Int J Earth Sci (Geol Rundsch) (2009) 98:1189–1217
DOI 10.1007/s00531-008-0407-z

ORIGINAL PAPER

# End-Permian to mid-Triassic termination of the accretionary processes of the southern Altaids: implications for the geodynamic evolution, Phanerozoic continental growth, and metallogeny of Central Asia

**W. J. Xiao · B. F. Windley · B. C. Huang ·
C. M. Han · C. Yuan · H. L. Chen ·
M. Sun · S. Sun · J. L. Li**

Received: 5 November 2007 / Accepted: 15 December 2008 / Published online: 8 January 2009
© Springer-Verlag 2009

**Abstract** The Altaids is one of the largest accretionary orogenic collages in the world with the highest rate of Phanerozoic continental growth and significant metallogenic importance. It is widely accepted that subduction-related orogenesis of the Altaids started in the late Precambrian and gradually migrated southward (present coordinates). However, it is uncertain when and how the building of the Altaids was finally completed. Based on structural geology, geochemical, geochronological, and paleomagnetic data, this paper presents late Paleozoic to early Mesozoic accretionary tectonics of two key areas, North Xinjiang in the west and Inner Mongolia in the east, together with neighboring Mongolia. The late Paleozoic tectonics of North Xinjiang and adjacent areas were characterized by continuous southward accretion along the wide southern active margin of Siberia and its final amalgamation with the passive margin of Tarim, which may have lasted to the end-Permian to early/mid-Triassic. In contrast, in Inner Mongolia and adjacent areas two wide accretionary wedges developed along the southern active margin of Siberia and the northern active margin of the North China craton, which may have lasted to the mid-Triassic. The final products of the long-lived accretionary processes in the southern Altaids include late Paleozoic to Permian arcs, late Paleozoic to mid-Triassic accretionary wedges composed of radiolarian cherts, pillow lavas, and ophiolitic fragments, and high-pressure/ultrahigh-pressure metamorphic rocks. Permian Alaskan-type zoned mafic-ultramafic complexes intruded along some major faults of the Tien Shan. We define a new Tarim suture zone immediately north of the Tarim craton that is probably now buried below the Tien Shan as a result of northward subduction of the Tarim block in the Cenozoic. The docking of the Tarim and North China cratons against the southern active margin of Siberia in the end-Permian to mid-Triassic resulted in the final closure of the Paleoasian Ocean and terminated the accretionary orogenesis of the southern Altaids in this part of Central Asia. This complex geodynamic evolution led to formation of giant metal deposits in Central Asia and to substantial continental growth.

**Keywords** End-Permian to mid-Triassic termination · Accretionary process · Southern Altaids · Geodynamic evolution · Continental growth · Metallogeny · Central Asia

## Introduction

A huge orogenic collage, the Altaids (or Central Asian Orogenic Belt, Central Asian Mobile Belt, Central Asian

---

W. J. Xiao (✉) · B. C. Huang · C. M. Han · S. Sun · J. L. Li
State Key Laboratory of Lithospheric Evolution,
Institute of Geology and Geophysics,
Chinese Academy of Sciences, 100029 Beijing, China
e-mail: wj-xiao@mail.igcas.ac.cn

B. F. Windley
Department of Geology, University of Leicester,
Leicester LE1 7RH, UK

C. Yuan
Guangzhou Institute of Geochemistry,
Chinese Academy of Sciences,
510640 Guangzhou, China

H. L. Chen
School of Earth Sciences, Zhejiang University,
310027 Hangzhou, China

M. Sun
Department of Earth Sciences,
The University of Hong Kong, Hong Kong, China

Orogenic System), lies between the Siberian and Russian cratons to the north, and Tarim and North China cratons to the south (Fig. 1). It encompasses an immense area from the Urals in the west, through Kazakhstan, NW China, Mongolia, and NE China to the Okhotsk Sea in the Russian Far East (Zonenshain et al. 1990; Mossakovsky et al. 1993; Şengör et al. 1993; Badarch et al. 2002; Xiao et al. 2004a, b; Windley et al. 2007; Briggs et al. 2007).

The Altaids is one of the largest and most complex accretionary collages that was responsible for considerable Phanerozoic juvenile crustal growth (Şengör et al. 1993; Jahn 2004; Jahn et al. 2000, 2004). The prolonged accretionary processes that started at 1.0 Ga resulted in considerable enlargement of the Asian continent (Şengör et al. 1993; Heubeck 2001; Torsvik and Cocks 2004). The many ophiolites in the Altaids are most likely remnants of a SW Pacific-type archipelago that contained many small ocean basins (Hall 2002, 2008). This huge accretionary collage has a long strike-length and history that makes it ideal for studying the relationships between the end of accretion, i.e., closure of an ocean basin, and the end of collision.

The juvenile crustal formation was associated with metallogenic processes that generated numerous mineral deposits including world-class gold, silver, copper–molybdenum, lead–zinc and nickel of late Proterozoic to Mesozoic age (Cole 2001; Rui et al. 2002; Goldfarb et al. 2003; Seltmann et al. 2003; Yakubchuk et al. 2001; Yakubchuk 2004; Han et al. 2006a, b).

Despite its importance, our understanding of the Altaids is limited, because of insufficient detailed studies throughout the vast area. As a result, many published syntheses describing the Paleozoic tectonic evolution of the orogenic collage are controversial. Numerous fundamental problems are still unresolved, in particular the timing of the final phase of amalgamation along the southern margin of Siberia; proposals range from the Ordovician-Silurian (Tang 1990; He et al. 1994; Tang and Yan 1993; Han et al. 1997; Kheraskova et al. 2003), to Devonian-early Carboniferous (Hendrix et al. 1996; Yue et al. 2001; Solomovich and Trifonov 2002; Charvet et al. 2007; Wang et al. 2007a). However, considerable continental growth (Jahn et al. 2000, 2004; Jahn 2004; Chen et al. 2000; Chen and Jahn 2002, 2004) and massive metallogenesis (Li et al. 1998, 1999; Heinhorst et al. 2000; Seltmann and Porter 2005) occurred in the Carboniferous-Permian, and some large-scale metallogenesis even in the Triassic.

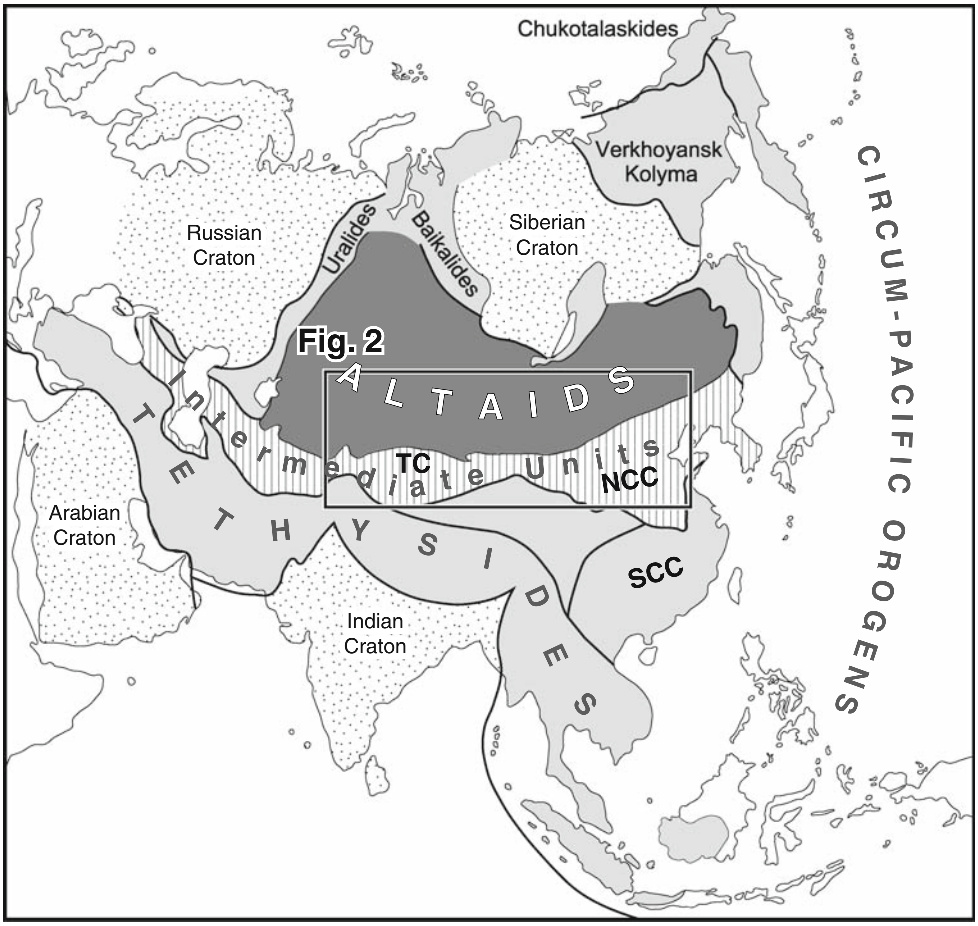


**Fig. 1** Simplified tectonic map of the Altaids (Modified after Şengör et al. 1993; Xiao et al. 2008a). *TC* Tarim craton, *NCC* North China craton, *SCC* South China craton

Furthermore, there are reports of younger late Carboniferous to Permian subduction-related geological events (Sun et al. 1991; Buslov et al. 2001; Badarch et al. 2002; Xiao et al. 2003b; 2004a; b; Li 2006; Cocks and Torsvik 2007; Johnson et al. 2007; Rippington et al. 2008), which are important to study, because they provide information on the time of suturing. A systematic investigation of the final termination time of the Altaids is thus important for a better understanding of the continental growth, of the basic architecture of this accretionary orogen, and of their inter-relationships with metallogeny. However, the increasing amount of controversial data seems to be pointing to the fact that the closure of the southern Altiad ocean was not a simple process that gave rise to single, linear collision and suture zone, and that the timing of the suture formation may have been diachronous along its 3,000 km length. We will consider some of the variables that may have been responsible for these complex processes.

In spite of differing tectonic models, it is widely accepted that the Altaids grew generally southward from Siberia and southern Mongolia (Zonenshain et al. 1990; Şengör and Okurogullari 1991; Mossakovsky et al. 1993; Şengör and Natal'in 1996b; Dobretsov 2003). Therefore, the southern part of the Altaids in China, Mongolia, Kyrgyzstan and surrounding regions provides the best data to study the processes and timing of the final amalgamation processes that took place between the accretionary southern active margin of Siberia and the northern margins of the Tarim and North China cratons (Fig. 1). This paper thus discusses the tectonic history of the southern Altaids with emphasis on its final amalgamation by connecting terminal geodynamic processes to those of continental growth and metallogeny.

## Geological background and previous work

The southern Altaids is here defined as the southernmost part of the orogenic collage best preserved in North Xinjiang and Inner Mongolia in NW China, and in southern Mongolia (Fig. 1). This part of the orogen was mainly constructed by convergent processes between the southern active margin of the Siberia craton to the north and the northern margins of the Tarim and North China cratons to the south. A common characteristic feature of the southern Altaids is the complex but recurrent arrangement of dominantly accretionary prism and magmatic arc material, interspersed with slivers of oceanic crust and minor massifs of older continental crust (Şengör et al. 1993; Xiao et al. 2003a; Jahn et al. 2004). The two southerly cratons (Tarim and North China) both have Archean-Proterozoic basement with Paleozoic to Cenozoic cover rocks (Lu et al. 2002; Kusky et al. 2007; Zhao et al. 2002, 2004, 2007). The docking of these two cratons to the southern active accretionary margin that had grown from the Siberian craton closed the intervening Paleoasian Ocean and terminated the accretionary orogenic processes of the southern Altaids.

Many key aspects of the southern Altaids have been well studied, including:

- regional studies (Wang and Liu 1986; Zonenshain et al. 1990; Windley et al. 1990; Li et al. 2003; Helo et al. 2006; Shu et al. 2002; Shu and Wang 2003);
- ophiolites (Allen et al. 1992; Wang and Fan 1997; Buchan et al. 2001, 2002; Matsumoto and Tomurtogoo 2003; Jian et al. 2005, 2008);
- sedimentary basins (Hendrix et al. 1996, 2000; Lamb and Badarch 1997, 2000; Lamb et al. 2001; Graham et al. 2001);
- deformation and structures (Laurent-Charvet et al. 2002, 2003; Graham et al. 2001; Briggs et al. 2007);
- high-pressure/ultra-high-pressure metamorphism (Tang 1990; Tang and Yan 1993; Gao et al. 1995; Gao and Klemd 2001; 2003; Klemd 2003; Klemd et al. 2005; de Jong et al. 2006; Zhang et al. 2005; 2007a);
- isotopes and geochronology (Jahn et al. 2000; Jahn 2004; Chen and Jahn 2002; Wu et al. 2007; Kröner et al. 2007); and
- paleomagnetism and reconstructions (Filippova et al. 2001; Bykadorov et al. 2003; Li 2006; Windley et al. 2007; Cocks and Torsvik 2007).

Many models derived from studies of the northern margins of the Tarim and North China cratons mutually differ in particular concerning the manner and time of their docking to the active margin of southern Siberia, the mutual structural relationships between their different key tectonic units, and the individual crustal history and geometry of the units. In this paper we aim to address many of these problems by evaluating the relevant data and accordingly produce a new tectonic model for this part of Central Asia. In view of the fact that the Altaids is mostly composed of accretionary rocks, in this paper, we use these studies plus our own data to address many of these differences, emphasizing the youngest assemblages in subduction-related accretionary wedges and associated magmatic arcs. We will describe these two regions outlined in Fig. 2: Northern Xinjiang and adjacent areas in the west, and western Mongolia and Inner Mongolia in the east. Available high-resolution isotopic age data especially SHRIMP U-Pb on zircons, and fossils including radiolaria in the youngest assemblages (Tables 1, 2, 3) that incorporate all the information listed above provide the evidence for the timing of final amalgamation.

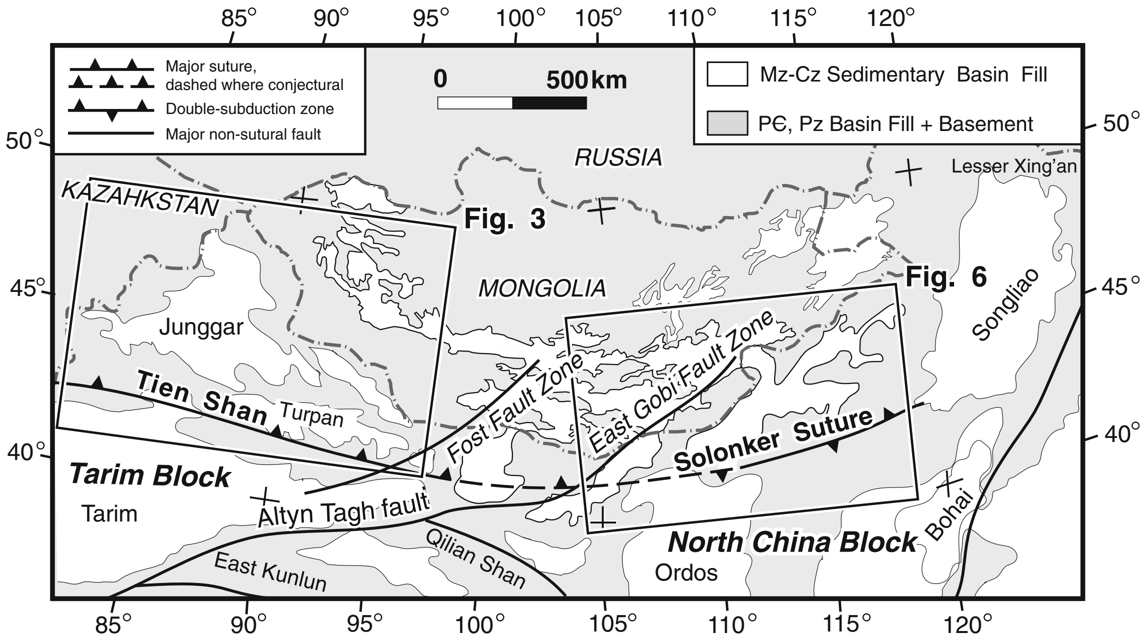


**Fig. 2** Schematic map illustrating the Altaids in China and Mongolia with Figs. 3 and 6 outlined

**Table 1** Late Paleozoic geochronological data and radiolaria from subduction–accretion complexes in the southern Altaids in Xinjiang and adjacent areas, which predate the terminal collisional processes

| Tectonic units | Rocks | Method | Ages (Ma) | References |
|---|---|---|---|---|
| Chinese Altay metamorphic arc volcanic rocks | Gneiss | SHRIMP | 281 ± 3 | Hu et al. (2006) |
| Chinese Altay | Mafic granulite | SHRIMP | 279 ± 6 | Chen et al. (2006) |
| | Granitic gneiss and metapelitic schist | In situ ion-microprobe Th–Pb | 278 ± 9<br>275 ± 8<br>259 ± 10 | Briggs et al. (2007) |
| | Metasediments | Chemical Th-U-total Pb isochron | 261–268 | Zheng et al. (2007a, b) |
| Tien Shan ophiolitic mélange | Pillow lava | SHRIMP | 325 ± 5 | Xu et al. (2006a, b) |
| Tien Shan high-temperature metamorphic complex | Granulite | SHRIMP | 299 ± 5 | Li and Zhang (2004) |
| Alaskan-type complex | Gabbro | SHRIMP | 285 ± 1 | Qin (2000) |
| | Gabbro | SHRIMP | 269 ± 2 | Zhou et al. (2004b) |
| | Gabbro | SHRIMP | 284 ± 8 | Wu et al. (2005) |
| | Gabbro | LA-ICP-MS | 281 ± 1 | Mao et al. (2006) |
| Ophiolite in the southern Tien Shan | Chert | Radiolarian fossils | Late Permian | Li et al. (2005) |

## North Xinjiang and adjacent areas

### Northern Xinjiang of China

Northern Xinjiang is a key area in the southern Altaids, connecting the Kazakhstan orogenic belt to the west and Mongolian-Chinese Inner Mongolia orogenic belt to the east (Figs. 2, 3). Northern Xinjiang is divisible into the following tectonic/orogenic belts: the Chinese Altay, the East and West Junggar, and the Tien Shan (also called Tian Shan or Tianshan, Fig. 3). The Chinese Altay, the northernmost belt, is connected northwards to the Siberian active margin in Kazakhstan and Russia (Xiao et al. 2004a, 2004b, 2006a, 2008a; Dobretsov et al. 2006; Van der Voo et al. 2006; Abrajevitch et al. 2007). The Junggar basin is situated between the Chinese Altay and the Tien Shan. The

**Table 2** Late Paleozoic geochronological data from subduction-accretion complexes in the southern Altaids in Inner Mongolia and adjacent areas (modified after Miao et al. 2007), which predate the terminal collisional processes

| Tectonic units | Rocks | Method | Ages (Ma) | References |
|---|---|---|---|---|
| Ondor Sum ophiolitic mélange | Pillow lava | SHRIMP | ∼260 | Miao et al. (2007, 2008) |
| Banlashan ophiolitic mélange | Cumulate gabbro | SHRIMP | 256 | Miao et al. (2007) |
| Solun Obo (Solonker) ophiolitic mélange | Cumulate gabbro | SHRIMP | 279 ± 10 | Miao et al. (2007) |
| Solonker ophiolitic mélange | Plagiogranite, gabbro, and diabase | SHRIMP | 299–246 | Jian et al. (2007) |
| Balengshan ophiolitic mélange | Cumulate gabbro | Rb-Sr isochron | 262 | Wang and Liu (1986) |
| Hegenshan ophiolitic mélange | Cumulate gabbro | SHRIMP | 295 ± 15 | Miao et al. (2007) |
|  | Mafic dike | SHRIMP | 298 ± 9 | Miao et al. (2007) |
|  | Plagiogranite, gabbro, and diabase | SHRIMP | 275 | Jian et al. (2007) |
|  | Mafic lava | Ar–Ar | 293 ± 1 | Miao et al. (2007) |
| Kedanshan ophiolitic mélange | Plagiogranite | SHRIMP | 277 ± 4 | Jian et al. (2007) |
|  | Chert | Radiolaria | Mid-late Permian | Wang and Fan (1997) |
| Xilinhot complex | Gabbro | SHRIMP | 323 ± 5 | Jian et al. (2007) |
| Shuangjing complex | Granitic gneiss | SHRIMP | 283 ± 9 | Li et al. (2007) |
| Ophiolite near the Xar Moron River | Chert | Radiolaria | Late Permian | Wang and Fan (1997)Wang and Shu (2001) |
| Ophiolite in the Solonker suture | Chert | Radiolaria | Mid-Permian | Shang (2004) |

**Table 3** Early to mid-Triassic geochronological data from the southern Altaids in Xinjiang, inner Mongolia and adjacent areas

| Tectonic units | Rocks | Method | Age (Ma) | References |
|---|---|---|---|---|
| Tien Shan high-pressure/ ultrahigh-pressure metamorphic complex | Eclogite | SHRIMP | 233 ± 4–226 ± 4.6<br>234 ± 7 | Zhang et al. (2007a) |
| Hegenshan ophiolitic mélange | Plagiogranite, gabbro, diabase | SHRIMP | 250–275 | Jian et al. (2007) |
|  | Granodiorite dike | SHRIMP | 244 ± 4 | Miao et al. (2007, 2008) |
|  | Meta-mafic dike | Ar–Ar | 244 ± 2 | Robinson et al. (1999) |
| Banlashan ophiolitic mélange | Cumulate gabbro | SHRIMP | 256 | Miao et al. (2007) |
| Shuangjing complex | Gneissic granite | SHRIMP | 237 ± 3 | Li et al. (2006) |
|  | Granitic gneiss | SHRIMP | 226 ± 3 | Jian et al. (2007) |

Yili block is located between the western side of the Junggar basin and the northern side of the Tien Shan. West Junggar is the Chinese counterpart of the Kazakhstan orogenic belt, while East Junggar extends eastwards into Mongolia. The southern Tien Shan belt is the southernmost part of the southern Altaids. The Turfan or Tu-Ha basin is southeast of the Junggar basin and north of the Tien Shan. Our description of these belts is largely from north to south and from the oldest to the youngest.

