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PALEOZOIC ACCRETIONARY AND COLLISIONAL TECTONICS OF THE EASTERN TIANSHAN (CHINA): IMPLICATIONS FOR THE CONTINENTAL GROWTH OF CENTRAL ASIA

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ABSTRACT. This paper deals with the various tectonic units in the Chinese Eastern Tianshan orogenic collage in the Central Asian Orogenic Belt, and discusses the Paleozoic geological history of the several periods of accretion and collision of archipelago systems lying between the Tarim and southern Angaran continental margins. The Late Ordovician-Silurian to Early Devonian Eastern Tianshan archipelago was characterized by (a) the Harlik-Dananhu subduction system with a S-dipping polarity in the north; (b) a southerly N-dipping subduction system beneath the Central Tianshan arc in the middle; and (c) the South Tianshan ocean against Tarim in the south. During the Devonian to Early Carboniferous, N-dipping subduction led to the Harlik-Dananhu arc and the Kanggurtag forearc basin/accretionary complex. In the Early to Mid-Carboniferous, the magmatic front associated with the N-dipping subduction beneath the Dananhu-Harlik arc migrated southwards, forming the Yamansu arc constructed upon the Kanggurtag accretionary forearc. By the Late Carboniferous the Dananhu-Harlik arc was attached northwards to the Angaran margin, resulting in lateral enlargement of the Angaran continent. In the latest Carboniferous to Early Permian a multiple soft collision left wide suture zones in the south that include the ophiolite-strewn Aqikkuduk-Shaquanzi and Kumishi accretion-collision complexes, which were stitched by Early Permian post-collisional plutons. By re-defining and re-interpreting the various tectonic terranes, this paper presents a new, improved model for the Paleozoic evolution of this part of Central Asia.

INTRODUCTION

Formation of the Central Asian orogenic belt (CAOB), or Altaids, was dominated by the accretion of continental blocks, arcs, and accretionary complexes during Paleozoic time. Following assemblage of this tectonic amalgamation, the Tarim and North China blocks were accreted to Asia's southern margin, thus closing the Paleo-Asian ocean and forming a major suture zone in central-eastern Asia (Coleman, 1989; Windley and others, 1990; Şengör and others, 1993; Jahn, 2001; Bazhenov and others, 2003). It is heatedly debated whether the Central Asian Altaids was constructed by syn-subduction oroclinal bending of a single, long-lasting, subduction system (Şengör and others, 1993; Şengör and Natal'in, 1996), or by several subduction systems with different polarities and by the collision of micro-continents (Coleman, 1989; Mossakovsky and others, 1993; Hsü and others, 1995). In particular, the following question arises: in so far as Central Asia grew outwards from the Angaran craton, does forearc accretion (Şengör and others, 1993; Şengör and Natal'in, 1996) or backarc collapse (Hsü and others, 1995; Hsü and Chen, 1999) provide a more viable model to explain the development of this accretionary orogen?

The Chinese Eastern Tianshan is the easternmost segment of the Tianshan Mountain Range in the southern Altaids; it occupies a key position between the Central Asian orogenic belts to the west and east (fig. 1). Well-exposed ophiolitic, ultramafic, volcanic, and metamorphic rocks, along with mélanges and flysch sediments have been interpreted as relics of an orogenic collage that once existed in the Paleo-Asian ocean (Coleman, 1989; Windley and others, 1990; Xiao and others, 1992; Zhou and others, 2001a; Zhang and others, 2002, 2003, 2004). Therefore, the Chinese

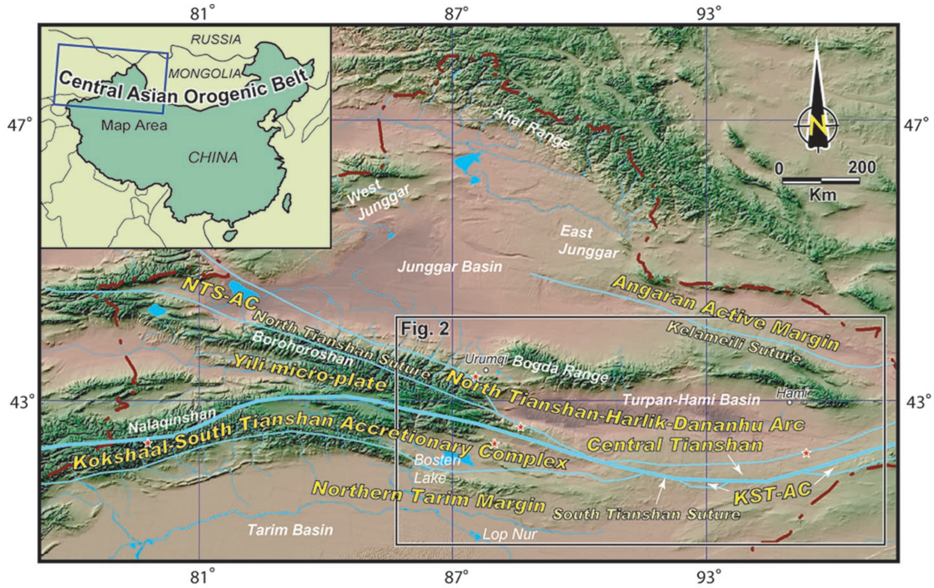

Fig. 1. Schematic map of Northern Xinjiang showing the main structures in the Eastern Chinese Tianshan (fig. 2) with emphasis on the Kokshaal-south Tianshan accretionary complex (KST-AC) in the central Asian orogenic belt. NTS-AC: North Tianshan accretionary complex. Dashed line outlines the North Xinjiang region. Stars are localities of blueschist /eclogite of late Paleozoic (modified after Gao and others, 1995; Liu and Qian, 2003; Xia and others, 2004).

Eastern Tianshan offers a special opportunity to study the Pre-Mesozoic assembly of Central Asia.

Diverse models have been applied to the Paleozoic geological evolution of the Chinese Eastern Tianshan (Windley and others, 1990; Carroll and others, 1990, 1995; Hendrix and others, 1992; Allen and others, 1993a; Fang, 1994; Zhang, 1994; He and others, 1994; Ma and others, 1997), but no consensus emerged. Particularly controversial are specific problems such as the polarity of subduction zones and the position of the final suture zone of the Paleo-Asian ocean (Ma and others, 1993, 1997; Yang and others, 1996). This paper aims to amplify current understanding of the Pre-Mesozoic assembly of Central Asia by describing the final collision of the Tarim block to the Angaran Paleozoic active margin of the CAOB. Our study is based on fieldwork through 1998 to 2001, during which time we analyzed the tectono-stratigraphic units in the Chinese Eastern Tianshan. We have integrated our field observations and interpretations with geochemical, geochronological and metallogenic data from key areas, and with existing literature. We place our observations into a plate tectonic framework and discuss the implications of our work for constraining recent controversies in this part of Central Asia.

REGIONAL GEOLOGY AND PREVIOUS MODELS

The Chinese Eastern Tianshan is a ca. 300 km wide orogenic collage that separates the Angaran continental margin to the north from the Tarim block to the south (figs. 1 and 2). The Chinese Eastern Tianshan is divisible into the northernmost Tarim block, southern Tianshan suture, Central Tianshan arc, Northern Tianshan suture, and North Tianshan arc. Windley and others (1990) suggested two collisions to explain the Paleozoic orogenic history of this mountain range; an older, southern collision

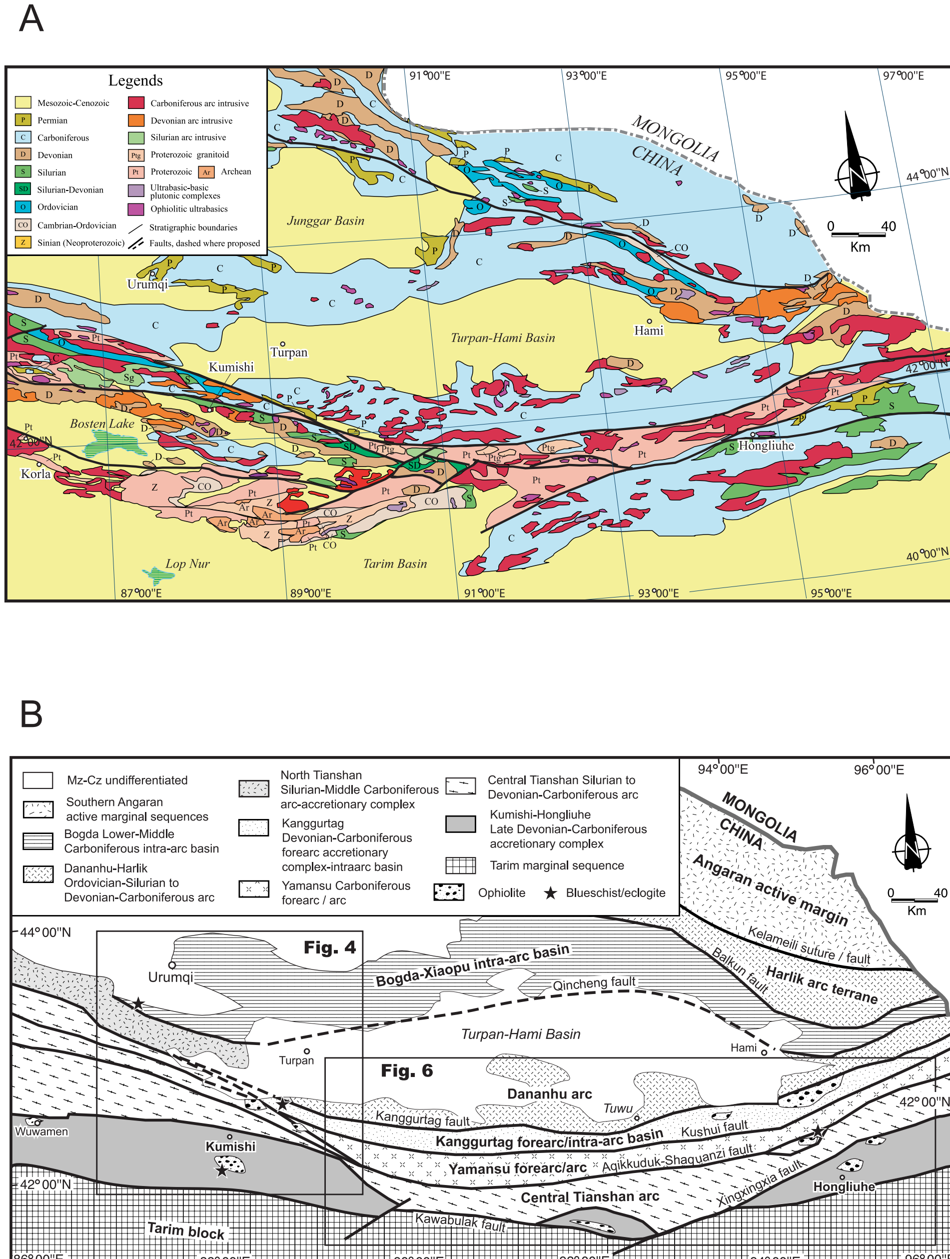

Fig. 2. (A) Geological map of the Eastern Chinese Tianshan with emphasis on the distribution of arc-related intrusives of Devonian-Carboniferous age (modified after Jiang and others, 2001a, 2001b; XBGMR, 1993; and our own observations). (B) Tectonic map of the Eastern Chinese Tianshan, central Asia (based on our observations and modified after XBGMR, 1993; Ma and others, 1997). Positions of figures 4 and 6 are shown.

