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PALEOZOIC MULTIPLE ACCRETIONARY AND COLLISIONAL PROCESSES OF THE BEISHAN OROGENIC COLLAGE

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ABSTRACT. The Beishan orogenic collage is located in the southernmost part of the Altaids, and connects the Southern Tien Shan suture to the west with the Solonker suture to the east. The orogen was previously regarded as early Paleozoic in age in contrast to the surrounding southern Altaid collages, which are Late Paleozoic or even Early Mesozoic. This paper reviews the tectonic units of the Beishan orogen, which along a north-south traverse consists of several arcs and ophiolitic mélanges. These tectonic units were thrust imbricated and overprinted by strike-slip faulting during Permian-Triassic times, and the youngest strata involved in the deformation are Permian. Stitching plutons are Late Permian in age. Peaks of magmatic-metamorphic-tectonic activity, and paleomagnetic and paleogeographic data indicate that the Beishan orogenic collage evolved by development of several, Early to Mid-Paleozoic arcs in different parts of the Paleoasian Ocean. The Late Paleozoic collage is characterized by three active continental margins or island arcs that are separated by two ophiolitic mélanges. The northernmost active margin is represented by the Queershan arc, which may have lasted until the Permian. The Shibanshan unit is the southernmost, subduction-related continental arc along the northern margin of the Dunhuang block. In the Late Carboniferous to Permian the eastern end (promontory) of the Tarim Craton probably collided with the Chinese eastern Tien Shan arc, forming a new active continental margin, which interacted with the Beishan Late Paleozoic archipelago, generating a complicated subduction-accretionary orogen; this is suggested to be one of the last phases in the development of the long-lived Altaid accretionary orogenesis. The new model for this orogen bridges the gap between the western and eastern ends of the southern Altaids. The modern Timor-Australia collision zone with its many surrounding arcs is an appropriate analog for the Altaids in the Late Paleozoic.

Key words: Beishan, Permian, accretion, Altaids

INTRODUCTION

The Altaids in Central Asia are composed of Neoproterozoic-Phanerozoic accretionary orogenic collages that extend from the southern margins of the Siberian and East European Cratons to the northern margins of the Tarim and North China Cratons (fig. 1) (Şengör and others, 1993; Mossakovsky and others, 1993; Windley and others, 2007). They have alternatively been termed the "Central Asian Fold Belt" or "Central Asian Orogenic Belt" (Mossakovsky and others, 1993; Zorin and others, 1993; Jahn, 2001; Jahn and others, 2000, 2004; Buslov and others, 2001; Dobretsov and Buslov, 2004; Filippova and others, 2001; Bykadorov and others, 2003; Yakubchuk, 2008).

Compared with the linear, narrow Circum-Pacific and Tethyan orogens (fig. 1), the Altaids have a very high width-length aspect ratio (Jahn, 2001; Kröner and others, 2007; Wu and others, 2007). The Altaids developed by multiple accretionary and

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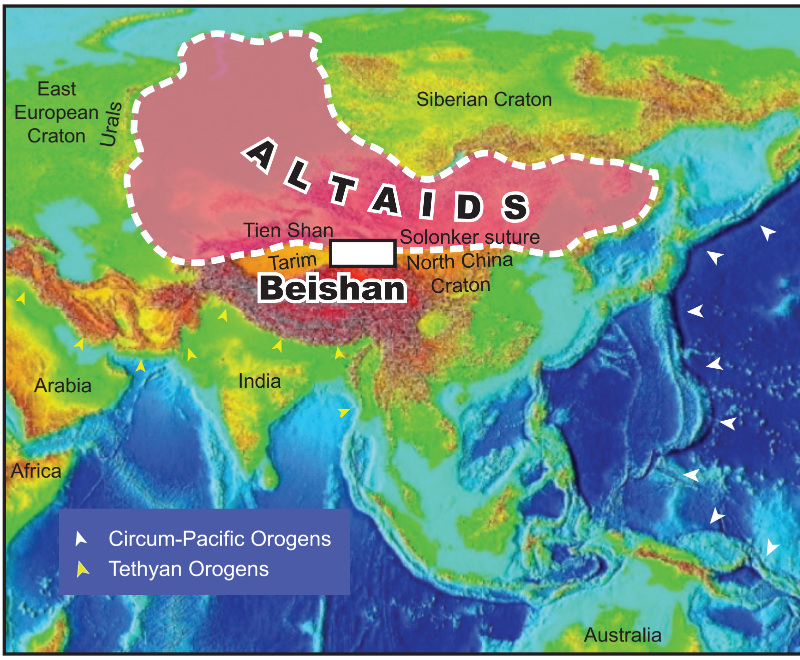

Fig. 1. Topographic map showing the three major types of orogens. The Altaids or Central Asian Orogenic Belt, composed of complicated orogenic collages between the Siberian, East European, Tarim and North China Cratons, as shown by a transparent reddish color with the Beishan orogenic collage marked by a rectangle. The Tethyan and Circum-Pacific orogens are marked by yellow and white arrows, respectively.

collisional events into an archipelago (Sun and others, 1991; Jahn, 2001; Kröner and others, 2007; Litvinovsky and others, 2002; Wu and others, 2007). These events gave rise to one of the world's largest orogens with many world-class mineral deposits (Şengör and Okurogullari, 1991; Şengör and others, 1993; Kerrich and others, 2000; Seltmann and others, 2001; Yakubchuk and others, 2001; Rui and others, 2002; Goldfarb and others, 2003; Seltmann and others, 2003; Xiao and others, 2004a; Yakubchuk, 2008). Accordingly, the Altaids provide important constraints on the processes of accretionary orogenesis, continental growth and metallogeny.

It is widely accepted that the Altaids formed by many stages of accretion that started at ~1.0 Ga (Khain and others, 2002). However, some fundamental questions are still controversial, such as: was the development of the Altaids completed in the Carboniferous (Şengör and others, 1993; Mossakovsky and others, 1993) or end-Permian to early Mesozoic (Ruzhentsev and others, 1989; Xiao and others, 2009a, 2009b), and to what extent did geodynamic processes contribute to the metallogeny?

The development of the Beishan orogenic collage encompasses the final attachment of the Tarim and North China Cratons to the southern accretionary orogenic collages of the southern Altaids (including southern Mongolia and China) as far as the Siberian Craton (Hendrix and others, 1996; Badarch and others, 2002; Helo and others, 2006; Johnson and others, 2007; Kröner and others, 2007; Lamb and others, 2008; Xiao and others, 2009b). This paper, based on our own work and a synthesis of published data, describes fundamental tectonic units and their mutual relationships, and uses them to discuss the Paleozoic accretionary tectonic history and its significance for the continental growth of Central Asia.

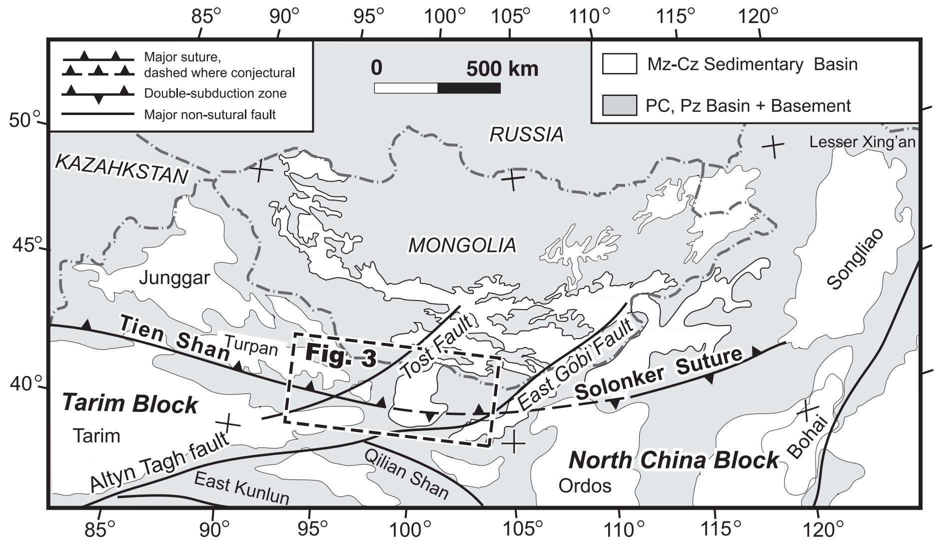

Fig. 2. Simplified tectonic map of the southern and eastern Altaids showing the tectonic position of the Beishan orogenic collage (modified after Hendrix and others, 1996; Ren, 1999; Lamb and Badarch, 2001; Ren and Xiao, 2002). PC, Pz, Mz, and Cz means Precambrian, Paleozoic, Mesozoic and Cenozoic, respectively. The position of figure 3 is marked.

REGIONAL GEOLOGY AND PREVIOUS MODELS

The accretion of the southern Altaids in the Paleozoic to early Mesozoic gave rise to the vast orogenic collages in Central Asia (Şengör, 1985; Mossakovsky and others, 1993; Şengör and others, 1993; Xiao and others, 2009a) that terminated diachronously along its final suture zone. In the west, the Southern Tien Shan suture (fig. 2) formed by closure of the southernmost Paleoasian Ocean between the Tarim Craton and the southern margin of the Altaids (Burtman, 1975; Windley and others, 1990; Allen and others, 1993; Che and others, 1994; Wang and others, 1994; Brookfield, 2000; Zhou and others, 2004a; Buslov and others, 2007), whereas in the east, the Solonker suture (fig. 2) formed by closure of another part of the southernmost Paleoasian Ocean between the North China Craton and the southern accretionary margin of the Altaids (Wang and Liu, 1986; Tang and Yan, 1993; Wang, 1996; Robinson and others, 1999; Xiao and others, 2003; Chen and others, 2008).

The Beishan orogenic collage, which is located between the Southern Tien Shan suture to the west and the Solonker suture to the east, forms a key area of the southern Altaids (fig. 2). Constituent rocks mainly range in age from late Precambrian to Mesozoic. The E-W-trending tectonic units are separated by E-W strike-slip faults, and are cut by later NE-trending strike-slip faults with complicated shear senses (figs. 3 and 4). Tectonically the Beishan orogenic collage is regarded as the eastern extension of the Chinese Tien Shan (Li, 1980; Liu and Wang, 1995). The easterly extension of the Beishan orogenic collage is not well defined, however, there are some ophiolites on a suture farther east, and it is generally agreed that this connects with the Solonker suture.

Previously, the Beishan orogenic collage was regarded as an Early Paleozoic orogen that terminated prior to the Silurian-Devonian because of the presence of Ordovician-Silurian arcs and ophiolites (Zuo and others, 1990a, 1990b, 2003). Even though some Late Paleozoic ophiolites and arcs were discovered (Gong, 1997), the Beishan collage was still largely thought of as an Early Paleozoic orogen, which evolved

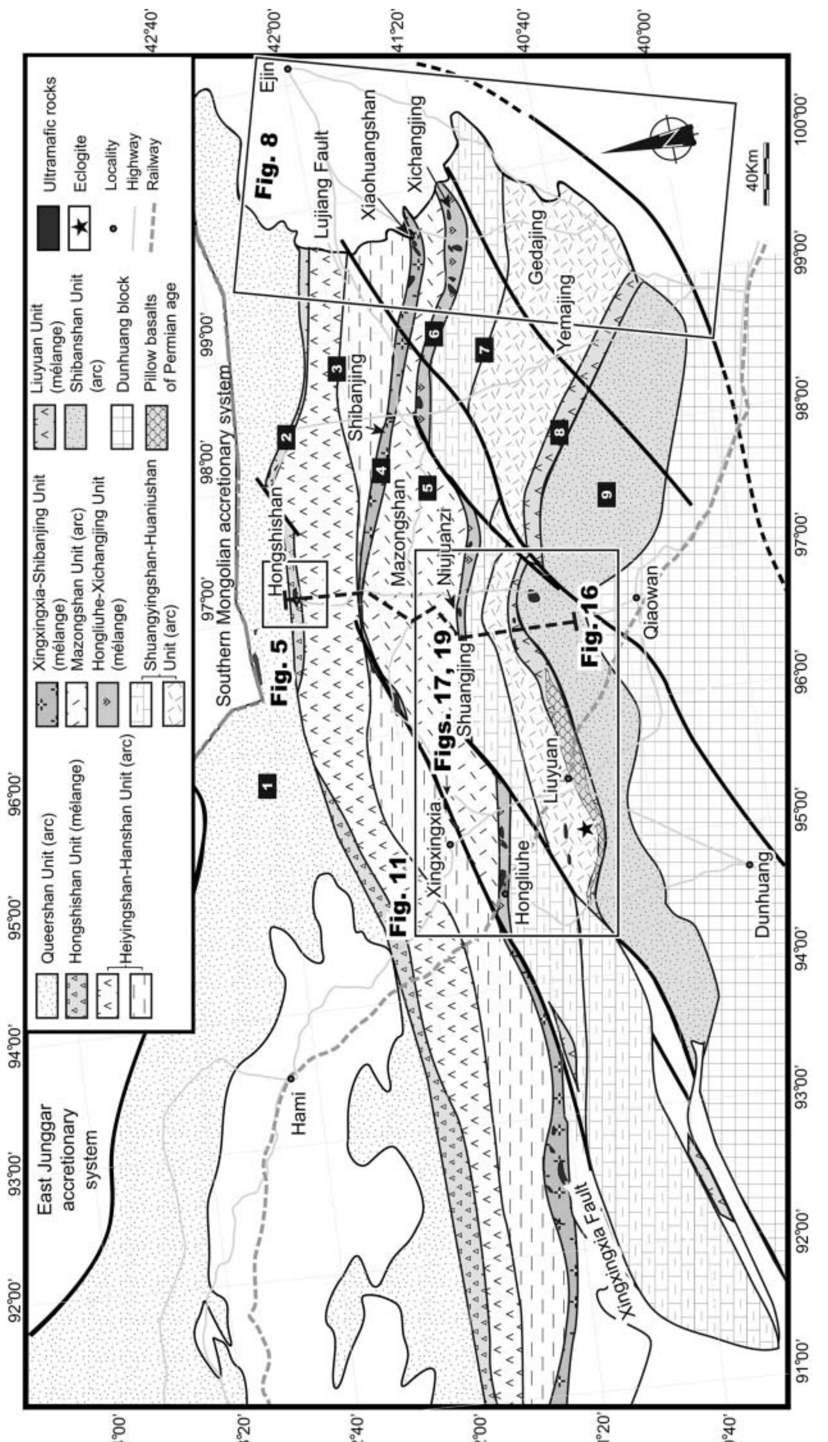

Fig. 3. Simplified tectonic map of the Beishan orogenic collage and its adjacent area showing the tectonic subdivisions (modified after Zuo and others, 1990a, 1990b, 1991; He and others, 2002; Wang and others, 2007b; Xu and others, 2008, 2009; Mao, ms, 2008). The varied lithologies of different strata, indicated by white numbers in black boxes are illustrated in figure 4. Figures 5, 8, 11, 16, 17, and 19 are marked.

