Paleozoic structural and geodynamic evolution of eastern Tianshan (NW China): welding of the Tarim and Junggar plates

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Chinese East Tianshan is a key area for understanding the Paleozoic accretion of the southern Central Asian Orogenic Belt. A first accretion-collision stage, before the Visean, developed the Eo-Tianshan range, which exhibits north-verging structures. The geodynamic evolution included: i) Ordovician-Early Devonian southward subduction of a Central Tianshan ocean beneath a Central Tianshan arc; ii) Devonian oceanic closure and collision between Central Tianshan arc and Yili-North Tianshan block, along the Central Tianshan Suture Zone; iii) Late Devonian-earliest Carboniferous closure of a South Tianshan back-arc basin, and subsequent Central Tianshan-Tarim active margin collision along the South Tianshan Suture Zone. A second stage involved: i) Late Devonian-Carboniferous southward subduction of North Tianshan ocean beneath the Eo-Tianshan active margin (Yili-North Tianshan arc); ii) Late Carboniferous-Early Permian North Tianshan-Junggar collision. The Harlike range, unit of Mongolian Fold Belt, collided with Junggar at Mid-Carboniferous, ending a north-dipping subduction. The last CAOB oceanic suture is likely the North Tianshan Suture Zone, between Yili-North Tianshan and Junggar. During the Permian, all the already welded units suffered from a major wrenching, dextral in Tianshan, sinistral in Mongolian Fold Belt, due to opposite motion of Siberia and Tarim.

Introduction

Northern Xinjiang, in NW China, was formed during the Paleozoic through progressive accretion of different blocks onto the southern margin of Siberia including: continental slivers, arcs, accretionary complexes, that built the southern part of the Central Asia Orogenic Belt (CAOB): the Altaïds (Sengör et al., 1993; Natal'in and Sengör, 2004; Xiao et al. 2004a, b, Windley et al., 2007).

The Tianshan range, extending over 3000 km from NW China to Kazakhstan and Kyrgyzstan, and separating the Tarim basin to the south from the Junggar basin to the north (Figure 1), is a key area for understanding the Paleozoic evolution of Central Asia and testing the tectonic models proposed for the CAOB. Two main stages of accretion/collision have been advocated (Coleman, 1989; Windley at al., 1990; Allen et al., 1992; Berzin et al. 1994; Shu et al., 1999, 2002; Laurent-Charvet, 2001; Laurent-Charvet et al., 2002, 2005; Charvet et al., 2001, 2004).

Tectonically, the Chinese Tianshan is usually divided into North, Central, and South Tianshan (NTS, CTS, STS), and, in the western part, the so-called Yili Block (Figure 1). The present boundaries between NTS, CTS, and STS are typically marked by strike-slip shear zones post-dating the collisional events. The most conspicuous one, separating CTS from NTS (Shu et al., 1998, 1999) is named the Main Tianshan Shear Zone (MTSZ) (Laurent-Charvet et al., 2002, 2003, 2005). In addition, the Cenozoic tectonism, due to Eurasia-India collision, is responsible for the recent southward thrusting of STS onto the Tarim, and for the northward thrusting of NTS onto the Junggar plate (Molnar and Tapponnier, 1975; Tapponnier and Molnar, 1979; Nelson et al., 1987, Ren et al., 1987; Windley et al., 1990; Avouac et al., 1993; Hendrix et al., 1994; Lu et al., 1994, 2005; Cunningham et al., 1996; Allen et al., 1999; Burchfiel et al., 1999; Poupinet et al., 2002; Shu et al., 2003; Wang et al., 2004; Charreau et al., 2005, 2006; Wang et al., 2006, 2007b). This has resulted in reworking and alteration of the Paleozoic structures.

In proposed models, the vergence and significance of Paleozoic deformations have been extensively debated, partly due to a lack of precise structural and kinematic analysis, as well as an absence of reliable data constraining the timing of various events. This paper will focus on the Middle and Late Paleozoic evolution of the region, emphasizing structural development prior to strike-slip shearing, and is based on a decade of field-based observation. Analysis of regional and micro-scale structures, as well as chronological constraints, will be set out along several cross-sections, made mainly in East Tianshan (to the east of Urumqi) and in the eastern part of West Tianshan. Comparison and correlation with new data obtained in West Tianshan, in the Yili Block (Wang et al., 2006, 2007a, b, c) will be discussed. Finally a geodynamic model for evolution of the region will be presented, as well as a broader correlation with further West Tianshan and Mongolia, placing the tectonic evolution of the Tianshan in the context of the Paleozoic geological history of Central Asia.

General geological setting

The boundaries of different units are typically delineated by large strike-slip faults.

NTS is the tectonic unit located to the north of the Main Tianshan Shear Zone (MTSZ, 2 Figure 1) (Laurent-Charvet et al., 2002, 2003) or Borohoro Fault (Zhao et al., 2003), or Junggar Fault (Sengör and Natal'in, 1996); its north-western extension is called North