accreted a north-facing passive continental margin on the north side of the Tarim block to an active continental margin on the southern side of a central elongate continental tract, the Central Tianshan arc (Allen and others, 1993a). A younger collision accreted the northern side of the Central Tianshan arc to the North Tianshan island arc, giving rise to the Northern Tianshan suture (Allen and others, 1993a). However, some Chinese geologists favor an Early Paleozoic closure for the Northern Tianshan suture (Zhu and others, 2002). For instance, Ma and others (1997) suggested the final suturing occurred along the Kelameili suture in the Mid-Carboniferous, but Yang and others (1996) and Zhou and others (2001b) favored the Kanggurtag zone located between the Kanggurtag and Kushui faults for the termination of the Paleo-Asian ocean in the late Carboniferous. These models are different from those suggested by Windley and others (1990) and Allen and others (1993a) who studied the Chinese Tianshan mainly along transects in the western part of the Chinese Eastern Tianshan. Recently Dumitru and others (2001) ascribed the latest Paleozoic cooling episode to deformation and exhumation induced by the collision of the Tarim-Central Tianshan composite arc with the North Tianshan arc, and proposed that the collision occurred diachronously east-west along the length of the Tianshan in Late Carboniferous-Early Permian time. Carroll and others (2001) systematically described Sinian through Permian tectonostratigraphy in the northwestern part of the Tarim block, and proposed that a flexural foredeep formed along the northern Tarim margin in response to Early Carboniferous collision between Tarim and the Yili block (Carroll and others, 1995; Gao and others, 1998; Allen and others, 1999; Chen and others, 1999). Zhou and others (2001a) inferred that a N-dipping subduction beneath the Central Tianshan arc continued in the Chinese Western Tianshan through the Early Carboniferous. Carroll and others (1995, 2001) and Allen and others (1999) also suggested that the collision between the Tarim block and the Central Tianshan arc might not have occurred until the Middle Carboniferous. Therefore, the exact position and timing of the final suturing of the Chinese Eastern Tianshan is not unanimously agreed. Therefore the exact suturing and the termination of the Paleo-Asian ocean in this part of Central Asia require re-evaluation. The many models reflect the present paucity of data. There is no consensus on the definition of the various tectonic units in the Chinese Eastern Tianshan. Expansion and improvement of the data set for this orogen are crucial in order to develop a tectonic framework and to define viable models for the evolution of Central Asia. We describe below the tectonic units from north to south.

SOUTHERN ANGARAN COMPOSITE ARC-KELAMEILI SUTURE ZONE

The northernmost tectonic domain discussed in this paper is the East Junggar arc and associated accretionary complex, forearc basin succession and ophiolite, which forms a composite arc domain along the southern Angaran active margin. One important element is the Kelameili ophiolite that crops out mainly along the Kelaimeili fault (fig. 2B), containing serpentinized peridotite, serpentinite, pyrolite, gabbro, rodingite and basalt, overlain by chert (Ma and others, 1997). The ophiolite was interpreted as remnants of a Middle Paleozoic Kelameili ocean which separates the Angaran plate to the north from the East Tianshan domain to the south. The geochemistry of the ophiolite suggests a supra-subduction zone origin in a forearc setting (Wang and others, 2003). The chert yields Devonian and Carboniferous radiolaria (Ma and others, 1997; He and others, 2001). A number of isotopic dates on the ophiolite indicate an Early Paleozoic age for the ocean floor (Hu and others, 2000). The rocks are structurally imbricated with strongly deformed Devonian-Carboniferous arc volcanic rocks. Fracture zones in the ultramafic rocks are filled with steeply dipping chlorite-quartz schist, some of which is imbricated with quartz-schist within a strongly sheared accretionary wedge. Volcanic and associated pyroclastic rocks, and turbidites, ranging from Ordovician-Silurian to Devonian-Lower Carboniferous in age, of possible forearc basin origin were also imbricated into the accretionary wedge (Xiao and others, 2004).

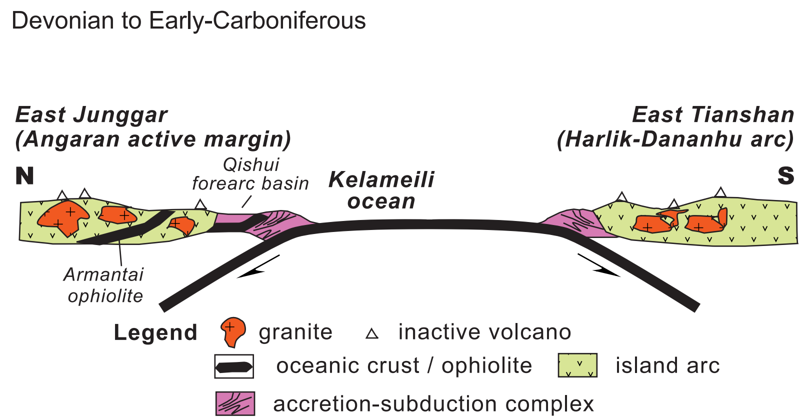

Fig. 3. A tectonic model for the Kelameili suture zone showing two way subduction in the Devonain-Early Carboniferous (modified after Ma and others, 1993; 1997; Li and others, 2001; Xiao and others, 2004).

This southern Angaran composite arc was the backstop of the Kelameili ophiolite and accretionary wedge (fig. 3). According to Fang (1994) and Ma and others (1997), a southward subduction zone beneath the East Tianshan resulted in the formation of the Harlik-Danahu arc where calc-alkaline arc volcanics and related basins are distributed. Gu and others (1999) conducted a systematical investigation on the granites in the Kelameili-Harlik belt, and they have found that granitic rocks of calc-alkaline geochemistry, affiliated to the B-type subduction at active margin, are distributed along the Kelameili fault southeastwards to Harlik on both sides of the Kelameili ophiolitic zone. Therefore, two arc systems were active along the southern and northern edges of the Kelameili ocean during the Middle Paleozoic (fig. 3), which amalgamated together in the Middle Carboniferous (Ma and others, 1997).

HARLIK-DANANHU ARC SYSTEM

South to the Kelameili fault, the Harlik-Dananhu arc and the Xiaopu-Bogda intra-arc basin crop out along the northern edges of the Turpan-Hami basin (figs. 2B and 4). This arc system can be correlated with the North Tianshan arc of Windley and others (1990) and Allen and others (1993a), where imbricated mid-Carboniferous volcanics have been thrust southwards over Lower Permian and Jurassic sediments (exposed along the Tuokexun-Baiyanghe road) (fig. 5).

In the north the Harlik arc (fig. 2B) was interpreted by Ma and others (1997) to be a Devonian-Carboniferous arc related to south-dipping subduction of the Kelameili ocean. The oldest rocks are Lower Ordovician metamorphosed clastics, volcaniclastics, tholeiites and andesites (Ma and others, 1997; Li and others, 2003). The overlying Upper Ordovician is mainly composed of slightly metamorphosed clastics, volcanics and minor marbles. These rocks belong to an Ordovician immature island arc created by south-dipping subduction of the Kelameili oceanic floor (Ma and others, 1997). In Devonian and Carboniferous time, it developed into a mature arc with Devonian mafic and felsic volcanic rocks and Carboniferous flysch sediments. Granitoids in the Harlik and Balkun ranges with isotopic ages ranging from 330 to 310 Ma intruded the Harlik arc (Ma and others, 1997).

The southern part of the arc system (figs. 2B and 6), composed of Ordovician to Devonian-Carboniferous volcanic and pyroclastics rocks, makes up the so-called Dananhu arc, which mainly crops out along the southern edge of the Turpan-Hami basin. Recently Ordovician-Silurian calc-alkaline volcanic rocks of possible active

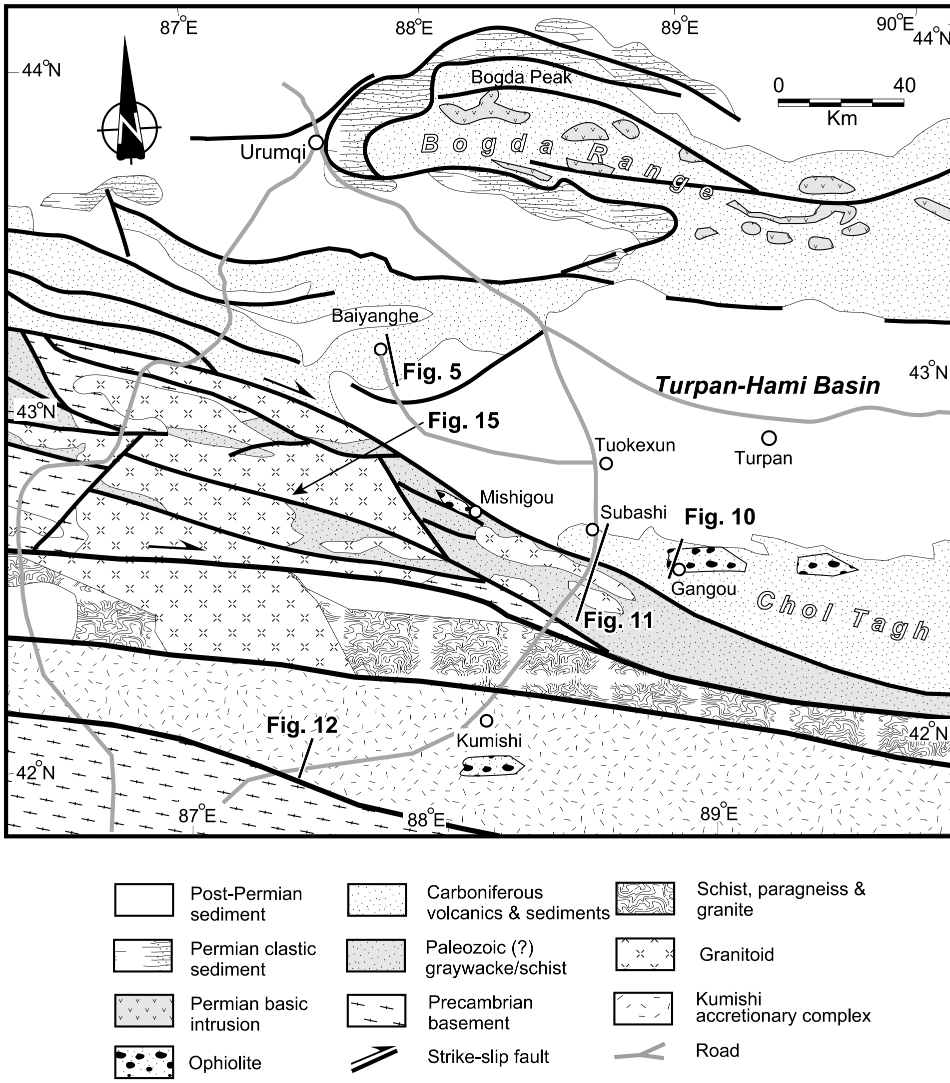

Fig. 4. Geological map of the Bogda-Chol Tagh area in the Eastern Chinese Tianshan (modified after Allen and others, 1993a). Localities of figures 5, 10, 11, 12, and 15 are shown.