Subduction-related plutons and volcanic rocks occur widely in the Chinese Altay, Junggar, and Tien Shan mountain ranges of North Xinjiang. In the Chinese Altay many plutons and volcanic rocks, ranging from the early–middle Paleozoic (ca. 460–370 Ma) to Carboniferous (318 ± 6 Ma) and Permian (267 ± 4 Ma), have subduction-related geochemical signatures (Wang et al. 2006; Yuan et al. 2007; Sun et al. 2007). Significant 380–360 Ma siliciclastic volcanic-hosted massive sulphide (VMS) deposits with bimodal geochemistry occur in a major continental magmatic arc in the Chinese Altay (Goldfarb et al. 2003; Mao et al. 2005).

Briggs et al. (2007) concluded that the Chinese–Mongolia Altai experienced two phases of subduction: the first in the Ordovician–Devonian and the second in the late Carboniferous-early Permian, confirming that the youngest arc-related event was as young as the early Permian. In the Chinese Altay a major continental magmatic arc contains 380–360 Ma siliciclastic volcanic-hosted massive sulphide (VMS) deposits that have bimodal geochemistry (Goldfarb et al. 2003; Mao 2005). Granitic gneiss and

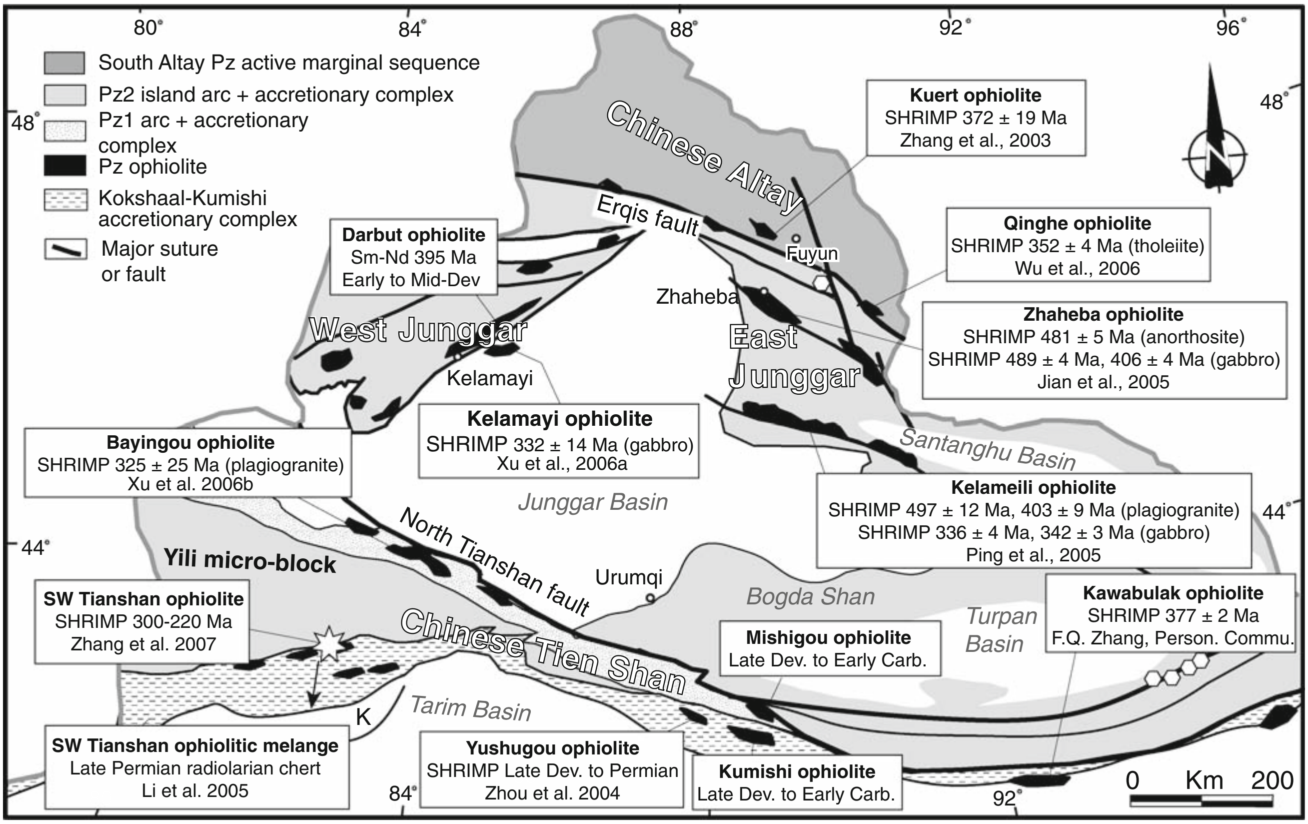


**Fig. 3** Tectonic map of Northern Xinjiang showing the major arcs and ophiolites (after Xiao et al. 2004a, b; 2008a). Some middle to late Paleozoic isotopic ages of ophiolitic mélanges are shown (Zhang et al. 2003; Zhou et al. 2004a; Ping et al. 2005; Wu et al. 2006). *K* Kalpin

metapelitic schist from the Chinese Altay dated by the in situ ion-microprobe Th–Pb technique have weighted mean U–Pb ages of 278 ± 9, 275 ± 8, and 259 ± 10 Ma (Briggs et al. 2007). Monazites from greenschist/amphibolite-grade metasediments in the Chinese Altai, dated by the chemical Th–U-total Pb isochron method (CHIME), have Permian metamorphic ages of 261–268 Ma that were interpreted by Zheng et al. (2007a) as the time of metamorphism of subducted crustal and oceanic material followed by rapid exhumation. This is in good agreement with SHRIMP U–Pb zircon ages of 290–270 Ma of nearby mafic granulites about 20 km east of Fuyun, Fig. 4 (Li et al. 2004).

A granitic orthogneiss with arc-related geochemistry in the Chinese Altay formed by subduction-related processes (Hu et al. 2006); the petrochemical data indicate that arc magmatism and metamorphism were approximately coeval with the peak age at 281 ± 3 Ma (SHRIMP zircon age).

In East Junggar the presence and tectonic setting of late Paleozoic calc-alkaline volcanic rocks has long been discussed (Lin et al. 1997; Xiao et al. 2006a; 2008c). At Zhaheba late Carboniferous intra-oceanic arcs (Long et al. 2006) are mainly composed of basalts and basaltic andesites (XBGMR 1993), are enriched in LILEs, have relatively depleted high field strength elements (HFSEs) and strongly negative Nb-Ta anomalies, all characteristic indicators of subduction (Long et al. 2006). They also have high radioactive Sr ($I_{Sr} = 0.705282–0.705420$) and low radioactive Nd ($\varepsilon_{Nd(t)} = +6.59–+7.58$). These characteristics, along with their low contents of Th (<0.55 ppm) and Pb (<3.52 ppm) and a high ratio of Ce/Pb (4–79) preclude the possibility of involvement of continental crust during the melting, and suggest that these lavas were most likely produced in an intraoceanic, subduction-related environment (Long et al. 2006).

The presence and tectonic setting of late Paleozoic calc-alkaline volcanic rocks have been discussed in East Junggar (Lin et al. 1997; Xiao et al. 2006a, 2008c). Early Carboniferous andesites, early Permian trachytes and mid-Permian basalts from the Santanghu Basin (Fig. 3), East Junggar, have enriched large ion lithophile elements (LILE) relative to HFSEs, strong negative anomalies in Ta and Nb relative to REE, and enriched light rare earth elements (LREE) relative to heavy rare earth elements (HREE); all these features are typical characteristics of subduction-related magmas (Zhao et al. 2006a). The

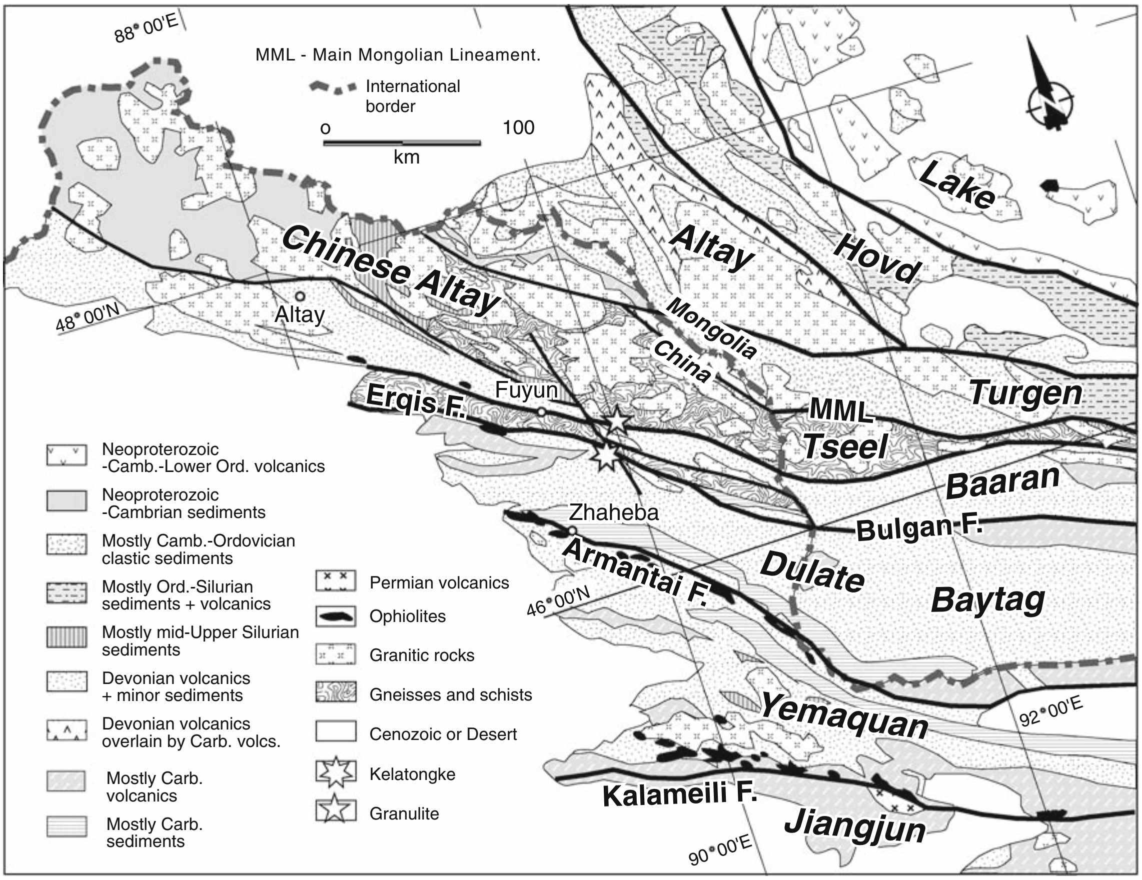


**Fig. 4** Tectonic map of the southern Altaids that crosses the Chinese–Mongolian border showing main tectonostratigraphic units (modified after Windley et al. 2002; Badarch et al. 2002; and Xiao et al. 2004b)

youngest calc-alkaline volcanic rocks in East Junggar have Carboniferous to late Permian ages based on fossils and K–Ar age dating (Lin et al. 1997; Liao and Wu 1998; Liu and Yin 2001; Zhao et al. 2006a), and are regarded as a result of Permian subduction either in an island arc or an active continental margin (Lin et al. 1997; Xiao et al. 2006a, b). Carboniferous-Permian dikes in southern Bogdashan are interpreted to represent late-stage arc or back-arc magmatic differentiates (Carroll et al. 1990; Allen et al. 1991).

According to Charvet et al. (2007) the evolution of the eastern Tien Shan included two stages of ocean floor closure. First, Ordovician-early Devonian oceans closed giving rise to the Central Tien Shan arc and suture zone in the Devonian, and South Tien Shan suture zone by the late Devonian, and second, further subduction of the North Tien Shan ocean led to formation of the Yili-North Tien Shan arc by the late Carboniferous and collision between the North Tien Shan and Junggar by the late Carboniferous. The last suture to form was the North Tien Shan suture between the Yili-North Tien Shan and Junggar by late Carboniferous.

South of the Junggar basin and north of the Tien Shan there is a long, wide belt of volcanic and volcaniclastic rocks that extends through the Yili block eastwards to the northern and southern sides of the Turfan (Tu-Hu) basin. The belt contains basalts, andesites, rhyolites, dacites, volcanic breccias, tuffs, and intermediate to felsic volcaniclastic rocks. Wang et al. (2007b) established that the volcanic rocks display calc-alkaline chemistry and prominent negative Nb and Ta anomalies consistent with subduction-related magmas, and HFSE-element concentrations indicative of a continental arc. The features indicate that the northern border of the Yili block was a continental active margin during the Carboniferous with final ocean closure in the late Carboniferous. Xia et al. (2004, 2008) investigated the geochemistry of similar volcanic and volcaniclastic rocks along the same belt (e.g. basalts, andesites, dacites, rhyolites, pyroclastic rocks and minor alkaline volcanic rocks) and concluded that they were derived from a mantle plume, and were erupted in a Carboniferous rift that belonged to a Large Igneous Province along the length of the Yili-Tien Shan belt. These conclusions seem incompatible with the arc-type lithological associations and arc-type chemistry of Wang et al. (2007b), and were dependant on the assumption that the Paleozoic ocean closed in the early Carboniferous, and on the unfounded speculation that this was followed by mantle delamination, which enabled new asthenosphere to upwell and produce the post-orogenic magmatism in a plume-generated rift. As far as we know, there is no geological evidence to indicate the presence of a major rift.

Adakitic rocks in the Chinese Altay, Junggar, and Tien Shan that formed in the late Carboniferous and Permian show typical subduction-related trace element chemistry and are associated with island arc volcanic rocks including Nb-enriched basalts and high-Mg andesites that are all imbricated with volcaniclastic rocks and accretionary wedges (Zhao et al. 2006b). $^{40}$Ar/$^{39}$Ar dating of the adakites, Nb-enriched basalts and arc volcanic rocks in the Tien Shan have plateau ages of 320 ± 1, 319 ± 2 and 306 ± 4 Ma, respectively (Wang et al. 2007c; Zhao et al. 2008). These adakitic rocks have SHRIMP zircon ages of 320–334 Ma (Zhao et al. 2008), which formed by melting of basaltic rocks underplated to the base of thickened lower crust at a depth of at least 50 km (Zhao et al. 2008). The wide extent of adakitic rocks in North Xinjiang might indicate either flat subduction or shallow subduction associated with bending of a subducting slab, which is very common in the Andean South American active margin (Kay 1978; Kay et al. 1988; Nelson 1996; Pankhurst et al. 1999; Gutscher et al. 1999, 2000a, 2000b; Rosenbaum et al. 2005).

Many granites, monzogranites, syenogranites and per-alkaline granites in the Chinese Altay and Eastern Junggar have Permian ages and positive $\varepsilon_{\mathrm{Nd}(T)}$ values, implying derivation by partial melting of juvenile material that was most likely previously subducted Paleozoic oceanic crust/mantle (Hu et al. 2000; Jahn 2004; Wu et al. 2002; Hong et al. 2003, 2004; Kovalenko et al. 2004). Some of these rocks contain Cu, Au and rare metal deposits (Hong et al. 2003, 2004; Kovalenko et al. 2004).

Many late Carboniferous-Permian ultramafic-mafic complexes in the Chinese Altay and Tien Shan are composed of peridotite, lherzolite, gabbro, olivine gabbro, hornblende gabbroic norite, pyroxenite diorite, and diorite, Fig. 4 (Xiao et al. 2004b). Several zoned mafic-ultramafic complexes occur along the southern side of the Erqis fault (Fig. 4) with an important Ni-Cu sulphide deposit at Kelatongke in the Altay (Goldfarb et al. 2003) that shows clear island-arc geochemical signatures, such as negative anomalies of Nb, Ta, Zr and Ti and enrichment in LILE (Han et al. 2007). Kelatongke has a Re–Os age of 305 ± 15 Ma (Han et al. 2007). In the Huangshan area, eastern Tien Shan, some ultramafic-mafic complexes are concentrically zoned from a dunite core that grades outwards through peridotite to olivine pyroxenite and hornblende gabbro (Ma et al. 1997); some of these contain Cu–Ni deposits (Xiao et al. 2004b; Zhou et al. 2004b; Zhang et al. 2008a). The Huangshanxi intrusion has a mean $^{206}$Pb/$^{238}$U age of 269 ± 2 Ma (Zhou et al. (2004a), the Huangshandong intrusion has a Re–Os age on sulphides of 284 ± 14 Ma (Zhang et al. 2008), and a gabbro from the Baishiquian intrusion (with a Ni–Cu deposit) has a SHRIMP U–Pb zircon age of 284 ± 8 Ma (Wu et al. 2005; Chai et al. 2008). The Baishiquan intrusion has trace element-isotopic data that indicate components of subducted oceanic crust (Chai et al. 2008).

These zoned ultramafic-mafic complexes occur as huge lenses parallel to the regional trend of sutures or arcs, and they were intruded into and were imbricated with intensely deformed, fossiliferous Devonian and Carboniferous strata. These zoned intrusions are identical to the Alaskan-type complexes associated with island arcs in Alaska, the Urals and Japan (Gu et al. 1994; Himmelberg and Loney 1995; Ishiwatari and Ichiyama 2004). Alaskan-type complexes have been described from arc, backarc and forearc settings associated with subduction zones, and they are typical plutonic constituents of subduction-related volcanic belts from the Archean (Brugmann et al. 1997) to the Neogene (Tistl et al. 1994). The Alaskan-type complexes indicate basaltic arc magmatism that is part of the magmatic evolution of the convergent continental margin in western Canada and southeastern Alaska (Taylor 1967; Himmelberg and Loney 1995; Nokleberg et al. 2005).

Because the zoned mafic-ultramafic intrusions in the Altay and Tien Shan have a late Carboniferous-early Permian age, Pirajno et al. (2008) reasoned that they must be younger than the time of formation of the last suture zone (if it were pre-late Carboniferous), and therefore speculated that the intrusions were generated in a post-tectonic/post-orogenic extensional regime related to a mantle superplume event, and they further suggested that their formation was possibly related to the mantle superplume events that gave rise to the Permian Siberian Traps in NE Russia and the Emeishan continental flood basalts in SE China. We find such speculation unreasonable, because there is no published supportive geochemical or isotopic evidence for a mantle plume derivation, and because it ignores the geochemical evidence from some intrusions of a subduction-generated arc origin (Han et al. 2007). We present our solution to this problem below.

The general view of North Xinjiang is that the northern margin of the Tarim craton remained a passive margin throughout most of the Paleozoic (Feng et al. 1989; Kwon et al. 1989; Coleman 1989; Coleman 1994; Xiao et al. 1994). In contrast, the southern active margin of the Siberian craton experienced a long history of southward accretion (Smethurst et al. 1998) that gave rise to a huge orogenic collage. Therefore, in this part of the southern Altaids, it is important to understand the manner, timing and polarity of subduction between the northern Tarim passive margin and the southern active margin of the Siberia craton in the southern Tien Shan, subjects which are currently highly controversial—see later (Laurent-Charvet et al. 2003; Wang et al. 2007a; Charvet et al. 2007).

Accretionary wedges are common in North Xinjiang, and many contain important ophiolites that represent the remnants of former oceanic crust/lithosphere. Most are arc-related, because their geochemistry shows that they were mostly generated in suprasubduction zones (SSZ) (Wang et al. 2003b). Structural and tectonostratigraphic data indicate that many ophiolites are fragmentary relicts emplaced within accretionary wedges (Xiao et al. 2003b; 2004a, b). Isotopic ages of some ophiolites yield early Paleozoic ages (Kwon et al. 1989; Jian et al. 2005; Xiao et al. 2006b). However, some recent SHRIMP U–Pb protolith ages indicate that some ophiolitic fragments are remnants of middle Carboniferous oceanic crust/lithosphere (Tables 1, 2, 3) (Xu et al. 2006a, b). Ophiolitic mafic fragments in the SW Tien Shan contain pillow-bearing eclogites, the protoliths of which are seamounts (Gao et al. 1995; Gao and Klemd 2001, 2003; Ai et al. 2006; Zhang et al. 2007a). The eclogites experienced several episodes of high/ultrahigh-pressure metamorphism that have SHRIMP U-Pb zircon ages of 340, 310, 280–290 Ma, and ca. 230 Ma (Tables 1, 3) (Gao et al. 1995; Gao and Klemd 2001, 2003; Zhang et al. 2007a). North of the southern Tien Shan accretionary wedge and parallel to the HP-UHP belt is a high-temperature (HT) granulite that has a protolith age of 299 ± 5 Ma and a peak metamorphic age of about 280–290 Ma (Table 1) (Li and Zhang 2004). The Ili-Central Tien Shan arc is situated north of the HT rocks. The fact that the HT belt occupies an arcward position and the HP belt an oceanward position in the southern Tien Shan is comparable to that in the Japanese Islands (Isozaki 1996, 1997a; Ota et al. 2004).

In accretionary wedges radiolarian cherts form an important datable component of preserved ocean plate stratigraphy that represents a ridge to trench transition, which documents the history of growth of the ocean and of the accretionary wedges (eg. Wakita and Metcalfe 2005). Late Devonian to early Carboniferous radiolarian cherts occur in early Paleozoic ophiolites along the Kelameili fault in East Junggar (Table 1) (Shu and Wang 2003). Radiolarian cherts in the southern Tien Shan (Liu 2001; Li et al. 2005) (Table 1) (Fig. 5) have ages of Carboniferous-late Permian, which should predate the final accretionary event. Furthermore, across the southern Tien Shan several sets of ocean plate stratigraphy each with distinctive radiolarian cherts young progressively southwards from the late Devonian-early Carboniferous to the Permian (Liu 2001, 2007; Li et al. 2005). We interpret this younging as a result of progressive oceanward and southward growth of the accretionary complexes, in a manner comparable to the progressive younging and oceanward growth of Mesozoic-Cenozoic accretionary complexes in Central Japan (Isozaki 1996, 1997b), and in East and Southeast Asia (Wakita and Metcalfe 2005).

The presence of regionally extensive, Triassic-early Jurassic collisional foreland basins along strike in western China and southern Mongolia (Carroll et al. 1990, 1995; Graham et al. 1990, 2001; Hendrix et al. 1992; Hendrix 2000; Johnson et al. 2001, 2003, 2007; Johnson 2004) would be expected after collision in the late Permian to early/middle Triassic.