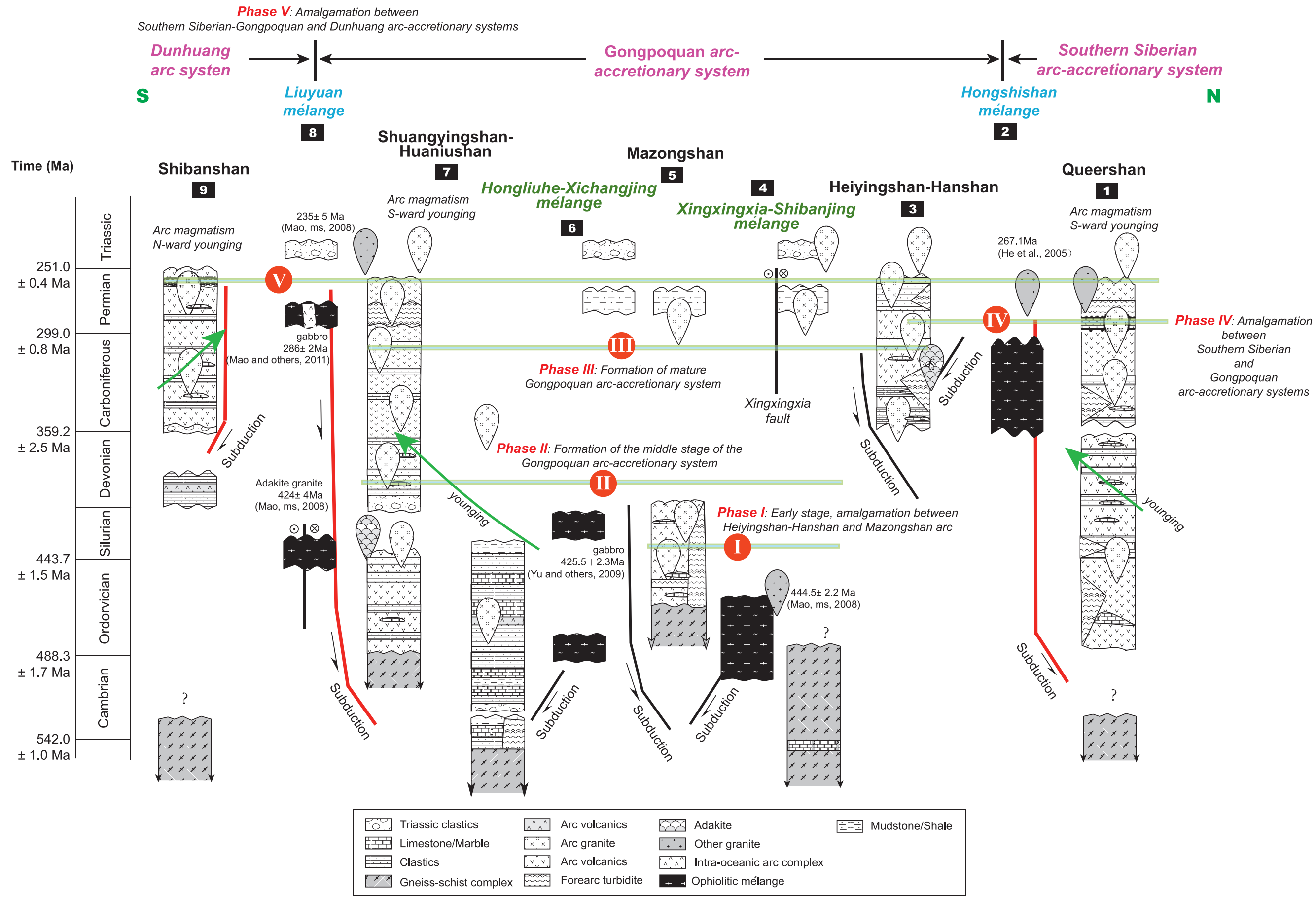

Fig. 4. Space-time diagram demonstrating the spatial and tectonic relationships among the tectonostratigraphic units of the Beishan orogenic collage (based on our own work and modified after Wang and others, 2007b; Xu and others, 2008, 2009; Mao, ms, 2008). White numbers in black boxes same as in figure 3.

into a continental rift in the Late Paleozoic (He and others, 2002; Xu and others, 2008, 2009). If this were the case, it would raise some interesting problems when the southern Tien Shan suture in the west is correlated with the Solonker suture in the east, particularly because both these sutures have been regarded either as Carboniferous or as end-Permian to Middle Triassic in age (Gao and others, 1999a; Gao and Klemd, 2001, 2003; Xiao and others, 2003, 2004a, 2008, 2009a, 2010a, 2010b; Zhang and others, 2005, 2007), whereas the Beishan suture in the middle was considered to be pre-Devonian. Consequently, the tectonic history, especially in the Late Paleozoic, of the Beishan collage is of key importance in understanding the late stages of tectonic evolution of the Altaids.

TECTONOSTRATIGRAPHIC FRAMEWORK

Geographically, Beishan is a mountainous area in western Gansu Province, which connects to the west with the Chinese Eastern Tien Shan in the Xinjiang Uygur Autonomous Region (fig. 3). In this paper, the Beishan orogenic collage is defined as a Neoproterozoic to Paleozoic-Mesozoic orogen that includes some eastern Tien Shan units in Xinjiang.

Tectonically, the Beishan can be extended to accretionary rocks in southern Mongolia (figs. 3 and 4). This Chinese-Mongolian accretionary orogen can be connected with that in East Junggar. Xiao and others (2004b, 2009b) presented a tectonic review of the Chinese East Junggar and eastern Tien Shan. The southernmost Beishan unit is the Dunhuang Block, and the eastern part of the Beishan collage is buried under sand.

Using geological, geochemical, tectonic and geophysical data, the Beishan orogenic collage is subdivided into several tectonic units that are described below from north to south. The relative and absolute time-scales of Gradstein and others (2004) are used.

Queershan Unit

In the far north the Queershan unit (unit 1 in figs. 3, 4 and table 1) includes several Ordovician to Permian arcs composed of mafic to intermediate volcanic and volcaniclastic rocks (table 1) (Zhao and others, 2003; Mao, ms, 2008). The unit consists of Ordovician basalts, felsic volcanic rocks, volcaniclastic rocks, tuffs, sandstones, slates and tuffaceous sandstones, together with some lenses of limestone, and volcanic rocks intercalated with turbidites; the volcanic rocks have a geochemical calc-alkaline signature (Zuo and others, 1990a, 1990b, 1991).

Silurian to Carboniferous arcs in the Queershan unit contain andesites, dacites, rhyolites, and andesitic and rhyolitic agglomerates, breccias and tuffs, which are intercalated with arkoses, graywackes, shales, and slates (Wang and others, 2004). Geochemical data from the intermediate to felsic rocks suggest that they were generated by calc-alkaline magmatism possibly in an island arc and/or continental marginal arc setting (Zuo and others, 1990a, 1990b, 1991).

Permian rocks mainly occur along the southern Queershan arc, in the Honshishan mélange (figs. 3 and 4). In the west, the Permian comprises clastic rocks intercalated with minor pyroclastic rocks and lenses of limestone, whereas in the east there are marine clastic rocks, bioclastic limestones, and cherts. In particular the Late Permian includes basalts, basaltic andesites, andesites, dacites, rhyolites, pyroclastic rocks, and clastic and carbonate sediments.

In the Late Carboniferous to Permian voluminous intermediate to felsic granitic rocks intruded the Queershan unit. Geochronological and geochemical data suggest that they were products of calc-alkaline magmatism in continental marginal arcs (Nie and others, 2002). Some granitic rocks exhibit high positive $\varepsilon_{Nd(t)}$ and Sm-Nd isotopic

TABLE 1

Characteristic rock assemblages and structures of tectonostratigraphic units in the Beishan and interpretations of tectonic settings

UNITS (N→S)	Queershan 1	Hongshishan 2	Heiyingshan-Hanshan 3	Xingxingxia-Shibanjing 4	Mazhongshan 5	Hongliuhe-Xichangjing 6	Shuangyingshan-Huaniushan 7	Liuyuan 8	Shibanshan 9
ROCK ASSEMBLAGES	Perm. gyw. shl. cong. sst. shl. lst. cht. bas. ads. Sil.-Carb. ark. gyw. shl. sla. inter. fel. vol. Ord. bas. fel. vol. sst., lst.	Ultramafic rocks,gab. bas. cht. gyw. tuff, sla. phylitte lst.	Fel. to inter. vol.clastic rocks inetrcalacted with cht., lst. Gneiss schist migmitite, quartzite and marble	Ultramafic rocks,mylonitic gab. Meta-bas. cht. gyw. tuff, sla. phylitte lst. Gneiss schist migmitite, quartzite and marble	Vol.metamorphic and clastic rocks	Ultramafic rocks,gab. plagiograbite, diabase, bas. cht. gyw. tuff, sla. phylitte lst.	**N:** Sil. quartzite silt. cht. slat. shl. lst Ord. cong. silt. cht. marble Camb. cht. sst. silt.slat. phylitte lst. Meta-sst. Gneiss schist migmitite, quartzite and marble of possible Proterozoic in age **S:** Carb.-Perm.mafic fel. inter. vol. Dev. Cong. Sst. bas. and. Rhyolite tuff lst Sil. quartzite silt. cht. slat. shl. lst Ord. cong. silt. cht. marble Metamorphic Ord. bas. and. Meta-sst. phyllite cht. lst. marble	Meta-peridotite, pyroxenite, gab. Diabase bas. cht.	Dev.- Perm. clastic and vol. Gneiss schist migmitite, quartzite and marble
STRUCTURES	S-ward thrust imbrication	N- and S-ward thrust imbrication	Mainly S-ward thrust imbrication	S-ward thrust imbrication	S-ward thrust imbrication	Mainly S-ward thrust imbrication	Mainly S-ward thrust imbrication	N- and S-ward thrust imbrication	N-ward thrust imbrication
PLUTONS	Inter.-fel.	granitoids	granitoids		granitoids		granitoids		granitoids
AGE CONSTRAINTS	Fossil and isotopic ages of Ord.-Perm.	*No high-resolution isotopic ages*	*No high-resolution isotopic ages*	Fossil and isotopic ages of Ord.-Sil.	Fossil and isotopic ages of Ord.-Perm.	Fossil and isotopic ages of Camb.-Perm. 425.5±2.3 Ma (Yu and others, 2006)	Fossil ages of Camb.-Sil. *No high-resolution isotopic ages*	286±2 Ma (Mao, ms, 2008)	Fossil and isotopic ages
INTERPRETATION	Ord.-Perm. active margin with N-ward subduction	Carb.-Perm. accretionary wedge and ophiolitic mélange with N- and S-ward subduction	Carb.arc with high-grade metamorphic basement of unknown ages	Ord.-Sil. accretionary wedge and ophiolitic mélange with mainly N-ward subduction	Ord.-Perm arc with high-grade metamorphic basement of unknown ages	Camb.-Sil. accretionary wedge and ophiolitic mélange, superimposed by some later rifting oceanic basins, with mainly N-ward subduction	Camb.-Perm. composite arc with high-grade metamorphic basement of unknown ages, including some ophiolitic mélanges	Carb.-Perm. accretionary wedge and ophiolitic mélange with N- and S-ward subduction	Paleozoic.- Early Perm. active margin with S-ward subduction

Abbreviations: ark., arkose; gyw., graywacke; seds., sediments; cong., conglomerate; lst., limestone; sst., sandstone; silt., siltstone; shl., shale; sla., slate; cht., chert; inter., intermediate; fel., felsic; bas., basalt; ads., andesite; gab., Gabbro; vol., volcanic rocks; Neoprot., Neoproterozoic; Camb., Cambrian; Ord., Ordovician; Sil., Silurian; Dev., Devonian; Carb., Carboniferous; Perm., Permian; Tria., Triassic; N, North; S, South.

Numbers under each unit are of tectonostratigraphic units in figs. 3, 4, 9, and 16.

values, which suggest that their source material in the mantle had a homogeneous isotopic composition (Liu and others, 2005).

In the western Queershan arc the Triassic Maanshanbei granite has a weighted mean U-Pb zircon age of 237.8 ± 4.3 Ma (Liu and others, 2006). Petrochemical and geochemical data indicate that this granite has a peraluminous to weakly peraluminous composition that is transitional between the calc-alkaline and high-K calc-alkaline series, a typical characteristic of high-Sr, late- or post-orogenic granites (Liu and others, 2006).

The subduction-related geochemical signature of magmatic rocks and their distribution in the Queershan arc indicates that they belonged to an Ordovician to Permian island arc or active continental margin of the Siberian Craton in the Paleoasian Ocean. Moreover, their general southward younging implies that there was southward accretion and continental growth along the southern margin of the Siberian Craton (present-day coordinates) (Liu and Wang, 1995). Available geological and geochronological data suggest that the accretion probably terminated by the Mid-Triassic (Xiao and others, 2009a; Xiao and others, 2010b).

Hongshishan Unit

To the south of the Queershan arc is the Hongshishan ophiolitic mélange, characterized by a matrix of serpentinites (unit 2 in figs. 3, 4 and table 1), situated in the Hongshishan fault zone (figs. 5, 6, and 7). The mélange contains marine sedimentary rocks, limestones and cherts, ultramafic and mafic ophiolitic rocks including pillow basalts, and mylonites in high-strain zones (Zuo and others, 1990a, 1990b, 1991). In places these rocks are tectonically juxtaposed.

The largest outcrop of the ophiolitic mélange at Hongshishan, about 50 km north of Mazongshan (fig. 3), is termed the Hongshishan ophiolite in the literature (Zuo and others, 1990a, 1990b, 1991). The ophiolitic mélange contains EW-trending tectonic blocks of serpentinized ultramafic rocks, gabbroic cumulate rocks, gabbros with minor diabase dikes, pillowed and non-pillowed basalts, cherts, and cherty mudstones (figs. 5 and 6). Ultramafic rocks contain podiform chromites (Wei and others, 2004; Huang and Jin, 2006a, 2006b). Geochemical data show that some basalts have a mid-ocean ridge signature (Wei and others, 2004; Huang and Jin, 2006b).