margin origin have been found by detailed geological mapping along the southern edge of the Turpan-Hami basin (Qin and others, 2002; Li and others, 2003). The Devonian Kalatag, Dananhu, Tousuquan, and Kanggurtag Formations mainly consist of basic lavas, pyroclastic rocks, clastic sediments, and calc-alkali felsic volcanic lavas and tuffs; the Carboniferous Xiaorequanzi Formation, the Qiatekaertag Group, and the Dikaner Formation mainly consist of lavas, pyroclastic rocks, graywacke, and carbonates. Devonian-Carboniferous tholeiitic basalt and calc-alkaline andesite were interpreted to be volcanic rocks of an island arc (Yang and others, 1996, 2000; Zhou and others, 2001b). SHRIMP zircon ages of 358 ± 7 Ma for a granodiorite, 383 ± 9 Ma for an arc granite (Song and others, 2002), and 334 ± 2 Ma for a plagioclase grano-porphyry (Liu Dequan, personal communication), indicate that the arc has a

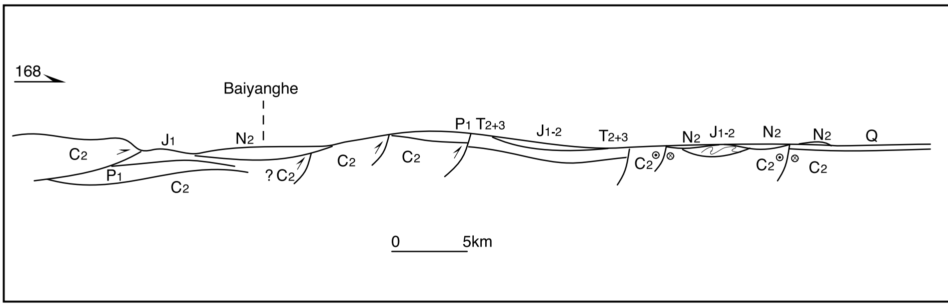

Fig. 5. Cross-section from Baiyanghe to Tuokexun demonstrating southward imbrication of Mid-Carboniferous volcanics and Lower Permian clastics. Section line is marked in figure 4. Q: Quaternary; N_2: Neogene; J_{1-2}, J_1: Lower-Middle Jurassic, Lower Jurassic terrigenous clastics and coal; T_{2+3}: Mid- and Upper Triassic terrigenous clastics; P_1: Lower clastics and limestones; C_2: Middle Carboniferous volcanics and volcaniclastics.

Mid-Devonian-Early Carboniferous age. This age is in agreement with isotopic data from the recently discovered Tuwu and Yandong island arc and its porphyry copper-gold deposits, with a U-Pb zircon age of 356 ± 8 Ma for granite of the Tuwu-Yandong porphyry copper mine and a $^{39}Ar/^{40}Ar$ age of 347 ± 2 Ma for a copper-bearing quartz vein (Qin, 2000; Qin and others, 2002). A Re-Os isochron date of 322.7 ± 2.5 Ma for the deposits (Rui and others, 2002) suggests that the arc magmatism lasted until the end of the Early Carboniferous. This southern Dananhu arc formed as a result of north-dipping subduction.

KANGGURTAG FOREARC ACCRETIONARY COMPLEX

In fault contact with the Dananhu arc to the north, the Kanggurtag forearc accretionary complex contains marine lavas and pyroclastic rocks that were thrust southward over the Yamansu forearc and arc (figs. 2B, 7, and 8). These rocks are subdivided into two major tectonic assemblages: strata in the southern part, and mélanges and broken formations in the northern part (Yang and others, 1996). The coherent strata include mainly volcano-sedimentary rocks that make up several formations of Lower to Mid-Carboniferous age. Geochemistry of tholeiitic rocks in these formations suggests an island arc origin (Yang and others, 1996).

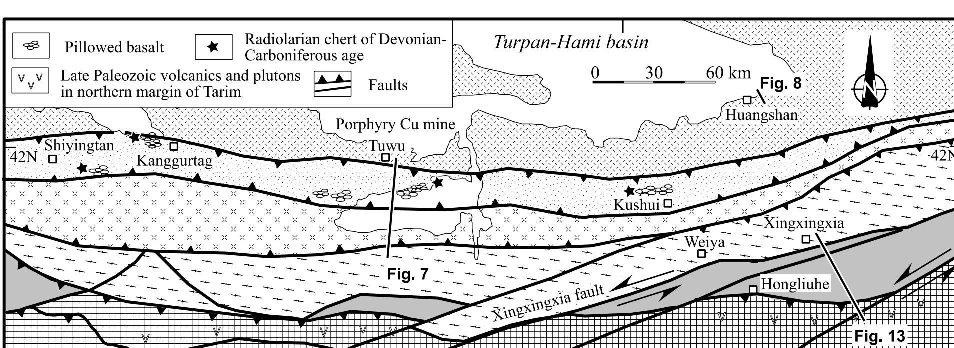

Fig. 6. Tectonic map of Kanggurtag-Hongliuhe area of the Eastern Chinese Tianshan (our observations incorporated with those of Ma and others, 1997). Fill patterns as in figure 2B except as indicated. Localities of figures 7, 8 and 13 are shown. See figure 2B for location.

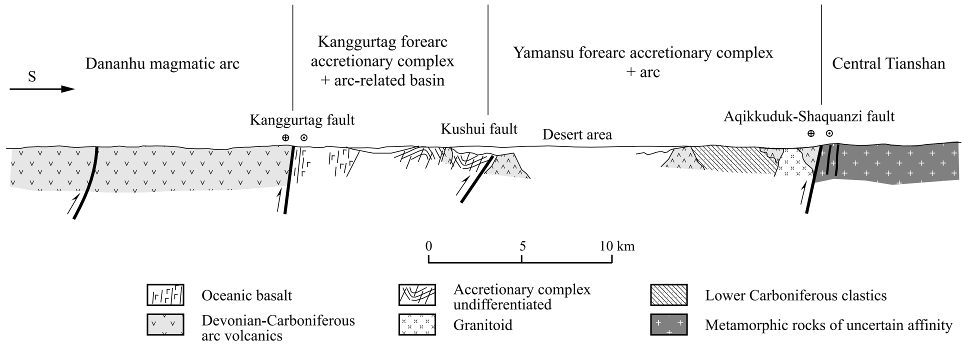

Fig. 7. The Tuwu cross-section demonstrating imbrication and thrusting of various tectonic units. Section line is marked in figure 6.

The broken formations and mélange include several Devonian-Carboniferous volcano-sedimentary rock formations (fig. 9) (Ji and others, 1994a; Yang and others, 1996; Ma and others, 1997; Zhou and others, 2001b). Meta-basaltic lava, spilite, keratophyre, tuff, chert and deep-sea turbidite were mutually imbricated into a 5-km-thick sequence. The Devonian to Carboniferous, partly mylonitized, siltstone, fine-grained sandstone, chert, spilite, tuffaceous sandstone, and limestone, are imbricated and structurally repeated by thrusts. Graywacke and turbidite are juxtaposed against mélanges that consist of blocks of black tuffaceous sandstone, felsic and basic lava, pillow lava, mylonitic graywacke, limestone, and chert in a matrix of graywacke, sandstone, siltstone, and mylonitized turbidite (Yang and others, 1996). Strong deformation has structurally repeated the thickness of the turbidite, and foliation has replaced original bedding. High and low strain zones were imbricated into thrust belts

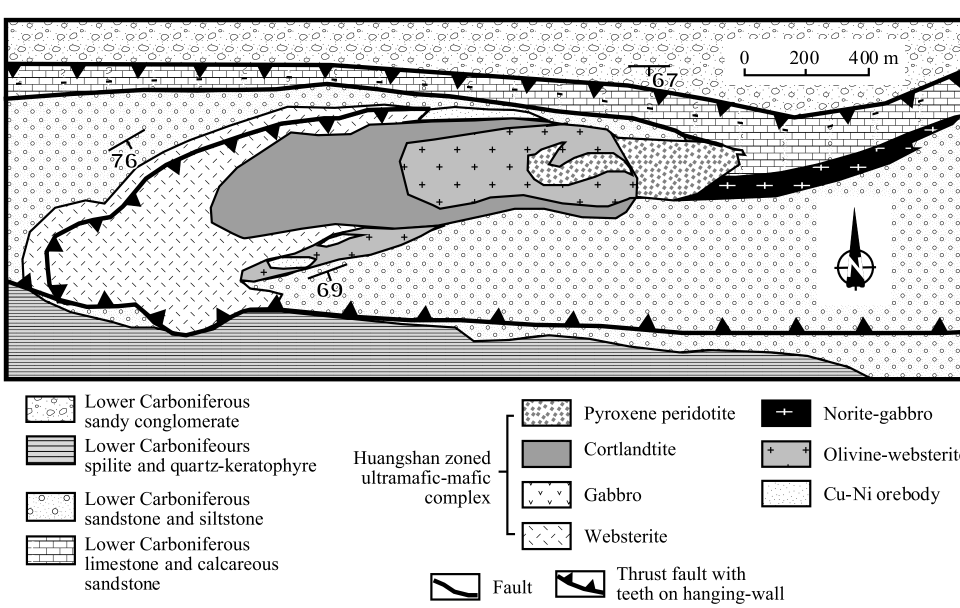

Fig. 8. Geological map of the Huangshan zoned ultramafic-mafic complex, see figure 6 for location.