## The adjacent area in Western Mongolia

East of North Xinjiang in China the Altaids extend into Mongolia. The isotopic ages of rock units in Mongolia are less well known than in China. Nevertheless, the tectonic units of the Mongolian belts can be extended into China and correlate well with those in the Chinese Altay, East Junggar, and part of the Eastern Tien Shan in China, as illustrated in Fig. 4 (Xiao et al. 2004a).

The Altay, Turgen, Tseel, and Baaran belts in Mongolia (Fig. 4) together form the eastern continuation of the predominantly magmatic belt of the Chinese Altay (Fig. 3). They mainly consist of Paleozoic arcs and accretionary wedges (Badarch et al. 2002; Xiao et al. 2004a). The Baytag arc in southern Mongolia extends westwards into the Dulate arc of the East Junggar of China—Figs. 3 and 4 (Badarch et al. 2002; Xiao et al. 2004a). This arc consists of Lower Devonian tholeiitic basalt, andesite, tuff, volcaniclastic rocks, Middle-Upper Devonian volcaniclastic sandstone, siltstone, chert, minor limestone, and coal-bearing mudstone, together with minor late Carboniferous

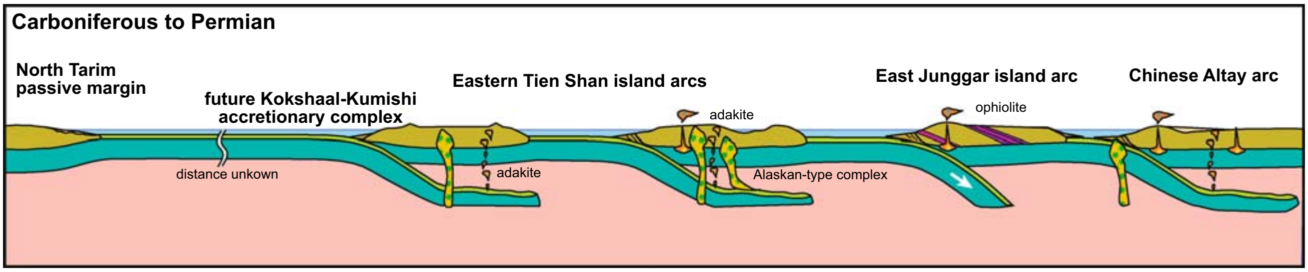


**Fig. 5** Conceptual cross-section illustrating evolution of subduction systems in the eastern part of Northern Xinjiang in the Carboniferous to Permian (from Xiao et al. 2008a)

granite and syenite and Permian felsic volcanic rocks (Badarch et al. 2002; Xiao et al. 2004a). The overall structure of this arc is characterized by imbricated thrust stacks, mélanges, high strain zones, and open to isoclinal folds (Badarch et al. 2002; Xiao et al. 2004a).

In Altan Uul and Nemegt Uul in southern Mongolia an intra-oceanic island arc was generated during the Carboniferous (Rippington et al. 2008). Thrust-bound sequences of highly fractured pillow basalt, cumulate gabbro, peridotite, serpentinite and jasperoid occur directly north of the arc rocks in at least three discrete belts and are interpreted to be fragments of an ophiolite. From combined field and petrological evidence Rippington et al. (2008) concluded that there is an east–west-trending, south-dipping late Carboniferous suture in Altan and Nemegt Uul in southern Mongolia.

In SW Mongolia and the equivalent section in China (Dulate) and in the Jiangjun belt farther south the subduction-accretion complexes young progressively southwards with the result that the youngest Permian rocks only occur in the far south (Fig. 4).

### Brief summary

In North Xinjiang-Western Mongolia data from predominant magmatic arcs, accretionary wedges, ophiolites, and Alaskan-type complexes summarized above all provide key evidence to confirm that accretion was active from the early Paleozoic to the end-Permian. The final docking of the Tarim craton to the southern active margin of the Siberia craton was not in the middle Paleozoic, but in the end-Permian based on the youngest Permian constituents involved in the accretionary units.

Şengör et al. (1993) proposed that the general accretionary geology of the Altaids could be accounted for by a single arc model (Şengör and Natal'in 1996a, b). However, the Chinese Altay (a Paleozoic Japanese-type arc with a possible Precambrian accreted fragment), some Paleozoic intra-oceanic islands arcs in Western and Eastern Junggar, and several island arcs in the Tien Shan all contain mutually different constituents, and so cannot be part of one single arc. Figure 5 shows that before the final docking the tectonic history was characterized by accretion of several arcs all created by northward subduction (Xiao et al. 2004a, b).

## Inner Mongolia and adjacent area

### Inner Mongolia of China

The Paleozoic Altaid orogen in Chinese Inner Mongolia has been called many names: "Manchurides" (Şengör and Natal'in 1996a, b), "Great Hinganling-Inner Mongolian orogenic belt" (Yin and Nie 1996), or "Central Asian Orogenic Belt" (Jahn et al. 2000; Xiao et al. 2003b; Windley et al. 2007; Kröner et al. 2007). The main part of Chinese Inner Mongolia (Fig. 6) is characterized by ENE-trending tectonic units composed of remnants of ophiolites, arcs, accretionary wedges and associated volcano-sedimentary rocks that formed during the final closure of the Paleoasian Ocean. An additional important element of the eastern Altaids is the Uliastai active continental margin (Fig. 6) (Lamb and Badarch 1997, 2000; Lamb et al. 2001; Xiao et al. 2003b), which had separated from the Siberia craton by the intervening Mongol-Okhotsk ocean that probably closed progressively eastwards in a scissor-like movement from the Triassic in western Mongolia (Zonenshain et al. 1990) to the Jurassic-early Cretaceous in eastern Mongolia (Tomurtogoo et al. 2005). In this paper we are mainly concerned with the convergence between the Uliastai active margin and the northern margin of the North China craton (Wang and Liu 1986; Xiao et al. 2003b) (Fig. 6). Unlike the passive margin of the Tarim craton and the southern active margin of the Siberia craton farther west in North Xinjiang that both underwent accretionary and collisional events, Chinese Inner Mongolia underwent convergence between the two active margins of South Mongolia (or South Gobi micro-continent) and the North China craton during most of the Paleozoic to give rise to the Solonker suture.

The major tectonic subdivisions of the Solonker suture, which is occupied by the Erdaojing accretion complex, are described below (Fig. 6). In the north the Uliastai active continental margin extends along the northern border of Inner Mongolia from Chagan Obo to Uliastai (Fig. 6), and to the south of the margin are the Hegenshan ophiolite-arc-accretion complex, and the Baolidao arc-accretion complex. To the south of the Solonker suture are the Ondor Sum subduction-accretion complex, the Bainiaomiao arc, and the North China craton (Xiao et al. 2003b).

At Uliastai a passive continental margin, comprising a basement of Proterozoic gneiss, schist and quartzite and Cambrian limestone and siltstone, was converted to an active continental margin in the Ordovician to Carboniferous (Hsü et al. 1991; Xiao et al. 2003b). The long-lived active continental margin arc is represented by Devonian, Carboniferous, and Permian calc-alkaline to alkaline magmatic rocks. A major Lower Permian continental volcanic arc is represented by andesite, tuff, and tuff breccia with sandstone, siltstone and conglomerate (Wang 1996; Xiao et al. 2003b).

The Hegenshan ophiolite-arc-accretion complex contains several ophiolitic fragments that are composed of dunite, gabbro, sheeted dikes, tholeiitic pillow basalt, radiolarian chert, and coral limestone (Tang 1990; Tang and Yan 1993). Many previous researchers considered the

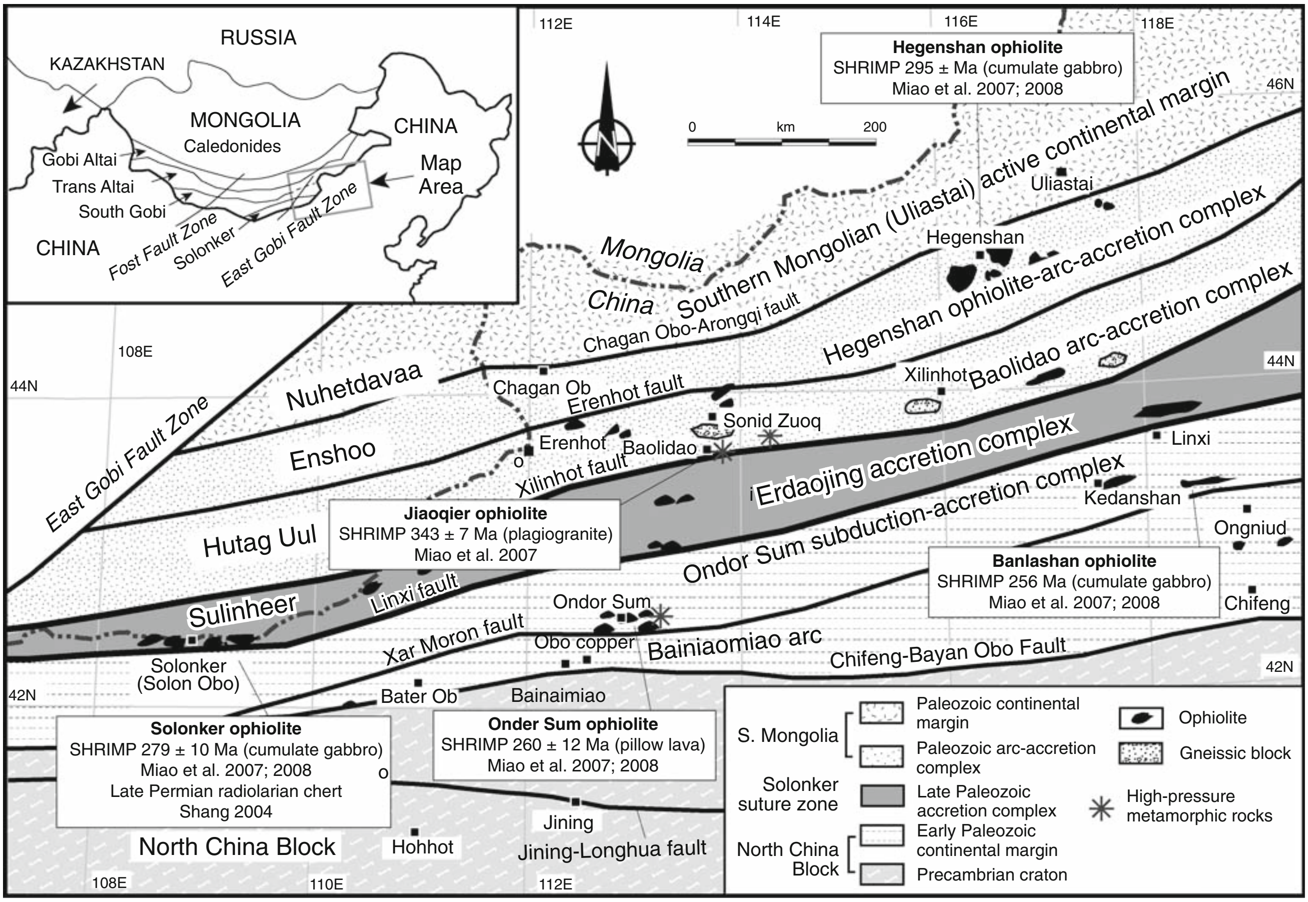


**Fig. 6** Tectonic map of central Inner Mongolia showing its structures and tectonic belts (compiled from Wang and Liu 1986; Tang 1990; Tang and Yan 1993; Hsü et al. 1991; IMBGMR 1991; Chen et al. 2000; Badarch et al. 2002 and Xiao et al. 2003a). For clarity, late Mesozoic-Cenozoic strata are not shown. Some middle to late Paleozoic isotopic ages of ophiolitic melanges are shown (modified after Miao et al. 2007, 2008). Insert is a simplified map of Asia showing the study area and the general tectonic divisions in southern Mongolia (modified after Lamb and Badarch 1997; Lamb et al. 2001, 2008)

Hegenshan ophiolite to have formed as a result of closure of the Paleoasian Ocean (Nozaka and Liu 2002). However, mafic rocks of the Hegenshan ophiolite have suprasubduction zone (SSZ-type) geochemical characteristics (Robinson et al. 1999), and accordingly it should be an arc-related SSZ-type ophiolite. The presence of middle to late Devonian radiolaria in some cherts led to a notion that the ophiolite was of Devonian age (Liang 1991). However, the nature of the contacts between these units is unclear (Robinson et al. 1999). The ophiolitic rocks are in fault contact with volcanic and sedimentary rocks of different ages ranging from Devonian to Permian (Wang and Liu 1986; Wang 1996; Xiao et al. 2003b; Jian et al. 2007). Borehole data indicate that the ophiolitic rocks have been thrust southward over early Permian volcanic rocks and early to mid-Jurassic clastic sediments (Hsü et al. 1991), and this idea was supported by magnetotelluric data that suggest that the ultramafic rocks of the ophiolite occur as allochthonous klippen (Bai et al. 1993a, b; Lu and Xia 1993). In summary, the geological and geophysical data indicate that the Hegenshan ophiolite is an imbricated component of a major accretionary wedge associated with the Solonker suture (Xiao et al. 2003b).

Recently acquired SHRIMP U–Pb zircon crystallization ages of the Hegenshan ophiolitic rocks include a basaltic dike at 298 ± 9 Ma (Table 2) (Jian et al. 2007, 2008; Miao et al. 2007, 2008), a cumulate gabbro at 295 ± 15 Ma (Jian et al. 2007, 2008; Miao et al. 2007, 2008), and a massive basalt has a whole-rock $^{40}$Ar/$^{39}$Ar age of 293 ± 1 Ma interpreted as the time of formation (Miao et al. 2007, 2008). An $^{40}$Ar/$^{39}$Ar age of 242 ± 2 Ma on a meta-mafic dike by Robinson et al. (1999) was interpreted to be represent the emplacement time of the ophiolite (Miao et al. 2007, 2008). Moreover, a granodiorite intruded into a Hengenshan serpentinized harzburgite, has a weighted mean SHRIMP U–Pb zircon age of 244 ± 4 Ma (Table 3) (Jian et al. 2007, 2008; Miao et al. 2007, 2008) interpreted as the emplacement age of a granitic crustal melt derived from tectonically and/or magmatically thickened crust shortly after closure of the Paleoasian Ocean.

These new geochronological data suggest that the Hegenshan ophiolite formed in the ocean in the Permian and was accreted in the early to mid-Triassic.

From Inner Mongolia northeastwards to the Lesser Xing'an Range (Fig. 2), a biotite-plagioclase gneiss from the Kele block that is situated within the eastern part of the orogen has a SHRIMP zircon protolith age of 337 ± 7 Ma and metamorphic overgrowth rims of 216 ± 3 Ma, which Miao et al. (2004) suggested were related to terminal collision between arcs to the north and south in the Triassic. They went on to point out that Triassic was a period of intensive and extensive collisional metamorphism and deformation throughout the Lesser Xing'an (Miao et al. 2004).

The Baolidao arc-accretion complex contains arc volcanic rocks and accretionary wedges. The arc is composed chiefly of variably deformed metaluminous to weakly peraluminous, hornblende-bearing gabbroic diorite, quartz diorite, tonalite and granodiorite, and contemporaneous volcanic rocks have geochemical data suggesting formation in island arc and back-arc settings (Chen et al. 2000; Xiao et al., 2003b). U–Pb zircon ages indicate that the bulk of the Baolidao rocks were emplaced at ca. 310 Ma in late Carboniferous time (Chen et al. 2000). A gabbro diorite has a SHRIMP U-Pb zircon age of 310 ± 5 Ma (Chen et al. 2009). The nearby, undeformed Halatu granites include muscovite/biotite-bearing monzogranite, granodiorite and leucogranite, some of which have geochemical signatures of crustal melt granites (Chen et al. 2000). Ophiolites and blueschists occur as faulted lenses in nearby north-dipping Carboniferous and early Permian clastic sediments, and are overlain unconformably by Upper Permian conglomerates (Wang and Liu 1986). The presence of late Permian ophiolitic mélanges and accretionary prisms suggests that this is not a Permian foreland basin, which could otherwise date the end of accretion. Chen et al. (2009) reported that one post-collisional granite has a mid-Triassic SHRIMP U-Pb age of 234 ± 7 Ma. Eruption of shoshonitic basalts took place at 224 ± 2 Ma (Jian et al. 2008). These all should be important constraints to date the end of accretion.

Several blocks of amphibolite facies gneissic rocks up to ca. 60 km long occur south and southeast of Xilinhot and south of Sonid Zuoqi in the Baolidao arc-accretion complex (Fig. 6). These high-grade metamorphic rocks were previously interpreted to belong to a continental block solely on the basis of their high-grade metamorphism and strong deformation (Wang and Liu 1986; Tang 1990). No precise isotopic ages were available to confirm this idea, only some controversial Pb–Pb or U-Pb ages of ca. 900 and 770 Ma (Kozakov et al. 1999). However, Shi et al. (2003) reported a SHRIMP detrital zircon age of 437 ± 3 Ma for a migmatitic paragneiss from these high-grade metamorphic rocks, and a magmatic age of 316 ± 3 Ma for a garnet-granite, which intruded paragneiss (Shi et al. 2003). The presence of a Silurian or even Devonian metamorphic age negates the possibility that the protoliths of the amphibolite facies gneisses were formed in the Precambrian. Shi et al. (2003) interpreted these turbiditic paragneisses as forearc sediments and Jian et al. (2008) suggested that ridge subduction was responsible for their metamorphism. Because the gneisses form isolated tectonic blocks in an ophiolitic mélange with blueschist, greenschist, meta-sandstone, and meta-volcanic rocks, some of which are late Devonian–early Permian in age, we currently interpret them as blocks that were accreted and incorporated into the subduction-accretion complex before the terminal closure of the Paleoasian Ocean (Xiao et al. 2003b).

The Solonker suture zone is more than 900 km long and 60 km wide and is marked by mélanges, and remnant of arcs and ophiolites, Fig. 6 (Xiao et al. 2003b; Chen et al. 2009). The suture zone contains the Erdaojing accretionary wedge (Xiao et al. 2003b) that comprises tectonic mélanges typical of a modern accretionary wedge, and coherent turbidites that occur with imbricated ophiolitic rocks, chert, marble, and arc volcanic rocks (Tang and Yan 1993; Wang and Liu 1986). The mélanges are characterized by lenses of mafic-ultramafic rocks, dolomite, quartzite, marble and blueschist within an argillite matrix (Tang 1990; Xu et al. 2001; Xiao et al. 2003b). In the Linxi area (Fig. 6) ophiolitic lenses of pyroxenite, layered gabbro, sheeted mafic dikes, basalt and chert occur in Lower Permian clastic sediments (Tang and Yan 1993; Wang and Liu 1986; Shao 1989).

Within the Erdaojing complex a cumulate gabbro from the Solon Obo ophiolite (Fig. 6), which straddles the China-Mongolia border, has a SHRIMP U-Pb age of 279 ± 10 Ma (Miao et al. 2007). Some sedimentary blocks in mélanges near Solonker contain middle Permian radiolaria (Shang 2004). These data suggest that the ophiolites were derived from the Permian Paleoasian oceanic crust/mantle and were most likely incorporated into the Erdaojing accretion complex after the late Permian.

The poorly exposed Ondor Sum subduction–accretion complex (Fig. 6) contains ophiolites, high-pressure rocks and granitic gneisses (Wang and Liu 1986; Tang 1990; Xiao et al. 2003b). In the well-exposed Ulan valley near Ondor Sum, ophiolitic pillow lavas and ocean plate stratigraphy occur in the south, folded phyllites in the centre, and thrusted mylonitic high-pressure rocks containing glaucophane and phengite in the north (Xiao et al. 2003b; Jian et al. 2007). All these rocks were juxtaposed in a south-directed thrust stack (Xiao et al. 2003b; Jian et al. 2007). An undeformed, but geochemically unanalyzed pillow lava from the southern ophiolite has a zircon SHRIMP age of ca 260 Ma (Miao et al. 2007), which provides a late Permian upper age limit for the accretionary wedge. Phengites from the northern high-pressure rocks yielded $^{40}$Ar-$^{39}$Ar ages of 453 ± 2 and 450 ± 2 Ma (de Jong et al. 2006), which suggest that a late Ordovician subduction complex was at one stage thrusted against a slice of Permian ocean (presumed) crust.

At Kedanshan along strike to the east (Fig. 6) a dismembered ophiolite contains thrust slices of peridotite, gabbro and basalt that are in fault contact with Silurian meta-sediments (Xiao et al. 2003b). Zircons from a plagiogranite of the Kedanshan ophiolite have a SHIRMP age of 277 ± 4 Ma (Jian et al. 2007). A cumulate gabbro from an ophiolitic fragment southwest of Kedanshan has a zircon SHRIMP U–Pb age of 256 ± 3 Ma (Miao et al. 2007). Some cherts in mélanges contain late Permian radiolaria (Wang and Fan 1997; Wang and Shu 2001). These dates confirm that the Ondor Sum accretionary wedge was still active in the end-Permian in this area.

The Ondor Sum complex also contains blocks of gneissic granite, orthogneiss, metamorphosed terrigenous sediments, marble, and mafic-ultramafic rocks of presumed oceanic origin, collectively referred to as the Suangjing complex (Jian et al. 2007). The orthogneiss, gneissic granite and some high-grade metamorphic rocks were previously considered to be Proterozoic or early Paleozoic in age (IMBGMR 1991), although no precise isotopic dates were known. However, new SHRIMP U–Pb zircon data show that a micaceous gneiss has an age of ~270 Ma (Miao et al. 2007), and gneissic granites have ages of 283 ± 9, 237 ± 3, and 229 ± 4 Ma (Li et al. 2007). These data led Li et al. (2007) to conclude that collision between the Siberian and North China Cratons may have begun in the mid-Permian and ended in the mid-Triassic.

The Bainaimiao arc, which is close to the northern margin of the North China craton, contains calc-alkaline tholeiitic basalts to minor felsic lavas, alkaline basalts, and agglomerates, volcanic breccias, tuffs, granodiorites, and granites (Tang 1990; Tang and Yan 1993), as well as granodiorite, quartz-diorite, and hornblende gabbro plutons that are intruded by feldspar-quartz porphyry. A granodiorite has a Sm–Nd isochron age of 429 Ma which gives a formation age for this arc which is close to the northern margin of the North China craton (Nie and Bjørlykke 1999).