The ophiolitic rocks are juxtapozed against Carboniferous calc-alkaline volcanic rocks, which have lithological and geochemical characteristics of an active continental margin arc (Wei and others, 2004; Huang and Jin, 2006a, 2006b). In the northern part of the mélange, thrusts have a southward vergence and in the south a northward vergence (fig. 6) (Wei and others, 2004; Huang and Jin, 2006b). The Hongshishan ophiolite has been generally considered to be Carboniferous-Permian in age based on some isotopic ages and fossils (Gong and others, 2002; Wei and others, 2004; Huang and Jin, 2006a, 2006b), but high-resolution isotopic ages are needed to constrain its age of formation and emplacement.

Heiyingshan-Hanshan Unit

South of the Hongshishan ophiolitic mélange is the Heiyingshan-Hanshan arc (unit 3 in figs. 3, 4 and table 1). In the northern part, it is called the Heiyingshan arc, which is composed of Carboniferous felsic volcanic rocks, and carbonates and clastic sedimentary rocks including terrestrial clastic rocks that are intercalated with cherts, limestones and volcanic rocks. Geochemical data show that the volcanic rocks have a calc-alkaline signature, indicating a subduction-related environment (Zuo and others, 1990b; Liu and Wang, 1995; Wei and others, 2004; Huang and Jin, 2006b).

In the center of the Beishan orogenic collage, and separated from the Heiyingshan arc to the north by the Lujing Fault, the Hanshan unit is characterized by high-grade metamorphic rocks that have undergone low P-high T metamorphism (Liu

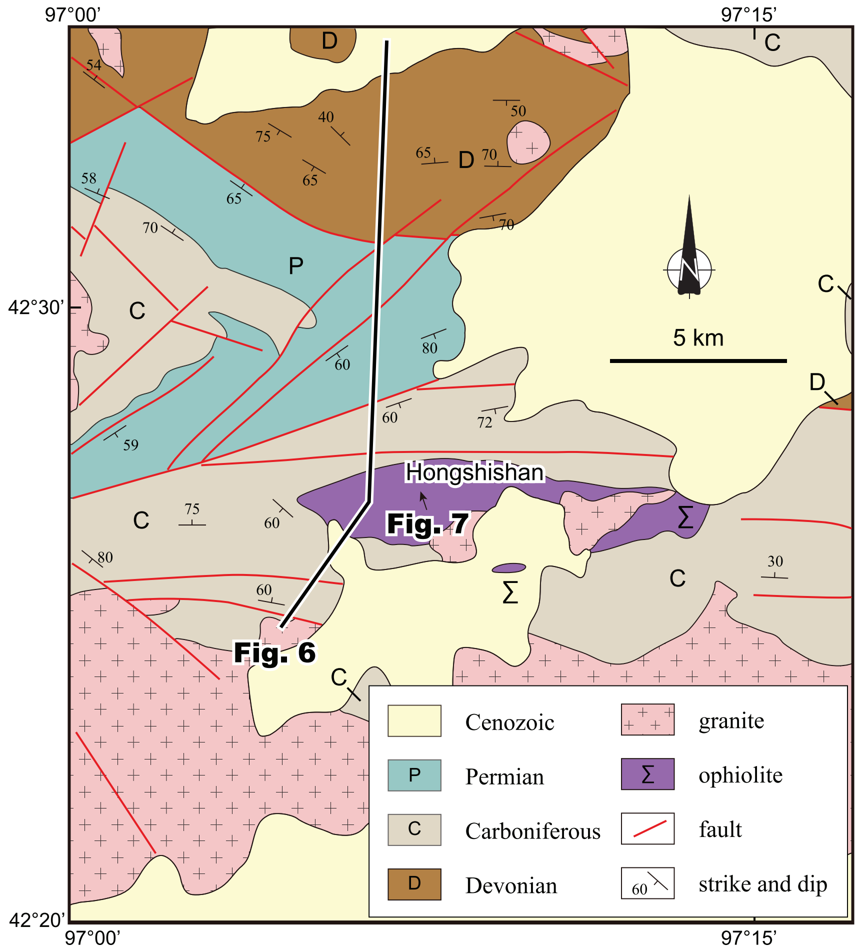

Fig. 5. Schematic geological map of the Hongshishan mélange (modified after Anonymous, 1971, 2004; Wei and others, 2004; Huang and Jin, 2006b). The positions of figure 6 (cross-section) and figure 7 are marked.

and Wang, 1995). Their metamorphic ages are poorly known and remain controversial.

These rocks have been considered to belong to a Paleozoic arc and its accretionary sequences (Anonymous, 1971, 1979; Liu and Wang, 1995). However, whole rock Rb-Sr ages and/or Sm-Nd model ages (Zuo and others, 1990a, 1990b; He and others, 2002; Nie and others, 2002) have yielded Precambrian ages.

The Hanshan arc contains many calc-alkaline granitic intrusions, the isotopic ages of which range from Carboniferous to Triassic on the basis of zircon U/Pb and muscovite Ar-Ar dating (Nie and others, 2002).

Xingxingxia-Shibanjing Unit

South of the Hanshan arc, the Xingxingxia-Shibanjing ophiolitic mélange forms a continuous EW-trending mélange (unit 4 in figs. 3, 4 and table 1) that is characterized by tectonic slices of ophiolitic rocks including meta-ultramafic rocks, mylonitic gabbros, meta-basalts and clastic rocks in a matrix of turbidities (Zuo and others, 1990a, 1990b; He and others, 2002; Nie and others, 2002). In addition, the mélange contains

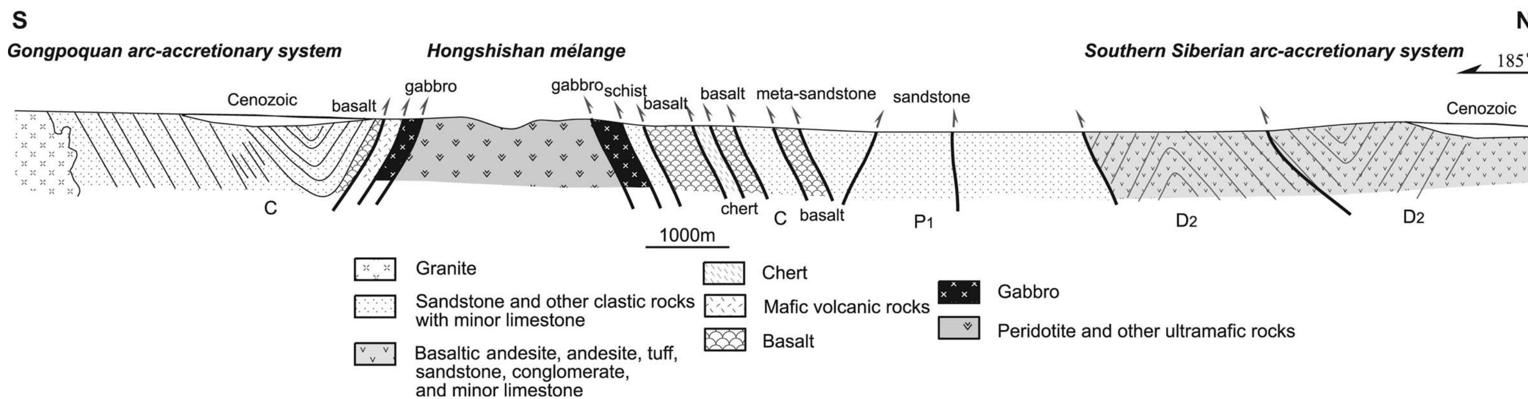

Fig. 6. Cross-section of the Hongshishan mélange (modified after Anonymous, 1971, 2004; Wei and others, 2004; Huang and Jin, 2006b). Position marked in figure 5.

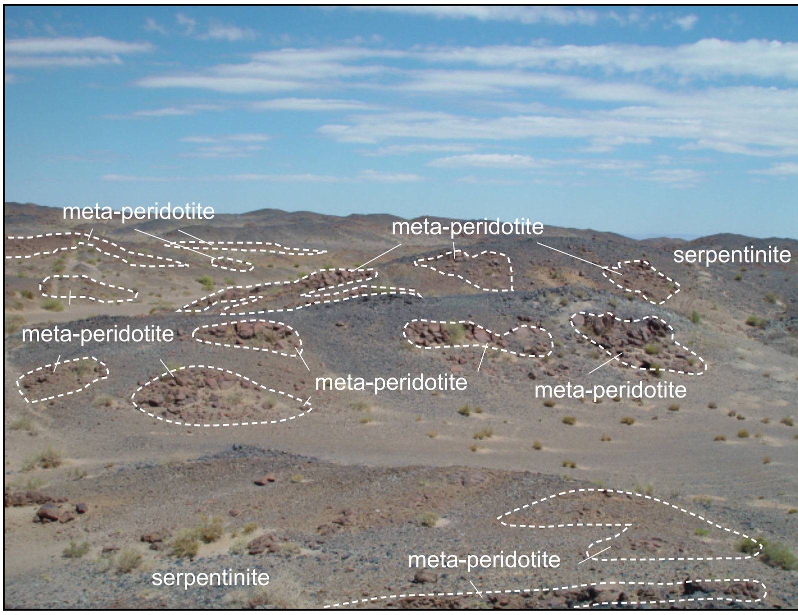

Fig. 7. Ultramafic rocks of the Hongshishan mélange. The brown rocks in the foreground and in hills in the background are meta-peridotite and the rocks elsewhere are sepentinized ultramafic rocks. Looking NE, Hongshishan. Position marked in figure 5.

blocks of gneiss, schist, migmatite and marble (Liu and Wang, 1995), the ages of which are controversial.

The major ophiolitic slices occur in two main localities, at Shibanjing and Xiaohuangshan (figs. 3 and 4) (Zuo and others, 1990a, 1990b; He and others, 2002; Nie and others, 2002).

Many ophiolitic rocks in the mélange have experienced amphibolite facies metamorphism (Zuo and others, 1990a, 1990b, 2003), but those in the Xiaohuangshan area were subjected to high-temperature metamorphism overprinted by intermediate-high-pressure metamorphism (Zhou and others, 2001b). However, the ages of metamorphism are not constrained (Zhou and others, 2001b). The rocks in this highly deformed mélange have fossil ages defined as Ordovician to Silurian (Zuo and others, 1990a, 1990b, 2003). Therefore the age of metamorphism could be younger than Silurian, and more geochronological work on these metamorphic rocks is needed.

Mazongshan Unit

Located between the Xingxingxia-Shibanjing ophiolitic mélange to the north and the Hongliuhe-Xichangjing ophiolitic mélange to the south (figs. 4, 8, and 9), the Mazongshan arc (unit 5 in figs. 3, 4 and table 1) is composed of Middle/Late Ordovician to Silurian volcanic rocks, metamorphic rocks and Late Paleozoic clastic sedimentary rocks.

The eastern part of this arc comprises weakly metamorphosed Late Paleozoic volcanic rocks including felsic extrusives, together with clastic sediments and turbidites (Zuo and others, 1991, 1990a). The oldest rocks are variably metamorphosed Middle to Late Ordovician felsic volcanic rocks and clastic sedimentary rocks including turbidites, intercalated with cherts, marbles and limestones (Zuo and others, 1991, 1990a). The Silurian stratigraphy is characterized by intermediate to mafic rocks

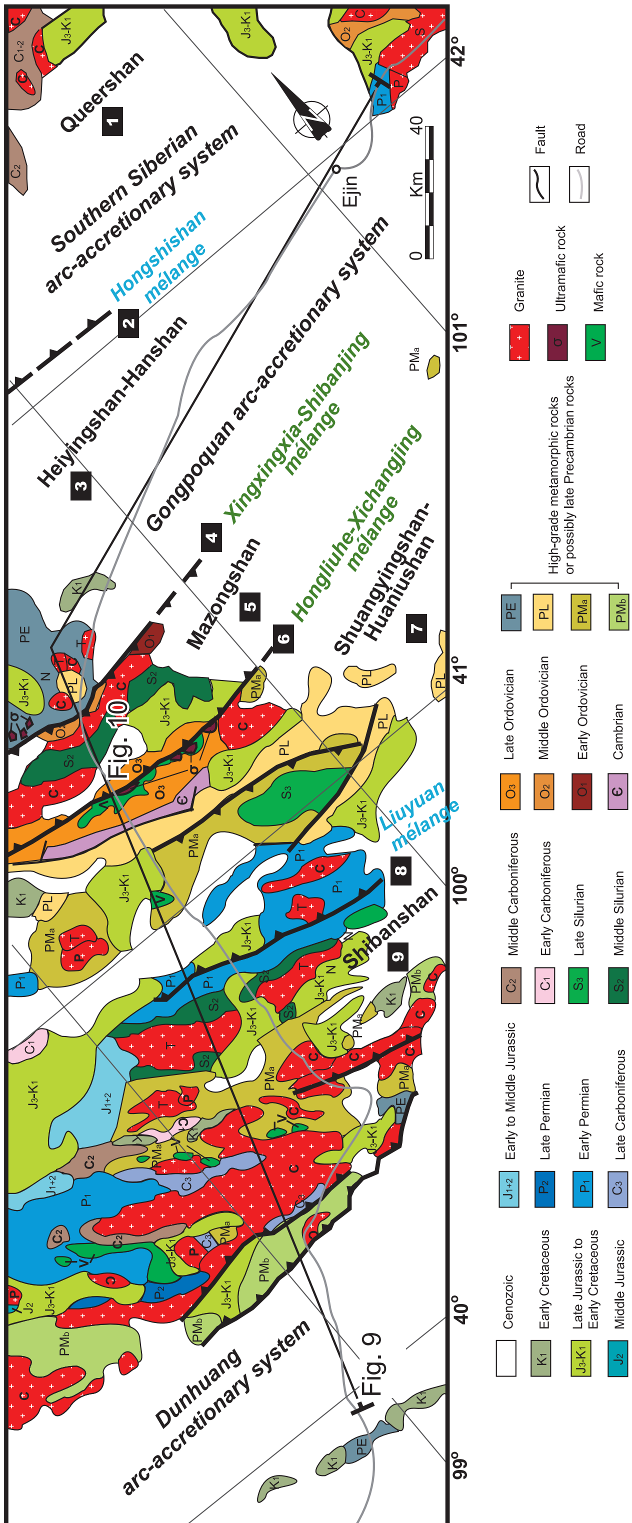

Fig. 8. Schematic geological map of the Xiaohuangshan-Xichangjing area (modified after Wang and others, 1997; Gao and others, 1999b). The locations of figure 9 (cross-section) and figure 10 are marked. White numbers in black boxes correspond to those in figure 3.