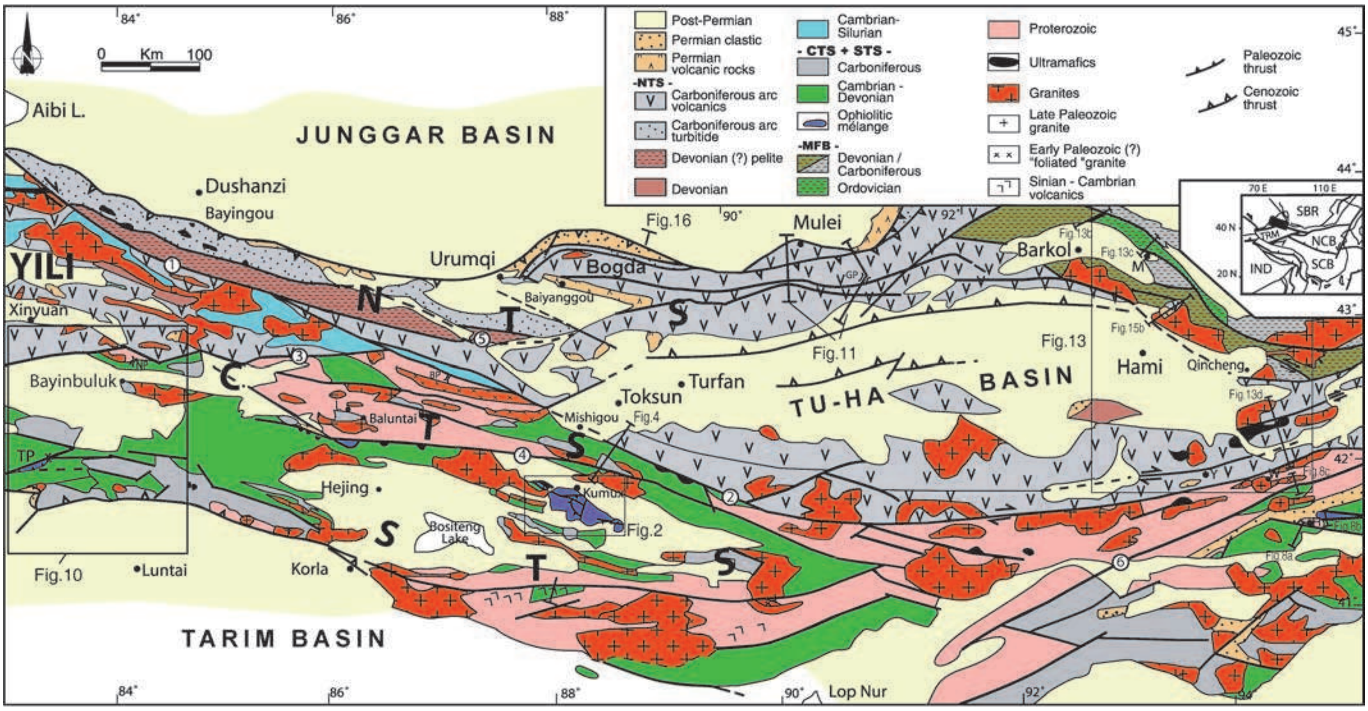

Figure 1 Schematic geological map of East Tianshan. Inset: IND: Indian continent; NCB: North China Block; SCB: South China Block; SBR: Siberia; TRM: Tarim Block. Faults: 1: North Tianshan Fault; 2: Main Tianshan Shear Zone (MTSZ); 3: Nalati Fault; 4: Baluntai Fault; 5: Houxia Fault; 6: Xingxingxia Fault. Localities: BP: Bing Pass; GP: Gaoquan Pass; NP: Nalati Pass; TP: Tieilimaiti Pass; H: Hongliuhe; L: Luotuogou; M: Miaoergou; W: Weiya; Y: Yamansu. Legend: NTS: North Tianshan; CTS: Central Tianshan; STS: South Tianshan; MFB: Mongolian Fold Belt.

Tianshan Fault (NTF) (Wang et al., 2007a, b; 1 Figure 1). To the east of Urumqi, this unit mainly consists of Late Devonian to Carboniferous calc-alkaline volcanic rocks and gabbro bodies of the Bogda arc s.l.; they crop out in two different strips, respectively to the south of Turfan-Hami (Tu-Ha) Basin (Figure 1) and to the north of it, where they build the Bogda arc s.st.. To the east of Hami, they interfere with the Mongolian Fold Belt. At the northern foot of Bogda mountain, Upper Carboniferous turbidites are locally preserved. West of Urumqi, such NTS turbidites are more extensive and they incorporate an ophiolitic mélange, well represented at Bayingou, south of Dushanzi (Figure 1). The ophiolitic remnants include cherts yielding Upper Devonian-Lower Carboniferous radiolarians and conodonts (Carroll, 1991; Xiao et al., 1992; Gao et al., 1998; Chen et al., 1999; Zhou et al., 2001a; Wang et al., 2007b). To the south of this turbiditic mélange-bearing subunit, lies another subunit consisting of deformed black mudstone and sandstone, as well as subordinate pebbly mudstone, minor chert and volcaniclastic rocks. These rocks are attributed to the Devonian (XBGMR, 1993) but remain undated. At Dushanzi, they exhibit a steeply dipping cleavage and some dextral kinematic features (Wang et al., 2007a, b, c) linked to a Late Permian dextral ductile shearing, as along the MTSZ (Shu et al., 1999; Laurent-Charvet et al., 2002, 2003). Around Urumqi, this unit is separated from the western end of the Bogda arc s.st. by the Houxia Fault (5 Figure 1); the MTSZ marks the boundary between the NTS and CTS, as it does from Bin Pass (BP Figure 1) to the east. To the west, the Yili Block, a triangular unit that widens westward, is bounded by the MTSZ-NTF to the north and by the Nalati Fault (3 Figure 1) to the south (Zhao et al., 2003, Wang et al., 2007a, c).

The nature and significance of the Yili Block and correlation between West and East Tianshan have long been debated. The Yili Block, considered a microcontinent by Allen at al. (1992), contains a Proterozoic basement and Lower Paleozoic sedimentary sequences deposited in a shelf and continental slope environment (XBGMR, 1993; Gao et al., 1998; Chen et al., 1999; Zhou et al., 2001a; Wang et al., 2006). It is commonly correlated to the CTS and called Yili-Central Tianshan (e.g. Gao et al., 1998, Gao and Klemb, 2003, Xiao et al., 2004b, Zhang et al., 2006). However the Lower Paleozoic succession differs from the CTS, and the Upper Paleozoic consists of sedimentary rocks and abundant Carboniferous calc-alkaline volcanic and plutonic rocks (Wang et al., 2006) yielding zircon U-Pb ages of 360-310 Ma (Zhu et al., 2005; Wang et al., 2007b). Geochemical data, including isotopic and trace element analyses, suggest an active margin setting (Zhu et al., 2005; Wang et al., 2006, 2007b) similar to the Bogda arc to the east. Therefore, it appears that the Yili unit must actually be regarded as the western equivalent of the NTS volcanic arc unit (Charvet et al., 2004; Wang et al., 2007b). In the western part of the Tianshan range, CTS is located to the south of Nalati Fault. The MTSZ-Borohoro Fault obliquely cuts different units of the NTS: Carboniferous turbidites and mélange, Devonian(?) pelite, Devonian-Carboniferous volcanic arc, and enters into the eastern part of the CTS.

The entire NTS can be interpreted as a Late Paleozoic continental active margin bordering a southward-subducting oceanic domain located between NTS and Junggar. This subduction produced: i) the volcanic arc represented in the east by the Bogda arc s.l. (Shu et al., 1999; Laurent-Charvet, 2001; Laurent-Charvet et al., 2005; Charvet et al., 2004), the volcanic Yili unit in the west (Wang et al. 2006, 2007b), and: ii) trench-fill turbitites of a subduction complex, better preserved in the western area (Chen et al., 1999; Zhou et al., 2001a) together with ophiolitic mélange, indicating a suture zone between NTS and Junggar block (Wang et al., 2007b). The main tectonic event took place before the deposition of unconformably overlying Middle Permian red beds (XBGMR, 1993; Allen et al., 1995; Shu et al., 1999; Laurent-Charvet, 2001; Laurent-Charvet et al., 2003; Charvet et al., 2001, 2004).

CTS and STS (Figure1) extend to the south of Nalati Fault (in the west, 3 Figure 1) and MTSZ (in the east, 2 Figure 1). The boundary between them is poorly defined and varies according to different authors. It is commonly regarded to lie along major faults: the Baluntai Fault running from south of Baluntai to north of Kumux (4 Figure 1) and the Xingxingxia Fault (6 Figure1) between Weiya (W) and Hongliuhe (H). However this terminology should be revised, taking into account the main paleogeographic characteristics of each domain.

CTS is characterized by a Proterozoic basement made of gneiss, amphibolites and marbles (XBGMR, 1993), overlain by Ordovician-Silurian arc-volcanic rocks, Silurian flysch (Ma et al., 1993, 1997; Shu et al., 1999, 2002; Laurent-Charvet et al., 2002; Charvet et al., 2004), and subduction-related Silurian-Lower Devonian plutons (Xu et al., 2006; Yang et al., 2006). Lower Carboniferous conglomeratic molasse, grading upward into shallow-marine sandstone and carbonate, clearly overlies various older rocks with angular unconformity (Carroll et al., 1995): e.g. i) the Ordovician or Silurian at Gangou, Kumux-Toksun section (Figures 1, 4) and Mishigou (Figures 1, 6) (XBGMR, 1993; Charvet et al., 2001; Laurent-Charvet, 2001; Shu et al., 2002; Laurent-Charvet et al., 2005), and to the NE of Bayinbuluk, ii) Proterozoic basement in the Baluntai area (Figure 1), iii) Devonian granite (Hu et al., 1986; Wang et al., 2007c) to the south of Bayinbuluk (Figures 1, 10). In contrast to the NTS, the Carboniferous rocks are almost exclusively sedimentary; they do not contain calc-alkaline volcanics. Rare volcanic rocks interbedded within the molasse, for instance at Luotuogou to the west of Baluntai (Figure 1), are alkaline and indicative of a post-tectonic rifting episode (Xia et al., 2004).