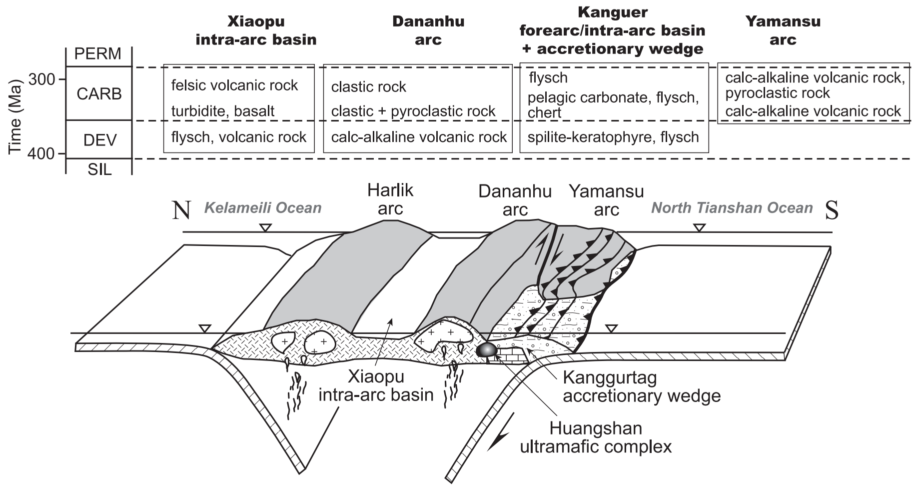

Fig. 9. Idealized model for the paleo-tectonic settings of the Harlik-Dananhu arc systems and Yanmansu forearc in Devonian-Carboniferous time.

(Yang and others, 1996; Ma and others, 1997). We interpret the mélange, thrust belts and their associated sediments in terms of an accretionary wedge. The geochemistry of imbricated pyroxenite, andesite, dacite, tuff, and volcanic breccia suggests an island arc source (Ji and others, 1994a).

Ophiolitic slices including serpentinite, pillowed basalt, meta-gabbro, meta-basalt, meta-diabase, meta-plagiogranite, quartz keratophyre, and chert have been structurally juxtaposed against graywacke, phyllite, sericite schist, and meta-tuff in the Kanggurtag area (Li and others, 2000). Geochemical data indicate that the ophiolitic rocks are remnants of oceanic crust (Li and others, 2000). Metamorphosed pillow basalt lavas have the geochemical signature of oceanic tholeiite (Zhou and others, 2001b). Yang and others (1998) reported Devonian to Carboniferous radiolaria, and Li and others (2003) discovered possible Late Silurian to Early Carboniferous radiolaria in cherts.

The interpretation of the whole set of rock assemblage of the Kanggurtag belt is controversial, and various tectonic settings have been suggested. For example, some geologists proposed that the Kanggurtag belt represents a suture zone separating Siberia to the north and the Tarim block to the south, based on the ophiolitic fragments found in the belt (Ji and others, 1994a; Yang and others, 1996; Ma and others, 1997; Zhou and others, 2001b). Others, however, favor an inter-arc basin origin for the Kanggurtag belt because of its distribution between the Harlik-Dananhu and Yamansu arcs (Ma and others, 1997; Shu and others, 2002). While we agree that there are some components of possible inter-arc basin, we also note a migration of magmatic front as indicated by the fact that the Harlik-Dananhu arc started in the Ordovician and has a relatively longer history than the Yamansu arc which is proposed to be active at Devonian-Carboniferous time (see next sub-section). Mélanges are not exclusive to a particular setting; nevertheless they are commonly associated and recognized in subduction-related environments. The composition and structures of these ophiolitic fragments, coherent and broken formations, together with mélange, are indicative of a Late Silurian to Carboniferous forearc basin and an accretionary wedge which can be correlated very well to the Cenozoic accretionary wedge found in Japan (Soh and others, 1998; Tagami and Hasebe, 1999; Taira, 2001) and other accretionary wedges

(Brandon and Vance, 1992; Şengör and others, 1993; Batt and others, 2001; Xiao and others, 2002a; Ring and Layer, 2003; Onezime and others, 2003; Hosseini-Barzi and Talbot, 2003). It is reasonable to relate this Silurian-Carboniferous Kanggurtag accretionary wedge to the northerly Ordovician to Devonian-Carboniferous Dananhu arc system rather than simply only to the younger, southerly Devonian-Carboniferous Yamansu arc. Although the possibility of back-arc origin can not be totally ruled out, the above-mentioned meta-basaltic lava, spilite, keratophyre, tuff, chert and deep-sea turbidite imbricated into a 5-km-thick sequence could have formed in a forearc or near-trench setting. This interpretation is in good agreement with the gold-copper deposit distribution and the Alaskan-type ultramafic-mafic complex.

Along the Kanggurtag fault is an ultramafic-mafic complex several hundred kilometers long that was previously thought to be an ophiolite representing a consumed ocean based on geochemical and geological study (Ji and others, 1999, 2000; Zhou and others, 2001b). The complex includes peridotite, lherzolite, gabbro, olivine gabbro, honblende gabbroic norite, pyroxenite diorite, and diorite. In the Huangshan area some ultramafic-mafic bodies (fig. 8) have concentric zones with a dunite core that grades outwards through peridotite to olivine pyroxenite and hornblende gabbro (Ma and others, 1997); some contain copper and nickel deposits (Hao and Zhang, 1988; Goldfarb, 1997). The zoned bodies intruded into and were imbricated with intensely deformed Devonian and Carboniferous strata. Geochemical data from the Huangshan complex suggest that these rocks are similar to oceanic tholeiite and MORB (Zhou and others, 2001b). We view these rocks as analogous to the Alaska-type zoned ultramafic complexes in the Togiak arc in Goodnews Bay in southwestern Alaska (Taylor, 1967; Goldfarb, 1997; Goldfarb and others, 2001) and to the Zhamashi ultramafic-mafic intrusive complex in the Qilian fold belt (Tseng and others, 2002). A U-Pb zircon age of 280 Ma (Qin, 2000; Qin and others, 2002) and SHRIMP zircon ages of 269.2 $\pm$ 3.2 Ma and 277.0 $\pm$ 1.6 Ma (Li and others, 2003) confirm that the ultramafic-mafic complex mainly formed in the Early Permian (Ji and others, 1999, 2000), which was simultaneous with the eruption of early Permian basic lavas and the intrusion of granitic plutons in the area. The Early Permian age and spatial association with the Kanggurtag and Yamansu arc-accretion complexes suggest that these rocks represent the final pulse of the Yanmansu arc, emplaced along the forearc accretionary belt between the Yanmansu arc and the continental margin backstop.

There are considerable gold deposits in this accretionary complex (Qin, 2000; Qin and others, 2002, 2003; Rui and others, 2002). The N-S distribution of porphyry-type gold-copper, orogenic-type gold, and epithermal gold is similar to that in Alaska (Goldfarb, 1997), where NE-dipping subduction of the Pacific ocean has given rise to a progressive sequence from orogenic gold to porphyry-type gold-copper deposits. Therefore distribution of gold deposits also supports the interpretation that the subduction polarity in the Chinese Eastern Tianshan was mainly to the north.

The Kanggurtag gold-copper metallogenic belt extends EW for ~600 km and NS for 100 km (fig. 6) and includes the region to the south of the Turpan-Hami basin. It constitutes one of most important gold-copper metallogenic belts and latent gold-copper-producing regions in China (Zhang and others, 2002, 2004; Qin and others, 2003). The gold deposit at Kangurtag Mine is an important representative of the belt. The host rocks of the gold deposit belong to the calc-alkaline volcanic series and consist of andesite, dacite, tuff and sub-volcanic rocks. A tonalite near the ore deposit played an important role in the ore-forming process. The gold ore bodies occur in a traverse zone that exhibits strong ductile to weak brittle deformation, and the specific ore-controlling structure is an EW-trending normal brittle-ductile shear zone (Zhang and others, 2002, 2004; Qin and others, 2003). The ore bodies are composed of Au-bearing altered volcanic rocks and a few Au-bearing sulfide-quartz veins. The explored orebodies extend below the surface for over 600 meters (Zhang and others, 2002, 2004).

The Shiyingtan (also called Xitan) mineralization zone (Pirajno and others, 1997; Zhang and others, 2002, 2004; Qin and others, 2003) is hosted in Late Carboniferous to Permian andesite (290-270 Ma, Rb-Sr isochron age, Zhang and others, 2000), ignimbrite, and volcanic breccia, which overlie widespread andesite and dacite in a Carboniferous island arc. The Shiyingtan gold deposit is an adularia-sericite-type epithermal gold-silver deposit according to Heald's classification (Ji and others, 1994a; Zhang and others, 2000).

The Kanggurtag accretionary complex also contains an EW-trending, N-dipping ductile shear zone that is over 500km long and 10-30km wide (Xu and others, 2003), and is composed of mylonites and mylonitized rocks. The well-developed deformation structures include S-C fabrics, a stretching lineation, and rotated porphyroclasts. Cleavage planes strike N-S and dip 70°~75°·N. Typical metamorphic mineral assemblages include actinolite, biotite and chlorite, indicating that the metamorphic grade of the ductile shear zone is lower greenschist facies; the ambient temperature was 350° to 500°C at a depth of 15 to 20km (Ma and others, 1997; Yang and others, 1998).

YAMANSU FOREARC-ARC

The Yamansu forearc-arc is characterized by lavas, volcaniclastic rocks and terrigenous clastic sediments interbedded with limestones (fig. 9). Basalt and andesite of Devonian age are imbricated with slightly metamorphosed fine-grained clastics and carbonate, and overlain by Carboniferous andesite, basalt, dacite, and rhyolite, with spilite and keratophyre. Some Upper Carboniferous andesite and rhyolite are interbedded with clastic sediments and limestone. The andesite has calc-alkaline geochemical patterns, and basalt shows oceanic tholeiite geochemical patterns, therefore indicating an island arc origin (Ji and others, 1994a, 1994b, 1999, 2000). There is considerable Au and volcanogenic-hosted massive sulfide (VHMS) Cu-Fe mineralization in these arc rocks. Lower Carboniferous strata are subdivided upwards into the Nanbeidagou, Aqishan and Yanmansu Formations. The Nanbeidagou Formation is composed of thick limestone and mylonitic carbonate. The Aqishan Formation consists of intermediate and felsic volcanics and pyroclastics, and the Yamansu Formation mainly contains limestone, clastics, spilite, keratophyre and pyroclastics.