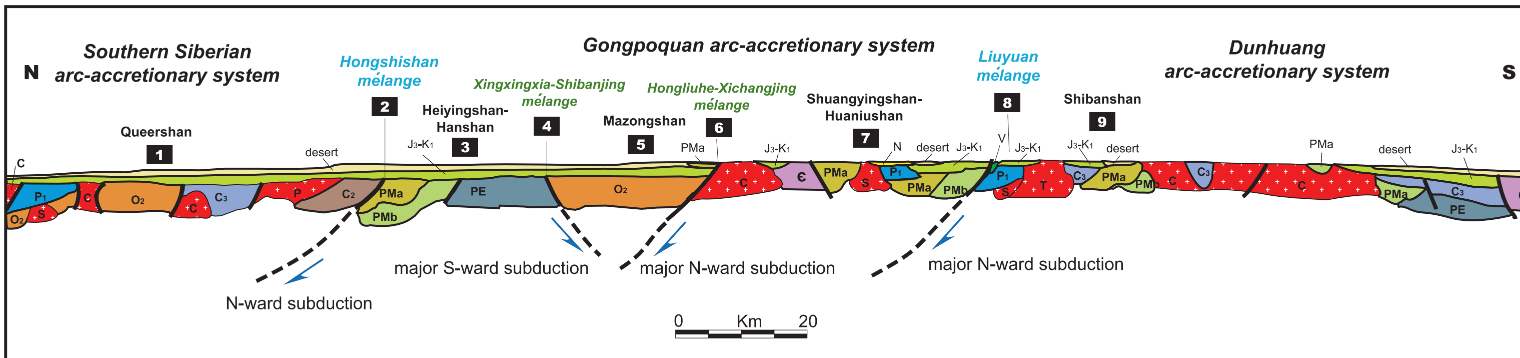

Fig. 9. Cross-section of the Xiaohuangshan-Xichangjing area (modified after Wang and others, 1997; Gao and others, 1999b). The deep crustal thrusts are from seismic profiles (modified after Wang and others, 1997; Gao and others, 1999b), and they are correlated and linked with well-defined thrusts on the surface. Some major subduction polarities are shown. Position of cross-section marked in figure 8. Legend is the same as on figure 8. White numbers in black boxes are the same as in figure 3.

intercalated with sandstones, marbles, and cherts. Geochemical data show that the volcanic rocks have a calc-alkaline signature (Zuo and others, 1991, 1990a; Liu and Wang, 1995).

The western part of this arc is mainly composed of high-grade metamorphic rocks including gneisses, schists and migmatites, but with some low-grade metamorphic rocks containing microfossils, indicating Neoproterozoic, Cambrian to Silurian ages (Zuo and others, 1991, 1990a; Liu and Wang, 1995; Dai and Gong, 2000; Du and others, 2003; Mao, ms, 2008). There are also various Permian sandstones, tuffaceous conglomerates, and purple mudstones.

The arc contains porphyritic intrusions, most of which have ages ranging from Late Ordovician (for example, 444 ± 2.2 Ma for a granite, Mao, ms, 2008) to Early Silurian (for example, 433 ± 6.7 Ma for a diorite (Dai and Gong, 2000).

Hongliuhe-Xichangjing Unit

Situated south of the Mazongshan arc, the Hongliuhe ophiolitic mélange (unit 6 in figs. 3, 4 and table 1) is mainly composed of (a) Cambrian, Ordovician and Silurian clastic rocks and pyroclastic rocks (b) many tectonic slices of ophiolitic rocks; and (c) Carboniferous to Permian clastic rocks including conglomerates, graywackes, tuffaceous siltstones, slates and cherts, and minor limestones (Zuo and others, 1991, 1990a; Liu and Wang, 1995; Nie and others, 2002; Gong and others, 2002). All these rocks are juxtaposed against each other by thrusts.

The lower Paleozoic rocks have been metamorphosed mostly into greenschist facies and deformed. Slices of ophiolitic rocks crop out within Ordovician-Silurian clastic sedimentary rocks and turbidites (Zuo and others, 1991, 1990a; Liu and Wang, 1995; Nie and others, 2002; Gong and others, 2002). From west to east along this ophiolitic mélange there are major fault-bounded bodies of ophiolite in the Hongliuhe, Niujuianzi, and Xichangjing areas (figs. 3, 8, 9, 10, 11, and 12); the main lithologies include ultramafic rocks, cumulate gabbros, gabbros, plagiogranites, diabases, basalts and cherts. Zircons from a gabbro in the Hongliuhe area yielded a U-Pb age of 426 ± 2 Ma (Yu and others, 2000, 2006).

The Hongliuhe ophiolitic mélange also contains Permian massive and pillow basalts that are intercalated with tuffaceous sandstones, siltstones, cherts and limestones (Zhao and others, 2004, 2006a), and Triassic molasse-like clastic sedimentary rocks.

Shuangyingshan-Huaniushan Unit

Farther south is the Shuangyingshan-Huaniushan arc (unit 7 in figs. 3, 4 and table 1). The Shuangyingshan area is mainly composed of Late Proterozoic and Early Paleozoic clastic rocks and carbonates. There are Neoproterozoic meta-sedimentary rocks (Zuo and others, 1991, 1990a; Liu and Wang, 1995; Nie and others, 2002; Gong and others, 2002). These Neoproterozoic rocks have no isotopic age data and their assigned age is based on some regional correlations (Zuo and others, 1991, 1990a; Liu and Wang, 1995; Dai and Gong, 2000; Nie and others, 2002; Gong and others, 2002; Du and others, 2003). At the base of the Cambrian in China is a bed of tillite and some phosphorous-rich deposits, which is a typical character of the lowest Cambrian (Zuo and others, 1991, 1990a; Liu and Wang, 1995; Nie and others, 2002; Gong and others, 2002). Trilobites and brachiopoda/gastropoda confirm a Cambrian age (Zuo and others, 1991, 1990a; Liu and Wang, 1995; Nie and others, 2002). Ordovician sedimentary rocks include clastic rocks and carbonates that contain graptolites, trilobites and brachiopoda/gastropoda (Zuo and others, 1991, 1990a; Liu and Wang, 1995; Nie and others, 2002; Gong and others, 2002). Minor Silurian rocks are present including clastic rocks and carbonates (fig. 4 and table 1).

Fig. 10. (A) Plagiogranite dike *ca.* 8 meters wide (marked) in black gabbro, Xichangjing ophiolitic mélange along the Jinta-Ejin highway. Looking NE, circled scientist for scale. (B) A block of gabbro-diabase in a matrix of serpentinite, Xichangjing, scientist *ca.* 1.7 m high for scale. Position marked in figure 8.

The Shuangyingshan unit contains intrusive granitic bodies formed at active margins, the ages of which range from Neoproterozoic to Mesozoic by U-Pb zircon and muscovite Ar-Ar dating (Zuo and others, 1991, 1990a; Liu and Wang, 1995; Nie and others, 2002; Gong and others, 2002).

South of the Shuangyingshan unit is the Huaniushan arc, composed of metamorphosed Paleozoic rocks and Mesozoic clastic sedimentary rocks (figs. 3 and 4). The oldest rocks are basalt and basaltic andesites that have no precise isotopic ages, and

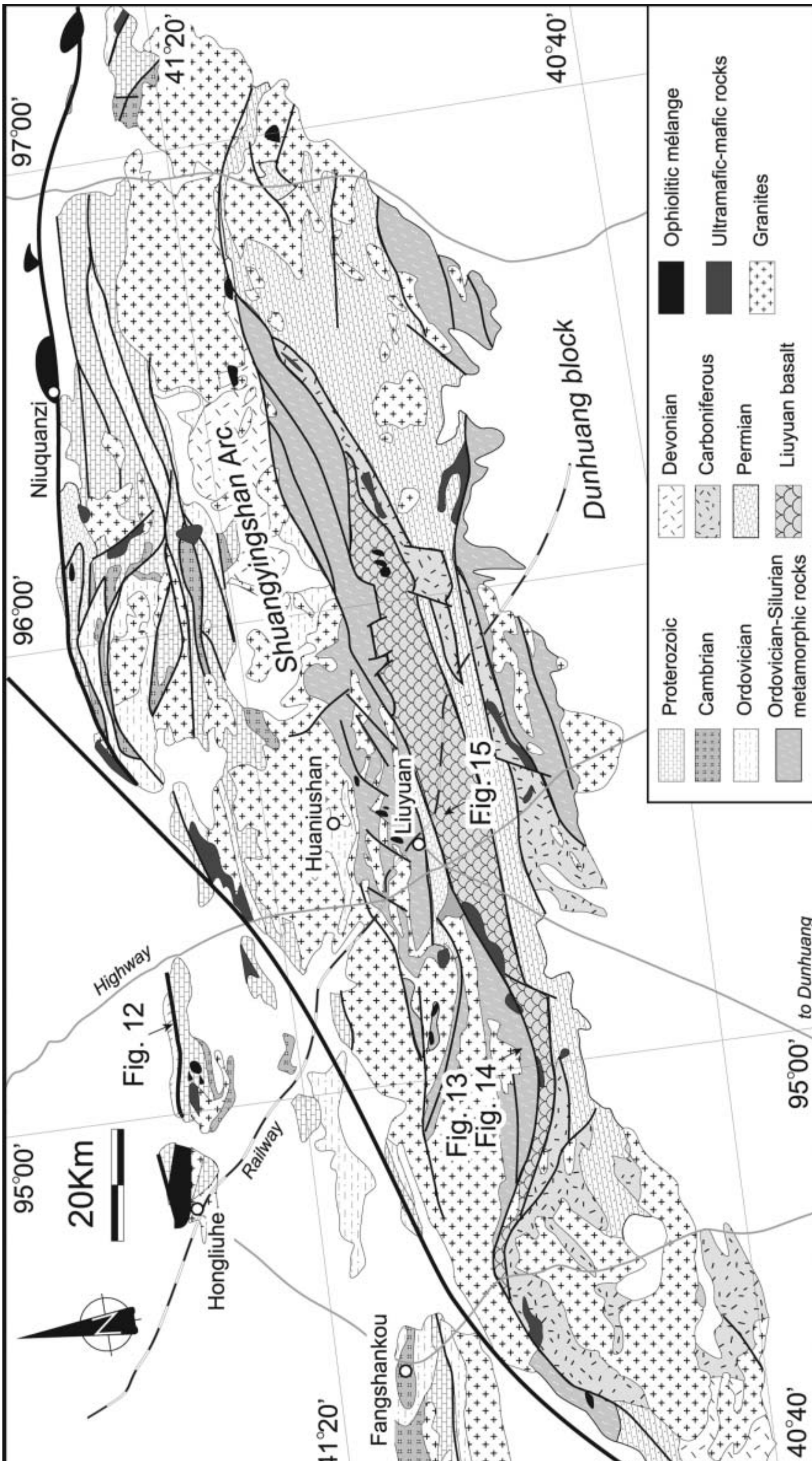

Fig. 11. Schematic geological map of the Hongliuhe-Liuyuan area showing the tectonic units including ophiolitic mélanges and ultramafic/mafic rocks. Lithologies are varied and illustrated in figure 4. The locations of figures 12, 13, 14, and 15 are marked.

Fig. 12. Photograph of ptygmatically folded quartz/granite vein in siliceous marble of possible Proterozoic age. A well-developed, steeply plunging lineation is parallel to the fold axes (marked by a pen) and seen on the foliation surface of mafic schist on the back-wall. Looking NW, Zhaobishan. Position marked in figure 11.

meta-sandstones, phyllites, cherts, limestones, and marbles that contain trilobites, which indicate an Ordovician age (Zuo and others, 1991, 1990a; Liu and Wang, 1995; Nie and others, 2002; Gong and others, 2002; Mao, ms, 2008). The volcanic rocks have a calc-alkaline geochemical signature (Zuo and others, 1991, 1990a). The arc also contains gneisses, quartz schists, migmatites, meta-sandstones and -conglomerates, phyllites, and marbles with Silurian fossils, together with felsic and intermediate volcanic and pyroclastic rocks. These high-grade rocks are preserved in fault juxtaposition against younger rocks (Mao, ms, 2008).

The Huaniushan arc contains packages of Devonian conglomerates, sandstones, basalts, andesites, rhyolites, agglomerates, tuffs, and limestones. Carboniferous-Permian rocks are mainly distributed in the southern part of the arc. There are Carboniferous terrestrial clastic sediments, which probably were deposited in an arc-related basin or forearc basin, basalts, felsic to intermediate volcanic and pyroclastic rocks and minor limestones, and Permian felsic to intermediate volcanic and clastic sedimentary rocks including turbidites (Zuo and others, 1991, 1990a; Liu and Wang, 1995; Nie and others, 2002; Gong and others, 2002; Mao, ms, 2008).

The Huaniushan arc contains an ophiolitic mélange composed of blocks of gneiss, schist, mylonite, migmatite, marble, ultramafic rocks and chert in a matrix of turbiditic sandstone. The ages of these mélange rocks and of the mélange itself are not known with certainty and this has led to much speculation with estimates ranging from Precambrian to Carboniferous (Zuo and others, 1990a, 1991; Liu and Wang, 1995; Gong and others, 2002; Nie and others, 2002).

Farther south is a 10 km-wide belt of mylonitic augen orthogneisses that contain many lenses of eclogites up to several hundred meters long (figs. 13 and 14). The protolith and metamorphic ages of these eclogites are mostly oceanic (Qu and others,

Fig. 13. Outcrop photos showing boudins of eclogite in mylonitic augen orthogneiss. Arrows indicate dextral strike-slip shown by the shapes of the boudins. (A) Looking NW, Gubaoquan. (B). Looking NW, Gubaoquan, hammer for scale. Position marked in figure 11.