A major recent breakthrough in the tectonic study on the North China craton was the recognition of an active continental arc on its northern side in which granitic plutons have SHRIMP zircon intrusion ages of 311 ± 2, 324 ± 6, 302 ± 4 and 310 ± 5 Ma (Zhang et al. 2007b, c). These Carboniferous plutons have for a long time been considered to belong to the early Precambrian basement of the North China craton (IMBGMR 1991). However, their calc-alkaline geochemistry and subduction-related I-type signature confirm that there was an Andean-style continental arc along the northern margin of the North China craton in the late Paleozoic (Xiao et al. 2003b; Zhang et al. 2007b, c).

Tuff beds in Upper Paleozoic sedimentary rocks are widespread along the northern margin of the North China craton (Zhang et al. 2007b, c). Geochemical analyses of the tuffs from an area west of Beijing indicate they have a calc-alkaline volcanic arc composition (Zhang et al. 2007b, c). One tuff west of Beijing (39°56′57″, 115°55′30″) has a SHRIMP zircon $^{206}$Pb/$^{238}$U weighted mean age of 296 ± 4 Ma (Zhang et al. 2007b, c), and an ash sample from Upper Paleozoic strata from Daqingshan, south of Hohhot, has a SHRIMP U–Pb concordia age of 290 ± 6 Ma (Cope 2003; Cope et al. 2005). These dated volcaniclastic rocks indicate that the northern side of the North China craton was an active continental margin in the Permian.

From their re-evaluation of the most reliable isotopic data from the Solonker suture zone (Chen et al. 2009) concluded that they constrain the timing of collision to between 296 and 234 Ma.

## The adjacent area in Southern Mongolia

The tectonic belts just described above continue west into the southern part of Mongolia, west of the international boundary as shown in the inset of Fig. 6. On a bigger picture they form part of the South Gobi and Solonker zones. They are divisible into the following belts, which from north to south include: the Gobi Altay, Trans-Altay, South Gobi, and Solonker (see insert map in Fig. 6) (Ruzhentsev et al. 1985; Carroll et al. 1990; Hendrix et al. 1992; Graham et al. 1993; Ruzhentsev and Burashnikov 1995; Ruzhentsev and Pospelov 1992; Johnson et al. 2001, 2007; Badarch et al. 2002; Johnson and Graham 2004a, b; Cope et al. 2005). The eastern section of this transect can be further subdivided into several terranes, namely the Nuhetdavaa, Enshoo, Hutag Uul, and the Sulinheer (Solonker) (Badarch et al. 2002). These terranes correlate well with the tectonic assemblages described above in Inner Mongolia of China (Fig. 6).

The Nuhetdavaa terrane is the western continuation of the Uliastai active continental margin (Xiao et al. 2003a). It mainly consists of gneiss, amphibolite, schist, marble, sandstone, siltstone, limestone, minor conglomerate, and volcanic rocks of probable early to middle Paleozoic age (Badarch et al. 2002). Silurian clastic sediments contain *Tuvaella* brachiopods. The presence of Devonian andesite, tuff, rhyolite, and volcaniclastic rocks (Badarch et al. 2002) indicates a mid-Paleozoic arc. Carboniferous to Permian volcanic and marine sedimentary rocks of the middle Gobi volcanic-plutonic belt (Badarch et al. 2002) probably formed in a late Paleozoic active margin based on the sedimentary, geochemical, structural and tectonic data (Lamb and Badarch 2001; Lamb et al. 2008; Johnson et al. 2007).

The Enshoo terrane contains ophiolitic fragments of dunite, gabbro, sheeted dikes, tholeiitic pillow basalt, radiolarian chert, and coral limestone (Tang 1990; Tang and Yan 1993; Badarch et al. 2002). The Enshoo arc comprises variably metamorphosed and sheared gneiss, quartzo-feldspathic schist, Devonian to Permian calc-alkaline basalt, andesite, dacite, tuff, volcaniclastic rocks, and minor limestone, some of which contain cold water fusulinids and brachipods (Ruzhentsev et al. 1985; Ruzhentsev and Burashnikov 1995; Ruzhentsev and Pospelov 1992; Badarch et al. 2002). Badarch et al. (2002) regarded the Enshoo terrane as a Devonian island arc, but in its eastern extension in China the Hegenshan ophiolite-arc-accretion complex has accretion ages as young as early to mid-Triassic.

The Hutag Uul terrane is the western extension of the Baolidao arc-accretion complex in China (Xiao et al. 2003b). This terrane consists mainly of gneiss, schist, migmatite, marble, quartzite, limestone, and meta-sandstone of unknown age. Much work (Lamb and Badarch 1997; Lamb et al. 2001; Webb and Johnson 2006) has shown that most rocks in this terrane, which were previously mapped as Precambrian on account of their high-grade and strong deformation, are actually Mesozoic tectonites with probable Paleozoic arc-related protoliths. Middle to late Paleozoic rocks also occur in this terrane including Devonian basalt, andesite, dacite, tuff, volcaniclastic rocks, minor pillow lavas, coral-bearing limestone, Carboniferous volcaniclastic rocks, Permian marine sedimentary and volcanic rocks (Badarch et al. 2002), and marine flysch as young as early Triassic (Ruzhentsev et al. 1985, 1989; Ruzhentsev and Pospelov 1992). The terrane was intruded by subduction-related tonalite, diorite, and granodiorite of Devonian- Carboniferous age (Badarch et al. 2002).

The Sulinheer terrane is the western continuation of the Solonker suture and Erdaojing accretionary wedge (Ruzhentsev et al. 1989; Badarch et al. 2002; Xiao et al. 2003b). It chiefly consists of fragments of ophiolite, mélange, and late Permian olistostrome. There are also Carboniferous clastic rocks, limestone, Pennsylvanian-Lower Permian limestone, and Upper Permian clastic rocks (Badarch et al. 2002). Blocks of tholeiitic pillow basalt, tuff, radiolarian chert, and massive limestone occur in a matrix of clastic sediments with ages ranging from mid-Paleozoic to Permian.

### Brief summary

In Inner Mongolia arcs, accretionary wedges and ophiolites all contain key evidence that indicates that growth of the Altaids took place by successive phases of accretion from the early Paleozoic to the early-middle Triassic. Figure 7 shows a possible tectonic scenario for the evolution history. The two wide Carboniferous-Permian accretionary wedges on either side of the Paleoasian Ocean amalgamated, giving rise to the Solonker suture in the end-Permian to mid-Triassic (Xiao et al. 2003b; Li et al. 2007; Chen et al. 2009).

## Discussion

### Biogeography and unconformable Molasse

In the Himalayas the time of change from marine sediments to unconformable molasse-like terrestrial fresh-water sediments may mark the timing of collision between the India and Tibet continental plates and the time of closure of Tethys (Searle et al. 1987; Yin and Harrison 2000). However, accretionary orogens are usually composed of ophiolitic fragments, mélanges, olistrostomes, and coherent sedimentary units of huge thickness (Wiedicke et al. 2001; Ogawa 2001; Jolivet et al. 2003; Konstantinovskaya and Malavieille 2005; Glen et al. 2007). In Japan the presence of undeformed, clastic, terrestrial or arc-derived sediments unconformable on deformed accreted rocks with marine

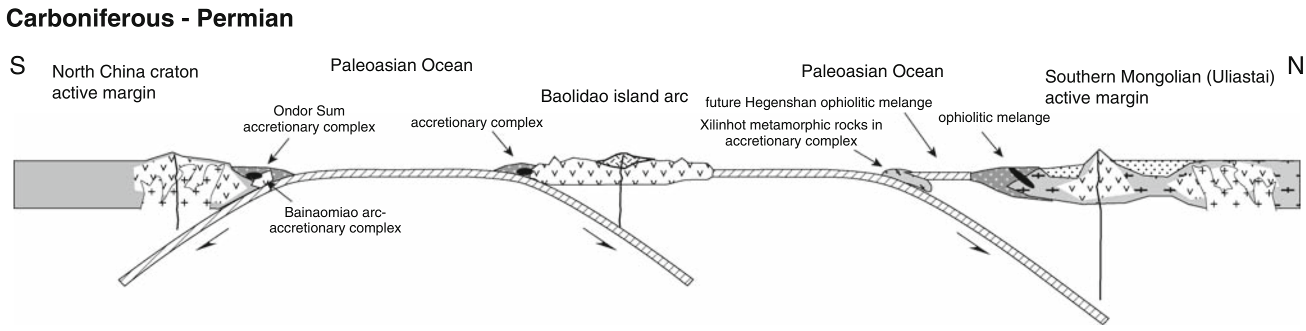


**Fig. 7** Schematic cartoon demonstrating the tectonic evolution of the Paleo-Asian Ocean and the multiple subduction systems in the Carboniferous-Permian (modified after Xiao et al. 2003a)

sediments can mark the boundary between a forearc basin and underlying accreted rocks from the trench, and also geophysical profiles and onland sections show small clastic sedimentary basins overlying unconformably accreted rocks in the trench (Pickering and Taira 1994). Therefore, care must be taken in interpreting unconformable clastic sediments. For example, in Inner Mongolia early Permian sandstones and conglomerates with abundant marine shelly and plant fossils overlie early Permian turbidites interpreted to belong to an accretionary wedge; Jian et al. (2007) suggested that these sedimentary relations give the maximum age of final suturing of that part of the Altaids. However, in so far as the overlying sediments are marine, and in view of the modern Japanese examples given above, this conclusion seems unlikely.

Nevertheless, in Inner Mongolia and the Tien Shan there is a major unconformity in many places that separates Upper Permian, deformed and metamorphosed accretionary rocks below from unmetamorphosed, undeformed mid-upper Triassic terrestrial clastic, often red-bed, sediments above (Xiao et al. 2003b, 2008a). These overlying red-bed, terrestrial sediments were probably derived by erosion of mountains elevated as a result of preceding collision tectonics, and therefore they have special significance for the timing of suture formation along the southern Altaids, because all subduction-accretion should have been ended by the time of the unconformity.

These relations are in good agreement with the line of distribution of the cold-water Boreal Angaran species in mostly terrigeous sediments and warm-water paleoequatorial Cathaysian fossils in mostly limestones and reefs, which approximately coincides with the Tien Shan-Solonker suture (Wang and Liu 1986; Dewey et al. 1988; Tang 1990; Tang and Yan 1993; Guo 2000; Manankov et al. 2006). The advanced research on biostratigraphy, paleobiogeography and paleogeography of Permian species throughout central and eastern Asia (e.g. Manankov et al. 2006; Shen et al. 2006; Shi 2006) provides us with an important constraint on tectonic development. The most relevant conclusion is that mixing of cold- and warm-water faunas reached a climax in the Wordian (270.6–265.8 Ma) (Shi 2006) largely within the Solonker suture zone east of the western end of the North China craton. The faunal data show that the Tien Shan-Solonker ocean closed in a scissor-like motion with the molasse terrestrial deposits in northeastern China indicating the final closure of the ocean was in the late Permian (Shen et al. 2006).

## Paleomagnetic data

The end-Permian to mid-Triassic termination model may be incompatible with the paleomagnetic data from the western part of the Southern Altaids. Figure 8 is a summary of paleomagnetic data for the Siberian and Tarim cratons and the southern Kazakhstan arcs. Van der Voo (1993) pointed out that the Siberian craton would have been very close to the Tarim craton since ca. Devonian-Carboniferous time according to mid-late Paleozoic paleolatitudes. However, in an updated view, Smethurst et al. (1998) put the Siberian craton in a more northerly position, which is almost 40 degrees north of the Tarim craton in Devonian-Carboniferous time (Fig. 8). For the late Devonian paleolatitude of the Siberian craton, more recent data indicate that the Siberian craton was near 30°N (Kravchinsky et al. 2002). Paleomagnetic data show that the latitude of the Tarim craton at the interval between the end-Permian and Triassic was very

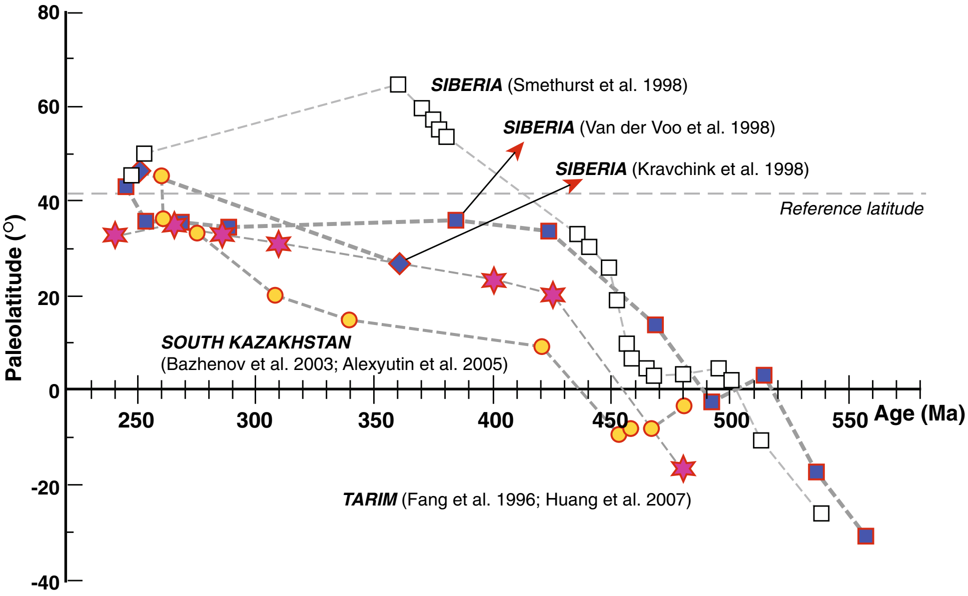
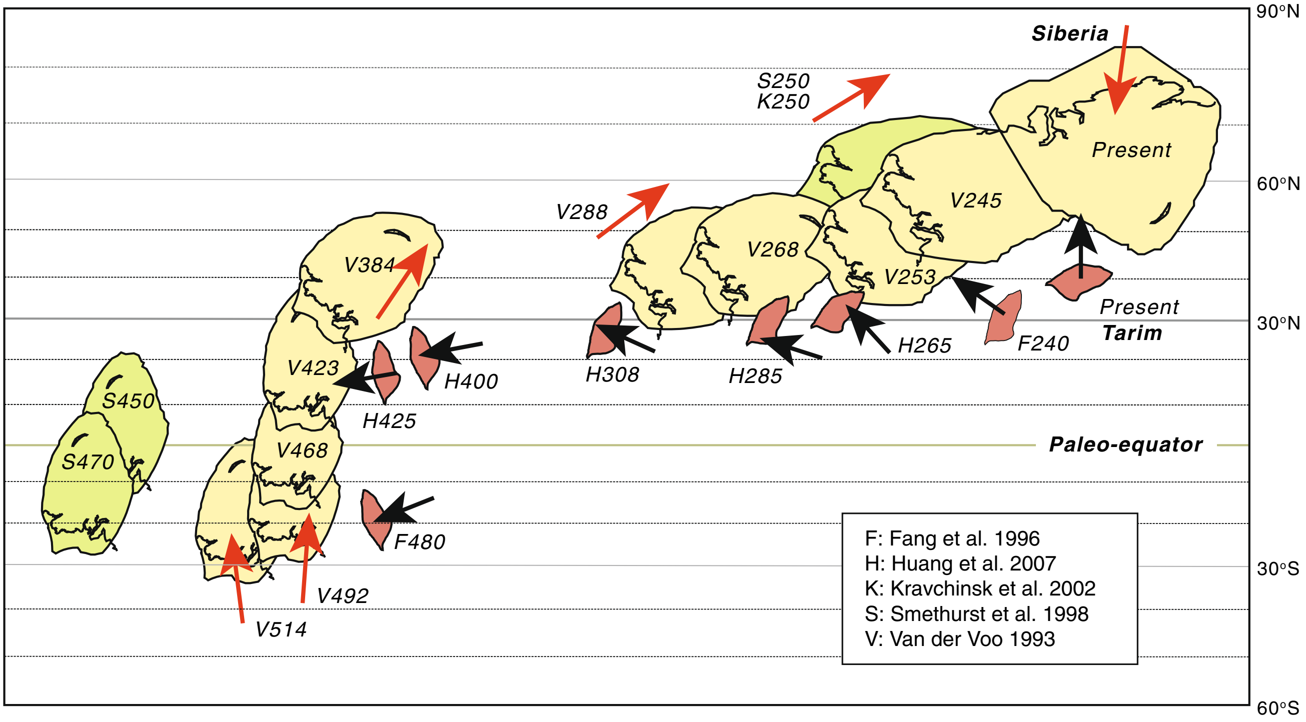


**Fig. 8** Paleomagnetic data for Siberia, South Kazakhstan, and Tarim cratons (modified after Van der Voo 1993; Van der Voo et al. 2006; Fang et al. 1996; Smethurst et al. 1998; Kravchinsky et al. 2002; Bazhenov et al. 2003; Huang et al. 2005, 2007). Star for Tarim, Circle for Southern Kazakhstan, and diamond, open and solid box for Siberia from various references indicated

close to that of the accretionary marginal sequences lying to the north including those in the Junggar and Tien Shan (Li et al. 1989, 1991; Li 1990). However, it is important to note that the paleolatitude differences between these Central Asian cratons or continental arcs were not large after 500 Ma (Fig. 8). If a small difference of the paleolatitudes means an approaching, near-collisional situation, these cratons and continental arcs would have collided in the early Paleozoic, which is negated by the data in this paper.

Considering the paleolatitude distributions of the Siberia, Kazakhstan, and Tarim cratons, which are illustrated in Figs. 8 and 9, the differences of these cratonic blocks or continental arcs (Kazakhstan, see Şengör et al. 1993) were very small during the whole Paleozoic. Considering the differences between the Siberia and Tarim cratons, the end-Permian should have been the time when these cratons were close. Also, the orientation of the Siberia and Tarim cratons during the Paleozoic (Fig. 9) clearly shows that the present EW long axis of the Tarim craton was N–S-oriented and remained the same until after 240 Ma, while the Siberian craton more or less kept its present up-side-down orientation. These relations suggest that the separation between the Siberia and Tarim cratons during the Paleozoic may have been similar to that in the present-day Pacific, where two cratons (Eurasia and North America) are oriented longitudinally and without considerable latitude differences. This scenario is in good agreement with most reconstructions that show relations between Eurasia and Gondwana (Nie 1991; Kravchinsky et al. 2002; Fortey and Cocks 2003; Lawver et al. 2003; Huang et al. 2005; Abrajevitch et al. 2007). The end-Permian to Triassic termination model agrees relatively well with the paleomagnetic and geological data for the eastern part of the Southern Altaids, where the North China craton collided with the southern Siberian active margin (including the eastern Southern Mongolia-Gobi) in the late Paleozoic to early Mesozoic (Zhao 1990; Enkin et al. 1992; Dobretsov et al. 1995; Smethurst et al. 1998; Thomas et al. 2002; Torsvik and Cocks 2004; Cocks and Torsvik 2007).

The Permian-Triassic termination model might initially seem incompatible with a recent model of fault-controlled, pendulum-style indentation of the Kazakhstan (Ili) block into the Tien Shan collages between Junggar and Tarim (Wang et al. 2007a). We agree that considerable displacements may have taken place on large-scale strike-slip faults or as a result of block rotation (Shu et al. 1999; Laurent-Charvet et al. 2002, 2003; Wang et al. 2007b; Charvet et al. 2007). However, there are two possibilities concerning such a tectonic environment; post-orogenic (Wang et al. 2007a) or syn-orogenic (Xiao et al. 2006a;



F: Fang et al. 1996
H: Huang et al. 2007
K: Kravchinsk et al. 2002
S: Smethurst et al. 1998
V: Van der Voo 1993

**Fig. 9** Paleo-positions for Siberia and Tarim implied by APW paths and some key paleomagnetic poles for the two continents (Modified after Van der Voo 1993; Van der Voo et al. 2006; Fang et al. 1996; Smethurst et al. 1998; Kravchinsky et al. 2002; Bazhenov et al. 2003; Huang et al. 2005, 2007). *Red arrows* denote the present south pole of Siberia, *black bold arrows* represent the present north pole of Tarim. Note that the relative position of the two continents does not represent the paleopalinspastic reconstruction. The *green* and *yellow* colors for Siberia from various references indicated

2008a, b). If the large-scale relative motions between the Kazakhstan (Ili)-Junggar tract and the Southern Altaid orogenic collages are valid, as supported by paleomagnetic data, we suggest that the syn-orogenic rotation model is more viable, if the movements took place in an active margin, thus negating the need for indentation of a relatively thin continental Kazakhstan (Ili)-Junggar tract into two already-amalgamated, rigid plates (Tarim and Siberia).

The presence of strong, late Permian thrusting and Permo-Triassic orogen-parallel strike-slip faulting might create a problem for the Permo-Triassic termination model, if these structures were post-orogenic (Laurent-Charvet et al. 2002, 2003; Chen and Arakawa 2005). However, these structures need not be post-orogenic, because in modern active margins and ancient orogens such as Alaska and the American Cordillera, there are many comparable syn-subduction thrusts and orogen-parallel strike-slip faults (Kusky et al. 1997; Gutscher et al. 1998; Kusky and Bradley 1999).

## Subduction polarity

The polarities of subduction zones during the closing stages of the Paleo-Asian ocean are important to constrain, and have been much discussed. The polarity of subduction in the eastern part of the Altaids has proved less controversial. It has long been widely accepted that there was northward subduction under the Uliastai active continental margin (Şengör et al. 1993; Şengör and Natal'in 1996a; Miao et al. 2007; Windley et al. 2007; Chen et al. 2009). Xiao et al. (2003b) proposed that there was southward subduction under a narrow accretionary wedge in front of the North China craton, although without evidence of a continental margin magmatic arc. However, Zhang et al. (2007c, 2008b) reported Carboniferous to early Permian hornblende-bearing granitic plutons (324 ± 6–274 ± 6 Ma) that were emplaced in an Andean-type, active continental arc on the northern margin of the North China craton, confirming that southward subduction also contributed to the closure of the Paleo-Asian ocean. From these relations Zhang et al. (2008b) concluded that final amalgamation of the Mongolian arc terranes with the North China craton occurred in the late Permian to earliest Triassic.