Li and others (2002a) reported Devonian radiolarian chert in the East Yamansu Valley. The ages indicate that subduction had started at least in Devonian time. However, the isotopic ages of volcanic rocks range from 330 Ma to 340 Ma (Li and others, 1998); Ji and others (1994a) reported a Rb-Sr age of 300 ± 13 Ma and a Pb-Pb zircon age of 299 ± 16 Ma for rhyolites in these volcanic rocks (Zhang and others, 2000). These dates are in good agreement with isotopic ages 290 to 300 Ma for volcanic rocks in the Yamansu area (Li and others, 1998). Granodiorites that intrude the arc have isotopic Rb-Sr ages of 315 Ma (Yang and others, 1998). All these isotopic ages indicate that subduction may have lasted to the Late Carboniferous; the Late Carboniferous arc magmatism moved seaward to the accretionary wedge. Permian volcanic-sedimentary rocks are sparsely distributed above the arc; they are characterized by basalt and dacite (Yang and others, 1998). We interpret these Permian volcanic rocks as a continuation of the Devonian-Carboniferous arc.

NORTH TIANSHAN ACCRETIONARY COMPLEX

The North Tianshan suture or the Aqqikkudug-Shaquanzi ophiolite-bearing zone (Shu and others, 2002) is a main lineament structure in the Chinese Tianshan Mountains, along which occur remnants of accretion-collision complex composed of ophiolitic slices and mélange. The Mishigou and Gangou ophiolites located south of Tuokexun (figs. 4, 10 and 11) have been well studied by both Chinese and interna-

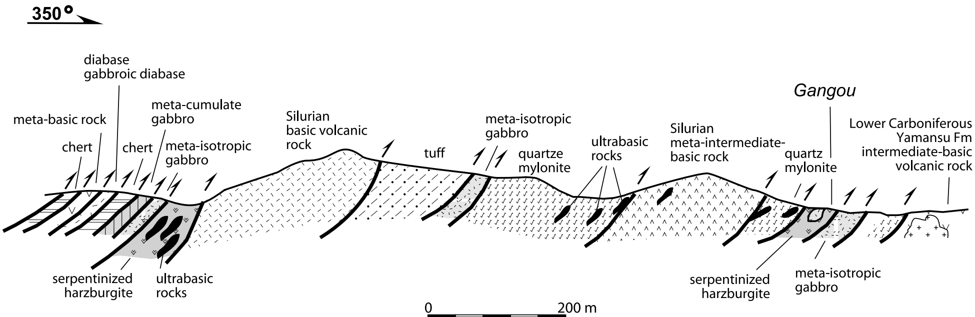

Fig. 10. Cross-section of the ophiolitic mélange zone in Gangou, Tuokexun, demonstrating northward imbrication of the Gangou Silurian-Early Carboniferous accretionary wedge. Section line is marked in figure 4.

tional geologists (Windley and others, 1990; Allen and others, 1993a; Zhang, 1994; Zhou and others, 2001a; Shu and others, 2002).

The Gangou ophiolite occurs along the Aqikkuduk-Shaquanzi fault and connects to the west with the Mishigou ophiolite (fig. 4). In Gangou, serpentinized harzburgite, dunite, meta-gabbroic diabase, meta-cumulate gabbro, meta-isotropic gabbro, mafic lava, and chert (fig. 10) are imbricated with arc-related sediments of possible Silurian age (XBGMR, 1993). However, this ophiolite has been regarded as an eastern extension of the Bayingou ophiolite in the Chinese Western Tianshan which yields microfossils including radiolaria and conodonts of Late Devonian-Early Carboniferous age (Xiao and Tang, 1991; Gao and others, 1998; Qin, 2000; Qin and others, 2002).

Several fault-bounded basic granulite blocks have been identified along the eastern segment of this ophiolite-bearing zone (Shu and others, 2002). According to the systematical work done by Shu and others (1996, 1999, 2002), these granulite

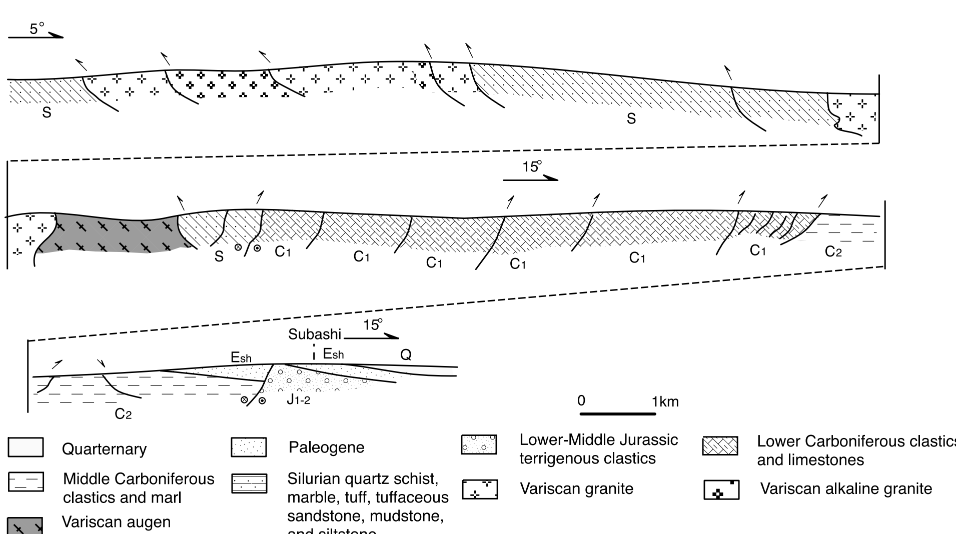

Fig. 11. Cross-section along the Tuokexun-Kumishi highway demonstrating imbrication and thrusting of Silurian and Carboniferous strata, Central Tianshan Arc. Section line is marked in figure 4.

blocks together with some gabbro and amphibole schist occur as tectonic slices imbricated within the mélange zone. Crossite-bearing schist blocks were found within the volcanic rocks and graywacke at Tuzileike and Tianhu, south of Hami at the eastern segment, and phengite schist blocks at Wusitegou south of Tuokexun and north of Mishigou at the western segment (figs. 1, 2B and 4; Ma and others, 1993; Gao and others, 1995; Shu and others, 1999, 2002; Liu and Qian, 2003). Liu and Qian (2003) reported a 345 Ma age for phengite from these high-pressure rocks, although no details were presented.

All these features lead us to conclude that the complicated assemblage of ophiolite, high-pressure-rock, granulite, pillow lava, chert, and turbidite may indicate remnants of an accretionary wedge. They are related to a north-dipping, Paleozoic subduction system based on the spatial distribution of an associated North Tianshan arc in the north and the ophiolite in the south (Ma and others, 1997; Zhang and others, 2000; Hu and others, 2000).

Central Tianshan Arc

The Central Tianshan arc is located between the Aqikkuduk-Shaquanzi fault which separates the North Tianshan to the north, and the Kawabulak fault which separates the South Tianshan to the south (fig. 2). The Central Tianshan has been regarded as a composite volcanic arc, which is composed of calc-alkaline-type basaltic andesite, volcanoclastics, minor I-type granite and granodiorite, and Precambrian basement rocks in amphibolite facies, extends along the northern margin of the Central Tianshan arc system (fig. 2A). The Precambrian basement of this arc consists of gneiss, quartz schist, migmatite, and marble (fig. 11), and has U-Pb and Sm-Nd ages that range from 1400 Ma to 1800 Ma (Chen and others, 1999; Hu and others, 2000). As this arc has a basement of 1400 Ma gneiss, quartz schist, migmatite, and marble, it should be an Andean-type margin. An Ordovician-Silurian volcanic-sedimentary assemblage was identified including Ordovician basalt, andesite, dacite, rhyolite, graywacke and Silurian turbidite (Shu and others, 2002). Gao and others (1998) suggested that Middle Ordovician magmatic arc volcanic and plutonic rocks were mainly distributed in the northern margin. This arc has been defined as the east extension of the Yili micro plate where a Paleozoic magmatic arc occurs along the Borohoroshan in the north, and Nalaqinshan in the south (fig. 1). Early Silurian and Early Carboniferous active margin sequences are widely exposed in these Central Tianshan magmatic arcs (Fang, 1994; Zhang, 1994; Zhou and others, 2001b). Silurian terrestrial clastic rocks and limestones are succeeded by Devonian limestones and terrestrial clastic rocks. Overlying these terrestrial clastic rocks and limestones are Early Carboniferous volcanic rocks. Carboniferous fossils have been discovered in some Proterozoic rocks which were regarded as remnants of volcanic arc because of their calc-alkalic geochemistry (Fang, 1994; Zhou and others, 2001b). They are imbricated with deformed volcanics, clastics, limestones, and ultramafic rocks (Fang, 1994). Therefore the Central Tianshan arc could have been as young as Carboniferous, although not precisely constrained. High-resolution isotopic dating needs to be done to further constrain the younger arc activity. Granitic rocks of possible Carboniferous age (XBGMR, 1993), which are usually called Variscan granitic rocks in the literature (Solomovich and Trifonov, 2002), intruded the Silurian volcano-clastic and sedimentary sequence (fig. 11).

Some volcanics of Carboniferous age whose geochemistry shows affinities of rifting were identified in the central part of the Yili micro-block (Central Tianshan arc) in the Chinese Western Tianshan, and in the central part of the Bogda Range and south of Tuwu in the Harlik-Dananhu arc (see figs. 1 and 2B for these localities) in the Chinese Eastern Tianshan (Xia and others, 2004). According to Xia and others (2004), the Carboniferous basic volcanics most likely originated from an asthenospheric oceanic-island-basalt-like mantle source ($^{87}Sr/^{86}Sr_{(t)}$ = 0.703-0.705, $\varepsilon_{Nd\ (t)}$ = +4 to +7). We note that all these sections of Xia and others (2004) are located in the Central Tianshan or Harlik-Dananhu arcs to the north of the South Tianshan suture, therefore representing Carboniferous rift-related volcanism in these arc terranes.

Li and others (2001) reported U-Pb zircon ages from the Hongliuhe granodiorite (441 ± 2 Ma) and granite (441 ± 3 Ma), indicating that magmatism started in the latest Ordovician. A Rb-Sr isochron age of 402 ± 3 Ma for a biotite granite with an arc geochemical signature was reported along the Tuokexun-Korla highway (Che and others, 1994; Li and others, 2001), north of the Kumishi accretionary complex (see next section below). Zhou and others (2001a) noted an Early Carboniferous magmatic arc along the southern edge of the Central Tianshan arc. All these facts indicate that the Central Tianshan arc magmatism probably began in the Late Ordovician-Silurian to Early Carboniferous. Hu and others (2000) suggested that the Central Tianshan and Tarim were not an integrated plate until they were amalgamated together in the Late Paleozoic on the basis of Nd isotopic study on the basement rocks of the Central Tianshan and Tarim. These authors stated that the ε_{Nd} values between the Central Tianshan arc and Tarim show a distinct boundary. In summary, from the above arguments we follow Hu and others (2000) in suggesting that the Central Tianshan arc was remnant of an Andean-type magmatic arc possibly with N-dipping subduction polarity underneath its southern margins in the Late Ordovician-Silurian to Devonian-Early Carboniferous.