2011); they have been regarded as Neoproterozoic (Mei and others, 1998; Lu and others, 1999; Yu and others, 1999; Liu and others, 2002; Yang and others, 2006). The augen gneisses contain many lenses and porphyroclasts of granitic gneiss that appear

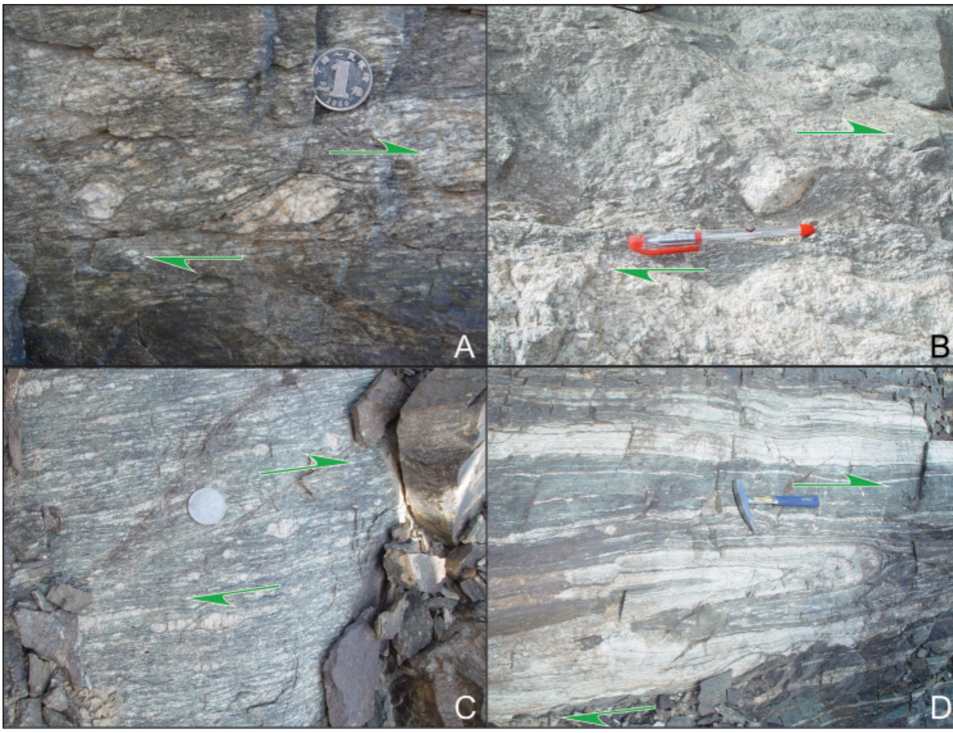

Fig. 14. Four outcrop photos of mylonitic augen orthogneisses in the Gubaoquan area that host the boudins of eclogite seen in figure 13. Figures (A), (B), and (C) show asymmetrical porphyroclasts of granitic gneiss that indicate dextral strike-slip. Figure (D) shows isoclinal folds in banded mylonitic orthogneiss. Coin, pen, or hammer for scale.

to be remnants of the gneiss protolith. The porphyroclasts have been rotated into asymmetrical shapes that indicate a consistent dextral sense of movement within the augen gneiss belt (fig. 14).

The Huaniushan arc contains many granitic intrusions that have calc-alkaline trace element signatures. Some granodiorite plutons have U-Pb zircon ages that cluster around 380 ± 12 Ma, indicating an important Devonian intrusive event (Zuo and others, 1991, 1990a; Liu and Wang, 1995; Nie and others, 2002; Gong and others, 2002). Nie and others (2002) obtained $^{40}Ar/^{39}Ar$ ages of 352 to 250 Ma for the granitoids, with the granitoids of 270 to 250 Ma in age defined as post-collisional intrusions (Jiang and Nie, 2006).

Liuyuan Unit

Farther south is a roughly EW-trending, continuous ophiolitic belt, termed the Liuyuan complex (unit 8 in figs. 3, 4 and table 1) that contains many tectonic slices of ophiolitic rocks and remnants of active continental margin rocks (Zuo and others, 1991, 1990a; Liu and Wang, 1995; Nie and others, 2002; Gong and others, 2002).

The Liuyuan unit contains a major ophiolitic belt that includes peridotites, pyroxenites, gabbros, diabase dikes, massive and pillow basalts, and cherts. The basalts and gabbros have a MORB and IAT geochemical signatures (Mao, ms, 2008; Mao and others, 2011). In the Liuyuan area one can observe excellent outcrops of pillow basalts, tuffs and cherts that are mostly in mutual fault contact, and juxtaposed against

Fig. 15. Photograph showing south-directed thrusts in a major duplex in imbricated basalts. The younging directions of the pillows (marked by white arrows) outline the shapes of folds. Geologist for scale. Looking NE, Liuyuan. Position marked on figure 11.

Permian tuffaceous sandstones, phyllites and limestones (fig. 15). The detailed field geology and thrust tectonics of these rocks are presented in separate publications (Mao, ms, 2008; Mao and others, 2010; Mao and others, 2011).

Shibanshan Unit

The southernmost unit of the Beishan orogenic collage is the Shibanshan arc, which is situated on the northern margin of the Dunhuang Block (unit 9 in figs. 3, 4 and table 1). The southern part of the arc, near Dunhuang, comprises an assemblage of granitic gneisses, schists, quartz schists and migmatites, the ages of which are poorly known and previously assigned as Precambrian or Ordovician-Silurian (Zuo and others, 1991, 1990a; Nie and others, 2002).

The main rocks in the unit are Devonian, Carboniferous, and Permian in age (Zuo and others, 1990a; Zhao and others, 2006a). The Devonian rocks, distributed in the west of the arc, include clastic rocks, and slates intercalated with welded tuffs and limestones. Widespread Carboniferous rocks comprise clastic sedimentary rocks, slates, phyllites, limestones, felsic to intermediate volcanic and pyroclastic rocks. The Permian is composed of volcanic and pyroclastic assemblages, and lenses of limestone (fig. 3 and table 1).

The Shibanshan arc contains many intrusive granitic bodies of Late Permian to Triassic age as indicated by U-Pb zircon and muscovite Ar-Ar dating (Zuo and others, 1991, 1990a; Liu and Wang, 1995; Nie and others, 2002; Gong and others, 2002).

TECTONIC ASSEMBLAGES

The Beishan orogenic collage includes Ordovician-Silurian and Late Paleozoic assemblages.

Early to Mid-Paleozoic Tectonic Assemblages

The Early-Middle Paleozoic history of the Beishan orogenic collage was characterized by the development of many magmatic arcs and ophiolitic mélanges with a complicated evolution, which has been well described in the literature (Zuo and others, 1991, 1990a; Liu and Wang, 1995; Nie and others, 2002; Gong and others, 2002). However, our recent results, combined with published data (Gu and others, 1994; Gong and others, 2002; He and others, 2002; Zhao and others, 2003; Zhou and others, 2004b; Xiao and others, 2004b; Wang and others, 2004; Mao and others, 2005; Han and others, 2006; Huang and Jin, 2006b) require modification to the Early-Middle Paleozoic tectonic evolution of the Beishan orogenic collage.

The Gongpoquan arc-accretionary system contains two major early Paleozoic ophiolitic mélanges (Shibanjing and Hongliuhe), which separate individual arcs that contain possible old materials (figs. 3, 4, 8, 9 and 16). The Shibanjing mélange is regarded as a remnant of an Early Cambrian to Silurian ocean (Zuo and Li, 1996; Zuo and others, 2003). The Xichangjing part of the Hongliuhe ophiolitic mélange has long been considered to represent an ocean that lasted from the Cambrian until at least the Ordovician-Silurian, because the mélange contains Middle to Late Ordovician radiolarians and Silurian conodonts (Zuo and Li, 1996; Zuo and others, 2003). Moreover, the idea that the Hongliuhe mélange represents an Early Paleozoic ocean was confirmed by a U-Pb zircon age of 425.5 ± 2.3 Ma for a gabbro in the Hongliuhe ophiolite (Yu and others, 2000, 2006). The presence of young basalts of Permian age along and north of the Early Paleozoic Hongliuhe ophiolitic mélange belt (Zhao and others, 2004) indicates a phase of ocean opening in the Late Paleozoic tectonic evolution of the Beishan.

The three magmatic arcs were previously considered to be rifted from the southern Dunhuang block. However, the Dunhuang block has isotopically-confirmed Archean to Early Proterozoic high-grade metamorphic rocks (Lu and others, 1999, 2002), whereas the Gongpoquan arc-accretionary system contains Phanerozoic fossils, and it is only "suspected" to contain old rocks (Zuo and others, 1990b; Zuo and others, 2003). In the southern Hanshan arc a granite yielded a U-Pb zircon age of 444.5 ± 2.2 Ma and in the Huaniushan arc an adakite has a U-Pb zircon age of 425 ± 2.3 Ma (Mao, ms, 2008), confirming the presence of early Paleozoic magmatism. So far, there is no evidence to suggest that the blocks, mélanges, or arcs are similar in type, age or derivation.

Late Paleozoic Tectonic Assemblages

The Late Paleozoic tectonic evolution of the Beishan orogenic collage is characterized by the development of three active continental margins and island arcs separated by two ophiolitic mélanges. The northernmost continental margin is represented by the Queershan arc, which lasted until the Permian, as part of the long-lived southern Siberian arc-accretionary system. The southernmost Shibanjing magmatic arc formed at an active continental margin along the northern margin of the Dunhuang block. The Hongshishan mélange of Carboniferous-Permian age bounds the southern margin of the Queershan arc, and the Permian Liuyuan mélange bounds the northern margin of the Shibanshan arc. Between these two Late Paleozoic mélanges is the Gongpoquan arc-accretionary system, which comprises several earlier amalgamated arcs.

TIMING OF THE MAJOR THRUST DEFORMATION

The amalgamation and accretion of the above tectonic units gave rise to strong Late Permian to Triassic deformation that includes thrust imbrication and strike-slip faulting.

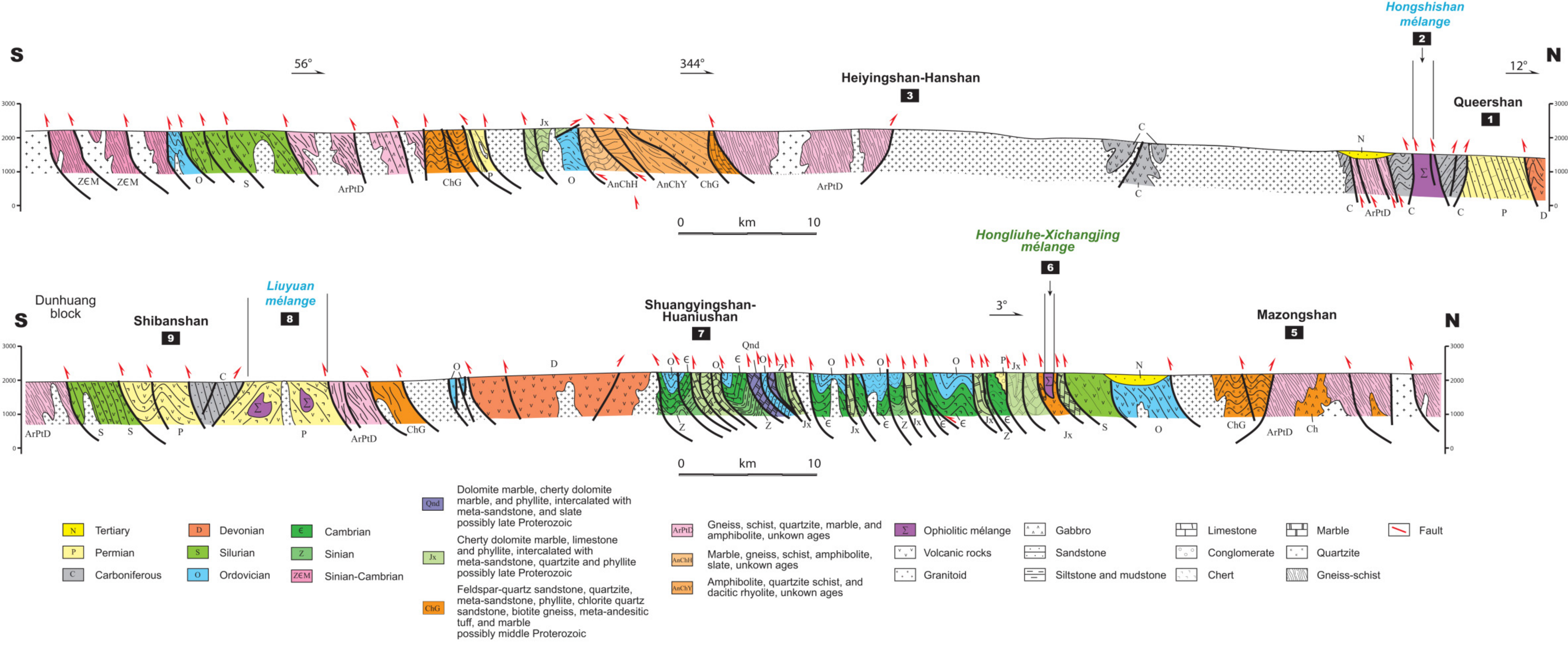

Fig. 16. General N-S cross-section of the Beishan orogenic collage (modified after Anonymous, 1971, 2001, 2004; Gong and others, 2002; Wei and others, 2004; Huang and Jin, 2006b). Position marked in figure 3. White numbers in black boxes are the same as in figure 3.

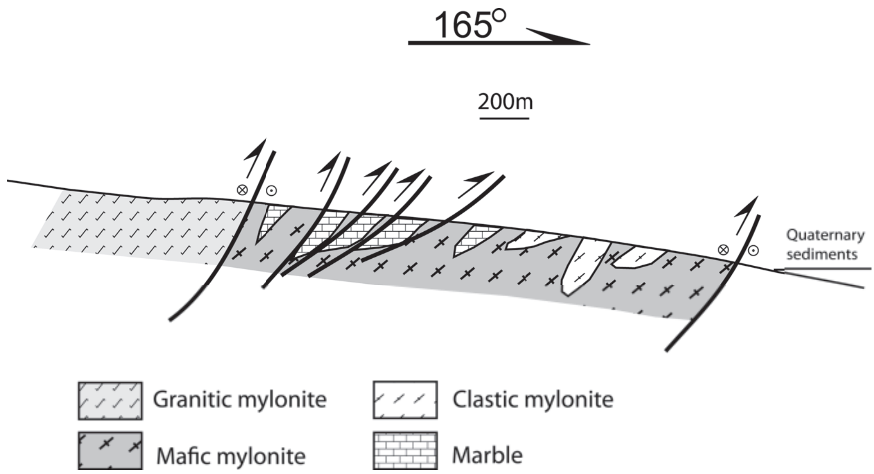

Fig. 17. Cross-section of the Xingxingxia Fault indicating dextral strike-slip faulting. Position marked on figure 3.