However, the subduction polarities in the western Altaids are currently controversial. Many authors have long agreed that the Tarim craton has a passive margin on its northern side (Allen et al. 1992; Carroll et al. 1995; Zhang 1994; Wang et al. 1995; Rui et al. 2002), and in the most recent tectonic review Gao et al. (2009) clearly indicate that Tarim had a passive margin on its northern side since 460 Ma. In contrast, Chen et al. (1999) proposed that the southern Tien Shan oceanic plate was subducted southwards beneath an active margin on the northern side of the Tarim craton. However, we emphasize the fact that no subduction-related rocks have been recorded anywhere along the northern margin of the Tarim craton, and this fact negates the southward subduction model. Recently, a new terrane called the "Central Tien Shan arc" was proposed to occupy a tectonic position between the already-existing Ili-Central Tien Shan to the north and the Tarim craton to the south (Charvet et al. 2007; Lin et al. 2009; Gao et al. 2009). These authors used the subduction record in this "arc terrane" to infer a southward subduction polarity of an oceanic plate in the Paleozoic. However, this new "Central Tien Shan terrane" is not the same as the well-defined and much quoted Ili-Central Tien Shan block. Accordingly, southward subduction beneath the new "central Tien Shan" terrane provides no information on the tectonic setting of the northern margin of the Tarim craton. We know of no evidence that indicates there was active subduction tectonics on the northern margin of the Tarim craton. HP-UHP eclogitic rocks occur on the southern side of the Ili-Central Tien Shan block, and because they contain zircons that have metamorphic rims with ages of 234–226 Ma Zhang et al. (2007a) concluded that the HP metamorphism formed as a result of collision between the Tarim and Yili-Central Tien Shan blocks in the early Triassic. However, HP metamorphism develops during subduction to eclogite-facies depths, soon after which exhumation must take place, and collision of plates occurs after that.

Predominant thrust-vergence in or against a suture zone may provide important information on the earlier polarity of subduction. From recent structural studies Charvet et al. (2007), Lin et al. (2009) and Gao et al. (2009) reported major north-vergent structures in the southern Tien Shan of China. From more detailed studies Wang et al. (1994) demonstrated that north-verging thrusts prevail in the northern part of the southern Tien Shan, but south-verging thrusts in the southern part of the southern Tien Shan. The fact that the Ili-Central Tien Shan arc is located to the north, the HP-UHP rocks and accretionary complex in the middle, and the Tarim passive margin to the south, which will be further discussed below, may indicate that the south-verging thrusts in the southern part of the southern Tien Shan could be the expression of a northward subduction. Of course, this needs further detailed structural and geochronological studies.

The 2007 international Middle Asian Seismic (MANAS) profile across the Kyrgyz and Chinese Tien Shan reported by Schelochkov et al. (2008) showed that the rigid Tarim lithosphere is thrust coherently northwards below the southern margin of the Tien Shan; also new tomographic images show high-speed anomalies dipping northwards below the southern margin of the Tien Shan. Also the southern side of the Tien Shan block against the Tarim craton to the south is marked by a major seismic anomaly that dips northwards under the Tien Shan (Wang et al. 2003a; Zhao et al. 2003). However, the age of formation of these geophysical anomalies is unknown.

## The northern margin of the Tarim craton

Because there is a current major controversy about whether the northern margin of the Tarim craton was passive (Allen et al. 1992; Carroll et al. 1995; Zhang 1994; Wang et al. 1995; Rui et al. 2002; Xiao et al. 2004b; Gao et al. 2009) or active (Charvet et al. 2007) in the late Paleozoic, it is useful here to summarize key sedimentary data, because they bear on the timing of the suture zone on the southern side of the Tien Shan. Most of the Precambrian Tarim basement is buried beneath a thick cover of Upper Proterozoic and Phanerozoic sediments of the Tarim basin. The northern margin of Tarim is dominated by a thick succession of Upper Carboniferous to Lower Permian platform carbonate sediments and reefs that were deposited on a north-facing passive continental margin prior to collision with the southern margin of the Tien Shan to the north (Allen et al. 1992, 1999; Graham et al. 1990; Windley et al. 1990). According to Lee (1985) Carboniferous fossiliferous platform carbonates reach a thickness of 1,500 m and locally 5,000 m. In the early Permian marine regression began, but still leaving locally more than 1,000 m of marine limestones and mudstones. By the late Permian continental red beds covered most of the Tarim. Chen and Shi (2003) published the first detailed lithostratigraphy and biostratigraphy, based on a synthesis of oil-company hydrocarbon borehole data, which outlined the depositional history of the Tarim basin. In the late Carboniferous to late Permian the northwestern margin of the basin was close to an open epeiric sea with the result that marine carbonate sediments with intermittent massive reefal carbonates accumulated on a major passive margin from the Baskirian-Moscovian boundary at 311.7 Ma in the Pennsylvanian late Carboniferous to the end of the Kungurian at 270.6 Ma in the late Permian, following the international time scale of Gradstein et al. (2004). Biozones throughout this period were defined in the Kalpin region of the northwestern Tarim basin (see Fig. 3) by brachiopods, fusulinids, conodonts, corals, and rarer ammonites and palynoflora (Chen and Shi 2003). Although terrestrial sediments were deposited in the centre of the Tarim basin from the mid-Artinskian stage in the Cisuralian epoch at ca. 280 Ma, the northern passive margin continued with deposition of shelf carbonates through the Qipan sedimentary cycle during the Kungurian stage from 275.6 Ma (mid-Permian) to 270.6 Ma (late Permian). The seas finally withdrew at the end of the Kungurian, after which the whole Tarim basin including the northern margin was covered with terrestrial red beds during the late Permian (Wang et al. 1992). Significantly the end of carbonate deposition in the late Kungurian at about 271 Ma was signaled by massive eruption of basaltic sills, after deeper water clastic sedimentation took place. These marine-nonmarine-basalt sill relations are very similar to those in the Alpine-Mediterranean region when carbonate platforms collapsed (and intruded by basalt sills), fragmented and subsided (with deposition of non-marine silts and sands) from the early Jurassic to the early Cretaceous (Jenkyns 1970) in advance of the Alpine collision tectonics. Unfortunately the demise of the carbonate platform along the northern Tarim has never been studied or interpreted in terms of the disintegration of a carbonate shelf. Instead the deposition of terrestrial sediments in the late Permian is interpreted only as a foreland basin controlled by southward-directed thrusts. In spite of these differences in interpretation of the sediment record, the data do suggest that the South Tien Shan suture zone must have formed by the end of the Permian (Nishidai and Berry 1990).

In contrast, Watson et al. (1987) suggested that collision of Tarim wtith the Junggar block to the north and that carbonate deposition on the northern side of Tarim was terminated in the latest Carboniferous. Nishidai and Berry (1990) followed these ideas stating that the Tarim platform collided with the Junggar block to the north in the late Carboniferous. From their structural studies integrated with the sedimentary records of Carroll et al. (1995), Charvet et al. (2007) concluded that the ocean on the northern side of the Tarim craton disappeared between the late Devonian and early Carboniferous during which the South Tien Shan suture zone formed and was buried under terrestrial sediments by the start of the Permian.

In summary, we suggest that the latest, up-to-date, and most detailed biostratigraphic data of Chen and Shi (2003) unequivocally indicate that the northern margin of the Tarim craton was passive and marine until 270.6 Ma in the late Permian, and therefore, the suture zone could not have formed before then.

This means that there must have been a suture (we call this the North Tarim suture) on the northern side of this passive margin to account for the closure of the ocean in the late Permian, but there is no such suture exposed today in the southern Tien Shan, where all ophiolitic mafic-ultramafic rocks are pre-Permian or pre-early Permian (e.g. Charvet al. 2007). So where is this final suture? The answer to this problem comes from Jacques Charvet (personal communication to BFW on 25 November 2008), who suggested that the North Tarim suture could have been subducted northwards under the Tien Shan during the Cenozoic subduction of the Tarim block as illustrated on the recent seismic reflection profiles (Schelochkov et al. 2008). The formation of such a suture in the late Permian would permit northwards subduction through much of the Permian under the active continental margin of the southern Tien Shan, and that would readily account for the Permian-age, Alaskan-type, zoned mafic-ultramafic complexes that are aligned along the southern margin of the southern Tien Shan that would have formed in an Alaskan-type environment of an active continental margin. This model would therefore not necessitate the introduction of a mantle plume in the Permian in the southern Tien Shan just in order to explain the occurrence of the zoned mafic-ultramafic complexes in so-called post-orogenic or post-collision times (i.e. Charvet et al. 2007; Pirajno et al. 2008).

The above idea of the former presence of a Permian subduction zone on the northern side of the Tarim craton is supported by Li et al. (2003) who pointed out that the narrow Kuluketaq massif (which is located between the South Tien Shan and the Tarim basin and consists of Precambrian crystalline rocks) contains a belt of Permian calc-alkaline magmatic rocks that have an active continental margin chemical affinity (Jiang et al. 2001), this implying that there was an open ocean on the northern side of Tarim subducting northwards under the Kuluketag block during the Permian. The late Permian North Tarim suture should today be below the Kuluketag block and below the southern margin of the South Tien Shan farther west.

## Tectonic model

The Altaids comprised the southern part of Eurasia in the late Paleozoic to early Mesozoic. Therefore the reconstruction of Eurasia cannot be undertaken without the detailed paleogeography of Central-East Asia, which is largely occupied by the Altaids. Based on the above points, and using published data, we propose a new model to explain the distribution and paleogeography of the Siberia, Tarim and North China cratons, and southern Mongolia in the late Permian (Fig. 10).

Some former reconstructions consistently placed the Tarim craton attached to southern Eurasia in the middle to late Paleozoic, and put the North China craton in the southern oceanic domain, detached from Eurasia (Şengör et al. 1993; Şengör and Natal'in 1996a, b). This would be

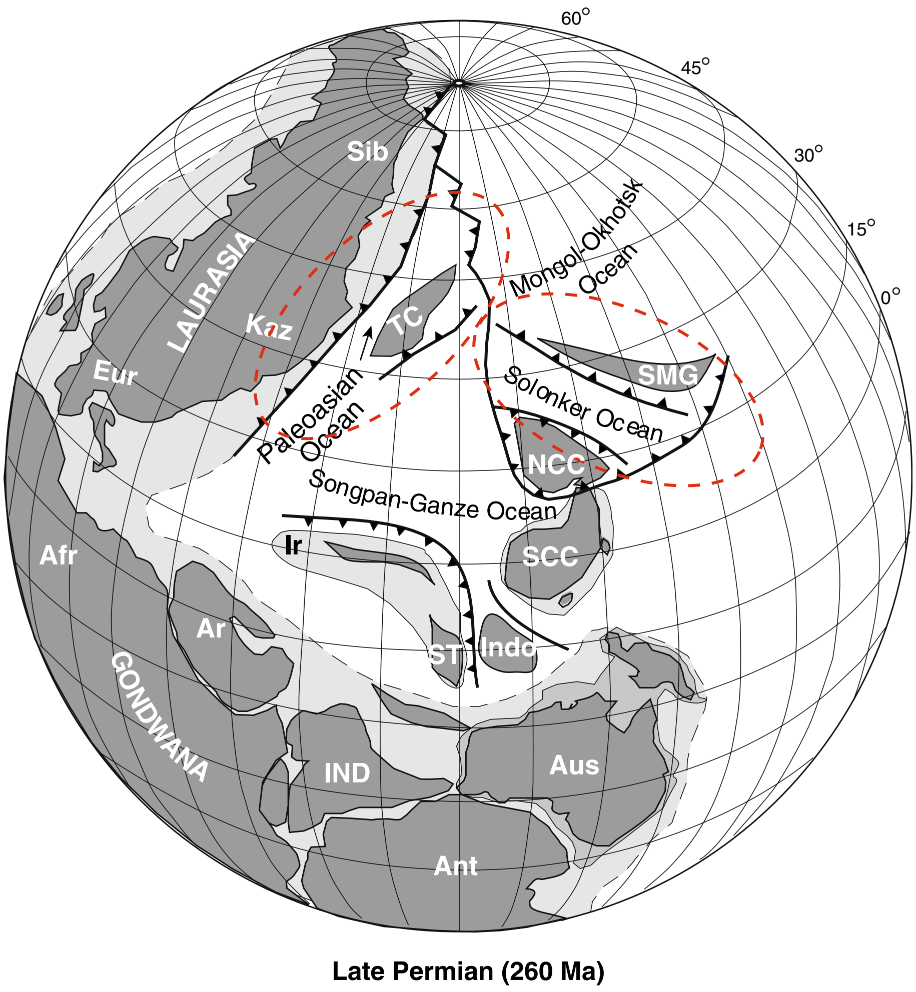


**Fig. 10** Schematic paleogeographic reconstruction of Laurasia and Gondwana in the late Permian showing the Paleoasian Ocean and Solonker Ocean (modified after Enkin et al. 1992; Torsvik and Cocks 2004; de Jong et al. 2006; Li 2006). *Afr* Africa, *Ant* Antarctica, *Ar* Arabia, *Aus* Australia, *Eur* Europe, *IND* India, *Indo* Indochina, *Ir* Iran, *Kaz* Kazakhstan, *NCC* North China craton, *SCC* South China craton, *Sib* Siberia, *SMG* Southern Mongolia-Gobi, *ST* Shan-Thai, *TC* Tarim craton. The *circular dashed lines* enclose the approximate position of the two key areas (North Xinjiang and Inner Mongolia) discussed in this paper. *Lines with barbs* indicate main subduction zones and their polarities of subduction

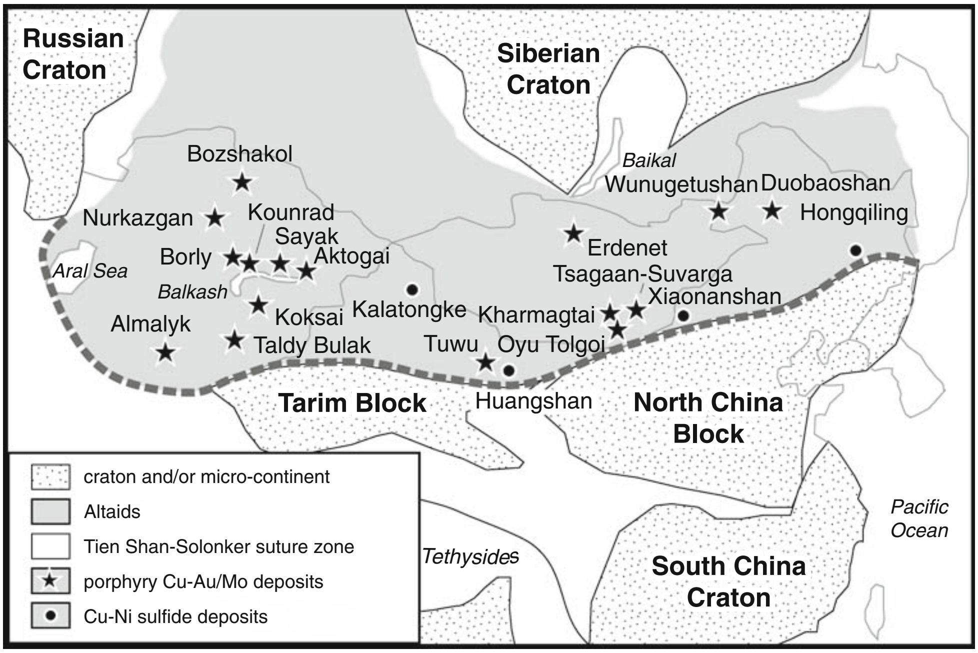


**Fig. 11** Schematic map of the Altaids showing principal mineral deposits which are linked to accretionary processes (modified after Seltmann and Porter 2005; Tang and Liu 1995; Han et al. 2006a, b). The *bold line* denotes the approximate position of the Tien Shan-Solonker suture

consistent with detailed paleomagnetic data that suggest progressive ocean closure and younging of suturing towards the east from the end-Permian in the Tien Shan to the early-mid Triassic in Inner Mongolia (Zhao 1990). Farther east in the Lesser Xing'an Range in NE China reliable data suggest that formation of the main suture zone was completed by collisional tectonism in the late Triassic at 216 ± 3 Ma (Miao et al. 2004); although Shen et al. (2006) preferred final closure of the ocean in the late Permian. Therefore, it seems to us that current information points to diachronous, scissor-like suturing between the western and eastern parts of the Altaids, as confirmed by biostratigraphic data of Shi (2006), in a manner not unlike the eastward younging of formation of the suture that closed the Mongol-Okhotsk ocean from the Triassic in western Mongolia (Zonenshain et al. 1990) to the Jurassic-early Cretaceous in eastern Mongolia and Siberia (Tomurtogoo et al. 2005). We agree with Johnson et al. (2007) that the earlier well-documented marine-nonmarine transition (Carroll et al. 1995; Hendrix et al. 1996; Lamb and Badarch 2001; Lamb et al. 2008) in the west of the southern Altaids compared with the east broadly supports a younging of collision eastwards.

## Implications for continental growth and metallogeny

The Phanerozoic crustal growth of the Altaids is well constrained by petrochemical and isotopic data. Sm–Nd isotopic data of granitic rocks indicate their juvenile character and short life, since separation of the source rocks or magmas from the mantle (Jahn 2004; Jahn et al. 2004; Zheng et al. 2007b; Kröner et al. 2007). However, we agree with Kovalenko et al. (2004) that the most likely source for the granites is juvenile lower crust of the accretionary orogen (Yuan et al. 2007).

The terminal orogenesis of the western Altaids was previously considered to be early or middle Paleozoic (Shu et al. 1999; Shu et al. 2002; Laurent-Charvet et al. 2002, 2003; Wang et al. 2007a, b; Charvet et al. 2007), but the recognition of younger (late Permian-middle Triassic) geological relationships and geodynamic events in the middle Altaids has refined the timing of the termination. This has implications for understanding the metallogenic history. For example, in the eastern Tien Shan several episodes of mineralization can be related to specific tectonic events (Han et al. 2006a, b; Zhang et al. 2008c): porphyry-type and volcano-sedimentary Cu deposits, island arc generation (c. 360–320 Ma); orogenic-type Au deposits, accretion-collision (c. 300–280); mafic-ultramafic Cu-Ni and epithermal Au deposits (Fig. 11), syn- to post-collision extension (c. 280–245 Ma); some Au and skarn W-Mo deposits, intracontinental extension (c. 240–220 Ma).

The southern Altaids is a Precambrian-early Mesozoic orogenic belt that provides excellent information on accretionary processes, metallogeny and continental growth that are complementary to the younger Phanerozoic accretionary orogens in Mesozoic-Cenozoic Japan, Alaska and the American Cordillera (Sample and Fisher 1986; Haeussler et al. 1995; Nelson 1996; Goldfarb et al. 1997; Hansen and Dusel-Bacon 1998; Nokleberg et al. 2005), and other accretionary orogens in the world (Bierlein et al. 2002; Gray et al. 2002; Glen et al. 2007).

### Problems with interpretations along the suture zone

It is important to acknowledge some of the problems encountered in interpreting a >3,000 km-long suture zone. With the large number of variable, often controversial, interpretations of relations along this length, it might be surprising if it were just a simple 'straight-line', orthogonal, continuous, simple closure like that of the Indus-Tsangbo suture. Indeed, because it is so often claimed that the Altaids formed by irregular archipelago-type accretion of multiple arcs, marginal basins, and several microcontinental blocks, comparable to that in Indonesia today (summarized in Xiao et al. 2008c), one might expect that the final suturing was also highly irregular along such a long closure zone. For example, sedimentary-stratigraphic relationships suggest that early indentation of a promontory or salient in the area of south-central Mongolia led to separation of the Junggar basin to the west from the Solonker ocean basin to the east (Johnson et al. 2007). Moreover, many differences between the western and eastern parts of the suture zone may make it difficult to correlate the timing of closure of the ocean. For example, many foreland-like basins have been reported in the west, but few in the east; this makes it difficult to compare post-amalgamation tectonic development (e.g. Junggar basin, Hendrix et al. 1992; Turpan-Hami basin, Wartes et al. 2002; N. Tarim, Chen and Shi 2003). Like the Himalayas, post-collisional thrusting was characteristic of the Tien Shan-Solonker orogenic belt. This NS-directed deformation is evident in the thrusted sediments and foreland basins in southern Mongolia and Inner Mongolia (e.g. Hendrix et al. 1992, 1996; Zheng et al. 1996; Dumitru and Hendrix 2001; Vincent and Allen 2001; Darby et al. 2001). Unfortunately, much of this post-collisional thrusting had the effect of obscuring evidence of many pre-collisional geological relationships and syn-collisional deformation.

## Conclusions

The late Paleozoic to early Mesozoic geodynamic processes of two key areas, North Xinjiang in the west and Inner Mongolia in the east, together with neighboring Mongolia, reveal that the building of the Altaids was finally completed between the late Permian and middle Triassic in the west and early/middle Triassic in the east. The late Paleozoic tectonics of North Xinjiang and adjacent areas were characterized by continuous southward accretion along the wide southern active margin of Siberia and its final amalgamation with the passive margin of Tarim by the end-Permian. In contrast, in Inner Mongolia and adjacent areas the development of accretionary wedges along the southern active margin of Siberia and the northern active margin of the North China craton may have lasted to the early/mid-Triassic. Farther east in NE China final collision probably took place in the late Triassic. In other words, the final closure of the Paleo-Asian ocean was diachronous along its >3,000 km length, and took place mainly in a complicated scissor-like fashion with the suture zone younging eastwards. However, it was not a simple, linear ocean closure and suture; it is more likely that a more complex development took place with, for example, salients, trapped ocean basins, irregular development of foreland basins, southwards and northwards subduction north of the North China craton versus northwards subduction away from the Tarim craton, and irregular post-collisional thrusting, which obscured many pre- and syn-collisional relationships. In our view, many of the diverse and varied opinions related to the timing of the suture formation owe their origins to such variations. Nevertheless, it seems to us that many of the controversial conclusions on the timing result from decisions made from study of just one discipline; only more multi-disciplinary studies will resolve such issues. The complex geodynamic evolution of the Altaids led to widespread post-collisional thrusting, mountain building, formation of giant metal deposits, and to substantial continental growth throughout Central Asia. The closure of the Paleo-Asian ocean gave rise to one of the longest and most spectacular suture zones in the world.