Along the northern boundary, marked by the MSTZ, relics of ophiolitic mélange are preserved discontinuously from Mishigou to Weiya. They include blocks of serpentinite, tectonite and cumulate peridotite, gabbro, marble, and chert in a highly schistose flysch/tuff matrix (Allen et al., 1992; Che et al., 1993, 1994; Ma et al., 1997; Laurent-Charvet, 2001; Guo et al., 2002; Shu et al., 2002, 2004). Rarely, blocks of: a sheeted dyke complex are present, such as in the Mishigou section (Ma et al., 1997; Laurent-Charvet, 2001); and HP-LT metamorphic rocks: phengite-schist at Wusitegou, NW of Mishigou (Gao et al., 1998), crossite-bearing schist at Tucileike, south of Hami (Ma et al., 1993). The ophiolitic remnants have a geochemical signature of normal oceanic domain (Ma et al., 1993; Laurent-Charvet, 2001; Guo et al., 2002). In the western Tianshan, to the west of Bayinbuluk basin, the equivalent of this suture is represented, to the south of Nalati Fault, by a HP metamorphic complex (Wang et al., 2007a, c), divided into two subunits: a northern one containing HP metamorphic blocks of blueschist and eclogite, a southern one composed of greenschist (Gao et al., 1995, 1999. Gao and Klemb, 2000, 2003; Wang et al., 2007a, c). The protoliths are interpreted as ocean-derived (Gao et al., 1995). The meta-basalts and volcaniclastic rocks show a MORB and OIB signature (Gao et al., 1995; Wang et al., 2007c). Regarding the dating, this mélange zone: the Aqqikudug-Weiya unit or suture zone (Guo et al., 2002; Shu et al., 2004), contains fossils in limestone, greywacke, and siltstone blocks of Ordovician-Silurian age (Che et al., 1994); a gabbro block yields a Rb-Sr whole rock age of 468 Ma and a deformed basalt an age of 422 Ma (Che et al., 1994). Marble blocks yield Silurian fossils (XBGMR, 1979, 1993; Gao et al., 1995). Isotopic datings of blueschist give ages of: 415 ± 2 Ma and 419.6 ± 4 Ma ($^{40}Ar/^{39}Ar$ on phengites, Gao et al., 1993); 439.4 ± 26.7 Ma ($^{40}Ar/^{39}Ar$ plateau age on pyroxene, Hao and Liu, 1993); 350–345 Ma (peak metamorphism) to 310 Ma (retrograde metamorphism) ($^{40}Ar/^{39}Ar$ datings on blueschists and greenschists, Xiao et al., 1992, Gao, 1993; Gao et al., 2000; Gao and Klemb, 2003; Klemb et al., 2005). Some Ar/Ar ages suggest a thermal rejuvenation (Wang et al., 2007a, c). Although not directly dated, the matrix contains, at Gangou, 461 Ma old terrigenous zircons and is intruded by a granodiorite yielding a U-Pb zircon age of 386.1 ± 4 Ma (Zhu et al., 2002). The formation age of the mélange is therefore likely Mid-Devonian; it cannot be younger than the earliest Carboniferous (Tournaisian) as the Visean molasse overlies the structures with an angular unconformity (Carroll et al., 1995).

In summary, from western to eastern Tianshan, CTS is bounded to the north by a reworked Devonian suture zone, the Central Tianshan Suture Zone (CTSZ), marked by an ophiolitic mélange and HP metamorphic rocks, and a former accretionary wedge linked to a southward subduction of an oceanic domain (Laurent-Charvet, 2001; Charvet et al., 2001, 2004; Guo et al., 2002; Shu et al., 2002, 2003; Zhou et al. 2004; Wang et al., 2007a, c).

STS is similar to CTS regarding the Proterozoic basement. However it differs in several aspects. The autochthonous Lower Paleozoic cover contains only sedimentary rocks: Upper Ordovician to Silurian limestones or limy turbidites, grading into an Upper Silurian calcareous flysch in the northern part, like between Tielimaiti Pass (TP) and Bayinbuluk (Figures 1, 10) (Wang et al., 1994; Laurent-Charvet, 2001); Lower Devonian limestones grading into cherty limestones, then cherts and a clastic series of sandstones with conglomeratic layers in the southern part, e.g. to the south of Tielimaiti Pass (Wang et al., 1994; Laurent-Charvet, 2001) or north of Hejing. These strata are locally metamorphosed and have experienced ductile deformation, especially in the south, and are affected by contact metamorphism due to granite intrusions.

The main characteristic is the existence of allochthonous units of ophiolites and ophiolitic mélanges, best represented in East Tianshan in Kumux and Hongliuhe areas (Figures 1, 2, 8) (Shu et al., 1997, 2002; Laurent-Charvet, 2001, Guo et al., 2002), and in West Tianshan by the Heiyingshan and Aheqi mélanges (Wang et al., 2007a, c). They locally include relics of blueschists (Gao et al., 1995, Liu and Qian, 2003). These units mark another suture zone: the South Tianshan Suture Zone (STSZ). The mélanges have been assigned initially to the Silurian, due to presence of Ordovician and Silurian fossils found in the limestone and chert blocks (XBGMR, 1959, 1983, 1993; Wu et al., 1990; Che et al., 1994; Shu et al., 2002; Guo et al., 2002). However, Lower-Middle Devonian radiolarians occur in a chert olistolith in the Liuhuangshan mélange near Kumux (Gao et al., 1998). In the mélange zone preserved at the southern foot of Tielimaiti Pass (Kule mélange) and in the Heiyingshan area (West Tianshan), radiolarians found in the matrix range from Upper Devonian to Lower Carboniferous (Wang et al., 2007c). Thus the probable formation age of the mélange is Latest Devonian or Earliest Carboniferous (Tournaisian), as it is unconformably overlain by Lower Carboniferous conglomerate (Visean) (Wang et al., 2007a, c). Recently established radiometric age data confirm that assumption. In Kumux area, Yushugou section (Fig. 3, 4a), granulite yields zircon U-Pb SHRIMP ages of 390 ± 11 Ma and 392 ± 7 Ma (Zhou et al., 2004); and a block of blueschist in the southern unit (Fig. 4a) gives an $^{40}Ar/^{39}Ar$ age of 360.7 ± 1.6 Ma (Liu and Qian, 2003). In west Tianshan, an undeformed gabbro in the Heiyingshan ophiolitic mélange gives, by zircon U-Pb LA ICP MS method, an age of 392 ± 5Ma (Wang et al., 2007c). Therefore, the oceanic lithosphere was, at least partly, created during the Early Devonian and obducted, together with HP metamorphic rocks, around the Devonian-Carboniferous boundary.