Permian-Triassic Thrusting and Imbrication

Thrusting and imbrication of different tectonic units is common in the Beishan orogenic collage, in which the youngest deformed rocks are Permian. These Permian rocks typically contain fossils (Zuo and others, 1990b; Liao and Wu, 1998; Liao and Liu, 2003; Zhao and others, 2006a, 2006b). These fossiliferous Permian rocks are subdivided into three belts: the northern, central, and southern (Zuo and others, 1990b).

The northern belt extends from the Hongshishan area in the west to the Lucaojing area in the east (Zuo and others, 1990b; Xu and others, 2008; Xu and others, 2009). It includes Early Permian feldspar-quartz schists, clastic sedimentary rocks, slates, tuffs that are intercalated with andesites, basalts, bioclastic limestones, together with rhyolites, dacites, and tuffaceous sandstones. This belt includes the Hongshishan ophiolitic mélange, which has an imbricated fan structure in which the youngest rocks are Permian (Wei and others, 2004; Huang and Jin, 2006a, 2006b; Mao and others, 2011).

The central Permian belt occurs in the center of the Beishan orogenic collage, roughly in the Hongliuhe, Yushishan, Jinwozi, Niujuanzi, and Gadajing areas (figs. 3, and 4) (Zuo and others, 1990b; Xu and others, 2008; Xu and others, 2009). The central belt contains similar rocks to the northern belt, with basalts together with cherts (Zuo and others, 1990b), and it includes the Hongliuhe-Xichangjing ophiolitic mélanges, and further east it extends to the south of the Xingxingxia-Shibanjing ophiolitic mélange.

In the northern part of the central Permian belt a huge mélange zone occurs more or less along the Xingxingxia strike-slip fault (Mao and others, 2011). Strongly deformed, highly metamorphosed rocks including granitic gneisses, schists, mylonites, mylonitic basalts, meta-basalts, and marbles are imbricated in south-directed thrust sheets (fig. 17) that have been thrust southwards over Permian clastic sedimentary rocks (Mao and others, 2011).

The southern Permian belt crops out in the Liuyuan to Yemajing areas and includes pillow basalts, mafic tuffs, gabbros, cherts, and volcaniclastic rocks (Zuo and others, 1990b), which are major components of the Liuyuan mélange (Zuo and others, 1990b; Xu and others, 2008, 2009).

In the northern part of the Gongpoquan arc-accretionary system, strongly deformed high-grade metamorphic rocks including gneisses, schists, and marbles with isoclinal folds have been thrust southwards over Permian clastic sediments. The contacts of these rocks are occupied by mylonites, which contain asymmetrical structures that indicate top-to-the-south movements (Mao and others, 2011). In the Hongliuhe area Permian clastic sediments have been deformed by huge recumbent folds that indicate roughly N-S convergence (Zuo and others, 1990a; Xu and others, 2008; Mao, ms, 2008). In the Yushishan area siliceous marbles that have been thrust northwards over ophiolitic slices (includes serpentinites, pyroxenites, gabbros, and basalts), have ptygmatic folds with well-developed lineations parallel to the fold axes.

The Liuyuan and surrounding areas contain many Permian rocks that are strongly deformed. Along the road-cut from Liuyuan to Qiaowan well-preserved pillow basalts are thrust southeastwards over fossiliferous Permian turbidites. Locally, pillows have been folded as indicated by their younging directions (fig. 15). Many examples of thrusting and imbrication of Permian turbidites and cherts can be recognized in these areas (Zuo and others, 1991, 1990a; Liu and Wang, 1995; Nie and others, 2002; Gong and others, 2002; Mao, ms, 2008).

A cross-section constructed across the Beishan orogenic collage shows that many tectonic units were subjected to imbrication and thrusting (fig. 16). The thrusts and imbricate structures indicate either northward or southward translation. For example, in the northern Hongshishan area thrusts indicate southward translation, but in the south northward translation is evident (fig. 16). In some modern accretionary wedges this is also very common, for instance, the accretionary wedge from south Alaska (Little and Naeser, 1989) and the Makran accretionary wedge in Iranian coastal area (Hosseini-Barzi and Talbot, 2003). In some ancient accretionary wedges, such as the Otago Schist, a Mesozoic accretionary prism in New Zealand, opposing thrust vergence is also observed (Gray and Foster, 2004).

In the Gongpoquan arc-accretionary system almost all the thrusts indicate southward movement, and the two major early Paleozoic ophiolitic mélanges (Shibanjing and Hongliuhe) occur in southward-directed thrust sheets imbricated within the whole arc-accretionary system (fig. 16). In the Liuyuan mélange zone, most thrusts have moved southwards, but some have northward vergence (fig. 16).

A combined geological and geophysical profile across the eastern part of the Beishan orogenic collage (figs. 8 and 9), suggests a major deep crustal level of thrusting that was predominantly to the south, except for the Shibanjing mélange that records north-directed thrusting. The combined synthetic cross-section has correlated surface structures and tectonic units with major deep thrusts demonstrated by geophysical profiling (Wang and others, 1997; Gao and others, 1999b). Because these structures correlate with the principal faults and the main ophiolitic mélange zones, we postulate that they were generated by major tectonic convergence in the Permian to Early Triassic, in which case major northward or northwestward subduction polarity may be inferred.

Permian Arc-Related Mafic-Ultramafic Complex

Several mafic-ultramafic complexes and associated mélanges are preserved along large-scale faults, such as the Xingxingxia Fault where there are several mafic-ultramafic complexes and associated mélanges, many of which are Permian in age (Xiao and others, 2004b; Mao and others, 2005; Han and others, 2006; Ao and others, 2010). In the southwestern corner of the Beishan area there are several mafic-ultramafic complexes, including Pobei and Heishan (fig. 18) (Mao and others, 2005; Han and others, 2006), which have been considered to be the product of a major plume that extended from Siberia to Tarim (Pirajno and others, 1997, 2008). However, recent geological, geochemical and geochronological studies indicate that these

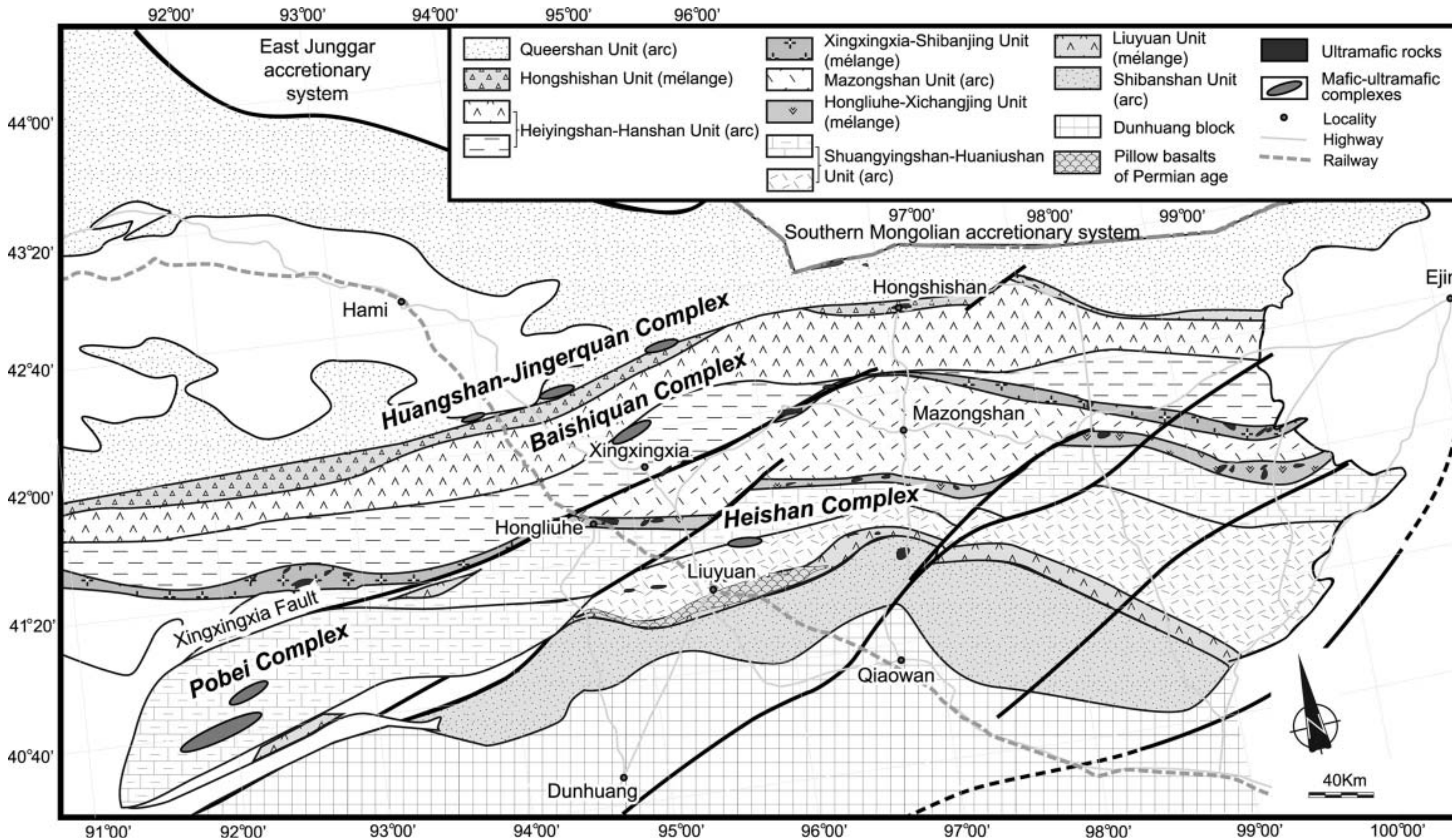

Fig. 18. Simplified tectonic map of the Beishan orogenic collage and its adjacent area showing the tectonic subdivisions and the distribution of ultramafic-mafic complexes (modified after Zuo and others, 1990a, 1990b, 1991; He and others, 2002; Wang and others, 2007b; Xu and others, 2008, 2009; Mao, ms, 2008).

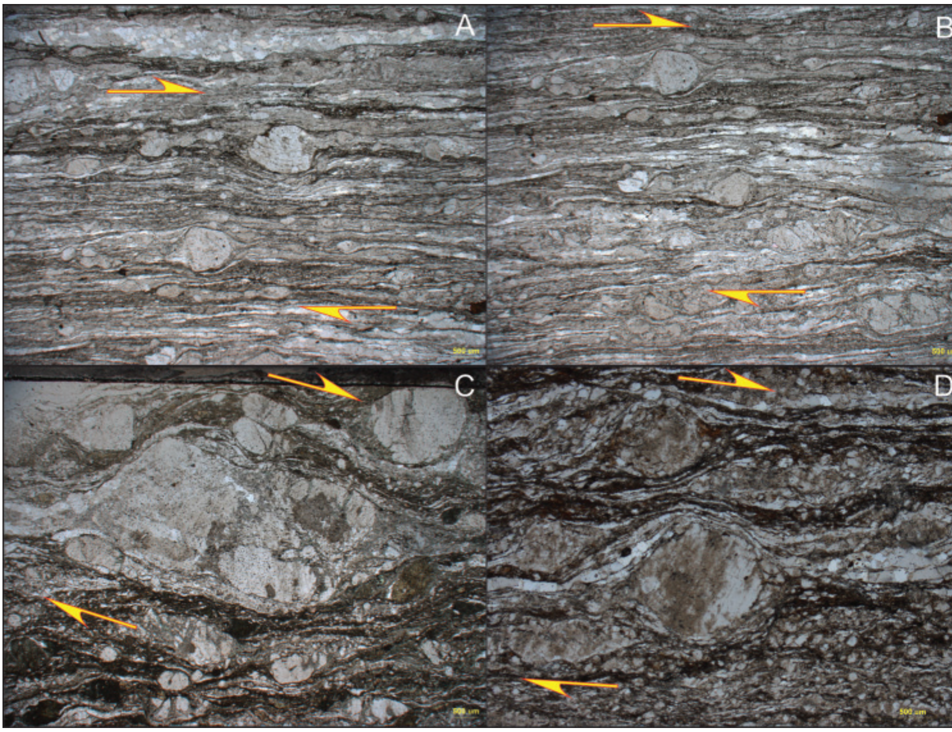

Fig. 19. Four photomicrographs showing asymmetrical feldspar porphyroclasts in mylonitic augen gneisses within the Xingxingxia Fault indicating dextral strike-slip motion. Position marked on figure 3.

are arc-related mafic-ultramafic complexes (Xiao and others, 2004b; Mao and others, 2005; Han and others, 2006; Ao and others, 2010; Xiao and others, 2010b); we interpret them as the latest product of subduction of an oceanic plate, or of a slab window created by subduction of an oceanic ridge.

In the Chinese Eastern Tien Shan there are similar Permian strike-slip faults (Shu and others, 1999, 2002; Laurent-Charvet and others, 2002, 2003; Charvet and others, 2007), and in the Huangshan, Xiangshan, and Jingerquan areas (Gu and others, 1994; Zhou and others, 2004b; Xiao and others, 2004b; Mao and others, 2005; Han and others, 2006) mafic-ultramafic complexes occur in regional ophiolitic mélanges and/or island arcs and have subduction-related geochemical signatures (Xiao and others, 2004b; Mao and others, 2005; Han and others, 2006).

Triassic Strike-slip Faulting

In addition to the strong thrusting and imbrication there was major strike-slip faulting in some mélanges of the Beishan collage. The Xingxingxia Fault (Mao and others, 2011) displays asymmetrical kinematic indicators showing top-to-the-south and dextral strike-slip shear senses (figs. 18 and 19) (Mao and others, 2011). According to the regional study of Xu and others (2008, 2009), in the Late Paleozoic-Early Mesozoic the Xingxingxia Fault mainly underwent dextral displacement; which is in good agreement with our observations. Of course, younger movements of possible Mesozoic to Cenozoic age may have caused sinistral displacements (Xu and others, 2008, 2009). It is important to note that the Xingxingxia Fault probably merges with the Altyn Tagh system further south, thus the Cenozoic sinistral slip that is obvious in figure 3 is not surprising.

Most importantly, along the fault and mélange there are in places Permian mafic volcanic rocks and clastic sediments that are strongly thrust-imbricated and juxtaposed against a variety of rocks of different ages. These mélanges also include many strongly deformed mafic-ultramafic rocks, cherts, pelagic and semi-pelagic sedimentary rocks, and turbidites (Xu and others, 2008, 2009; Mao, ms, 2008).