**Acknowledgments** Jinyi Li, Jun Gao, Laicheng Miao, Xiaoping Long, Keda Cai, and Kenny Wong are acknowledged for collaboration and discussions. We sincerely appreciate the thorough comments, suggestions, and criticisms of four formal Journal reviewers, Cari Johnson, Dick Glen, and two anonymous ones, and of guest-editor Alfred Kröner, which substantially improved the manuscript, as did a final survey of Dick Glen and an anonymous referee, for all of which the authors are sincerely grateful. This study was financially supported by funds from the Major State Basic Research Development Program of China (2007CB411307), National 305 Project (2007BAB25B04), and the National Science Fund for Distinguished Young Scholars (40725009). This paper is a contribution to the ILP (ERAs and Topo-Central Asia) and IGCP 480 projects.

## References

Abrajevitch A, Van der Voo R, Levashova NM, Bazhenov ML (2007) Paleomagnetic constraints on the paleogeography and oroclinal bending of the Devonian volcanic arc in Kazakhstan. Tectonophysics 441:67–84

Ai YL, Zhang LF, Li XP, Qu JF (2006) Geochemical characteristics and tectonic implications of HP-UHP eclogites and blueschists in southwestern Tianshan, China. Prog Nat Sci 16:624–632

Allen MB, Windley B, Zhang C, Zhao ZY, Wang GR (1991) Basin evolution within and adjacent to the Tien Shan Range, NW China. J Geol Soc Lond 148:369–378

Allen MB, Windley BF, Zhang C (1992) Palaeozoic collisional tectonics and magmatism of the Chinese Tien Shan, central Asia. Tectonophysics 220:89–115

Allen MB, Vincent SJ, Wheeler PJ (1999) Late Cenozoic tectonics of the Kepingtage thrust zone: interactions of the Tien Shan and Tarim Basin, northwest China. Tectonics 18:639–654

Badarch G, Cunningham WD, Windley BF (2002) A new terrane subdivision for Mongolia: implications for the Phanerozoic crustal growth of Central Asia. J Asian Earth Sci 21:87–110

Bai DH, Zhang L, Kong XR (1993a) A magnetotelluric study of the Paleozoic collision zone in the east of Inner Mongolia, II: two-dimensional modelling. Acta Geophys Sin 36:773–783

Bai DH, Zhang L, Kong XR (1993b) A magnetotelluric study of the Paleozoic collision zone in the east of Inner Mongolia, I: observations and data analysis. Acta Geophys Sin 36:326–336

Bazhenov ML, Collins AQ, Degtyarev KE, Lavashova NM, Mikolaichuk AV, Pavlov VE, Van der Voo R (2003) Paleozoic northward drift of the North Tien Shan (Central Asia) as revealed by Ordovician and Carboniferous paleomagnetism. Tectonophysics 366:113–141

Bierlein FP, Gray DR, Foster DA (2002) Metallogenic relationships to tectonic evolution—the Lachlan Orogen, Australia. Earth Planet Sci Lett 202:1–13

Briggs SM, Yin A, Manning CE, Chen Z-L, Wang X-F, Grove M (2007) Late Paleozoic tectonic history of the Ertix Fault in the Chinese Altai and its implications for the development of the Central Asian Orogenic System. Geol Soc Am Bull 119:944–960

Brugmann GE, Reischmann T, Naldrett AJ, Sutcliffe RH (1997) Roots of an Archean volcanic arc complex: the Lac des Iles Area in Ontario, Canada. Precambrian Res 81:223–239

Buchan C, Cunningham D, Windley B, Tomurhuu D (2001) Structural and lithological characteristics of the Bayankhongor ophiolite zone, central Mongolia. J Geol Soc Lond 158:445–460

Buchan C, Pfänder J, Kröner A, Brewer TS, Tomurtogoo O, Tomurhuu D, Cunningham D, Windley BF (2002) Timing of accretion and collisional deformation in the Central Asian orogenic belt: implications of granite geochronology in the Bayankhongor ophiolite zone. Chem Geol 192:23–45

Buslov MM, Saphonova IY, Watanabe T, Obut OT, Fujiwara Y, Iwata K, Semakov NN, Sugai Y, Smirnova LV, Kazansky AY (2001) Evolution of the Paleo-Asian Ocean (Altai-Sayan Region, Central Asia) and collision of possible Gondwana-derived terranes with the southern marginal part of the Siberian continent. Geosci J 5:203–224

Bykadorov VA, Bush VA, Fedorenko OA, Filippova IB, Miletenko NV, Puchkov VN, Smirnov AV, Uzhkenov BS, Volozh YA (2003) Ordovician-Permian Palaeogeopgraphy of Central Eurasia: development of Palaeozoic petroleum-bearing basins. J Petrol Geol 26:325–350

Carroll AR, Liang Y, Graham SA, Xiao X, Hendrix MS, Chu J, McKnight CL (1990) Junggar basin, northwestern China: trapped Late Paleozoic ocean. Tectonophysics 181:1–14

Carroll AR, Graham SA, Hendrix MS, Ying D, Zhou D (1995) Late Paleozoic tectonic amalgamation of northwestern China: sedimentary record of the northern Tarim, northwestern Turpan, and southern Junggar basins. Geol Soc Am Bull 107:571–594

Chai FM, Zhang ZC, Mao JW, Dong LH, Zhang ZH, Wu H (2008) Geology, petrology and geochemistry of the Baishiquan Ni-Cu-bearing mafic-ultramafic intrusions in Xinjiang, NW China: implications for tectonics and genesis of ores. J Asian Earth Sci 32:218–235

Charvet J, Shu L, Laurent-Charvet S (2007) Paleozoic structural and geodynamic evolution of eastern Tianshan (NW China): welding of the Tarim and Junggar plates. Episodes 30:162–185

Chen B, Arakawa Y (2005) Elemental and Nd-Sr isotopic geochemistry of granitoids from the West Junggar foldbelt (NW China), with implications for Phanerozoic continental growth. Geochim Cosmochim Acta 69:1307–1320

Chen B, Jahn B-M (2002) Geochemical and isotopic studies of the sedimentary and granitic rocks of the Altai orogen of northwest China and their tectonic implications. Geol Mag 139:1–13

Chen ZQ, Shi GR (2003) Late Paleozoic depositional history of the Tarim basin, northwest China: an integration of biostratigraphic and lithostratigraphic constraints. Am Assoc Petroleum Geol Bull 87:1323–1354

Chen B, Jahn B-M (2004) Genesis of post-collisional granitoids and basement nature of the Junggar Terrane, NW China: Nd-Sr isotopic and trace element evidence. J Asian Earth Sci 23:691–703

Chen CM, Lu HF, Jia D, Cai DS, Wu SM (1999) Closing history of the southern Tianshan oceanic basin, western China: an oblique collisional orogeny. Tectonophysics 302:23–40

Chen B, Jahn B-M, Wilde S, Xu B (2000) Two contrasting Paleozoic magmatic belts in northern Inner Mongolia, China: petrogenesis and tectonic implications. Tectonophysics 328:157–182

Chen HL, Yang SF, Li ZL, Yu X, Xiao WJ, Yuan C, Li JL (2006) Zircon SHRIMP U-Pb chronology of the Fuyun basic granulite and its tectonic significance in the Altaid orogenic belt. Acta Petrologica Sin 22:1351–1358

Chen B, Jahn BM, Tian W (2009) Evolution of the Solonker suture zone: constraints from zircon U-Pb ages, Hf isotopic ratios and whole-rock Nd-Sr isotope compositions of subduction- and collision-related magmas and forearc sediments. J Asian Earth Sci 34:245–257

Cocks LRM, Torsvik TH (2007) Siberia, the wandering northern terrane, and its changing geography through the Palaeozoic. Earth Sci Rev 82:29–74. doi:10.1016/j.earscirev.2007.1002.1001

Cole A (2001) Gold mineralization in the southern Tien Shan, central Asia: Tectonic setting, characteristics, exploration criteria. In: Seltmann S, Jenchuraeva R (eds) Paleozoic geodynamics and gold deposits in the Kyrgyz Tien Shan. Natural History Museum, London, UK. IGCP 373 Field Conference, IAGOD Guidebook Series, vol 9, London, pp 71–78

Coleman R (1989) Continental growth of Northwest China. Tectonics 8:621–635

Coleman RG (1994) Reconstruction of the Paleo-Asian Ocean: Proceeding of the 29th International Geological Congress. Part B. VSP, Utrecht, p 186

Cope TD (2003) Sedimentary evolution of the Yanshan fold-thrust belt, Northeast China. Unpublished PhD thesis, Stanford University, Stanford, p 230

Cope T, Ritts BD, Darby BJ, Fildani A, Graham SA (2005) Late Paleozoic sedimentation on the northern margin of the North China block: implications for regional tectonics and climate change. Int Geol Rev 47:270–296

Darby BJ, Davis GA, Zheng Y (2001) Structural evolution of the southwestern Daqing Shan, Yinshan belt Inner Mongolia. In: Hendrix MS, Davis GA (eds) Paleozoic and Mesozoic Tectonic Evolution of Central Asia—from Continental Assembly to Intracontinental Deformation. Geological Society of America Memoir, vol 194, pp 199–214

de Jong K, Xiao WJ, Windley BF, Masago H, Lo C-H (2006) Ordovician $^{40}Ar/^{39}Ar$ phengite ages from the blueschist-facies Ondor Sum subduction-accretion complex (Inner Mongolia) and implications for the early Palaeozoic history of continental blocks in China and adjacent areas. Am J Sci 306:799–845

Dewey JF, Shackleton R, Chang CF, Sun Y (1988) The tectonic evolution of the Tibetan Plateau. Phil Trans R Soc Lond A327:379–413

Dobretsov NL (2003) Evolution of the structures of Urals, Kazakhstan, Tien Shan, and Altai-Sayan region within the Ural-Mongolian fold belt. Russ Geol Geophys 44:5–27

Dobretsov NL, Berzin NA, Buslov MM (1995) Opening and the tectonic evolution of Paleo-Asian ocean. Int Geol Rev 35:335–360

Dobretsov NL, Buslov MM, Zhimulev FI, Travin AV, Zayachkovsky AA (2006) Vendian-Early Ordovician geodynamic evolution and model for exhumation of ultrahigh- and high-pressure rocks from the Kokchetav subduction-collision zone (northern Kazakhstan). Russ Geol Geophys 47:424–440

Dumitru TA, Hendrix MS (2001) Fission-track constraints on Jurassic folding and thrusting in southern Mongolia and their relationship to the Beishan thrust belt of northern China. In: Hendrix MS, Davis GA (eds) Paleozoic and Mesozoic tectonic evolution of Central and Eastern Asia—from continental assembly to intra-continental deformation. Geological Society of America Memoir, vol 194, pp 215–229

Enkin RJ, Yang Z, Chen Y, Courtillot V (1992) Paleomagnetic constraints on the geodynamic history of the major blocks of China from Permian to the present. J Geophys Res 97B(13):953–13989

Fang DJ, Jin GH, Jiang LP, Wang PY, Wang ZL (1996) Paleozoic paleomagnetic results and the tectonic significance of Tarim Plate. Chin J Geophys 39:522–532 (in Chinese with English abstract)

Feng Y, Coleman RG, Tilton G, Xiao X (1989) Tectonic evolution of the West Junggar region, Xinjiang, China. Tectonics 8:729–752

Filippova IB, Bush VA, Didenko AN (2001) Middle Paleozoic subduction belts: the leading factor in the formation of the Central Asian fold-and-thrust belt. Russ J Earth Sci 3:405–426

Fortey RA, Cocks LRM (2003) Palaeontological evidence bearing on global Ordovician-Silurian continental reconstructions. Earth Sci Rev 61:245–307

Gao J, Klemd R (2001) Primary fluids entrapped at blueschist to eclogite transition: evidence from the Tianshan meta-subduction complex in northwestern China. Contrib Mineral Petrol 142:1–14

Gao J, Klemd R (2003) Formation of HP-LT rocks and their tectonic implications on the western Tianshan orogen, NW China: geochemical and age constraints. Lithos 66:1–22

Gao J, He GQ, Li MS, Xiao XC, Tang YQ (1995) The mineralogy, petrology, metamorphic PTDt trajectory and exhumation mechanism of blueschists, south Tianshan, northwestern China. Tectonophysics 250:151–168

Gao J, Long L, Klemd R, Qian Q, Liu D, Xiong X, Su W, Liu W, Wang Y, Yang F (2009) Tectonic evolution of the South Tianshan orogen and adjacent regions, NW China: geochemical and age constraints of granitoid rocks. Int J Earth Sci (in press)

Glen RA, Meffre S, Scott RJ (2007) Benambran Orogeny in the eastern Lachlan Orogen, Australia. Aust J Earth Sci 54:385–415

Goldfarb RJ, Groves DI, Gardoll S (1997) Metallogenic evolution of Alaska. Econ Geol 9:4–34

Goldfarb RJ, Mao JW, Hart C, Wang DH, Anderson E, Wang ZL (2003) Tectonic and metallogenic evolution of the Altay Shan, northern Xinjiang Uygur Autonomous Region, northwestern China. In: Mao JW, Goldfarb RJ, Seltmann R, Wang DH, Xiao WJ, Hart C (eds) Tectonic Evolution and Metallogeny of the Chinese Altay and Tianshan. IAGOD Guidebook Ser. 10. CERCAMS/NHM, London, pp 17–30

Gradstein FM, Ogg JG, Smith AG (2004) A geologic time scale. Cambridge University Press, Cambridge, p 589

Graham SA, Brassell S, Carroll AR, Xiao X, Demaison G, McKnight CL, Liang Y, Chu J, Hendrix MS (1990) Characteristics of selected petroleum-source rocks, Xinjiang Uygur Autonomous Region, northwest China. Am Assoc Petrol Geol Bull 74:493–512

Graham SA, Hendrix MS, Hendrix MS, Wang LB, Carroll AR (1993) Collisional successor basins of western China: impact of tectonic inheritance on sand composition. Geol Soc Am Bull 105:323–344

Graham SA, Hendrix MS, Johnson CL, Badamgarav D, Badarch G, Amory J, Porter M, Barsbold R, Webb LE, Hacker B (2001) Sedimentary record and tectonic implications of Mesozoic rifting in southeast Mongolia. Geol Soc Am Bull 113:1560–1579

Gray DR, Foster DA, Bierlein FP (2002) Geodynamics and metallogeny of the Lachlan Orogen. Aust J Earth Sci 49:1041–1056

Gu L, Chu J, Guo J, Liao J, Yan Z, Yang H, Wang J (1994) The east Xinjiang-type mafic-ultramafic complexes in orogenic environments. Acta Petrol Sin 10:339–356

Guo FX (2000) Affinity between Paleozoic blocks of Xinjiang and their suturing ages. Acta Geol Sin 74:1–6

Gutscher MA, Kukowski N, Malavieille J, Lallemand S (1998) Episodic imbricate thrusting and underthrusting: analog experiments and mechanical analysis applied to the Alaskan accretionary wedge. J Geophys Res Solid Earth 103:10161–10176

Gutscher MA, Olivet JL, Aslanian D, Eissen JP, Maury R (1999) The "lost Inca Plateau": cause of flat subduction beneath Peru. Earth Planet Sci Lett 171:335–341

Gutscher M-A, Maury R, Eissen J-P, Bourdon E (2000a) Can slab melting be caused by flat subduction? Geology 28:535–538

Gutscher M-A, Spakman W, Bijwaard H, Engdahl ER (2000b) Geodynamics of flat subduction: seismicity and tomographic constraints from the Andean margin. Tectonics 19:814–833

Haeussler PJ, Bradley D, Goldfarb RJ, Snee LW, Taylor CD (1995) Link between ridge subduction and gold mineralization in southern Alaska. Geology 23:995–998

Hall R (2002) Cenozoic geological and plate tectonic evolution of SE Asia and the SW Pacific: computer-based reconstructions, model and animations. J Asian Earth Sci 20:353–431

Hall R (2008) The Eurasian SE Asian margin as a modern example of an accretionary orogen. In: Cawood P, Kröner A (eds) Accretionary Orogens in space and time. Geological Society of London, Special Publication

Han B, Wang S, Jahn B-M, Hong D, Kagami H, Sun Y (1997) Depleted mantle source for the Ulungur River A-type granites from North Xinjiang, China: geochemistry and Nd-Sr isotopic evidence, and implications for the Phanerozoic crustal growth. Chem Geol 138:135–159

Han CM, Xiao WJ, Zhao GC, Mao JW, Li SZ, Yan Z, Mao QG (2006a) Major types, characteristics and geodynamic mechanism of Late Paleozoic copper deposits in Northern Xinjiang, Northwestern China. Ore Geol Rev 28:308–328

Han CM, Xiao WJ, Zhao GC, Mao JW, Rui ZY, Yang JM, Wang ZL (2006b) Geological characteristics and genesis of the Tuwu porphyry copper deposit, Hami, Xinjiang, Central Asia. Ore Geol Rev 29:77–94

Han CM, Xiao WJ, Zhao GC, Qu WJ, Du AD (2007) Re–Os dating of the Kalatongke Cu–Ni deposit, Altay Shan, NW China, and resulting geodynamic implications. Ore Geol Rev 32:452–468. doi:10.1016/j.oregeorev.2006.11.004

Hansen VL, Dusel-Bacon C (1998) Structural and kinematic evolution of the Yukon-Tanana upland tectonites, east-central Alaska: a record of late Paleozoic to Mesozoic crustal assembly. Geol Soc Am Bull 110:211–230

He GQ, Li MS, Liu DQ, Zhou NH (eds) (1994) Palaeozoic crustal evolution and mineralization in Xinjiang of China. Xinjiang People's Publishing House, Urumqi, p 437

Heinhorst J, Lehmann B, Ermolov P, Serykh V, Zhurutin S (2000) Paleozoic crustal growth and metallogeny of Central Asia: evidence from magmatic-hydrothermal ore systems of Central Kazakhstan. Tectonophysics 328:69–87

Helo C, Hegner E, Kröner A, Badarch G, Tomurtogoo O, Windley BF, Dulski P (2006) Geochemical signature of Paleozoic accretionary complexes of the Central Asian Orogenic Belt in South Mongolia: constraints on arc environments and crustal growth. Chem Geol 227:236–257

Hendrix MS (2000) Evolution of Mesozic sandstone composition, southern Junggar, northern Tarim, and western Turpan basins, Northwest China: a detrital record of the ancestral Tian Shan. J Sediment Res 70:520–532

Hendrix MS, Graham SA, Carroll AR, Sobel ER, McKnight CL, Schukein BJ, Wang Z (1992) Sedimentary record and climatic implications of recurrent deformation in the Tian Shan: evidence from Mesozoic strata of the north Tarim, south Junggar, and Turpan basins, northwest China. Geol Soc Am Bull 104:53–79

Hendrix MS, Graham SA, Amory JY, Badarch G (1996) Noyon Uul Syncline, southern Mongolia; lower Mesozoic sedimentary record of the tectonic amalgamation of Central Asia. Geol Soc Am Bull 108:1256–1274

Heubeck C (2001) Assembly of central Asia during the middle and late Paleozoic. In: Hendrix MS, Davis GA (eds) Paleozoic and Mesozoic tectonic evolution of Central and Eastern Asia: from continental assembly to intracontinental deformation. Geological Society of American Memoir, vol 194, pp 1–22

Himmelberg GR, Loney RA (eds) (1995) Characteristics and petrogenesis of Alaskan-type ultramafic-mafic intrusions, southeastern Alaska. U.S. Geol Survey Prof Pap 1564:47

Hong D, Wang S, Xie X, Zhang J, Wang T (2003) Granitoids and related metallogeny of the Central Asian orogenic belt. In: Mao J, Goldfarb R, Seltmann R, Wang D, Xiao W, Hart C (eds) Tectonic Evolution and Metallogeny of the Chinese Altay and Tianshan. IAGOD Guidebook Ser. 10. CERCAMS/NHM, London, pp 75–106

Hong D, Zhang J, Wang T, Wang S, Xie X (2004) Continental crustal growth and the supercontinental cycle: evidence from the Central Asian Orogenic Belt. J Asian Earth Sci 23:799–813

Hsü KJ, Wang QC, Li JL, Hao J (1991) Geologic evolution of the Neimonides: a working hypothesis. Eclogae Geol Helv 84:1–35

Hu A, Jahn B-M, Zhang G, Chen Y, Zhang Q (2000) Crustal evolution and Phanerozoic crustal growth in northern Xinjiang: Nd isotopic evidence. Part I. Isotopic characterization of basement rocks. Tectonophysics 328:15–51

Hu A, Wei G, Deng W, Chen L (2006) SHRIMP zircon U–Pb dating and its significance for gneisses from the southeast area to Qinghe County in the Altai, China. Acta Petrol Sin 22:1–10

Huang BC, Piper JDA, Wang YC, He HY, Zhu RX (2005) Paleomagnetic and geochronological constraints on the post-collisional northward convergence of the southwest Tian Shan, NW China. Tectonophysics 409:107–124

Huang BC, Piper JDA, Zhang CX, Li ZY, Zhu RX (2007) Paleomagnetism of Cretaceous rocks in the Jiaodong Peninsula, eastern China: insight into block rotations and Neotectonic deformation in eastern Asia. J Geophys Res 112:B03106. doi: 03110.01029/02006JB004462

IMBGMR (1991) Regional Geology of Nei Mongol (Inner Mongolia) Autonomous Region, Bureau of Geology and Mineral Resources of Inner Mongolia. Geological Memoirs, Ser. 2, Geological Publishing House, Beijing, p 725 (in Chinese with English summary)

Ishiwatari A, Ichiyama Y (2004) Alaskan-type plutons and ultramafic lavas in Far East Russia, Northeast China, and Japan. Int Geol Rev 46:316–331

Isozaki Y (1996) Anatomy and genesis of a subduction-related orogen: a new view of geotectonic subdivision and evolution of the Japanese islands. Island Arc 5:289–320

Isozaki Y (1997a) Jurassic accretion tectonics of Japan. Island Arc 6:25–51

Isozaki Y (1997b) Contrasting two types of orogen in Permo-Triassic Japan: accretionary versus collisional. Island Arc 6:2–24

Jahn B-M (2004) The Central Asian Orogenic Belt and growth of the continental crust in the Phanerozoic. In: Malpas J, Fletcher CJN, Ali JR, Aitchison JC (eds) Aspects of the Tectonic evolution of China. Special Publications. Geological Society, London, vol 226, pp 73–100