SOUTH TIANSHAN SUTURE: KUMISHI ACCRETIONARY COMPLEX

The South Tianshan suture mainly occurs along the southern margin of the Yili-Central Tianshan arc from the Chinese Western Tianshan to the Eastern Tianshan, extending some 1500 kilometers in the Chinese Tianshan (fig. 1). However, discontinuous slivers of ophiolites occur above and within deformed Paleozoic sediments along a wide zone between the South Tianshan suture and northern margin of the Tarim block (Windley and others, 1990; XBGMR, 1993; Allen and others, 1993a). On the geological map (fig. 2A) several separate ophiolitic units may represent remnants of accreted Mid-Devonian to Early Carboniferous ocean basins. This belt includes a wide zone of various types of rock units, including ophiolite, mélange, blueschist/eclogite, radiolarian chert, and volcaniclastic rock, which we define here in this paper as Kumishi accretionary complex, the eastern extension of the Kokshaal-South Tianshan accretionary complex (fig. 1).

The Kumishi ophiolite is well representative of this belt (fig. 12). The main rocks are dunite, plagioclase lherzolite, harzburgite, gabbro, diorite, spilite, chert, and radiolarian chert (Ma and others, 1997). At Yushugou a highly metamorphosed ophiolite is imbricated with Lower to Mid-Devonian volcanic and volcaniclastics rocks (Windley and others, 1990; XBGMR, 1993; Allen and others, 1993a). According to Wang and others (1999), the Yushugou section mainly consists of, from north to south, (1) hypersthene garnet amphibolite derived from tholeiitic basalt, meta-basaltic sandstone, meta-graywacke and meta-pelite; (2) garnet-bearing lherzolitic granulite and websteritic granulite; a so-called granulite facies ophiolitic tholeiitic basalt and ultramafic-mafic cumulate; (3) meta-peridotite; and (4) Lower to Mid-Devonian volcanic and volcaniclastic rocks thrust over a possible Carboniferous granite (XBGMR, 1993).

In the easternmost part of the Eastern Tianshan, the Hongliuhe ophiolite consists of peridotite, cumulate gabbro, diabase, pillowed basalt, and chert imbricated with Ordovician-Silurian terrestrial clastic and volcanic rocks. The geochemistry of the ophiolitic rocks demonstrates a MORB origin (Jiang and others, 2001a). REE analyses of the ophiolite indicate LREE depletion (Jiang and others, 2001a), which may be indicative of a mature basin. In a Cr-Y diagram samples from the ophiolite are distributed in the area of overlap between MORB and IAT (Jiang and others, 2001a).

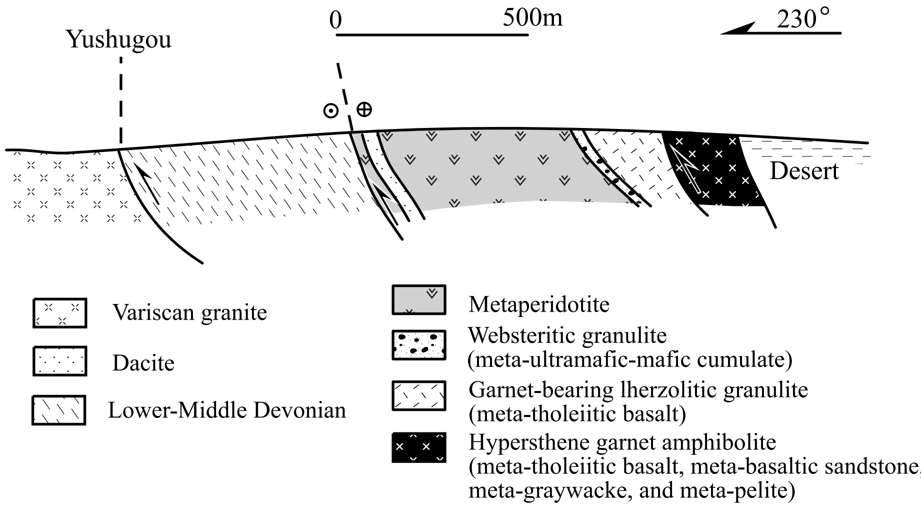

Fig. 12. The Yushugou cross-section demonstrating imbrication and thrusting of various tectonic units of the Yushugou ophiolitic mélange (our observations, and modified after Allen and others, 1993a; Wang and others, 1999). Section line is marked in figure 4.

SHRIMP zircon age dating of the Yushugou high-pressure granulite facies rocks yields a formation age of 596 ~ 430 Ma, and a metamorphic age of 398 ± 4 Ma (Zhou Ding-Wu, 2003, personal communication). The fact that the ages of the Yushugou granulite-ophiolite span some 200 Ma, and that these rock units are imbricated in thrust sheets, indicates that the Yushugou granulite-ophiolite is an exposed remnant of a long-lived accretionary wedge. We interpret the metamorphic age of the Yushugou high-pressure granulite as the record of one important phase of forearc accretion, which progressively scraped off oceanic fragments of various ages. This scenario is consistent with a U-Pb zircon age of 378 ± 6 Ma for the cumulate gabbro from the Yushugou ophiolite in the west (Jiang and others, 2001b), a SHRIMP zircon age of 377 ± 4 Ma for the ophiolite at Kawabulak in the centre (Zhang Fuqin, personal communication), and a U-Pb zircon age of 425.5 ± 2.3 Ma in the east (Li and others, 2002a); we interpreted these isotopic dates as the age of crystallization formation of the ocean floor.

The different rock assemblages and ages of the ophiolitic fragments together with their structural relations with diagnostic sediments and metamorphic rocks indicate that the Kumishi complex is a huge accretionary wedge accreted to the south of the Central Tianshan. However, the time when north-dipping subduction started beneath the southern central Tianshan terrane is not well constrained.

The Ordovician arc magmatism and Rb-Sr age (see the section above) of 402 ± 3 Ma for the central Tianshan arc indicates that subduction of the southern Tianshan oceanic crust probably took place in Ordovician-Late Silurian time. Jiang and others (2001a) reported Ordovician-Silurian radiolaria from cherts and fine-grained clastics in the ophiolite south of Kumishi (fig. 2B). We interpret these as recording the Ordovician-Silurian ridge-trench transition setting, which was later incorporated into the Kumishi accretionary complex. This huge accretionary prism can be correlated with that in the Wawumen area (fig. 4), where ophiolitic components were juxtaposed against Upper Silurian-Lower Devonian terrigenous clastic rocks, carbonate, and chert.

Late Devonian to Early Carboniferous ophiolites are imbricated with volcanic and volcaniclastic rocks, and with blueschist and eclogite (Xiao and others, 1992; Gao and others, 1998). A ^{40}Ar-^{39}Ar date of 350.89 ± 1.96 Ma for glaucophane from the Changawuzi high-pressure metamorphic belt provides a key age for the northward subduction of the southern Tianshan oceanic crust (Xiao and others, 1992). Liu and Qian (2003) reported blueschist and eclogite along the southern part of the Yushugou ophiolite (figs. 1 and 2B). They obtained an ^{40}Ar-^{39}Ar age of 360.7 ± 1.6 Ma for blueschist along the Yushugou ophiolite. In the same area, Liu and Qian (2003) also found C-type and B-type eclogites, and coesite pseudomorphs were discovered within garnets in the B-type eclogite, indicating possible ultra-high-pressure metamorphism. The presence of Early Carboniferous blueschist facies metamorphic rocks along the suture belt between the Central Tianshan arc and Tarim and a coeval magmatic arc along the southern edge of the Central Tianshan arc have led Zhou and others (2001a) to conclude subduction beneath the Central Tianshan arc continued through the Early Carboniferous in the Chinese Western Tianshan. This notion is supported by recent studies of tectonostratigraphy and metamorphic petrology (Gao and others, 1998; Chen and others, 1999) and discovery of Early Carboniferous radiolarian fossils (Liu, 2001; Li and others, 2002b).

The ages of the ophiolites indicates that N-dipping subduction may have continued in the Late Devonian. Ophiolitic ultrabasic and basic complexes occur along the boundary between the Central Tianshan and Tarim blocks. Peridotite, basalt, and chert were imbricated with Late Devonian-Early Carboniferous sediments, which together form part of the accretionary prism.

A systematic study of the calc-alkaline granitoids along the southern Central Tianshan indicates that I-type diorite yields a U-Pb zircon age of 298 Ma, a porphyry granite has U-Pb zircon age of 284.4 ± 1.5 Ma (Jiang and others, 1999). Coleman (1989) interpreted alkalic granites as post-collisional “anorogenic granites”, and alkali-feldspar granites have U-Pb zircon ages of 264.6 ± 1.2 Ma and 259.9 ± 2.6 Ma (Jiang and others, 1999). These ages of the anorogenic granitoids indicate the collision between the Central Tianshan and Tarim blocks lasted to the Late Carboniferous (Coleman, 1989; Shu and others, 1999, 2002; Xia and others, 2004). Li and others (2002a) suggested that the final closure of the South Tianshan ocean was in the Early Permian based on the fact that the earliest molasses sediments appeared in Permian. Accordingly, post-collision thrusting and strike-slip faulting may have taken place in the Late Permian (Shu and others, 1999, 2002; Cunningham and others, 2003).