Some of the major strike-slip faults can be connected to the regional large-scale strike-slip fault systems, for instance, the Altyn Tagh, Tost and East Gobi Fault zones (fig. 2) (Ritts and Biffi, 2000; Davis and others, 2001; Johnson and others, 2001; Cope, ms, 2003; Johnson and others, 2003; Johnson, 2004; Johnson and Graham, 2004a, 2004b; Ritts and others, 2004; Cope and others, 2005; Darby and others, 2005; Cope and Graham, 2007; Johnson and others, 2007). These strike-slip fault systems mostly record multiple phases of movements (Ritts and Biffi, 2000; Graham and others, 2001; Yue and others, 2003, 2004; Ritts and others, 2004; Johnson, 2004; Webb and Johnson, 2006).

Timing of Major Thrust Deformation

Major thrust deformation includes structures that correlate with the principal faults and the main ophiolitic mélange zones. We have postulated that the major thrusting deformation of the accretionary tectonics was generated by major tectonic convergence in the Permian to Early Triassic, in which case major northward or northwestward subduction polarity may be inferred.

Late southward directed thrusting was recognized in the Beishan and adjacent areas (Zheng and others, 1996). This time of thrusting was bracketed by the fact that the youngest stratigraphic unit truncated by klippen is a Lower-Middle Jurassic coal-bearing unit and the fact that the extensional metamorphic complex was dated at 153 to 155 Ma, which Zheng and others (1996) thought should postdate the thrusting. Many investigations have been undertaken on the Mesozoic deformation in the southern Mongolia and China-Mongolia border area (Davis and others, 2001; Johnson and others, 2001; Cope, ms, 2003; Johnson and others, 2003; Johnson, 2004; Johnson and Graham, 2004a, 2004b; Cope and others, 2005; Cope and Graham, 2007; Johnson and others, 2007), and mostly these deformation events are later than the major tectonic events related to the closure of the Paleoasian Ocean (Darby and others, 2001; Johnson and others, 2001; Lamb and Badarch, 2001; Yue and others, 2001; Davis and others, 2002), which could not have been related to those in the Beishan discussed in this paper. However, these data are mainly from southern Mongolia and the China-Mongolia border area, a possible far-field effect of the subduction of the Mongol-Okhotsk Ocean several hundreds of kilometers to the north (Tomurtogoo and others, 2005; Kelty and others, 2008). Furthermore, the late southward thrusting involves mainly the Lower-Middle Jurassic coal-bearing unit whereas the thrusting in the Beishan area developed within ophiolitic mélanges and arc complexes. Even though the later thrusting would have overprinted the older one, which is a common case in accretionary orogens, the major thrusting deformation in the ophiolitic mélanges can still be recognized (see Cawood, 1984; Cawood and others, 2009). Some large-scale strike-slip faulting of Triassic age translated and cut nearly all these tectonic units which indicates that the major deformation related to the accretionary orogenesis should be older than Triassic.

Therefore the major deformation related to the accretionary orogenesis can be bracketed by the youngest strata found in the mélanges and arc complexes which were postdated by Late Permian-Triassic strike-slip faulting.

TECTONIC EVOLUTION

The Beishan orogenic collage of the southern Altaids records an important accretionary history for which several tectonic models have been proposed. The

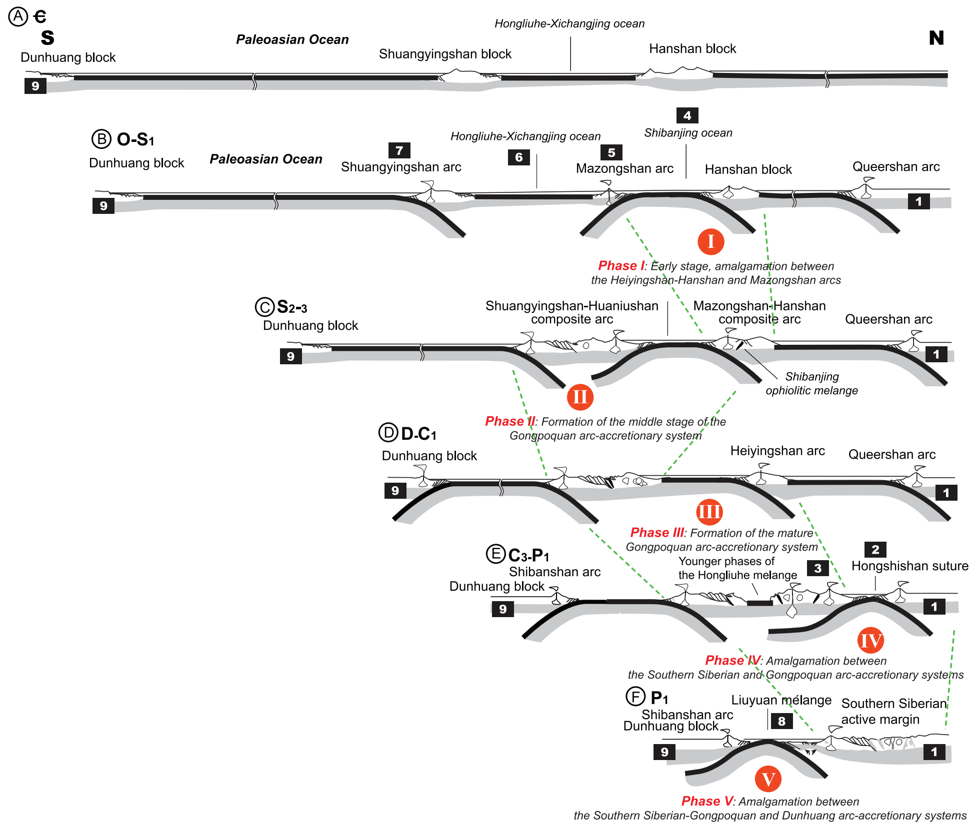

Fig. 20. Figures A–F: Sequential diagrams demonstrating the tectonic evolution of the Beishan orogenic collage in the Paleozoic (based on our own work and modified after He and others, 2002; Mao, ms, 2008). White numbers in black boxes correspond to those in figure 3.

availability of recent multi-disciplinary data (Gu and others, 1994; Gong and others, 2002; He and others, 2002; Zhao and others, 2003; Zhou and others, 2004b; Xiao and others, 2004b; Wang and others, 2004; Mao and others, 2005; Han and others, 2006; Huang and Jin, 2006b) enables us to present a viable model of the tectonic evolution.

Figures 4 and 20 demonstrate the spatial-temporal relationships between the various juxtaposed tectonic units. Although more high-resolution isotopic ages and detailed field studies are still required, an appreciation of the main peaks of magmatic-metamorphic-tectonic activity, and of recent paleomagnetic and paleogeographic data, will enable us to construct a robust and viable tectonic model. Therefore, before we present a detailed tectonic evolution, we shall briefly discuss these key datasets.

Magmatic-Metamorphic-Tectonic Peaks of Activity

In the construction of the Beishan orogenic collage there were two peaks of magmatic activity, in the Silurian-Early Devonian and Late Permian-Triassic, and a major peak of metamorphism in the Late Permo-Triassic (Mu and others, 1992). This is in good agreement with a 250 Ma magmatic-metamorphic peak in North Xinjiang based on an analysis of isotopic age data including detrital zircon ages (Hu and others, 2000) and the fact that North China rocks derived from the Solonker suture region have detrital age peaks at 400, 310, 295, and 260 Ma (Cope, ms, 2003; Cope and others, 2005, 2007; Cope and Graham, 2007). This is also consistent with the main intrusion time of mafic-ultramafic complexes in the Late Carboniferous-Permian (Gu and others, 1994; Zhou and others, 2004b; Xiao and others, 2004b; Mao and others, 2005; Han and others, 2006), and with the main period of stitching granitic intrusions being the Late Permian-Triassic (Zuo and others, 1990a, 1991; Liu and Wang, 1995; Nie and others, 2002; Gong and others, 2002).

Permian-Triassic tectonic events are well documented in the Beishan and adjacent areas (Xiao and others, 2008); these include large-scale thrusting, strike-slip faulting, and uplift (Lamb and Badarch, 1997; Cunningham and others, 2003; Cope, ms, 2003; Cope and others, 2005, 2007; Johnson and others, 2007; Lamb and others, 2008). The youngest strata involved in the thrust imbrication are of Permian age (Mao, ms, 2008).

All the above data-sets suggest that the Permian to Early Triassic was an important period, when the Beishan and adjacent areas experienced strong deformation, magmatism, and metamorphism during the last phases of accretionary orogenesis in the southern Altaids (Xiao and others, 2004a, 2009a, 2009b).

Paleomagnetic Data

Paleomagnetic data provide a powerful tool to decipher the fundamental tectonic geometry of ancient oceans and orogens. According to relatively reliable paleomagnetic data, the Siberian Craton was aligned in a north-south orientation, and accordingly its southern (present-day coordinates) Early Paleozoic active margin was positioned farther to the north (Van der Voo, 1993; Fang and others, 1996; Smethurst and others, 1998; Kravchinsky and others, 2002; Van der Voo and others, 2006; Huang and others, 2008). The orientations of the Tarim Craton and the active margin of the Dunhuang block were also likely aligned north-south with the Paleoasian Ocean between them, a geography similar to that of the present-day Pacific Ocean that separates the Eurasian continent to the west and the American continents to the east (Van der Voo, 1993; Fang and others, 1996; Smethurst and others, 1998; Kravchinsky and others, 2002; Van der Voo and others, 2006; Huang and others, 2008). The whole accretionary system of the southern Early Paleozoic active margin of the Siberian Craton subsequently rotated during the Late Permian-Triassic into its present-day orientation (Huang and others, 2008; Xiao and others, 2009a).

Paleomagnetic data also suggest that some arcs collided scissor-style with the first contact in the west, and closure moving progressively eastward along the Shibanjing ophiolitic mélange during the Middle Silurian (Huang and others, 1999, 2000, 2002). This kind of collision can well explain the formation of a composite arc (Santosh and others, 2009; Xiao and others, 2010a). Unfortunately, no Late Paleozoic paleomagnetic data from the Dunhuang block are available to better constrain the Late Paleozoic tectonic amalgamation history.

Paleogeographic Data

The distribution of Silurian and Devonian fauna indicate that the Beishan orogenic collage belonged to the Siberian paleogeographic domain (Rong and Zhang, 1982; Zhang, 1994; Torsvik and Cocks, 2004), because the southern (present-day coordinates) Early Paleozoic active margin of the Siberian Craton was located in a northerly latitude far from the Tarim Craton and the active margin of the Dunhuang block that was farther south. The southern early Paleozoic active margin of the Siberian Craton rotated in the Late Permian-Triassic into its present-day position (Xiao and Kusky, 2009; Xiao and others, 2009a, 2010a).

A systematic Early Carboniferous paleogeographic study (Zhang and Wang, 1996) demonstrated that the brachiopod fauna are similar in the Siberian Craton and the Kazakhstan block. All the floras are Angaran-type (Zhang and Wang, 1996). This reveals that in the Late Devonian-Early Carboniferous the Siberian Craton moved generally southward to be finally amalgamated with the Kazakhstan block and its surrounding arcs and/or terranes (Xiao and others, 2009a, 2010b). Results of tectonic investigations of Late Paleozoic accretionary events and of the Late Carboniferous suture confirm this paleogeographic scenario (Safonova and others, 2004; Rippington and others, 2008). However, in the Early Carboniferous the Kazakhstan block and the Tarim Craton must have been approaching each other, because they show mixed fauna. For instance, brachiopoda in the Kazakhstan block are different from that in the Tarim Craton, but foraminifera, fusulinas, and corals in the Kazakhstan block are similar to those in the Tarim Craton. The floras of the Tarim Craton are characterized by a lack of Angaran-type species (Zhang and Wang, 1996). The biota of the Tarim Craton was different from that of Siberia, which implies that they were separated by a major ocean; the Paleoasian Ocean. However, the Tarim Craton was not far from the Kazakhstan block, which means the Paleoasian Ocean was shrinking. The Late Carboniferous distribution of the Angara and Cathayasia floras and marine fauna show that the Angara floras were distributed north of the Hongshishan suture and the tectonic units south of the Hongshishan suture are characterized by Carboniferous marine fauna and the Cathaysia floras was only distributed south of the Duhuang block (Yue and others, 2001). This nearly continuous, wide boundary zone that is composed of mixed flora extends westward to the Tien Shan and eastward to the Inner Mongolia (Dewey and others, 1988), and should define an important divide in Central Asia in the Late Paleozoic (Xiao and others, 2008, 2009a, 2010b).

In the Early Permian the Angaran and Cathaysian floras began to mix in the Beishan area (Guo, 2000). This suggests that there was close contact between some parts of the northerly accretionary systems and the Siberian Craton, and the southerly distributed Tarim Craton and Dunhuang block. This was probably the situation in the Chinese eastern Tien Shan, when the Tarim Craton collided with the Central Tien Shan arc in the Late Carboniferous-Early Permian. However, in the Early Permian the flora in the Shibanshan arc belonged to the European-American domain (Zhu, 1997, 2001; Zhou and Yang, 2005), whereas the flora in the Turpan basin in the Eastern Tien Shan, which was roughly in the same tectonic position as the Gongpoquan and Queershan arcs, still had Angaran-type flora. In the Late Permian the flora in the Turpan basin were predominantly Angaran-type but were mixed with minor Cathaysian species. Some mixture of Angaran and Cathaysian floras was found in the Shibanshan area, which was on the northern margin of the Dunhuang block. This means that there was still an open ocean between the Beishan–Tien Shan archipelago to the north and the northern active margin of the Dunhuang block and Tarim Craton to the south in the Early Permian, although some parts could have been in initial contact.

We have proposed that this important biogeographic boundary, which is distributed along the Tien Shan–Solonker suture, indicates that at least in the Late Carboniferous, the Tarim and North China blocks were tectonically separated from the Siberia accretionary system. Therefore, the final amalgamation between these arcs, blocks and cratons took place in the Late Permian to Early-Middle Triassic (Xiao and others, 2008, 2009a, 2010b).

Tectonic Evolution Model

We have used the geological, geochemical and geophysical data summarized above in this paper to construct the following model for tectonic evolution of the Beishan orogenic collage.

