan arc from the Western Tien Shan to the Eastern Tien Shan, extending some 1500 km in the Chinese Tien Shan.

The northern Tarim domain was mainly a continental margin, which remained passive during the Paleozoic. Some of its Precambrian basement rocks were thrust southward over its northern marginal sequences. Combining other Paleozoic biogeographic data in the Paleozoic (Guo, 2000, 2001), we propose that this boundary along the southern Tien Shan, corresponding to the above-mentioned paleogeographic boundary, should be the major suture zone along which the Tarim block got docked to the southern Siberian active continental margin in the late Permian.

Paleomagnetic data show that it is in the Permian that the Tarim block got docked to the northern accretionary marginal sequences including those in the Junggar and Altay domains (Li et al., 1989, 1991). This is also in good agreement with the paleomagnetic and geological data of Levashova et al. (2003) and Collins et al. (2003) who concluded that today's strongly curved volcanic belt of Kazakhstan is an orocline, deformed most before mid-Permian. The so-called Kazakhstan orocline, however, has been reinterpreted recently by Windley et al. (2007) as having a more complicated arc–arc collision scenerio.

All in all, the Northern Xinjiang orogenic collage, composed of various Paleozoic tectonic domains, provides one of the almost completely exposed traverses from the southern Siberian margin to the northern Tarim block. A summary of its tectonic evolution and reconstruction for this part of central Asia is given as follows (Figs. 7–9).

During early Paleozoic times, the Chinese Altay–East Junggar–Eastern Tien Shan domain was more closely located to Siberia, while the Tarim domain was near the opposite side of the Paleoasian Ocean. The West Junggar and Yili domains occupied an intermediate position near the Kazakhstan block in the early Paleozoic Paleoasian basin. The various tectonic elements of the West Junggar

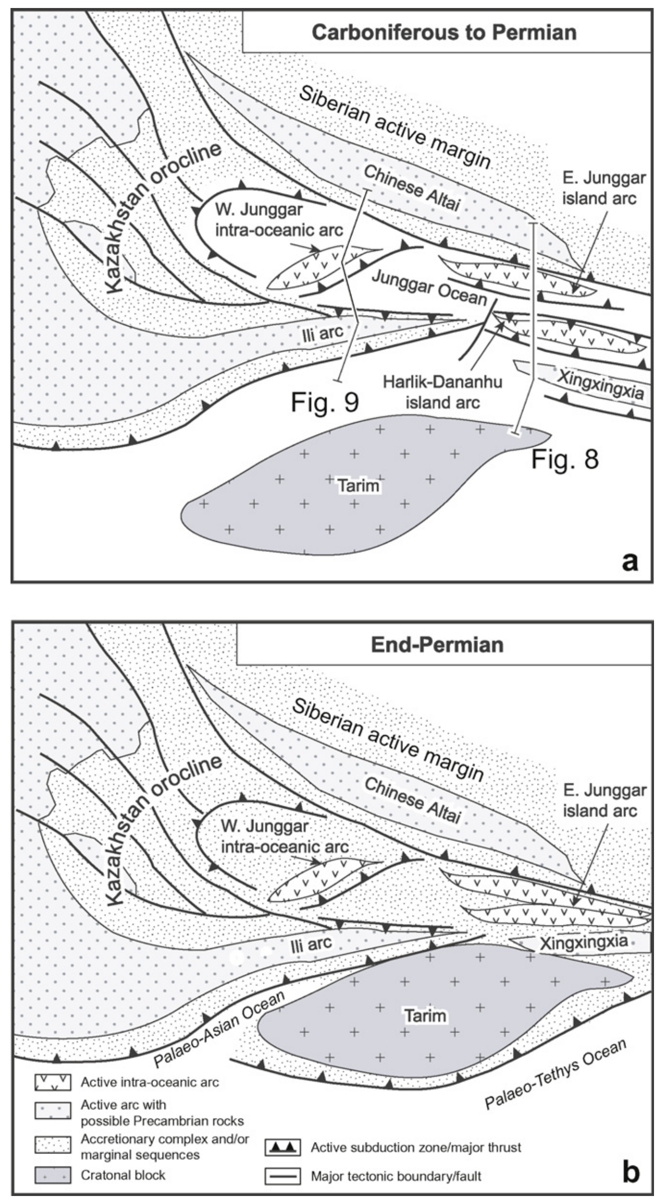

Fig. 7. Schematic Paleogeographic map of Northern Xinjiang in late Paleozoic. (a) Carboniferous to Permian. (b) End-Permian. The Kazakhstan orocline is modified after Şengör et al. (1993). Bold lines are major faults and those with barbs representing subduction zones. The cross-section line of Figs. 8 and 9 is marked.