TARIM MARGIN

The Tarim block has a variably deformed and metamorphosed basement of Archaean-Proterozoic to Early Paleozoic sediments (XBGMR, 1993; Hu and others, 2000). The basement is characterized by an Archaean bi-modal suite [high-grade tonalite-trondhjemite-granodiorite (TTG) gneisses and amphibolites] and Proterozoic granitic gneisses that have model ages (T_{DM}) ranging from 3.2 to 2.2 Ga (Hu and others, 2000). During the Early Paleozoic the northern Tarim block was a stable marine platform with continental rifts (Jiang and others, 2001a) developed over Precambrian continental basement and free from major clastic input (Windley and others, 1990; Allen and others, 1993a). A north-facing passive margin was previously proposed along the northern margin of the Tarim block in the late Paleozoic (Windley and others, 1990; Graham and others, 1990; Allen and others, 1993a). However, Jiang and others (2001a) reported a belt of plutons which contain olivine gabbro, gabbro, gabbroic diorite, diorite, quartz diorite and granite along the northern margin of the Tarim block. These rocks show a calc-alkaline geochemical signature (Jiang and others, 2001a). Volcanic rocks (basaltic andesite-dacite-rhyolite) are intercalated with mica-schist, mica-quartz-schist, marble, quartzite, and calcareous schist along the

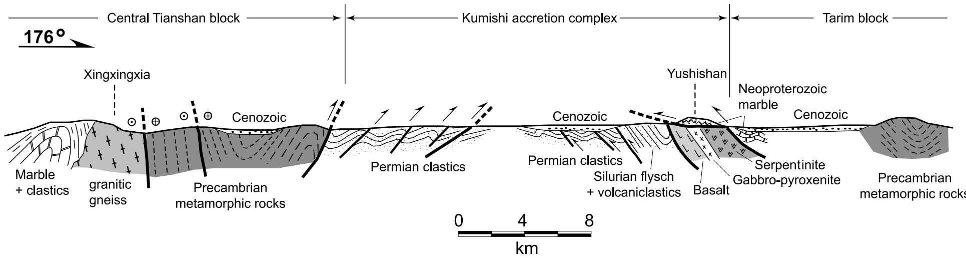

Fig. 13. Xingxingxia-Yushishan cross-section demonstrating imbrication and thrusting of various tectonic units of the Kumishi accretionary complex between Central Tianshan and Tarim (modified after Li and others, 2003). Section line is marked in figure 6.

southern side of the Kumishi ophiolite (Jiang and others, 2001b). These volcanic rocks include basaltic andesite, andesite, andesitic lava, andesitic crystal tuff, dacitic lithic breccia, rhyolitic crystal tuff, rhyolitic tuffaceous lava and rhyolite. Geochemical studies suggest a rifting origin along the northern margin of the Tarim block (Jiang and others, 2001b).

The volcanic rocks with Rb-Sr ages of 378 ± 6 Ma, 354 ± Ma, 349 ± 16 Ma, and 328 ± 10 Ma, and plutons with U-Pb zircon ages of 363 ± 2 Ma indicate that rifting may have occurred along the northern margin of the Tarim block in the Late Devonian to Early Carboniferous (Jiang and others, 2001a, 2001b).

This rifting also affected the east segment of the Chinese Tianshan and Beishan. Some gold deposits, such as the Mazhuangshan gold deposit located in the border area of the Xinjiang Urgur Autonomous Region and Gansu province (figs. 1 and 2A), were controlled by the superimposition of a volcanic basin on the rifted margin. The Lower Carboniferous Mazhuangshan Formation comprises acidic volcanic breccia and intermediate-basic lava, and subvolcanic quartz porphyry, feldspar quartz porphyry, rhyolite porphyry, granodiorite porphyry, diabase veins, and cryptoexplosive rocks, which have isotopic ages of 301 ± 21 Ma and 303 ± 26 Ma by Rb-Sr age dating (Li and others, 1998, 1999).

From this information we infer a transition from a passive margin to rifted margin at least in the Late Devonian to Early Carboniferous. This volcanic belt has been correlated to the northern margin of the Tarim block in the Chinese Western Tianshan, where a Permian volcanic-plutonic belt consisting of granite, granodiorite, plagiogranite, adamellite, grano-porphyry, dacite, rhyolite porphyry, and diorite was interpreted as a marginal magmatic arc associated with a S-dipping subduction of the South Tianshan ocean (Chen and others, 1999). Although this scenario could be possible, Zhou and others (2001a) recently demonstrated that, in the Chinese Western Tianshan, subduction in the Late Carboniferous-Early Permian was mainly northward (present-day coordinates) beneath the Yili-Central Tianshan. As multiple-phase strike-slip faulting has complicated the correlation between the Western and Eastern Tianshan (Shu and others, 1999, 2000; Cunningham and others, 2003), one possibility for this difference could be that the South Tianshan ophiolitic belt may vary along strike. Systematic geochemical and geological investigations are needed to further constrain the subduction-related signature of the plutons along the northern margin of the Tarim block (Chen and others, 1999; Zhou and others, 2001a).

Large-scale southward and northward (fig. 13) thrusting, that involved ophiolites and metamorphic rocks of uncertain affinity, has obscured structural evidence for constraining the original subduction polarity of the South Tianshan ocean basin. Figure 12 demonstrates the northward thrusting in the southern part and southward thrusting in the northern part of the Kumishi ophiolitic mélange zone (fig. 13). However, as mentioned above, the rifted passive margin of Tarim is located in the south, which collided with the Central Tianshan arc and its southerly Kumishi accretionary complex to the north. These events clearly indicate a N-dipping subduction polarity, that is, the South Tianshan oceanic crust was subducted northward beneath the Central Tianshan arc, as indicated in our model (see next section).

DISCUSSION AND CONCLUSION

Tectonic Model

We have subdivided the geology of the Chinese Eastern Tianshan into several tectonic elements: continental margin arcs, island arcs, ophiolites, accretionary wedges, and turbidite overlap sequences. Based on these interpretations, we synthesize the geological history of the Eastern Tianshan as follows (fig. 14).

From the Late Ordovician-Silurian (fig. 14A) north of the Central Tianshan and Tarim, the central Asian archipelago was characterized by: (a) the Harlik-Dananhu subduction zone with a S-dipping polarity, which created the Harlik arc in the north; (b) southerly N-dipping subduction system beneath the Central Tianshan arc in the middle; and (c) the South Tianshan ocean against Tarim in the south (fig. 14A). During the Devonian to Early Carboniferous (fig. 14B), N-dipping subduction took place beneath the Dananhu-Harlik arc, giving rise to the Kanggurtag forearc basin/accretionary complex. In Early to Mid-Carboniferous time (fig. 14C), the N-dipping subduction beneath the Dananhu-Harlik arc may have generated backarc extension, leading to formation of the Xiaopu inter-arc basin between the Harlik and Dananhu arcs, and the magmatic front migrated southwards forming the Yamansu arc constructed upon the Kanggurtag accretionary forearc. By the Late Carboniferous (fig. 14D), the Dananhu-Harlik arc system was attached northwards to the Angaran margin, resulting in lateral enlargement of the Angaran continent. In the latest Carboniferous to Early Permian (fig. 14E), multiple soft collisions left a suture zone represented by the North Tianshan accretion-collision complex that includes ophiolitic fragments. This orogenic system was stitched by Early Permian post-tectonic plutons.

Rhyolitic porphyry in the Kanggurtag gold mine yields a whole-rock Rb-Sr age of 300 $\pm$ 3 Ma and a zircon age of 299 $\pm$ 19 Ma. Mylonitic andesites in the Kanggurtag and Shiyingtan gold mines (fig. 6) have Rb-Sr ages of 290 $\pm$ 5 Ma and 285 $\pm$ 12 Ma (Zhang and others, 2002). These ages indicate that the Kanggurtag accretionary process may have lasted to the Early Permian. Wang and others (2002) reported isotopic ages of 260 $\sim$ 280 Ma for large-scale ductile shear zones in the Kanggurtag area, which they thought were post-subduction structures. Thus we conclude that subduction ceased in the Early Permian and collision took place in the late Early Permian. Post-tectonic thrusting (possibly Triassic) was mainly southward (fig. 15).

Paleogeographic Boundary Between Angara and Tarim

The Chinese Eastern Tianshan extends eastwards through the Beishan orogenic belt to Inner Mongolia (Hsü and others, 1991; XBGMR, 1993; Zhou and Graham, 1996; Yue and Liou, 1999; Yue and others, 2000). The location of the boundary between Angara and Tarim has long been controversial. Ma and others (1997) proposed that the Kelameili ophiolite is a Carboniferous relict in the final suture between the Angara and the Tarim blocks. However, many workers have found that the *Tuvaella* fauna of Angaran affinity crosses the Kelameili fault (Su, 1981; Li and others, 1990; Yang and others, 1996; Ma and others, 1997; He and others, 2001). This evidence precludes the possibility that the Kelameili ophiolite is a relict of the final Carboniferous suture between the Angara and the Tarim blocks.

Dewey and others (1988) and Searle (1991) discussed the southern limit of the Angara flora in Central Asia and placed it as a line that passes approximately along the

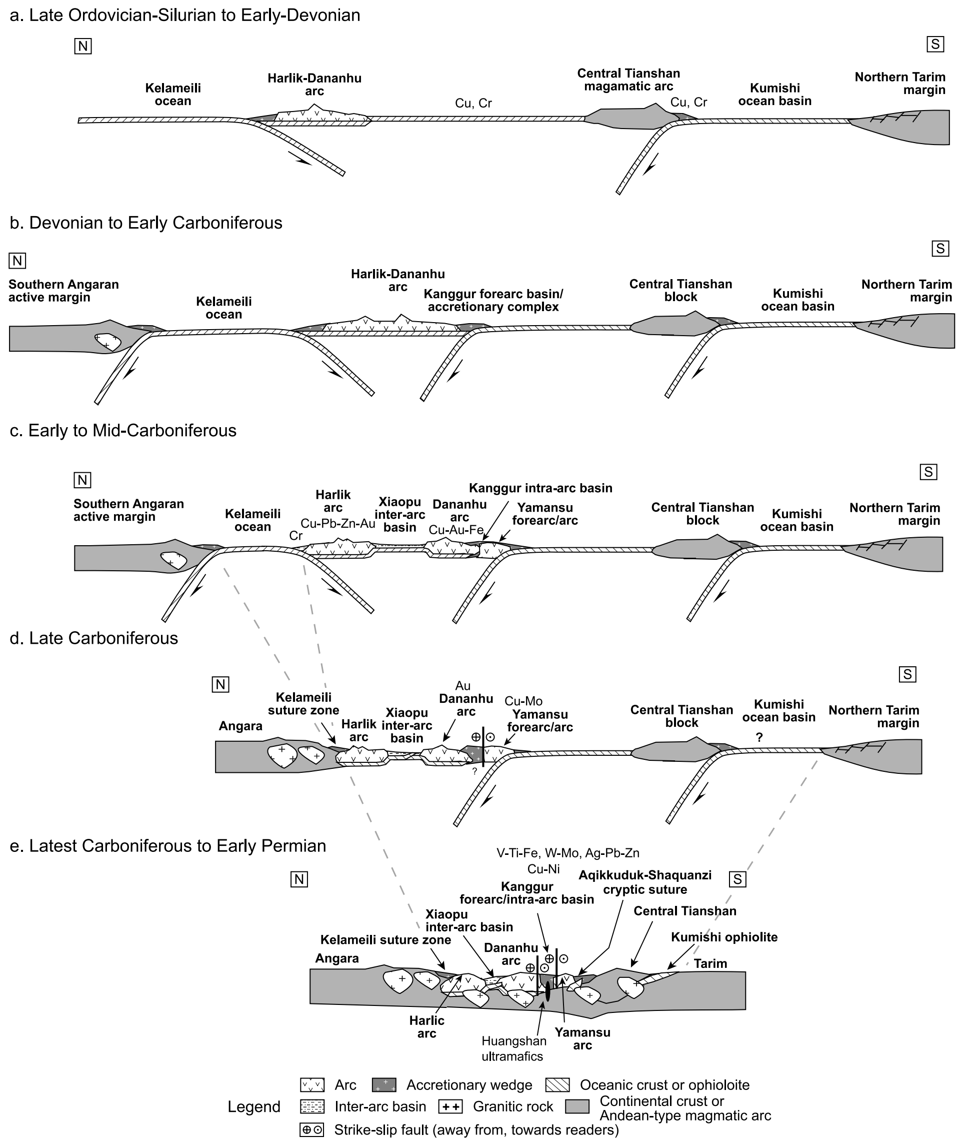

Fig. 14. Schematic cross-sections showing tectonic evolution of the Eastern Chinese Tianshan. (a) Late Ordovician-Silurian to Early-Devonian; (b) Devonian to Early Carboniferous; (c) Early to Mid-Carboniferous; (d) Late Carboniferous; (e) Latest Carboniferous to Early Permian. See text for discussion.