In the Cambrian the Dunhuang block, located in the south, and the Queershan arc, in the north, were separated by the Paleoasian Ocean, the paleogeography of which included several blocks including Dunhuang, Shuangyingshan and Hanshan blocks (figs. 4 and 20A). The Hongliuhe-Xichangjing Ocean, a branch of the Paleoasian Ocean, was probably located between the Shuangyingshan and Hanshan blocks.

In the Ordovician to Early Silurian, the Queershan arc developed on the Siberian active margin above a north-dipping subduction zone (fig. 20B). Several nearby arcs were separated by intervening ocean basins. The intraoceanic Hanshan and Shuangyingshan arcs were situated above north-dipping subduction zones, but the Mazongshan arc was probably associated with south-dipping and north-dipping subduction zones.

In the Middle Silurian the Hanshan and Mazongshan arcs amalgamated, forming a composite Mazongshan-Hanshan arc; this was the early stage of formation of the Gongpoquan arc-accretionary system (Phase I, figs. 4 and 20C). The Shibanjing ophiolitic mélange may have been obducted northwards onto the Hanshan arc (fig. 20B).

In the Late Silurian to Early Devonian the ocean(s) between the Mazongshan-Hanshan arcs, represented by the Hongliuhe ophiolitic mélange, may have closed and the Hanshan arc became attached to the Gongpoquan arc; this was the middle stage of formation of the Gongpoquan arc-accretionary system (Phase II, figs. 3 and 20C). In D_2 time a new south-dipping subduction zone was created below the Dunhuang block. An intraoceanic arc (Heiyingshan) may have been generated by north-dipping subduction in the oceanic basin between the Queershan arc and the Gongpoquan arc-accretionary system (fig. 20D).

In the Middle to Late Carboniferous (fig. 20E), the Heiyingshan arc was attached to the Gongpoquan arc-accretionary system, giving rise to the mature stage of formation of the Gongpoquan arc-accretionary system (Phase III, figs. 3 and 20E). This left a two ocean-three block geometry in which there were three active margins or arcs separated by two oceans, which remained until the end of the Early Permian.

After the Carboniferous, the Paleoasian Ocean became gradually narrower and the Hongshishan ocean was bordered by two subduction zones beneath the Gongpoquan and Queershan arcs (fig. 20F). As convergence continued between these arc-accretionary systems, the two final ocean basins of the Paleoasian Ocean continued to subduct by double subduction zones (fig. 20F).

During the Late Carboniferous to Early Permian, the Hongshishan ocean was consumed by the two subduction zones beneath the Gongpoquan arc-accretionary system and the Queershan arc (fig. 20E). The young phases of the Hongliouhe ocean formed in the middle of a composite arc. The eastern Tien Shan end (promontory) of the Tarim Craton was probably in contact with arcs along the southern Siberian active margin, but leaving a remnant ocean (southern Tien Shan ocean) to the west (fig. 21). This formed a special active margin in the Tien Shan–Beishan junction area (fig. 21). In the meantime, several multiple arcs in the Chinese eastern Tien Shan were still above their subduction zones, and the Gongpoquan arc-accretionary system could have been interacting with this active margin. A mid-ocean ridge in the northerly Hongshishan ocean could have been subducting beneath the special active margin, generating Alaskan-type mafic-ultramafic complexes in the Chinese eastern Tien Shan to the west. Finally the Hongshishan ocean closed (Phase IV, figs. 3 and 20). Similar ridge subduction from the southerly Liuyuan ocean could have given rise to the emplacement of Alaskan-type mafic-ultramafic complexes into the southwest corner of the Beishan area, this being complicated by strike-slip faulting (fig. 21).

The double subduction zones consumed the Paleoasian Ocean to the south, and in the Permian all accretion was terminated (fig. 20), giving rise to the final amalgamated Beishan orogenic collage in the southern Altaids (Phase V, figs. 3 and 20).

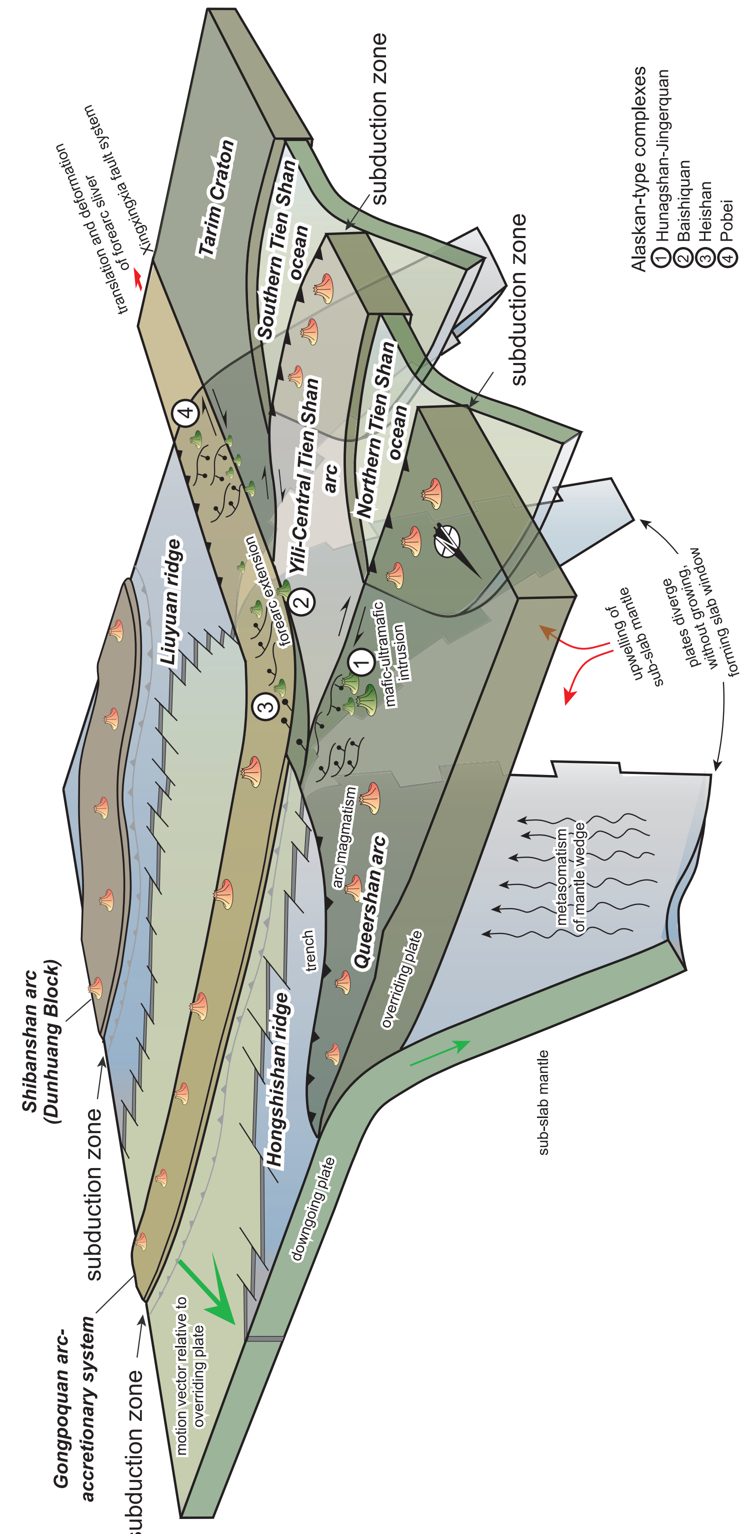

Fig. 21. Speculative but viable 3D diagram illustrating the tectonic evolution of the Beishan orogenic collage from the Late Carboniferous to Early Permian.

DISCUSSION

Correlations Along the Southern Altaids

The western segment of the final suture zone of the southern Altaids, the Southern Tien Shan suture, can be traced all the way along the Chinese Tien Shan (Allen and others, 1993; Zhou and others, 2001a; Xiao and others, 2010b, 2004a, 2004b; Shu and others, 2002; Laurent-Charvet and others, 2003; Charvet and others, 2007; Wang and others, 2007a) to the Kyrgyzstan Tien Shan and via there northward to the Urals (Konopelko and others, 2007; Biske and Seltmann, 2010). Although there are many different ideas about the time of the orogenesis along the southern Tien Shan, it is accepted that this orogen experienced a long-lived subduction-accretion history. Recently, based on the youngest component of Permian age and the youngest UHP metamorphic rocks found along the suture belt of the southern Tien Shan, it can be postulated that the majority of the Southern Tien Shan suture was formed in the Late Carboniferous to Permian and the termination of accretionary orogenesis even occurred at the end-Permian to mid-Triassic, as indicated by Late Carboniferous high-pressure/ultrahigh-pressure metamorphic belts and other geological and paleomagnetic data (Burtman, 1975; Windley and others, 1990; Allen and others, 1993; Che and others, 1994; Wang and others, 1994; Brookfield, 2000; Zhou and others, 2004a; Buslov and others, 2007; Xiao and others, 2009a, 2009b). The various tectonic units can be correlated across the Xingxingxia Fault although the Beishan may have more complicated components than shown in figure 3. The complicated situation across the Tien Shan and Beishan has been discussed by the international community (Zhou and Graham, 1996; Yang and others, 1997). Here we propose a new interpretation, which is illustrated in figure 21 with the Tarim block in the south, Yili-Central Tien Shan in the middle, and the Southern Siberian accretionary margin represented by the Queershan arc in the north. The three major tectonic units of the Tien Shan joined in the eastern part, leaving two seaways of the Southern Tien Shan Ocean and the northern Tien Shan Ocean (fig. 21). The Xingxingxia Fault probably marks the attachment of the Beishan to the Tien Shan, across which in the Beishan there was the Dunhuang block represented by the Shibanshan arc in the south, the Gongpoquan arc-accretionary system in the middle, and the southern Siberian accretionary margin represented by the Queershan arc in the north (fig. 21). Two spreading ridges were subducted beneath the Tien Shan, generating more ultramafic-mafic complexes and more large-scale strike-slip faulting (fig. 21).

The eastern segment of the final suture zone of the southern Altaids, the Solonker suture, records closure of another branch of the southernmost Paleoasian Ocean in the Permian to Mid-Triassic (Wang and Liu, 1986; Tang and Yan, 1993; Wang, 1996; Robinson and others, 1999; Xiao and others, 2003, 2009a; Chen and others, 2008). However, the tectonic history was even more complicated, because the Circum-Pacific and Paleoasian Ocean plates were subducted in the Triassic beneath the eastern end of the tectonic collage in northeast China (Wu and others, 2002, 2007).

Tracing this late Paleozoic to early Mesozoic suture zone from west to east, the Beishan orogenic collage in the central part documents an important stage of end-Paleozoic accretion and final amalgamation of the Dunhuang block to the southern Siberian accretionary system.

The Gongpoquan arc-accretionary system appears to have an identical history to the Yili-Central Tien Shan arc or accretionary system in the Chinese Tien Shan to the west. Although the Carboniferous-Permian Southern Tien Shan suture was blocked in the Chinese Eastern Tien Shan, because this was the first contact point in the long amalgamation history between the Siberian active margin and the Tarim Craton and Dunhuang block, the Permian Liuyuan mélange zone (fig. 21) occupied a very similar suture zone, which appears to be identical to the southern Tien Shan suture zone.

Although more detailed work is required for confirmation, it is likely that the Liuyuan mélange extended eastwards and connected with the Ugger Us ophiolites, and farther east to the Solonker suture in Inner Mongolia (fig. 2) (Wu and others, 1998; Xiao and others, 2009a). Some ophiolitic mélanges have been found along the Ugger Us area and the main structure lines are more or less parallel to those in the Beishan with NE-trends (Wu and others, 1998). The formation ages of these ophiolitic mélanges are defined as Carboniferous to Permian (Wu and others, 1998; Wang and others, 1998).

However, the tectonic framework in the connection area between the Liuyuan, Ugger Us and Solonker sutures is complicated as large-scale strike-slip faults systems, such as the Altyn Tagh and East Gobi Faults, translated the various tectonic units (Ritts and Biffi, 2000, 2001; Yue and others, 2001, 2003; Cope, ms, 2003; Ritts and others, 2004; Cope and others, 2005). The coverage of deserts in this vast area makes a detailed investigation of the surface structures difficult. More integrated geophysical and geological investigations should be conducted in this area to resolve these issues.

The eastern part of the Central Asia Orogenic Belt is further complicated by reworking in association with Pacific subduction along the East Asia margin since latest Triassic times (Wilde and others, 2009; Zhou and others, 2009).

Modern Analog

The present-day Australia-Timor collision zone provides a modern analog of the Beishan orogenic collage (Hall, 2002; Stern, 2010). Australia could be regarded as equivalent to the Tarim Craton. If another continent could exist to the east, then it could be regarded as the North China Craton. The arc-accretionary systems in between (archipelagos near Papua New Guinea) could be equivalent to the Beishan orogenic collage. Van Staal and others (1998) proposed a forward model of plate motions of the SE Asia-SW Pacific region at 45 Ma into the future when continental collisions will be taking place and relative plate motions will cease, so forming a complicated orogenic collage along the southeastern margin of the Australian plate. We further postulate that if another continent (we assume it would be equivalent to the North China Craton) would move northward to the orogenic collage along the eastern margin of Australia plate, a more complicated accretionary and collisional scenario would appear.

Significance for Accretionary Orogenesis

Accretionary orogenesis has played an important role in the geological history of our planet (Cawood and Buchan, 2007; Condie, 2007; Cawood and others, 2009; Brown, 2009). The accretionary and collisional orogenesis of the Altaids offers an ideal template to analyze the causes, effects and results of such processes. Accretionary orogenesis typically generates an orogenic collage that is as broad as it is long, and it evolves for a long period of time, which may encompass several important stages of orogenesis. The Altaid accretionary processes started at least by 1.0 Ga in the north with generation of a supra-subduction zone ophiolite (Khain and others, 2002), after which accretionary growth migrated and became younger southwards from southern Siberia all the way to the Tien Shan–Beishan orogenic collages in China and southern Mongolia. This long-lasting accretion terminated at the latest in the Mid-Triassic in the southernmost Altaids (Xiao and others, 2004a, 2009a, 2009b). Accretion and crustal growth continued elsewhere as a result of closure of the Mongol-Okhotsk ocean in the Jurassic to Early Cretaceous (Tomurtogoo and others, 2005), and also by subduction of the Circum-Pacific plate in the Mesozoic-Cenozoic (Hou and Boucot, 1990; Soloviev and others, 2006; Wilde and others, 2009). Thus the growth of a supercontinent is inevitably related to a long succession of accretionary and collisional events, well exemplified by the history of the Altaids.

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