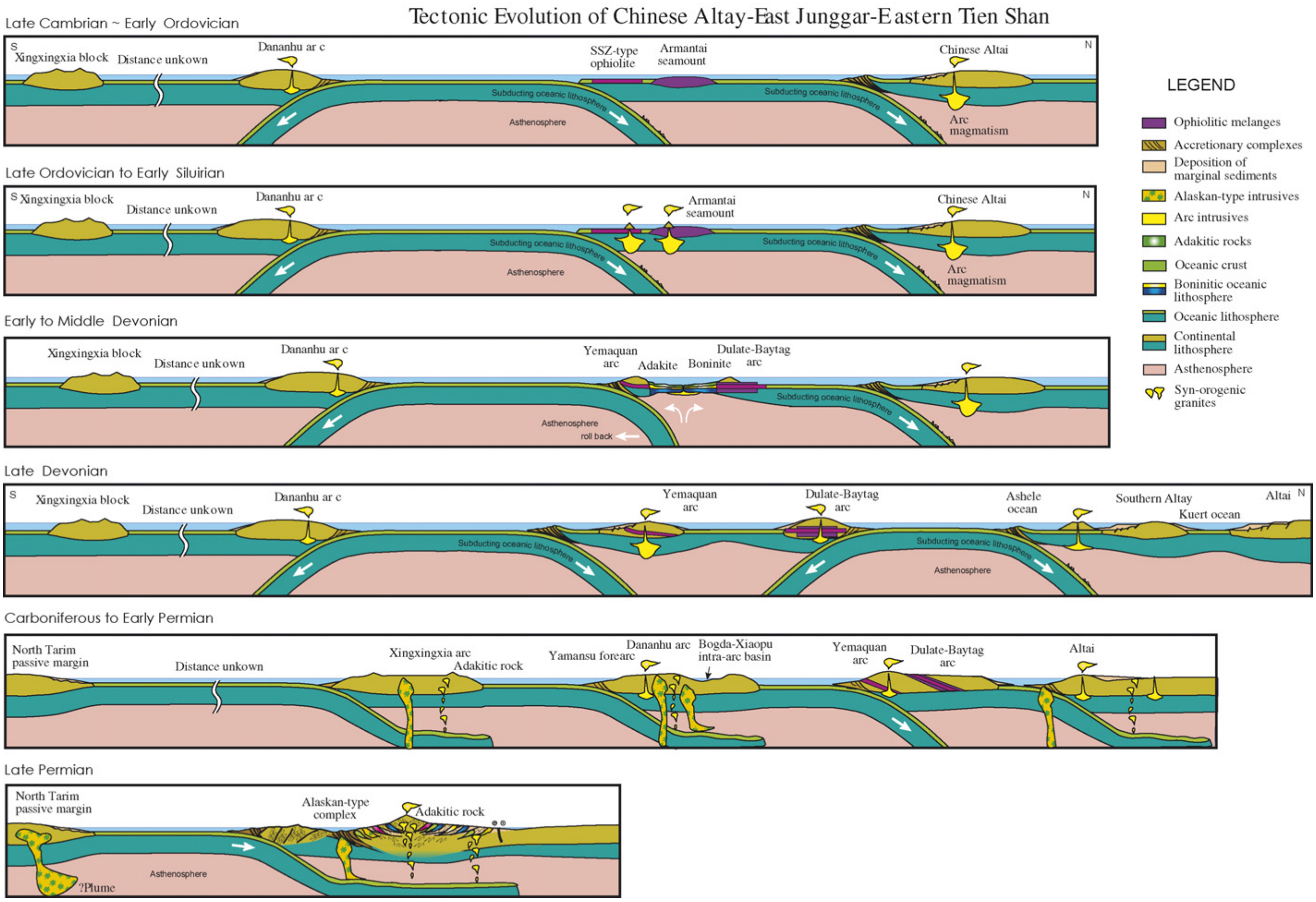

Fig. 8. Conceptual cross-section of multiple subduction systems in the eastern part of Northern Xinjiang in late Paleozoic. The Kokshaal–Kumishi accretionary complex was the product of the late Paleozoic accretion–subduction along the southern Tien Shan (from Xiao et al., 2004a,b; Xiao et al., 2006b).

and Yili domains drifted northwards and approached the Chinese Altay–East Junggar–Eastern Tien Shan active margin of the Siberian craton in the late Paleozoic. Subsequent complicated amalgamation processes of these domains squeezed the archipelago systems of these domains, leading to the closure of the Paleoasian Ocean and formation of a complicated orogenic collage between Siberian craton and the Tarim block in the Permian. These multiple accretion processes significantly contributed to the lateral growth of central Asia.