Tianshan-Hegenshan suture which they defined to be south of the Turpan-Hami Basin. Also marked is the approximate southern limit of mixed Angara and North China flora south of the Angara flora line (Dewey and others, 1988; Searle, 1991). These two lines together give a mixed zone of Angara and North China flora which we think has key importance for understanding the interaction and boundary between the Angara plate and the Tarim-North China plate, which is very close to the final suture zone. Guo (2000) pointed out that the Yili-Central Tianshan block was far away from the Tarim block based on the distribution of Middle-Late Devonian brachiopod

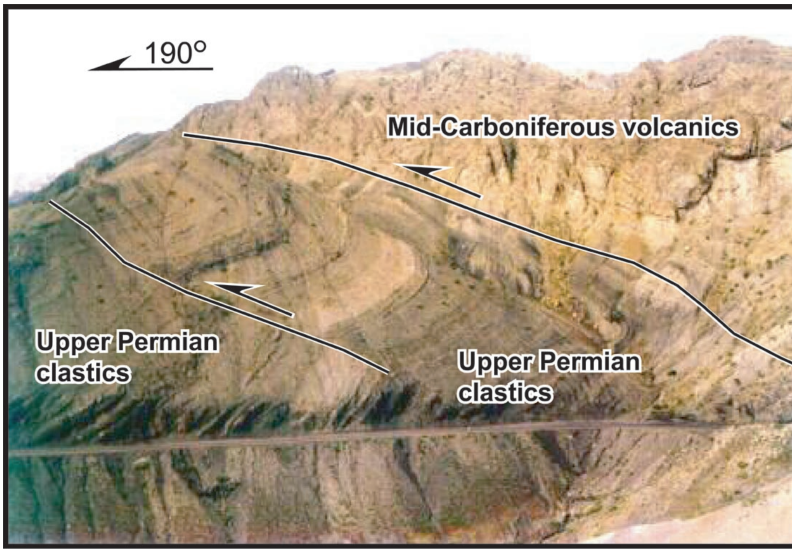

Fig. 15. Photograph demonstrating thrusting of Mid-Carboniferous volcanic rocks southward over Upper Permian clastics. Looking west. The road cliff is about 50 m high. See figure 4 for location.

fossils. The Yili-Central Tianshan block and the Yamansu arc eventually went close to Angaran in the late Early Permian. Moreover, Li and others (2002b) found Late Permian radiolarian fossils in the Chinese Western Tianshan. Based on the above arguments, we suggest that the northern boundary of the Central Tianshan block, the North Tianshan accretion-collision complex, was the suture zone representing the final termination of the Central Asian orogenesis in Permian time. This scenario is consistent with Permian paleobiogeographic differences on either side of the Tianshan Suture (Smith, 1988).

Further east, across the Altyn Tagh strike-slip system, this Permian suture can be traced to the Solonker suture where many accretion-subduction complexes and ophiolites record Late Paleozoic accretion and Permian collision (Şengör and others, 1993; Şengör and Natal'in, 1996; Xiao and others, 2003a). To the west, as mentioned above, the correlation becomes difficult due to large-scale strike-slip faulting. However, Late Carboniferous-Permian suture belts can be found both along the Yili-Central Tianshan (Zhou and others, 2001a). The southerly distributed Qinbulak-Qawabulak fault (Allen and others, 1993a), which is often an 8-km-wide HP-LT belt of thrust sheets (Gao and others, 1995), formed on the site of a Late Paleozoic suture between the Tarim-Southern Tianshan and the Yili-Central Tianshan (Gao and others, 1998), where Late Permian radiolarian fossils were found (Li and others, 2002b). The main tectonic assemblages along this fault form a huge accretionary wedge, which can be traced to the west as far as the Aral Sea and is referred to as the Turkestan-Kokshaal accretion-subduction complex in the Central Asian republics to the west (Allen and others, 1993a; Brookfield, 2000). The northerly one, called the Borohoro-North Tianshan suture, also can be traced westwards to the Central Asian republics. These two Late Paleozoic subduction-collision systems bound the so-called Kazakhstanian Orocline of Şengör and Natal'in (1996).

Northward- and Southward- Growing Orogenic Models

The orogenic processes along the southern Angara continent were characterized by a general southward migration. This migration is in good agreement with the conclusions of Şengör and others (1993). However, our evidence suggests that there were several subduction systems with different polarities.

Post-collisional, 236 Ma and 212 Ma granites (Coleman, 1989; Yang and others, 1996) provide age constraints for the collisional event which finally closed the ocean between the Angaran continent and Tarim block. The North Tianshan-Solonker ophiolitic zone was the terminal suture zone of the Central Asian orogenic belt in the Paleozoic to the Early Permian. This orogenic process resulted from the destruction of the Turkestan ocean and the collision of the accreted Angaran continental margin with the Tarim-North China blocks (fig. 14).

Coexistence of epithermal and orogenic gold deposits within the Eastern Tianshan also points to a complex scenario of northerly- and southerly-directed subduction (Rui and others, 2002). The Shiyingtan ore body and other shallow level deposits of the Kanggurtag gold belt occur north of the main suture (fig. 6), thus indicating that subduction of South Tianshan oceanic crust had a north-directed polarity. This pattern is in accordance with that within the Central Asian Republics where epithermal and porphyry deposits are generally situated north of the main suture and north of the large orogenic deposits (Rui and others, 2002).

Solomovich and Trifonov (2002) reported Permian post-collisional granitoids along the boundary between Central Tianshan and Tarim. This observation may suggest that during the process of suturing Tarim to the Angaran continent, collision diachronously took place in Kyrgyzstan, the Chinese Tianshan, and then in the Solonker suture (Şengör and Natal'in, 1996; Xiao and others, 2003a). Complicated progressive suturing of the central Asian orogenic collage is supported by paleomagnetic data (Zhao and others, 1990). Large-scale, syn-tectonic and post-tectonic strike-slip faulting took place in Permian time (Wang and others, 2002; Laurent-Charvet and others, 2003; Xu and others, 2003).

Implications for Reconciliation of the Orogenic Controversy

This tectonic scenario gives us a hint that the early subduction-accretion systems between the northern Tarim block and the southern Angara continent grew seawards, at a time when subduction polarity changed from southward to northward, or vice versa. The two subduction-accretion collages collapsed, terminating the Paleo-Asia Ocean (Coleman, 1989; Heubeck, 2001; Xiao and others, 2003a).

Hsü and others (1995) and Hsü and Chen (1999) use a backarc accretion model to describe the Paleozoic orogeny in the North Xinjiang area. According to this model, orogens like the central Asian orogenic belts have an archipelago paleogeography like the present-day SW Pacific. The Chinese Tianshan orogen has this paleogeography. The Late Paleozoic, in particular Carboniferous, collision of the two archipelagos of the Angaran and Tarim continents, now juxtaposed in the Tianshan region in central Asia (Solomovich and Trifonov, 2002), can be correlated with the European Variscides. The Tianshan and European Variscides form part of a ca. 8000 km long orogenic belt caused essentially by the Late Paleozoic collision of Laurasia and Gondwana and intervening micro-plates (Matte, 1991; Oncken, 1997; O'Brien, 2000; Soriano and Cacas, 2002; von Raumer and others, 2003; Onezime and others, 2003). However, no typical backarc basins existed in the vast area of the North Xinjiang area based on geochemical and regional study of the ophiolites (Wang and others, 2003). Only the Xiaopu basin can be interpreted as a backarc basin in the Eastern Tianshan, which later closed and contributed to the architecture of the Tianshan orogen. From this point of view, it is hard to use backarc collapse as the only mechanism to explain the Chinese Eastern Tianshan.

Şengör and Natal'in (1996) suggested that Central Asia is a Turkic-type orogen characterized by a single trench that retreated towards the ocean, and by arc magmatism that moved toward the front of the accretionary wedge. The accretionary wedges, with their arc plutonic and volcanic rocks, were later thrust upon the passive continental margin of the continental block on the other side of the arc after ocean closure. In the Chinese Eastern Tianshan the general southward migration of the Angaran margin is well predicted by the model of Şengör and others (1993). However, the orogeny involved backarc basin closure, and the Turkic-type accretionary orogenesis was apparently complicated by collapse of different-polarity subduction systems. Thus in the Eastern Tianshan the orogeny is not strictly a "Turkic-type" orogeny; we refer to this process that produces this orogeny as a multiple accretionary orogenic process, the major features of which are (Xiao and others, 2003a, 2003b): (1) earliest accretion started with Japanese-type oceanward migration (Taira, 2001), but this accretion passed into a more complex archipelago arc-accretion style of tectonics similar to that in present-day southeast Asia (Hsü and others, 1995); (2) syn-tectonic and post-tectonic rifting may have occurred during the whole orogenic process (Allen and others, 1993b; Carroll and others, 1995, 2001; Wartes and others, 2002); and (3) subduction-related orogeny plays a fundamental role in Japan-type, Andean-type and in Mariana-type margin processes, in which forearc accretion is the principal mechanism but backarc closure also plays a key role (Şengör and Natal'in, 1996; Taira, 2001; Xiao and others, 2002a, 200b).

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