The geochemichal study of this ophiolite suggests a back-arc basin setting (Ma et al., 1993, 1997; Laurent-Charvet, 2001; Guo et al., 2002; Dong et al., 2005). Lastly, these ophiolite and ophiolitic mélanges are generally assumed to have been emplaced from north to south, onto the Tarim foreland, after a northward stage of subduction (Windley at al., 1990; Gao et al., 1992, 1998; Allen et al., 1992, Chen et al., 1999; Liu, 2001; Zhou et al., 2001a; Xiao et al., 2004b) and are thus rooted to the north. However, as we will see in the following section, kinematic studies indicate that these nappes were actually emplaced from south to north, in East Tianshan (Laurent-Charvet, 2001; Shu et al., 2002, 2003; Charvet et al., 2001, 2004; Laurent-Charvet et al., 2005), as well as in West Tianshan (Wang et al., 2007a, c). Therefore, the root is located to the south, between the ophiolite outcrops and the Tarim. Unfortunately, in West Tianshan, due to Cenozoic reactivation by southward thrusting (Molnar and Tapponnier, 1975; Tapponnier and Molnar, 1979; Nelson et al., 1987, Ren et al., 1987; Avouac and Tapponnier, 1993; Hendrix et al., 1994; Lu et al., 1994, 2005; Cunningham et al., 1996; Allen et al., 1999; Burchfiel et al., 1999; Poupinet et al., 2002; Shu et al., 2003; Charreau et al., 2005; Wang et al., 2007c), the root zone cannot be found and is now hidden. In East Tianshan, where the recent tectonism is dominated by wrenching (Lu et al., 2006), the original geometry, inherited from the Paleozoic, is less disturbed in the Hongliuhe area (Figures 1, 8) where a proximal mélange rich in Sinian marbles coming from the Tarim upper plate is overthrust northwards onto the ophiolitic mélange (Ma et al., 1997; Shu et al., 1997; Laurent-Charvet, 2001), despite a post-Permian reactivation.

The last and southernmost subunit corresponds to the deformed northern edge of Tarim, most often considered by other authors as a passive margin, although Xiao et al. (2004b) mention the possibility of an active margin, and Xiao et al. (2003) represent it as an active margin on their palinspastic maps. It contains Sinian to Ordovician platform sedimentary rocks: limestone, shale (Carroll et al., 1995). It is worth noting that the Sinian and Cambrian may contain intercalations of rifting-related volcanic rocks (Xia et al., 2004). The Silurian, overlying the older rocks with a slight unconformity (Carroll et al., 1995) begins with a conglomerate and includes several polygenetic conglomeratic layers in a flysch-like series. In the following section, this is interpreted as an olistostrome, with huge olistoliths, to the south of Hongliuhe, marking a period of instability. In northern Tarim the Devonian, not observed in the study area of Figure 1, consists of limestone covered by Middle Devonian-Lower Carboniferous cherts (Gao et al., 1998). Upper Devonian-Lower Carboniferous arc-related plutonic rocks occur at the northern edge of Tarim (Jiang et al., 2001). Close to the STS boundary, an angular unconformity is marked by the Lower Carboniferous through Lower Permian fluvial and marine deposits overlying Sinian to Devonian rocks (Carroll et al., 1995). Due to a transitional change of facies, Lower Carboniferous strata to the south consist of shallow-marine limestones (Carroll et al., 1995; Chen and Shi, 1999). The Lower Permian contains rift-related volcanic and volcaniclastic rocks dated at 295 ± 7 Ma by the K/Ar method (Zhou and Zhin, 1990) and 275–280 Ma by the $^{40}Ar/^{39}Ar$ method (Carroll et al., 1995). The Upper Permian detrital series is in turn unconformable (Carroll et al., 1995).

Structure of Central and South Tianshan

Structural data are reported along three main transects: from Kumux to Toksun (Figures 1, 2–7), Hongliuhe to Weiya (Figures 1, 8–9), and, for comparison, in the Bayinbuluk area of western Tianshan (Figures 1, 10).

Kumux-Toksun area

Outline

We will describe the Kumux ophiolitic zone and then cross-sections through CTS and CTSZ mélange.

Kumux ophiolitic zone. The likely best example of the South Tianshan ophiolitic zone, with the Yushugou ophiolitic body and the Tonghuashan-Liuhuangshan ophiolitic mélanges (Figures 2, 3), is exposed in this area.

• *Yushugou ophiolite*. The Yushugou ophiolitic body includes serpentinite, cumulate gabbro, basalt, amphibolite, pyroxenite and basic granulite. It tectonically overlies a block-bearing metaflysch, to the south, which is intruded and contact-metamorphosed by an undeformed granite (Figure 3a, b). This granite is undated but is similar to a neighbouring intrusion dated at 281 ± 3 Ma by the K/Ar method on biotite (Shu et al., 1998). The basal contact is marked by a zone of crushed serpentinite. To the north, the ophiolite is covered by Cenozoic rocks of the Kumux basin and the underlying unit cannot be seen. We assume it consists of Devonian schist and marble. The schistose metaflysch to the south, yielding Upper Silurian fossils in the marble blocks (Wu et al. 1990), is in fact Late Devonian-Early Carboniferous, as discussed earlier. A penetrative cleavage $S1^1$,

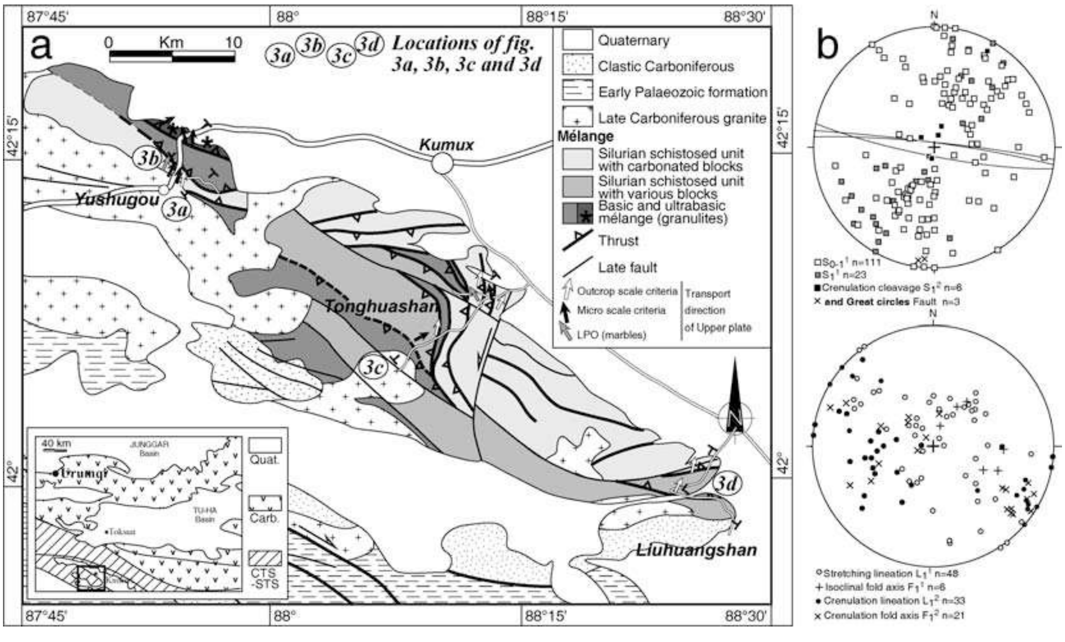

Figure 2 Schematic geological map and structural data of the Kumux ophiolitic zone, and location of sections of Figure 3.