Jahn B-M, Wu F-Y, Chen B (2000) Granitoids of the Central Asian Orogenic Belt and continental growth in the Phanerozoic. Trans R Soc Edinburgh Earth Sci 91:181–193

Jahn B-M, Windley B, Natal'in B, Dobretsov N (2004) Phanerozoic continental growth in Central Asia. J Asian Earth Sci 23:599–603

Jenkyns HC (1970) Growth and disintegration of a carbonate platform. Neues Jahrbuch Geol Paleontol Monatshefte 6:325–344

Jian P, Liu DY, Zhang Q, Shi YR, Zhang FQ (2005) SHRIMP dating of SSZ ophiolites from northern Xinjiang Province, China: implications for generation of oceanic crust in the Central Asian Orogenic Belt. In: Sklyarov EV (ed) Structural and tectonic correlation across the Central Asia orogenic collage: north-eastern segment. Guidebook and abstract volume of the Siberian Workshop IGCP-480. IEC SB RAS, Irkutsk, p 246

Jian P, Shi YR, Zhang FQ, Miao LC, Zhang LQ, Kröner A (2007) Geological excursion to Inner Mongolia, China, to study the accretionary evolution of the southern margin of the Central Asian Orogenic Belt. In: Liu DY, Natal'in B, Jian P, Kröner A, Wang T (eds) Abstract and excursion guidebook, Third International Workshop and Field Excursion for IGCP Project 480, pp 49–72

Jian P, Liu DY, Kröner A, Windley BF, Shi YR, Zhang FQ, Shi GH, Miao LC, Zhang W, Zhang Q, Zhang LQ, Ren JS (2008) Time scale of an early to mid-Paleozoic orogenic cycle of the long-lived Central Asian Orogenic Belt, Inner Mongolia of China: implications for continental growth. Lithos 101:233–259

Jiang CY, Mu YM, Zhao XN, Bai KY, Zhang HB (2001) Petrology and geochemistry of active continental-margin intrusive rock belt on the northern margin of the Tarim. Regional Geol China 20(2):158–163 (in Chinese with English abstract)

Johnson CL (2004) Polyphase evolution of the East Gobi basin: sedimentary and structural records of Mesozoic-Cenozoic intraplate deformation in Mongolia. Basin Res 16:79–99

Johnson CL, Graham SA (2004a) Cycles in perilacustrine facies of late Mesozoic rift basins, southeastern Mongolia. J Sediment Res 47:786–804

Johnson CL, Graham SA (2004b) Sedimentology and reservoir architecture of a synrift lacustrine delta, southeastern Mongolia. J Sediment Res 47:770–785

Johnson CL, Webb LE, Graham SA, Hendrix MA, Badarch G (2001) Sedimentary and structural records of late Mesozoic high-strain extension and strain partitioning, East Gobi basin, southern Mongolia. In: Hendrix MS, Davis GA (eds) Paleozoic and Mesozoic Tectonic Evolution of Central and Eastern Asia: from Continental Assembly to Intracontinental Deformation. Geological Society of America Memoir, vol 194, pp 413–434

Johnson CL, Greene TJ, Zinniker DA, Moldowan MJ, Hendrix MS, Carroll AR (2003) Geochemical characteristics and correlation of oil and nonmarine source rocks from Mongolia. Am Assoc Petrol Geol Bull 87:817–846

Johnson CL, Amory JA, Zinniker D, Lamb MA, Graham SA, Affolter M, Badarch G (2007) Sedimentary response to arc-continent collision, Permian, southern Mongolia. In: Draut A, Clift PD, Scholl DW (eds) Formation and applications of the sedimentary record in arc collision zones. The Geological Society of America Special Paper, vol 436, pp 363–390. doi: 10.1130/2007.2436(1116)

Jolivet L, Faccenna C, Goffe B, Burov E, Agard P (2003) Subduction tectonics and exhumation of high-pressure metamorphic rocks in the Mediterranean orogens. Am J Sci 303:353–409

Kay RW (1978) Aleutian magnesian andesites: melts from subducted Pacific oceanic crust. J Volcanol Geotherm Res 4:117–132

Kay SM, Maksaev V, Moscoso R, Mpodozis C, Nasi C, Gordillo CE (1988) Tertiary Andean magmatism in Chile and Argentina between 288° and 338°: correlation of magmatic chemistry with a changing Benioff zone. J Southeast Am Earth Sci 1:21–39

Kheraskova TN, Didenko AN, Bush VA, Volozh YA (2003) The Vendian-Early Paleozoic history of the continental margin of Eastern Paleogondwana, Paleoasian Ocean, and Central Asian Foldbelt. Russ J Earth Sci 5:165–184

Klemd R (2003) Ultrahigh-pressure metamorphism in eclogites from the western Tianshan high-pressure belt (Xinjiang, western China)-Comment. Am Mineral 88:1153–1156

Klemd R, Brocker M, Hacker BR, Gao J, Gans P, Wemmer K (2005) New age constraints on the metamorphic evolution of the high-pressure/low-temperature belt in the western Tianshan Mountains, NW China. J Geol 113:157–168

Konstantinovskaya EA, Malavieille J (2005) Accretionary orogens: erosion and exhumation. Geotectonics 39:69–86

Kovalenko VI, Yarmolyuk VV, Kovach VP, Kotov AB, Kozakov IK, Salnikova EB, Larin AM (2004) Isotopic provinces, mechanism of generation and sources of the continental curst in the Central Asian mobile belt: geological and isotopic evidence. J Asian Earth Sci 23:605–627

Kozakov IK, Kotov AB, Salikova EB, Kovach VP, Kirnozova TI, Berezhnava NG, Lykin DA (1999) Metamorphic age of crystalline complex of the Tuva-Mongolia massif: U-Pb geochronology of granitoids. Petrology 7:177–191

Kröner A, Windley BF, Badarch G, Tomurtogoo O, Hegner E, Jahn BM, Gruschka S, Khain EV, Demoux A, Wingate MTD (2007) Accretionary growth and crust-formation in the Central Asian Orogenic Belt and comparison with the Arabian-Nubian shield. In: Hatcher RD Jr, Carlson MP, McBride JH, Martínez Catalán JR (eds) 4-D Framework of Continental Crust. Geological Society of America Memoir, vol 200, pp 181–209. doi: 110.1130/2007.1200(1111)

Kravchinsky VA, Konstantinov KM, Courtillot V, Savrasov JI, Valet J-P, Cherniy SD, Mishenin SG, Parasotka BS (2002) Palaeomagnetism of East Siberian traps and kimberlites: two new poles and palaeogeographic reconstructions at about 360 and 250 Ma. Geophys J Int 148:1–33

Kusky TM, Bradley DC (1999) Kinematic analysis of melange fabrics: examples and applications from the McHugh Complex, Kenai Peninsula, Alaska. J Struct Geol 21:1773–1796

Kusky TM, Bradley DC, Haeussler PJ (1997) Progressive deformation of the Chugach accretionary complex, Alaska, during a Paleogene ridge-trench encounter. J Struct Geol 19:139–157

Kusky TM, Windley BF, Zhai MG (2007) Tectonic evolution of the North China Block: from orogen to craton to orogen. In: Zhai MG, Windley BF, Kusky TM, Meng QR (eds) Mesozoic subcontinental lithospheric thinning under Eastern Asia. Geol Soc, London, pp 1–34

Kwon ST, Tilton GR, Coleman RG, Feng Y (1989) Isotopic studies bearing on the tectonics of the west Junggar region, Xinjiang, China. Tectonics 8:719–727

Lamb MA, Badarch G (1997) Paleozoic sedimentary basins and volcanic-arc systems of Southern Mongolia: new stratigraphic and sedimentologic constraints. Int Geol Rev 39:542–576

Lamb MA, Badarch G (2000) Paleozoic sedimentary basins and volcanic-arc systems of southern Mongolia; new stratigraphic and sedimentologic constraints. In: Ernst WG, Coleman Robert G (eds) Tectonic studies of Asia and the Pacific Rim. Bellwether Publishing for the Geological Society of America, Columbia

Lamb MA, Badarch G (2001) Paleozoic sedimentary basins and volcanic arc systems of southern Mongolia: new geochronological and petrographic constraints. In: Hendrix MS, Davis GA (eds) Paleozoic and Mesozoic tectonic evolution of Central and Eastern Asia, pp 117–149

Lamb MA, Hanson AW, Graham SA, Badarch G, Webb LE (2001) Left lateral sense offset of Upper Proterozoic to Paleozoic features across the Gobi Onon, Tost, and Zuunbayan faults in southern Mongolia and implications for other central Asian faults. Earth Planet Sci Lett 173:183–194

Lamb MA, Badarch G, Navratil T, Poier R (2008) Structural and geochronologic data from the Shin Jinst area, eastern Gobi Altai, Mongolia: implications for Phanerozoic intracontinental deformation in Asia. Tectonophysics 451:312–330

Laurent-Charvet S, Charvet J, Shu L, Ma R, Lu HF (2002) Paleozoic late collisional strike-slip deformations in Tianshan and Altay, Eastern Xinjiang, NW China. Terra Nova 14:249–256

Laurent-Charvet S, Charvet J, Monie P, Shu L (2003) Late Paleozoic strike-slip shear zones in eastern central Asia (NW China): New structural and geochronological data. Tectonics 22:1009

Lawver LA, Dalziel IWD, Gahagan LM, Martin KM, Campbell DA (2003) The PLATES 2003 Atlas of Plate Reconstructions (750 Ma to Present Day). PLATES Progress Report No. 280–0703, UTIG Technical Report No. 190, p 97

Lee KY (1985) Geology of the Tarim basin with special emphasis on petroleum deposits, Xinjiang Uygur Zizhiqu, Northwest China. US Open File Report, OF85-0616, pp 1–55

Li YP (1990) An apparent polar wander path from the Tarim Block, China. Tectonophysics 181:31–41

Li JY (2006) Permian geodynamic setting of Northeast China and adjacent regions: closure of the Paleo-Asian Ocean and subduction of the Paleo-Pacific Plate. J Asian Earth Sci 26:207–224

Li Q, Zhang LF (2004) The P-T path and geological significance of the low-pressure granulite-facies metamorphism in Muzhaerte, Southwest Tian Shan. Acta Petrol Sin 20:583–594

Li YP, Sharps R, McWilliams M, Nur A, Li Y, Li Q, Zhang W (1989) Paleomagnetic results from Late Paleozoic dikes from the northwestern Junggar Block, northwestern China. Earth Planet Sci Lett 94:123

Li Y, Sharps R, McWilliams M, Li Y, Li Q, Zhang W (1991) Late Paleozoic paleomagnetic results from the Junggar block, Northwestern China. J Geophys Res 96B:16,047–16,060

Li HQ, Xie CF, Chang HL (1998) Study on metallogenetic chronology of nonferrous and precious metallic ore deposits in northern Xinjiang. China Geological Publishing House, Beijing, p 220

Li HQ, Chen FW, Cai H, Liu HQ (1999) Study on isotopic chronology of the Mazhuangshan gold mineralization, Eastern Xinjiang. Sci Geol Sin 34:251–256

Li JY, Xiao WJ, Wang KZ, Sun GH, Gao LM (2003) Neoproterozoic-Paleozoic tectonostratigraphic framework of Eastern Xinjiang, NW China. In: Mao JW, Goldfarb R, Seltmann R, Wang DH, Xiao WJ, Hart C (eds) Tectonic evolution and metallogeny of the Chinese Altay and Tianshan. International association on the genesis of ore deposits (IAGOD) Guidebook Ser. 10, IGCP 473 Workshop 2003. Urumqi. Natural History Museum, IAGDO/CERAMS, London, pp 31–74

Li YJ, Sun LD, Wu HR, Wang GL, Yang CS, Peng GX (2005) Permo-Carboniferous radiolaria from the Wupatarkan Group, west terminal of Chinese South Tianshan. Chin J Geol 40:220–226

Li JY, Gao LM, Sun GH, Li YP, Wang YB (2007) Shuangjingzi middle Triassic syn-collisional crust-derived granite in the east Inner Mongolia and its constraint on the timing of collision between Siberian and Sino-Korean paleo-plates. Acta Petrol Sin 23:565–582

Li ZL, Chen HL, Yang SF, Dong CW, Xiao WJ, Li JL, Ye Y, Wang J (2004) Discovery and genetic mechanism of basic granulite in the Altay orogenic belt, Xinjiang, NW China. Acta Geol Sin (Eng edn) 78:177–185

Liang R (1991) The characteristics of the ophiolite sequences and its rock associations in central and eastern Inner Mongolia. In: Ishii K, Liu XY, Ichikawa K, Huang B (eds) Pre-Jurassic geology of Inner Mongolia. China-Japan Cooperative Research Group, China, pp 65–84

Liao ZT, Wu GG (1998) Oil-bearing strata of the Santanghu Basin in Xinjiang, China. Publishing House of Southeast University (in Chinese with English abstract), Nanjing, p 138

Lin KX, Yan CD, Gong WP (1997) Geochemistry and tectonics setting analysis of the Early Permian volcanic rocks in the Santanghu Basin, Xinjiang. Bull Mineral Petrol Geochem 16:39–42

Lin W, Faure M, Enami M, Wang B, Shu L, Wang Q (2009) Paleozoic tectonics of Southwestern Chinese Tianshan: new insights from the HP massif of Zhaosu-Teks area. In press, International Journal of Earth Sciences

Liu HF, Yin FJ (2001) A discussion on the age of Kalagang formation of the Santanghu basin in Xinjang, China. J Northwest Univ (Natural Science edn) 31:496–499 (in Chinese with English abstract)

Liu Y (2001) Early Carboniferous radiolarian fauna from Heyingshan south of Tianshan Mountains of China and its geological significance. Acta Geol Sin 75:101–109

Liu Y (2007) Radiolarian fossils of ophiolites in the southern Tien Shan and their tectonic implications. PhD thesis, Peking University, p 168

Long XP, Sun M, Yuan C, Xiao WJ, Chen HL, Zhao YJ, Chai KD, Li JL (2006) Genesis of Carboniferous volcanic rocks in the Eastern Junggar: constraints on the closure of the Junggar Ocean. Acta Petrol Sin 22:31–40

Lu SN, Yu HF, Jin W, Li HQ, Zheng JK (2002) Microcontinents on the eastern margin of Tarim paleocontinent. Acta Petrol Mineral 21:317–326 (in Chinese with English abstract)

Lu ZX, Xia HK (1993) Geoscience transect from Dong Ujimqin of Inner Mongolia to Donggou of Liaoning, China. Acta Geophys Sin 36:765–772

Ma RS, Shu LS, Sun J (1997) Tectonic evolution and metalogeny of eastern Tianshan Mountains. Geological Publishing House, Beijing, p 202

Manankov IN, Shi GR, Shen SZ (2006) An overview of Permian marine stratigraphy and biostratigraphy of Mongolia. J Asian Earth Sci 26:294–303

Mao JW, Goldfarb RJ, Wang YT, Hart CJ, Wang ZL, Yang JM (2005) Late Paleozoic base and precious metal deposits, East Tianshan, Xinjiang, China: characteristics and geodynamic setting. Episodes 28:23–36

Mao QG, Xiao WJ, Han CM, Sun M, Yuan C, Yan Z, Li JL, Yong Y, Zhang JE (2006) Zircon U-Pb age and the geochemistry of the Baishiquan marie-ultramafic complex in the Eastern Tianshan, Xinjiang province: constraints on the closure of the Paleo-Asian Ocean. Acta Petrologica Sin 22:153–162

Matsumoto I, Tomurtogoo O (2003) Petrological charateristics of the Hantaishir ophiolite complex, Altai region, Mongolia: coexistence of podiform chromitite and boninite. Gondwana Res 6:161–169

Miao LC, Fan WM, Zhang FQ, Liu DY, Jian P, Tao H, Shi YR (2004) Zircon SHRIMP geochronology of the Xinkailing-Kele complex in the northwestern Lesser Xing'an Range, and its geological implications. Chin Sci Bull 49:201–209

Miao L, Zhang F, Fan W, Liu D (2007) Phanerozoic evolution of the Inner Mongolia-Daxinganling orogenic belt in North China: constraints from geochronology of ophiolites and associated formations. In: Zhai MG, Windley BF, Kusky TM, Meng QR (eds) Mesozoic sub-continental lithospheric thinning under Eastern Asia. Special Publications, vol 206, Geological Society, London, pp 223–237

Miao LC, Fan WM, Liu DY, Zhang FQ, Shi YR, Guo F (2008) Geochronology and geochemistry of the Hegenshan ophiolitic complex: Implications for late-stage tectonic evolution of the Inner Mongolia-Daxinganling Orogenic Belt, China. J Asian Earth Sci 32:348–370

Mossakovsky AA, Ruzhentsev SV, Samygin SG, Kheraskova TN (1993) The Central Asian fold belt: geodynamic evolution and formation history. Geotectonics 26:455–473

Nelson EP (1996) Suprasubduction mineralization: metallo-tectonic terranes of the southernmost Andes. Geophys Monogr 96:315–330

Nie S-Y (1991) Paleoclimatic and paleomagnetic constraints on the Paleozoic reconstructions of south China, north China and Tarim. Tectonophysics 196:279–308

Nie F, Bjørlykke A (1999) Nd and Sr isotope constraints on the age and origin of Proterozoic meta-mafic volcanic rocks in the Bainaimiao-Wenduermiao district, south-central Inner Mongolia, China. Continental Dyn 4:1–14

Nishidai T, Berry JL (1990) Structure and hydrocarbon potential of the Tarim basin (NW China) from satellite imagery. J Petrol Geol 13:35–58

Nokleberg WJ, Bundtzen TK, Eremin RA, Ratkin VV, Dawson KM, Shpikerman VI, Goryachev NA, Byalobzhesky SG, Frolov YF, Khanchuk AI, Koch RD, Monger JWH, Pozdeev AI, Rozenblum IS, Rodionov SM, Parfenov LM, Scotese CR, Scholl DW, Sidorov A (2005) Metallogenesis and tectonics of the Russian Far East, Alaska and the Canadian Cordillera. USGS Prof Pap 1697:397

Nozaka T, Liu Y (2002) Petrology of the Hegenshan ophiolite and its implications for the tectonic evolution of northern China. Earth Planet Sci Lett 202:89–104

Ogawa Y (2001) Duplex structures and their tectonic implication for the Southern Uplands accretionary complex. In: Clarkson Euan NK, Floyd James D, Stone P (eds) The Southern Uplands Terrane; tectonics and biostratigraphy within the Caledonian Orogen; proceedings. Royal Society of Edinburgh. Edinburgh

Ota T, Terabayashi M, Katayama I (2004) Thermobaric structure and metamorphic evolution of the Iratsu eclogite body in the Sanbagawa belt, central Shikoku, Japan. Lithos 73:95–126

Pankhurst RJ, Weaver SD, Herve F, Larrondo P (1999) Mesozoic-Cenozoic evolution of the North Patagonian Batholith in Aysen, southern Chile. J Geol Soc Lond 156:673–694

Pickering KT, Taira A (1994) Tectonosedimentation: with examples from the Tertiary-Recent of Southeast Japan. In: Hancock PL (ed) Continental deformation. Pergamon Press, Oxford, pp 320–354

Pirajno F, Mao JW, Zhang ZC, Zhang ZH, Chai FM (2008) The association of mafic-ultramafic intrusions and A-type magmatism in the Tian Shan and Altay orogens, NW China: implications for geodynamic evolution and potential for the discovery of new ore deposits. J Asian Earth Sci 32:165–183

Qin KZ (2000) Metallogeneses in relation to the Central Asian-style orogeny in northern Xinjiang. Postdoc Report, Institute of Geology and Geophysics, Chinese Academy of Sciences, Beijing, 194 pp

Rippington S, Cunningham D, England R (2008) Structure and petrology of the Altan Uul Ophiolite: new evidence for a Late Carboniferous suture in the Gobi Altai, southern Mongolia. J Geol Soc Lond 165:711–723

Robinson PT, Zhou MF, Hu XF, Reynolds P, Bai WJ, Yang J (1999) Geochemical constraints on the origin of the Hegenshan ophiolite, Inner Mongolia, China. J Asian Earth Sci 17:423–442

Rosenbaum G, Giles D, Saxon M, Betts PG, Weinberg RF, Duboz C (2005) Subduction of the Nazca Ridge and the Inca Plateau: insights into the formation of ore deposits in Peru. Earth Planet Sci Lett 239:18–32

Rui ZY, Goldfarb RJ, Qiu YM, Zhou TM, Chen RY, Pirajno F, Yun G (2002) Paleozoic-early Mesozoic gold deposits of the Xinjiang Autonomous Region, northwestern China. Mineral Deposit 37:393–418

Ruzhentsev SV, Burashnikov VV (1995) Tectonics of the Salairides in Western Mongolia. Geotectonics 29:25–40

Ruzhentsev SV, Pospelov II (1992) The southern Mongolian Variscan fold system. Geotectonics 26:383–395

Ruzhentsev SV, Badarch G, Veoznesenskaya TA (1985) Tectonics of the Trans-Altai zone of Mongolia (Gurvansaykhan and Dzolen ranges). Geotectonics 19:276–284

Ruzhentsev SV, Pospelov II, Badarch G (1989) Tectonics of the Mongolian Indosinides. Geotectonics 23:476–487

Sample JC, Fisher DM (1986) Duplex accretion and underplating in an ancient accretionary complex, Kodiak Islands, Alaska. Geology 14:160–163

Schelochkov GG, Zeigarnik VA, Molnar P (2008) Mountain building in Central Asia: international symposium geodynamics of intracontinental orogens and geoecological problems, Bishkek, Kyrgyzstan. Eos 89(41):393

Searle MP, Windley BF, Coward MP, Rex AJ, Rex D, Li TD, Xiao XC, Jan MQ, Thakur VC, Kumar S (1987) The closing of Tethys and the tectonics of the Himalaya. Geol Soc Am Bull 98:678–701

Seltmann R, Porter TM (2005) The porphyry Cu-Au/Mo deposits of Central Eurasia: 1. Tectonic, geologic and metallogenic setting and significant deposits. In: Porter TM (ed) Super porphyry copper and gold deposits: a global perspective. PGC Publishing, Adelaide, pp 467–512

Seltmann S, Shatov VV, Yakubchuk S (2003) Mineral deposit map of Central Asia. (Scale: 1:1,500,000) Natural History Museum, London