From the summery presented above, we conclude that, although with a general southward younging growth, there were multiple subduction systems existed in the long, complicated evolution history of the Paleoasian ocean that formed the Altaids. A number of the various terranes represent different parts of relicts of ancient subduction systems, mostly tectonically incorporated into accretionary complexes or constitute Andean-type magmatic arcs. Except for minor Precambrian rocks in some Andean-type magmatic arcs, such as the Chinese Altay and Yili, no significant old continents have been involved into the accretionary growth of the Altaids (Ma et al., 1997; Han et al., 1997; Qin et al., 1999; Qin, 2000; Hu et al., 2000; Jahn, 2001; Xiao et al., 2004a,b, 2006b).

6.3. Significance

Our tectonic analysis provides a basis for understanding the time-space evolution of the southern Altaids. It is clear now that the major accretionary events took place before the Triassic. Some important constituents, which caused the previous studies to suggest an earlier closure for the Paleoasian Ocean than the Permian, are actually the main components of a huge accretionary active margin. For example, based on the earlier discovery of Devonian radiolarian fossils and middle Paleozoic ages from some ophiolites, the final amalgamation time was regarded either as early to middle Devonian (Wang et al., 1990; Han et al., 1997) or late Devonian–early Carboniferous (Windley et al., 1990; Allen et al., 1993; Gao et al., 1995, 1998; Zhang et al., 2003a). However, the ophiolites are found either as slivers in accretionary complexes or fragments of marginal basins emplaced into convergent marginal sequences. Further more, some studies proposed that oceans in the Tien

Shan which is the southernmost orogenic collages of the Altaids could survive until as late as mid-Carboniferous on the basis of newly found Carboniferous ophiolites (Chen et al., 1999; Xu et al., 2006a,b; Li et al., 2003; Xiao et al., 2004a,b; Wu et al., 2006; Xiao et al., 2006b). Thus the formation ages of these ophiolites only indicate that the time when ocean existed or accretionary process was still active. This does not constrain the closure timing of the oceans.

The tectonic evolution and reconstructions of Northern Xinjiang suggests that no single mechanism of the three groups of models that we mentioned before can fully explain the tectonics in this part of central Asia. The oroclinal bending of a long-lived, single subduction system of Şengör et al. (1993) and Şengör and Natal'in (1996) can well explain the general southward growth of the orogenic collages and strike-slip duplication occurred in certain areas, but cannot explain the multiple accretionary processes happened in the early Paleozoic. The various terranes collision model (Coleman, 1989, 1994; Mossakovsky et al., 1994; Buslov et al., 2001, 2003; Windley et al., 2002; Badarch et al., 2002) can better evaluate the contributions of many different ophiolites and some of the possible Precambrian fragments; but fail to explain the fact that many ophiolites and older fragments are actually tectonically incorporated into accretionary complexes which usually can not be used to define large-scale collision events. Actually, ages of the so-called Precambrian continental blocks have been verified as mostly Paleozoic. The huge chains of double arc-backarc pairs (Yakubchuk, 2002, 2004) can better illustrate the back-arc geochemistry of ophiolites in central Asia; but defining all oceans as back-arc basins is obviously not a full scenario because major oceans like today's Pacific should have existed as evidenced by the paleogeographic boundary supported by stratigraphic, paleomagnetic and paleontological data.

Therefore, our tectonic analysis helps to reconcile the long-standing controversy concerning the final closure of Paleoasian Ocean and the way in which accretionary processes took place. We acknowledge that the reconstruction presented here is a preliminary one, and much work needs to be done by incorporating data from Kazakhstan and other areas in central Asia (Bykadorov et al., 2003; Filippova et al., 2001; Yakubchuk, 2005, 2008). This may give us a hint that accretionary orogens are characterized by multiple accretionary orogenic processes, the major features of which are: (1) earliest accretion started with Japanese-type oceanward migration (Taira, 2001), but this passed into a more complex archipelago arc-accretion style of tectonics similar to that in present-day southeast Asia (Coleman, 1989; Feng et al., 1989; Hsü, 1988, 1989, 1994; Konstantinovskaia, 2000; Xiao et al., 2004a,b); (2) Syn-tectonic and post-tectonic rifting might have existed during the whole orogenic process (Allen et al., 1993; Carroll et al., 1995; Hendrix et al., 1992, 1996. Wartes et al., 2002); and (3) subduction-related growth plays a fundamental role in build-