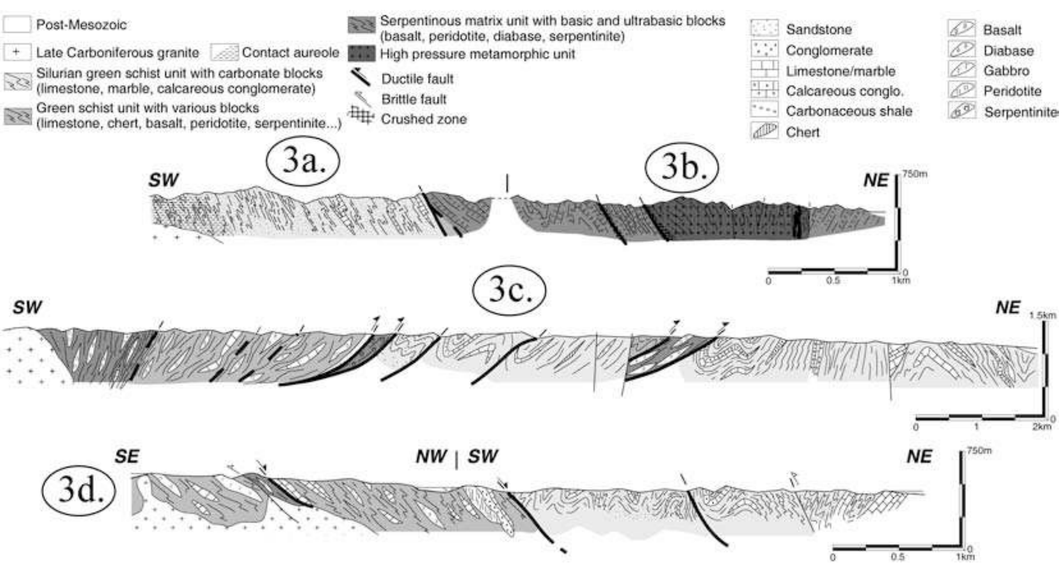

Figure 3 Geological cross-sections of the Kumux ophiolitic zone: a, b: Yushugou area; c: Tonghuashan; d: Liuhuangshan (see Figure 2 for location). Arrows along tectonic contacts refer to transport direction of upper plate.

almost parallel to the stratification plane S0, is cut in the fine-grained layers by an oblique crenulation cleavage S1[2].

The overlying unit is a mélange with a schistose serpentinitic matrix, including blocks of marble, basalt, peridotite, altered gabbro, dolerite. The blocks are also affected by the S1[1] cleavage but not S1[2]. This unit is about 1 km thick and is divided into two subunits by a fault. It is again in fault contact, marked by highly schistose serpentinite, with a unit of foliated granulite and pyroxenite. These rocks were derived from gabbro, basalt, and greywacke affected by HT metamorphism (Laurent-Charvet, 2001). Marble lenses contain calcite and clinopyroxene partly retrogressively metamorphosed into amphibole. Three successive parageneses can be recognized: an early eclogitic phase; a second granulitic event; a third amphibolite facies event formed during a retrograde stage (Laurent-Charvet, 2001). Late epidote and chlorite, infilling cracks, are associated with a greenschist facies during the last stage of retrogression. Thermobarometric studies indicate a peak temperature between 658 and 964°C and a peak pressure ranging from 0.88 to 1.5 Gpa, depending on the barometers used (Shu et al., 1996, 2004; Wang et al., 1998; 1999a,b,c; Liu and Qian, 2003). Isotopic dating of zircons by the U-Pb SHRIMP method gives ages of 390 ± 11 Ma, 392 ± 7 Ma (Zhou et al., 2004), and 398 ± 4 Ma (Zhou D.W. in Xiao et al., 2004b). On geochemical discrimination diagrams, the Yushugou granulite plots in the field of island arc tholeiite or MORB+VAB (Shu et al., 2004).

The last unit, again in fault contact, consists of layered gabbro and pyroxenite, showing a N120–160 trending foliation with a steep NE or SW dip. It disappears beneath the Recent deposits of the Kumux basin.

• *Tonghuashan and Liuhuangshan ophiolitic mélanges*. Located to the south of Kumux (Figure 2), these two mountains comprise hectometric to kilometric thrust sheets of mélange separated by early ductile thrusts or late brittle faults (Figure 3c, d). Three main types of mélange are recognized, based on the nature of matrix: 1) a matrix of greenschist including blocks of marble and limy conglomerate; 2) a tuffaceous matrix with blocks of quartzite, crinoidal limestone, red chert, gabbro, basalt, ultramafite, serpentinite; 3) a serpentinitic matrix with ultramafic blocks. The greenschist matrix is a metaflysch: alternation of sandstone and decimetric pelitic interbeds, with abundant chlorite on the cleavage planes of some schistose levels, and a few relics of HP blueschists in Tonghuashan (Gao et al., 1995). Abundant Ordovician-Silurian fossils occur in the limestone olistoliths and some cherts yield Silurian radiolarians (XBGMR, 1959; Wu et al., 1990; Che et al., 1994; Shu et al., 2002). But Lower-Middle Devonian radiolarians from chert of the Liuhuangshan mélange (Gao et al., 1998) lead to assignment of an age no older than Middle Devonian. Available isotopic datings on magmatic blocks are rare and not vary accurate (Rb-Sr whole rock and K/Ar methods): they provide ages of 351 ± 19 Ma, 340 ± 4 Ma, and 420 ± 14 Ma (Zhang and Wu, 1985; Ma et al., 1990; Wu et al., 1992).

Kumux-Gangou section. This section crosses the northern part of STS and the CTS, up to the Gangou mélange of CTSZ (Figure 4). It begins with a series of gneiss and micaschist including lenses of granitic mylonite (orthogneiss). The micaschist and paragneiss are interpreted as metaflysch, initially regarded as Silurian (Ma et al., 1990, 1993). To the north, the gneissic series, with a NE dipping foliation, includes lenses of amphibolite and marble. The amphibolites represent former mafic rocks included in the metamorphosed flysch. Therefore, this metamorphic series represents a mélange similar to those at Tonghuashan and Liuhuangshan, metamorphosed under low-amphibolite to greenschist facies conditions, and is an analog of the Silurian-Devonian schist-marble series cropping out along the northern edge of STS further to the west (Wang et al., 1994; Wang et al., 2007a, c).

A shear zone, several tens of meters wide, marks the conventional boundary with CTS (Ma et al., 1993; Shu et al., 1999, 1997, 2002; Laurent-Charvet, 2001). It corresponds to the Baluntai Fault. Kinematic criteria, associated to a conspicuous subhorizontal stretching lineation, clearly indicate dextral strike-slip motion (Laurent-Charvet, 2001). Alternating orthogneiss and paragneiss cropping out to the north are assumed to represent the CTS Proterozoic basement (Coleman, 1989; Allen et al., 1992; Gao et al., 1998; Shu et al., 1998, 2002; Laurent-Charvet, 2001). Intercalations of quartzite, micaschist, amphibolite, and marble are also present. The metamorphic rocks are cut by granites and granodiorites and undeformed dykes of pegmatite. Ages previously obtained for these granites and gneiss are about 460 Ma and between 830 to 1400 Ma respectively (Che et al., 1994; Ma et al., 1993). More recently, a zircon U/Pb age of 1013 ± 66 Ma and a zircon Pb/Pb age of 960 Ma were obtained (Hu et al., 1999). The pegmatites are likely associated with small late granitic plutons, dated as Permian (Wang et al., 2007c). The metamorphic series is affected by several dextral strike-slip shear zones as well as NW and SE verging structures (see below).