Şengör AMC, Natal'in B (1996a) Paleotectonics of Asia: fragments of a synthesis. In: Yin A, Harrison M (eds) The tectonic evolution of Asia. Cambridge University Press, Cambridge, pp 486–640

Şengör AMC, Natal'in B (1996b) Turkic-type orogeny and its role in the making of the continental crust. Annu Rev Earth Planet Sci 24:263–337

Şengör AMC, Okurogullari AH (1991) The role of accretionary wedges in the growth of continents: Asiatic examples from Argand to Plate Tectonics. Eclogae Geol Helv 84:535–597

Şengör AMC, Natal'in BA, Burtman US (1993) Evolution of the Altaid tectonic collage and Paleozoic crustal growth in Eurasia. Nature 364:209–304

Shang Q (2004) Occurrences of Permian radiolarians in central and eastern Nei Mongol (inner Mongolia) and their geological significance to the Northern China Orogen. Chin Sci Bull 49:2613–2619

Shao J (1989) Continental crust accretion and tectono-magmatic activity at the northern margin of the Sino-Korean plate. J SE Asian Earth Sci 3:57–62

Shen SZ, Zhang H, Shang QH, Li WZ (2006) Permian stratigraphy and correlation of Northeast China: a review. J Asian Earth Sci 26:304–326

Shi GR (2006) The marine Permian of East and Northeast Asia: an overview of biostratigraphy, palaeobiography and palaeogeographical implications. J Asian Earth Sci 26:175–206

Shi GH, Liu DY, Zhang FQ, Jian P, Miao LC, Shi YR, Tao H (2003) SHRIMP U-Pb zircon geochronology and its implications on the Xilin Gol Complex, Inner Mongolia, China. Chin Sci Bull 48:2742–2748

Shu LS, Wang YJ (2003) Late Devonian-Early Carboniferous radiolarian fossils from siliceous rocks of the Kelameili ophiolite, Xinjiang. Geol Rev 49:408–413

Shu LS, Charvet J, Guo LZ (1999) A large-scale dextral ductile strike-slip zone: the Aqqikkudug-Weiya zone along the northern margin of the Central Tianshan belt, Xinjiang, NW China. Acta Geol Sin 73:43–81

Shu LS, Charvet J, Lu HF, Laurent SC (2002) Paleozoic accretion-collision events and kinematics of ductile deformation in the eastern part of the southern-central Tianshan belt, Xinjiang, China. Acta Geol Sin 76:308–323

Smethurst MA, Khramov AN, Torsvik TH (1998) The Neoproterozoic and Paleozoic palaeomagnetic data for the Siberian platform: from Rodinia to Pangea. Earth Sci Rev 43:1–24

Solomovich LI, Trifonov BA (2002) Post-collisional granites in the South Tien Shan Variscan collisional belt, Kyrgyzstan. J Asian Earth Sci 21:7–21

Sun M, Yuan C, Xiao WJ, Long XP, Xia XP, Zhao GC, Lin SF, Wu FY, Kröner A (2007) Zircon U–Pb and Hf isotopic study of gneissic rocks from the Chinese Altai: progressive accretionary history in the early to middle Paleozoic. Chem Geol 247:352–383

Sun S, Li JL, Lin JL, Wang QC, Chen HH (1991) Indosinides in China and the consumption of Eastern Paleotethys. In: Muller DW, McKenzie JA, Weissert H (eds) Controversies in modern geology. Academic Press, London, pp 363–384

Tang K (1990) Tectonic development of Paleozoic fold belts at the north margin of the Sino-Korean craton. Tectonics 9:249–260

Tang HS, Liu YX (1995) Marginal metallogeny of Cu-Ni sulfide deposits. Miner Resour Geol 9:240–242 (in Chinese with English abstract)

Tang K, Yan Z (1993) Regional metamorphism and tectonic evolution of the Inner Mongolian suture zone. J Metamor Geol 11:511–522

Taylor HP (1967) The zoned ultramafic complexes of southeastern Alaska. In: Wyllie PJ (ed) Ultramafic and related rocks. Wiley, New York, pp 97–121

Thomas JC, Lanza R, Kazansky A, Zykin V, Semakov N, Mitrokhin D, Delcaux D (2002) Paleomagnetic study of Cenozoic sediments from the Zaisan basin (SE Kazakhstan) and the Chuya depression (Siberian Altay): tectonic implications for central Asia. Tectonophysics 351:119–137

Tistl M, Burgath KP, Höhndorf A (1994) Origin and emplacement of tertiary ultramafic complexes in Northwest Colombia: evidence from geochemistry and K–Ar, Sm–Nd, and Rb-Sr isotopes. Earth Planet Sci Lett 126:41–59

Tomurtogoo O, Windley BF, Kroner A, Badarch G, Liu DY (2005) Zircon age and occurrence of the Adaatsag ophiolite and Muron shear zone, central Mongolia: constraints on the evolution of the Mongol–Okhotsk ocean, suture and orogen. J Geol Soc Lond 162:125–134

Torsvik TH, Cocks RM (2004) Earth geography from 400 to 250Ma: a paleomagnetic, faunal and facies review. Journal of Geological Society, London 161:555–572

Van der Voo R (ed) (1993) Paleomagnetism of the Atlantic, Tethys and Iapetus Oceans. Cambridge University Press, Cambridge, p 411

Van der Voo R, Levashova NM, Skrinnik LI, Kara TV, Bazhenov ML (2006) Late orogenic, large-scale rotations in the Tien Shan and adjacent mobile belts in Kyrgyzstan and Kazakhstan. Tectonophysics 426:335–360

Vincent SJ, Allen MB (2001) Sedimentary record of Mesozoic intracontinental deformation in the eastern Junggar basin, northwestern China: response to orogeny at the Asian margin. In: Hendrix MS, Davis GA (eds) Paleozoic and Mesozoic tectonic evolution of Central and Eastern Asia—from continental assembly to intracontinental deformation. Geological Society of America Memoir, vol 194, pp 341–360

Wakita K, Metcalfe I (2005) Ocean plate stratigraphy in East and Southeast Asia. J Asian Earth Sci 24:679–702

Wang Y (1996) Tectonic evolutional processes of Inner Mongolia-Yanshan orogenic belt in Eastern China during the Late Paleozoic-Mesozoic. Geological Publishing House, Beijing, p 143 (in Chinese with English abstract)

Wang YJ, Fan ZY (1997) Discovery of the Permian radiolarian fossils in the ophiolites north of the Xar Moron River, Inner Mongolia, and its geological implications. Acta Palaeonol Sin 36:58–69

Wang Q, Liu XY (1986) Paleoplate tectonics between Cathaysia and Angaraland in Inner Mongolia of China. Tectonics 5:1073–1088

Wang YJ, Shu LS (2001) Two mistakes in the study of the formation age of the ophiolite belts, china. Acta Palaeontol Sin 40:529–532

Wang Q, Nishidai T, Coward MP (1992) The Tarim basin, NW China: formation and aspects of petroleum geology. J Petrol Geol 15:5–34

Wang B, Lang Z, Li X, Qu X, Li T, Huang C, Cui X (1994) Comprehensive survey of geological sections in the west Tianshan of Xinjiang, China. Science in China Press, Beijing, p 202 (in Chinese with long English abstract)

Wang GR, Cheng SD, Yang SD, Zhang ZM, Ouyang S (1995) Map of Tectonism-formation in the North Xinjiang, China and its neighboring area. China University of Geosciences Press, Wuhan

Wang Y, Mooney W, Yuan X, Coleman RG (2003a) The crustal structure from the Altai Mountains to the Altyn Tagh fault, northwest China. J Geophys Res 108(6):2322. doi:2310.1029/2001JB000552

Wang ZH, Sun S, Li JL, Hou QL, Qin KZ, Xiao WJ, Hao J (2003b) Paleozoic tectonic evolution of the northern Xinjiang, China: geochemical and geochronological constrains from the ophiolites. Tectonics 22:1014. doi:1010.1029/2002TC001396

Wang T, Hong D-W, Jahn B-M, Tong Y, Wang Y-B, Han B-F, Wang X-X (2006) Timing, petrogenesis, and setting of Paleozoic synorogenic intrusions from the Altai Mountains, Northwest China: implications for the tectonic evolution of an accretionary orogen. J Geol 114:735–751

Wang B, Chen Y, Zhan S, Shu LS, Faure M, Cluzel D, Charvet J, Laurent-Charvet S (2007a) Primary Carboniferous and Permian paleomagnetic results from Yili Block and their geodynamic implications on evolution of Chinese Tianshan Belt. Earth Planet Sci Lett 263:288–308

Wang B, Shu LS, Cluzel D, Faure M, Charvet J (2007b) Geochemical constraints on Carboniferous volcanic rocks of the Yili Block (Xinjiang, NW China): implication for the tectonic evolution of Western Tianshan. J Asian Earth Sci 29:148–159

Wang Q, Wyman DA, Zhao Z-H, Xu J-F, Bai Z-H, Xiong X-L, Dai T-M, Li C-F, Chu Z-Y (2007c) Petrogenesis of Carboniferous adakites and Nb-enriched arc basalts in the Alataw area, northern Tianshan Range (western China): implications for Phanerozoic crustal growth in the Central Asia orogenic belt. Chem Geol 236:42–64

Wartes MA, Carroll AR, Greene TI (2002) Permian sedimentary record of the Turpan-Hami basin and adjacent regions, northwest China: constraints on post-amalgamation tectonic evolution. Geol Soc Am Bull 114:131–152

Watson MP, Hayward AB, Parkinson DN, ZhM Zhang (1987) Plate tectonic history, basin development and petroleum source rock deposition onshore China. Mar Petrol Geol 4:205–225

Webb LE, Johnson CL (2006) Tertiary strike-slip faulting in southeastern Mongolia and implications for Asian tectonics. Earth Planet Sci Lett 241:323–335

Wiedicke M, Neben S, Spiess V (2001) Mud volcanoes at the front of the Makran accretionary complex, Pakistan. Mar Geol 172:57–73

Windley BF, Allen MB, Zhang C, Zhao ZY, Wang GR (1990) Paleozoic accretion and Cenozoic redeformation of the Chinese Tien Shan Range, Central Asia. Geology 18:128–131

Windley BF, Alexeiev D, Xiao W, Kröner A, Badarch G (2007) Tectonic models for accretion of the Central Asian Orogenic Belt. J Geol Soc Lond 164:31–47

Wu F-Y, Sun D-Y, Li H, Jahn B-M, Wilde S (2002) A-type granites in northeastern China: age and geochemical constraints on their petrogenesis. Chem Geol 187:143–173

Wu H, Li HQ, Mo XH, Chen FW, Lu YF, Mei YP, Deng G (2005) Age of the Baishiqun mafic—ultramafic complex, Hami, Xinjiang and its geological significance. Acta Geol Sin 79:498–502

Wu B, He GQ, Wu TR, Li HJ, Luo HL (2006) Discovery of the Buergen ophiolitic mélange belt in Xinjiang and its tectonic significance. Geol China 33:476–486 (in Chinese with English abstract)

Wu FY, Yang JH, Lo CH, Wilde SA, Sun DY, Jahn BM (2007) The Heilongjiang Group: a Jurassic accretionary complex in the Jiamusi Massif at the western Pacific margin of northeastern China. Island Arc 16:156–172

XBGMR (1993) Regional geology of Xinjiang autonomous region, geological memoirs, Ser. 1, no. 32, map scale 1: 1,500,000. Geological Publishing House, Beijing, p 841

Xia LQ, Xu XY, Xia ZC, Li XM, Ma ZP, Wang LS (2004) Petrogenesis of Carboniferous rift-related volcanic rocks in the Tianshan, northwestern China. Geol Soc Am Bull 116:419–433

Xia LQ, Xia ZC, Xu XY, Li XM, Ma ZP (2008) Relative contributions of crust and mantle to the generation of the Tianshan Carboniferous rift-related basic lavas, northwestern China. J Asian Earth Sci 31:357–378

Xiao XC, Tang YQ, Zhao M, Wang J (1994) Tectonic evolution of the Northern Xinjiang, NW. China: an introduction to the tectonics of the southern part of the Paleo-Asian Ocean. In: Coleman RG (ed) Reconstruction of the Paleo-Asian Ocean. Proceeding of the 29th international geological congress. Part B. VSP, Utrecht, pp 25–37

Xiao WJ, Han FL, Windley BF, Yuan C, Zhou H, Li JL (2003a) Multiple accretionary orogenesis and episodic growth of continents: Insights from the Western Kunlun Range, central Asia. Int Geol Rev 45:303–328

Xiao WJ, Windley BF, Hao J, Zhai MG (2003b) Accretion leading to collision and the Permian Solonker suture, inner Mongolia, China: termination of the Central Asian orogenic belt. Tectonics 22:1069. doi:1010.1029/2002TC1484

Xiao WJ, Windley BF, Badarch G, Sun S, Li JL, Qin KZ, Wang ZH (2004a) Palaeozoic accretionary and convergent tectonics of the southern Altaids: implications for the lateral growth of Central Asia. J Geol Soc Lond 161:339–342

Xiao WJ, Zhang LC, Qin KZ, Sun S, Li JL (2004b) Paleozoic accretionary and collisional tectonics of the Eastern Tianshan (China): implications for the continental growth of central Asia. Am J Sci 304:370–395

Xiao WJ, Han CM, Yuan C, Chen HL, Sun M, Lin SF, Li ZL, Mao QG, Zhang JE, Sun S, Li JL (2006a) The unique Carboniferous-Permian tectonic-metallogenic framework of Northern Xinjiang (NW China): Constraints for the tectonics of the southern Paleoasian Domain. Acta Petrol Sin 22:1362–1376

Xiao WJ, Windley BF, Yan QR, Qin KZ, Chen HL, Yuan C, Sun M, Li JL, Sun S (2006b) SHRIMP zircon age of the Aermantai ophiolite in the North Xinjiang, China and its tectonic implications. Acta Geol Sin 80:32–36

Xiao WJ, Han CM, Yuan C, Sun M, Lin SF, Chen HL, Li ZL, Li JL, Sun S (2008a) Middle Cambrian to Permian subduction-related accretionary orogenesis of North Xinjiang, NW China: implications for the tectonic evolution of Central Asia. J Asian Earth Sci 32:102–117. doi:110.1016/j.jseas.2007.1010.1008

Xiao WJ, Pirajno F, Seltmann R (2008b) Geodynamics and metallogeny of the Altaid orogen. J Asian Earth Sci 32:77–81

Xiao WJ, Windley BF, Yuan C, Sun M, Han CM, Lin SF, Chen HL, Yan QR, Liu DY, Qin KZ, Li JL, Sun S (2008c) Paleozoic multiple subduction-accretion processes of the southern Altaids. Am J Sci (accepted)

Xu B, Charvet J, Zhang F (2001) Primary study on petrology and geochronology of blueschists in Sunitezuoqi, northern Inner Mongolia. Chin J Geol 36:424–434

Xu X, He GQ, Li HQ, Ding TF, Liu XY, Mei SW (2006a) Basic characteristics of the Karamay ophiolitic mélange, Xinjiang and its zircon SHRIMP dating. Geol China 33:470–475

Xu XY, Xia LQ, Ma ZP, Xia ZC, Li XM, Wang LS (2006b) SHRIMP zircon U–Pb geochronology of the plagiogranites from Bayingou ophiolite in North Tianshan Mountains and the petrogenesis of the ophiolite. Acta Petrol Sin 22:83–94 (in Chinese with English abstract)

Yakubchuk A (2004) Architecture and mineral deposit settings of the Altaid orogenic collage: a revised model. J Asian Earth Sci 23:761–779

Yakubchuk AS, Seltmann R, Shatov V, Cole A (2001) The Altaids: Tectonic evolution and metallogeny. Soc Econ Geol Newslett 46:7–14

Yin A, Nie S (1996) A Phanerozoic palinspastic reconstruction of China and its neighboring regions. In: Yin A, Harrison TM (eds) The tectonic evolution of Asia. Cambridge University Press, Cambridge, pp 442–485

Yin A, Harrison TM (2000) Geological evolution of the Himalayan-Tibetan Orogen. Annu Rev Earth Planet Sci 28:211–280

Yuan C, Sun M, Xiao WJ, Li XH, Chen HL, Lin SF, Xia XP, Long XP (2007) Accretionary orogenesis of the Chinese Altai: insights from Paleozoic granitoids. Chem Geol 242:22–39

Yue Y, Liou JG, Graham SA (2001) Tectonic correlation of Beishan and Inner Mongolia orogens and its implications for the palinspastic reconstruction of north China. In: Hendrix MS, Davis GA (eds) Paleozoic and Mesozoic tectonic evolution of Central and Eastern Asia: from continental assembly to intracontinental deformation. Geological Society of America Memoir, vol 194, pp 101–116

Zhang CW (1994) Plate tectonics and its evolution of Eastern Xinjiang and adjacent areas. J Chengdu Inst Technol 2:1–10

Zhang HX, Niu HC, Terada K, Yu XY, Sato H, Ito J (2003) Zircon SHRIMP U-Pb dating on plagiogranite from the Kuerti ophiolite in Altay, North Xinjiang. Chin Sci Bull 48:2,231–232,235

Zhang LF, Song SG, Liou JG, Ai YL, Li X (2005) Relict coesite exsolution in omphacite from Western Tianshan eclogites, China. Am Mineral 90:181–186

Zhang LF, Ai YL, Li XP, Rubatto D, Song B, Williams S, Song SG DE, Liou JG (2007a) Triassic collision of western Tianshan orogenic belt, China: evidence from SHRIMP U–Pb dating of zircon from HP/UHP eclogitic rocks. Lithos 96:266–280

Zhang S-H, Zhao Y, Song B, Yang Y-H (2007b) Zircon SHRIMP U-Pb and in-situ Lu–Hf isotope analyses of a tuff from Western Beijing: evidence for missing Late Paleozoic arc volcano eruptions at the northern margin of the North China block. Gondwana Res 12:157–165

Zhang S-H, Zhao Y, Song B, Yang Z-Y, Hu J-M, Wu H (2007c) Carboniferous granitic plutons from the northern margin of the North China block: implications for a late Paleozoic active continental margin. J Geol Soc Lond 164:451–463

Zhang ZH, Mao JW, Du AD, Pirajno F, Wang ZL, Chai FM, Zhang ZC, Yang JM (2008a) Re–Os dating of two Cu-Ni sulfide deposits in northern Xinjiang, NW China and its geological significance. J Asian Earth Sci 32:204–217

Zhang S-H, Zhao Y, Kröner A, Liu XM, Xie LW, Chen FK (2008b) Early Permian plutons from the northern Northern China block: constraints on continental arc evolution and convergent margin magmatism related to the Central Asian Orogenic Belt. Int J Earth Sci. doi:10.1007/s00531-008-0368-2

Zhang LC, Qin KZ, Xiao WJ (2008c) Multiple mineralization events in the eastern Tianshan district, NW China: isotopic geochronology and geological significance. J Asian Earth Sci 32:236–246

Zhao G, Cawood PA, Wilde SA, Sun M (2002) Review of global 2.1–1.8 Ga orogens: implications for a pre-Rodinia supercontinent. Earth Sci Rev 59:125–162

Zhao J, Liu G, Lu Z, Zhang X, Zhao G (2003) Lithospheric structure and dynamic processes of the Tianshan orogenic belt and the Junggar basin. Tectonophysics 376:199–239

Zhao G, Sun M, Wilde SA, Li S (2004) A Paleo-Mesoproterozoic supercontinent: assembly, growth and breakup. Earth Sci Rev 67:91–123

Zhao GC, Kröner A, Wilde SA, Sun M, Li SZ, Li XP, Zhang J, Xia XP, He YH (2007) Lithotectonic elements and geological events in the Hengshan-Wutai-Fuping belt: a synthesis and implications for the evolution of the Trans-North China Orogen. Geol Mag 144:753–775

Zhao XX (1990) New paleomagnetic results from northern China: collision and suturing with Siberia and Kazakhstan. Tectonophysics 181:43–81

Zhao ZH, Guo ZJ, Han BF, Wang Y (2006a) The geochemical characteristics and tectonic-magmatic implications of the latest-Paleozoic volcanic rocks from Santanghu basin, eastern Xinjiang, northwest China. Acta Petrol Sin 22:199–214 (in Chinese with English abstract)

Zhao ZH, Wang Q, Xiong XL, Zhang HX, Niu HC, Xu JF, Bai ZH, Qiao YL (2006b) Two types of adakitic rocks in North Xinjinag. Acta Petrol Sin 22:1249–1265

Zhao ZH, Xiong XL, Wang Q, Wyman DA, Bao ZW, Bai ZH, Qiao YL (2008) Underplating-related adakites in Xinjiang Tianshan, China. Lithos 102:374–391

Zheng Y, Zhang Q, Wang Y, Liu R, Wang SG, Zuo G, Wang SZ, Lkaasuren B, Badarch G, Badamgarav Z (1996) Great Jurassic thrust sheets in Beishan (North Mountains): Gobi areas of China and southern Mongolia. J Struct Geol 18:111–1126

Zheng CQ, Kato T, Enami M, Xu XC (2007a) CHIME monazite ages of metasediments from Altai orogen in northwestern China: Devonian and Permian ages of metamorphism and their significance. Island Arc 16:598–604

Zheng JP, Sun M, Zhao GC, Robinson PT, Wang FZ (2007b) Elemental and Sr-Nd–Pb isotopic geochemistry of Late Paleozoic volcanic rocks beneath the Junggar basin, NW China: implications for the formation and evolution of the basin basement. J Asian Earth Sci 29:778–794

Zhou DW, Su L, Jian P, Wang RS, Liu XM, Lu GX, Wang JL (2004a) Zircon U–Pb SHRIMP ages of high-pressure granulite in Yushugou ophiolitic terrane in southern Tianshan and their tectonic implications. Chin Sci Bull 49:1415–1419

Zhou M-F, Lesher CM, Yang ZX, Li JW, Sun M (2004b) Geochemistry and petrogenesis of 270 Ma Ni-Cu-(PGE) sulfide-bearing mafic intrusions in the Huangshan district, Eastern Xinjiang, Northwest China: implications for the tectonic evolution of the Central Asian orogenic belt. Chem Geol 209:233–257

Zonenshain LP, Kuzmin MI, Natapov LM (1990) Geology of the USSR: a plate tectonic synthesis. Geodynamic series, vol 21. American Geophysical Union, Washington, DC, p 242