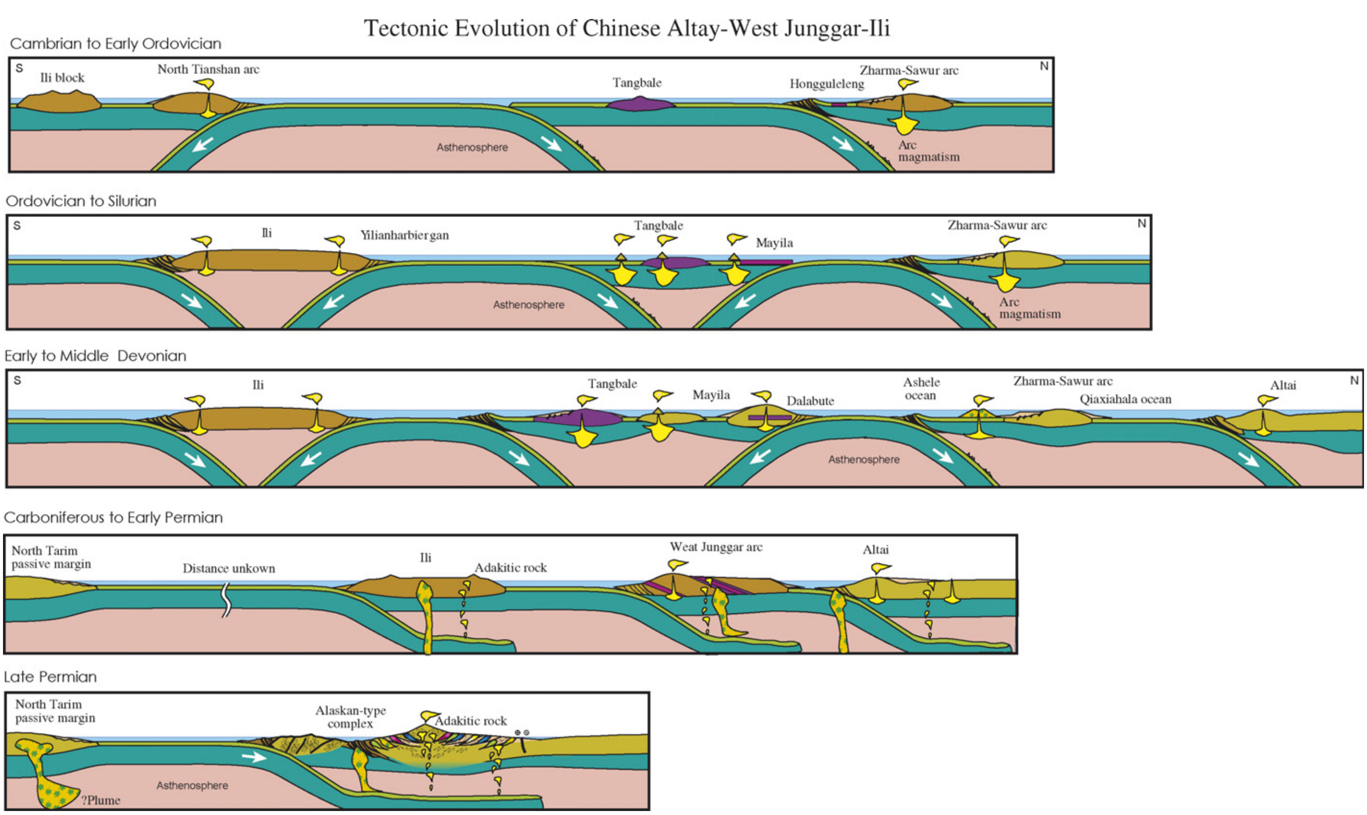

Fig. 9. Conceptual cross-section of multiple subduction systems in the western part of Northern Xinjiang in late Paleozoic. Legend is the same as that of Fig. 8.

ing of the Japan-type, Andean-type and in Mariana-type margin processes, in which forearc accretion is the principal mechanism but backarc closure also plays a key role (Şengör and Natal'in, 1996; Natal'in and Şengör, 2005; Xiao et al., 2002a,b, 2003, 2004a,b, 2005). The multiple accretionary processes led to significantly lateral growth of central Asia, shedding light on global reconstruction in the Paleozoic (Heubeck, 2001; Yakubchuk, 2002, 2004; Torsvik and Cocks, 2004).

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