A brittle normal fault (N100/75S) bounds the Proterozoic basement and Lower Paleozoic rocks. The contact is located between gneiss (foliation N85/55S) and less metamorphosed but schistose and lineated (S1 N100/46S, L1 N170/40) greenish metagreywacke, assigned to the Ordovician (Ma et al., 1993). This first outcrop of Ordovician volcaniclastic flyschoid series, about 500m wide, includes andesite, dated at 477 Ma by Rb/Sr method (Ma et al.,

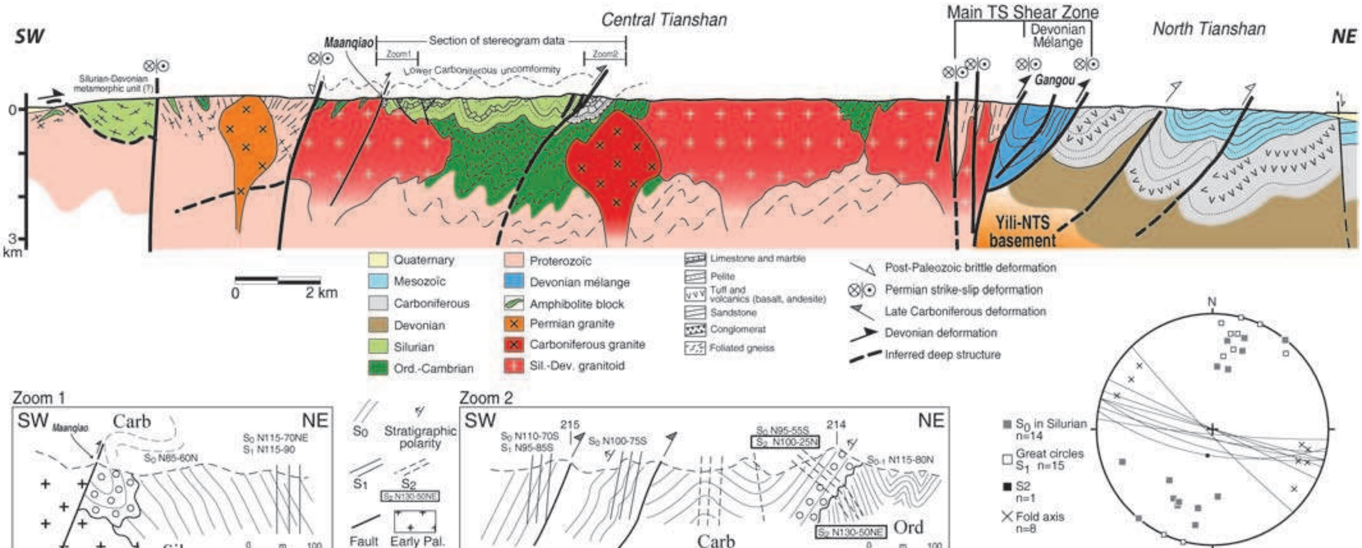

Figure 4 Synthetic cross-section of Central and North Tianshan along the Kumux-Toksun transect, and detailed structural data of some segments.

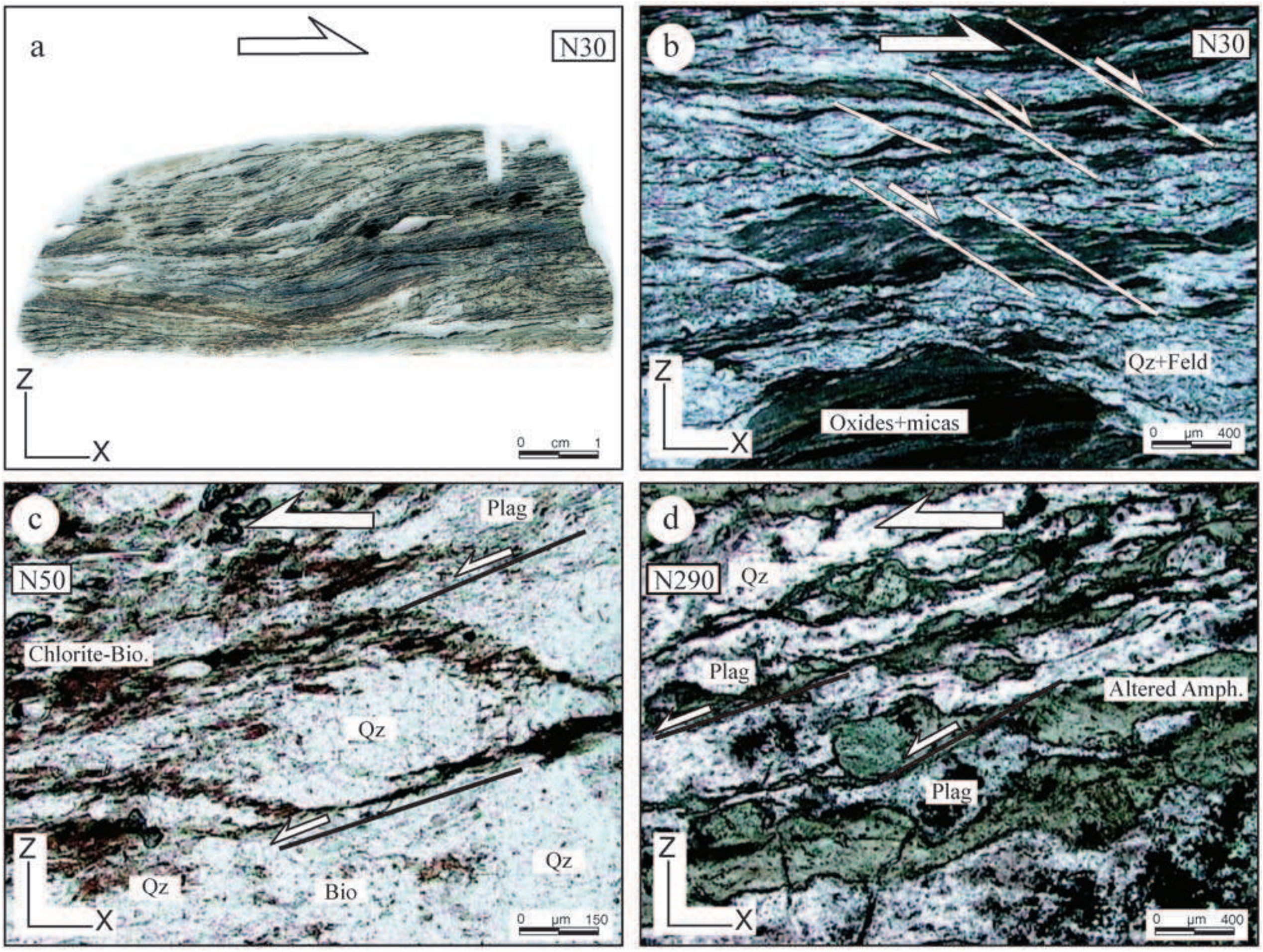

Figure 5 Kinematic criteria related to S1 in Kumux area: a: Sigmoidal quartz lens in a meta-sandstone of the Silurian flysch, Yushugou; b: Sigmoidal quartz (and pyrite with strain fringes) in a micro-sandstone of the Silurian fysch, PPL, Yushugou; c: Top-to-the N50 shear bands in a micaschist of the Devonian unit, PPL, Yushugou; d: Recrystallized shear-bands in an altered mylonitic gabbro, ultramafic unit, PPL, Yushugou.

1993), a diorite dated at 460 ± 4 Ma (Yang, 1988) by the same method, and yield fossils of Lower Ordovician age (Che et al., 1994; Zhou and Dean, 1996). Dioritic gabbros intruding the Ordovician sandstones and greywackes, are also foliated and contain oriented xenoliths. They have the geochemical characteristics of a continent-based volcanic arc setting, according to various discrimination diagrams (Laurent-Charvet, 2001). An intrusive granite, presumably of Middle Paleozoic age, appears to the north, at Maanqiao, in fault contact with non-schistose Carboniferous red conglomeratic molasse and sandstone (zoom1, Figure 4). These strata crop out over a narrow 10 m interval, are overturned (S0 N120/70NE) and overlie with unconformity Silurian flysch affected by a south-dipping schistosity (S0 N100/76N; S1 N50/50S). Numerous granitic pebbles in the conglomerate suggest that the molasse was deposited unconformably above both the Silurian and the granite.

The Silurian flysch contains: trilobites, graptolites, brachiopods, gastropods (Che et al., 1993, 1994), and in many places exhibits typical Bouma sequences and current marks.

Up-section, the formation grades into fine-grained sandstone, carbonaceous shale, and limestone. Coarse sandstone and massive limestone are more frequent to the north. Lastly, it is worth noting that tuffaceous layers, interbedded within the limestone and sandstone, in the northern quarter of the section, indicate volcanic activity lasting until the Silurian.

After about 9 km of outcrop of Silurian flysch, a south-dipping reverse fault marks the contact with the Lower Carboniferous conglomerate grading upwards into limestone beds. The conglomerate contains basalt, gabbro, schist, and granite pebbles, as well as huge blocks of grey Devonian limestone (Ma et al., 1993). At the northern end of this outcrop, the Carboniferous conglomerate overlies with a clear angular unconformity the schistose Ordovician greywackes (zoom 2, Figure 4). Two cleavages are observed; a first one is penetrative and restricted to the Ordovician layers, sub-parallel to S0 (S0-1 N115/80N at the contact); a second, less penetrative cleavage is present in both the Carboniferous (S0 N105/65S; S2 N95-100/25N) as well as the Ordovician (S2 N120-130/40-50NE); although it is absent in the southern part of the Carboniferous strip.

The Ordovician tuffaceous flysch and greywackes include basalt and andesite, and minor dacite and rhyolite, having a continent-based island arc signature (Laurent-Charvet, 2001; Shu et al. 2002). They are intruded by several granodioritic bodies and locally show traces (andalusite spots) of contact metamorphism. The granites are weakly deformed and may display a magmatic orientation. One has been dated at 457.4 ± 1.8 Ma by zircon U/Pb method (Han et al., 2004). Three bodies give TIMS U-Pb ages from 424.1 ± 1.1 Ma to 393.2 + 1.4 Ma and are calc-alkaline (Xu et al., 2006). Therefore, some of these granodioritic bodies appear to represent the deep part of an Ordovician-Early Devonian arc, as the aforementioned dioritic gabbros. A post-collisional intrusive is similarly dated at 327.3 ± 0.9 Ma (Xu et al., 2006).

The end of the CTS section is marked by a Proterozoic orthogneiss, cross-cut by doleritic dykes and granite similar to that seen elsewhere. The orthogneiss, in which foliation ranges from N85/65S to N60/80N, displays several dextral (mainly) and sinistral strike-slip mylonitic shear zones, which exhibit also thrust indicators. The gneiss is bounded to the north by a sub-vertical N100 trending fault, atop the Gangou mélange zone. The fault shows evidence of recent brittle motion and, as a branch of MTSZ, older ductile strike-slip shearing (Laurent-Charvet et al., 2002, 2003).

Gangou ophiolitic mélange. Between the gneiss and the NTS Carboniferous andesites, a mélange zone is composed of several fault-bounded units, two along the new Kumux-Toksun road, three along the old road, where the mélange zone is wider. Along the new road (Figure 4), the first unit consists of a clastic and tuffaceous series, similar to the Ordovician flysch but highly schistose (S1 N110/70S); the second unit is a mélange including various altered mafic and ultramafic rocks, and cherts blocks in a tuffaceous matrix. Along the old road, one can observe: a first unit to the south consisting of schistose greenish metaflysch, a middle one comprising a typical "coloured mélange", and a third northern one including blocks of serpentinite and granulite in a matrix of schistose tuffs. The coloured mélange yields olistoliths of serpentinite, gabbro, pyroxenite, basalt, metatuff, chert, and marble. This ophiolitic mélange (Allen et al., 1992; Ma et al., 1997; Laurent-Charvet, 2001; Guo et al., 2002; Shu et al., 2002, 2004) is a part of the suture zone accretionary wedge associated with the closure of a Tianshan paleo-ocean by southward subduction beneath CTS (Laurent-Charvet, 2001; Charvet et al., 2001, 2004; Guo et al., 2002; Shu et al., 2002, 2003; Zhou et al., 2004; Wang et al., 2007a, c). As previously discussed, the formation age is likely Devonian, constrained by the presence of Silurian fossils in the blocks together with a Lower Carboniferous unconformity and Mid-Devonian intrusion (Zhu et al., 2002). The early cleavage, bearing a rarely preserved stretching lineation trending N280-250, is frequently overprinted by a steep fabric linked with strike-slip motion, especially near the contacts. The contact between the mélange zone and North Tianshan Carboniferous volcanics is underlined by a cataclastic zone, with sigma-type objects indicating a top-to-the-north motion.

Structures and microstructures: polyphase deformation

We will not discuss the microstructures possibly inherited from pre-Paleozoic times within the Proterozoic basement, nor discuss in detail the recent brittle structures, instead we concentrate on deformations affecting the Paleozoic rocks. Three main stages of ductile deformation can be recognized: 1) pre-Carboniferous north-vergent folding and thrusting; 2) post-Carboniferous south-verging folding, which age is uncertain; 3) Permian right-lateral strike-slip. Late normal faulting can be also recognized.

Pre-Carboniferous north-verging folding and thrusting. Paleozoic structures created prior to the Carboniferous unconformity largely exposed in the CTS (Zeng et al., 1983), are ubiquitously north verging (Laurent-Charvet, 2001; Shu et al., 2002, 2004; Charvet et al., 2001, 2004; Wang et al., 2007a, c). This contrasts with previous interpretations assuming southward emplacement of nappes upon a Tarim passive margin (e.g. Windley et al., 1990; Allen et al., 1992). Without entering too much into detail, we record hereafter the main data.

In the Kumux ophiolitic area, all units show the effects of an early deformation under low to medium temperature conditions, marked by a cleavage $S1^1$ and a stretching lineation $L1^1$, reworked by north-verging decametric to millimetric folds linked to a cleavage $S1^2$, parallel to axial planes, and a crenulation lineation $L1^2$, born under low temperature conditions. These two families of tectonic features are interpreted as the effects of a deformation continuum, so we refer to the successive cleavages $S1^1$ and $S1^2$ rather than S1 and S2. Due to refolding, the stretching lineation is rather scattered in direction (Figure 2b), isoclinal and sheath folds $F1^1$ develop parallel to $S0\text{-}1^1$ and $L1^1$, particularly in the metaflysch and schistose matrix of the mélange, refolded by $F1^2$. Structures associated to $F1^2$ verge north, including sigmoidal quartz lenses (Figure 5a). In thin section, kinematic criteria linked to $L1^1$ are: sigmoidal quartz phenoclasts, asymmetric quartz pressure-shadows around pyrite, shear bands in schists or in gabbro (Figure 5b, c, d). They indicate a top-to-the-north (from NW to NE) sense of shear, under medium to low temperature conditions as suggested by the syntectonic minerals: chlorite and quartz. The latter does not show any high temperature dynamic recrystallization. The calcite LPO, studied by texture goniometer on marbles, suggests two directions of vergence: a north-

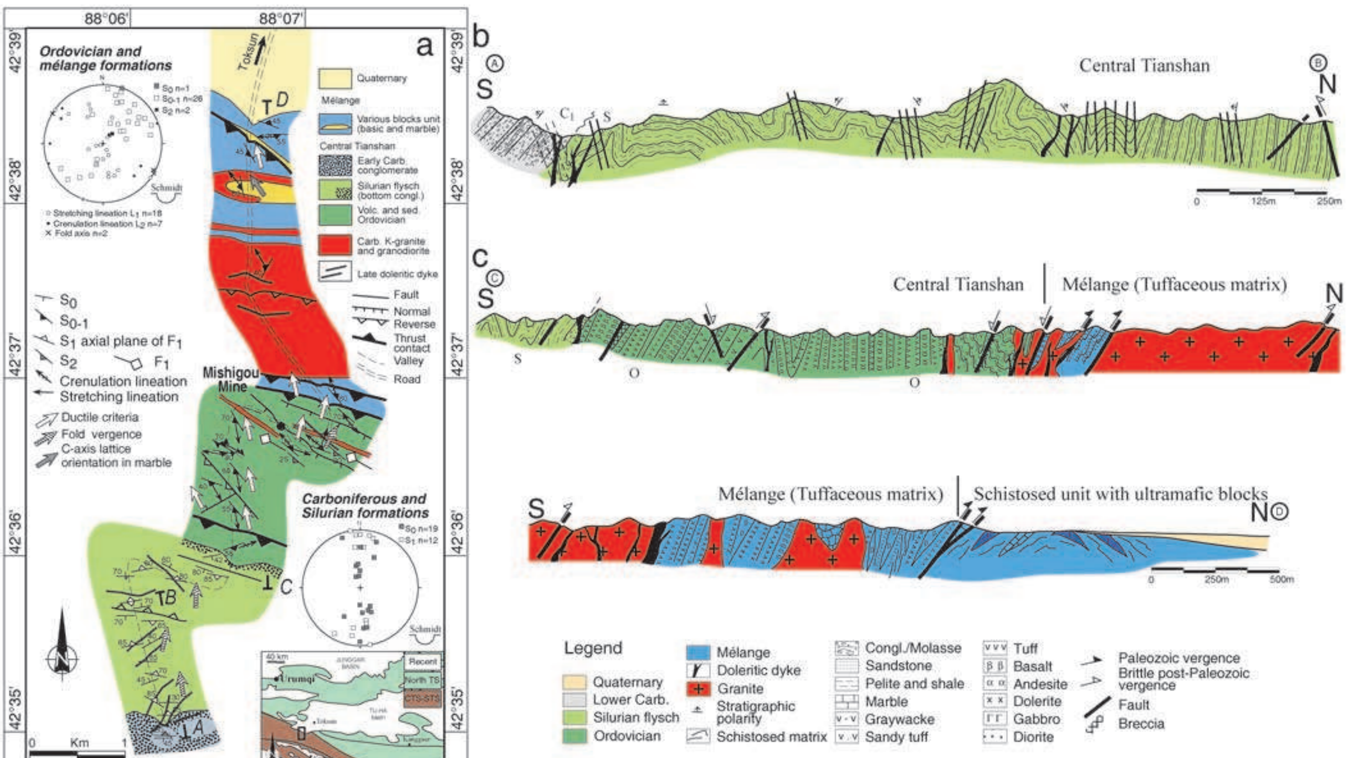

Figure 6: a: Geological and structural sketch map of Mishigou area, Central Tianshan. Stereograms of foliations, lineations, and fold axes. Location of sections A-B (b) and C-D (c); b: Outcrop section A-B in Silurian and Carboniferous clastic formations; c: Outcrop section C-D in the Ordovician volcanic series and the Mishigou mélange.

ern one in Tonghuashan, in agreement with other observations, and a southern one in Liuhuangshan and Yushugou, in low-T conditions (Laurent-Charvet et al., 2001). The latter is interpreted as the result of a secondary deformation.

In the Kumux-Toksun section, the CTS Paleozoic formations are affected by an early deformation marked mainly by north-vergent folds and a cleavage S1 well developed and sub-parallel to S0 in the Ordovician, that is less penetrative and parallel to axial planes in the Silurian (Figure 4). The Gangou mélange shows some relics of an early northward ductile shearing. The stretching lineation, oriented N250, is associated with kinematic indicators suggesting a NE-ward sense of shear. In CTS Proterozoic basement, for instance to the north of Kumux in a gneissic mylonite, a flat lying foliation locally bears a SE plunging lineation, associated with NW-directed kinematic features. We assume that it is related to the same event, in slightly higher temperature conditions marked by the presence of biotite.

Post-Carboniferous south-verging folding and thrusting. The Lower Carboniferous unconformity is folded. Along the Kumux-Toksun road (milestone 214), the Carboniferous basal conglomerate and overlying limestones are affected by a spaced cleavage N95-100/25N (Figure 8). This S2 is refracted to N130/50N in the underlying Ordovician, where it cuts the S0-1 N115/80N (zoom 2 Figure 4). S2 displays a fan-shaped attitude around fold axial planes near the unconformable contact and seems to vanish southward and is absent at Maanqiao. Determining the age of this deformation is difficult, as there is no direct unconformity on the top. It could be pre-Permian, Mesozoic, or even Cenozoic as is inferred for south-verging structures involving the Permian in West Tianshan (Wang et al., 2007a, c). However, here we prefer the hypothesis of a latest Carboniferous event, for the following reasons: 1) the closer outcrops of Permian, e.g. east of Gangou, display rather flat strata; 2) the fan-shaped cleavage in the Carboniferous beds of CTS is very similar to that developed in the southern unit of NTS volcanics, a structure which pre-dates the Permian unconformity and strike-skip shearing. Therefore, this south-verging folding might be due to the same event, responsible for the folding of North Tianshan, i.e. the second collisional stage involving NTS.

Some late south-vergent thrust planes and hectometric to kilometric folds in the Proterozoic basement of CTS, the low-T deformation of calcite in the Liuhuangshan marbles, and some top-to-the-SE sigmoidal structures in conglomeratic limestone blocks of Tonghuashan could be due to the same event, although this is uncertain. A thrust plane in amphibolite is cut by an undeformed, presumably Permian, pegmatitic dyke; so, a latest Carboniferous age is indeed possible.

Permian right-lateral strike-slip. In several places, and especially along the main faults (Baluntai Fault, MTSZ), a steep N100-120 trending foliation bears a sub-horizontal lineation. It affects the Gangou mélange, the Ordovician volcaniclastics, the granites, as well as the Proterozoic basement. A cleavage with the same attitude is also observed in the southern edge of NTS Carboniferous andesites (Laurent-Charvet, 2001; Laurent-Charvet et al., 2002, 2003). The kinematic criteria are clearly dextral. Some outcrops, in granitic mylonites, show metre-scale steep shear zones, trending around N40-60, bearing a sub-horizontal stretching lineation. These ductile faults yield sinistral shear criteria. They are interpreted as less developed conjugate faults of the main shear zone. In the gneissic basement, the strike-slip is sometimes accompanied by retrograde metamorphism, with biotite being tranformed into chlorite. Quartz LPO analysis confirms dextral motion and indicates, by the activation of basal plane gliding system, a temperature condition lower than 300°C (Laurent-Charvet, 2001; Laurent-Charvet et al., 2002, 2003). Lastly, isotopic datings on micas give ages of 290 Ma for a first stage in HT to MT conditions, and 250-245 Ma for a second stage in MT to LT conditions (Laurent-Charvet et al., 2003). Evidence of such Permian dextral strike-slip shearings extends to West Tianshan along the Nalati and others faults (Wang et al., 2007a, c).

Normal faulting. The main feature is the brittle south-dipping normal fault putting into contact the Proterozoic basement and the Ordovician in the southern part of CTS (Figure 4). Although the timing of displacement is unknown, it means that, prior to faulting, the Proterozoic basement was involved in northward thrusting over the Lower Paleozoic.

The Mishigou section

Some complementary information, regarding the Carboniferous unconformity, the Silurian-Ordovician relationships, and the ophiolitic mélange (Mishigou mélange), can be taken from the

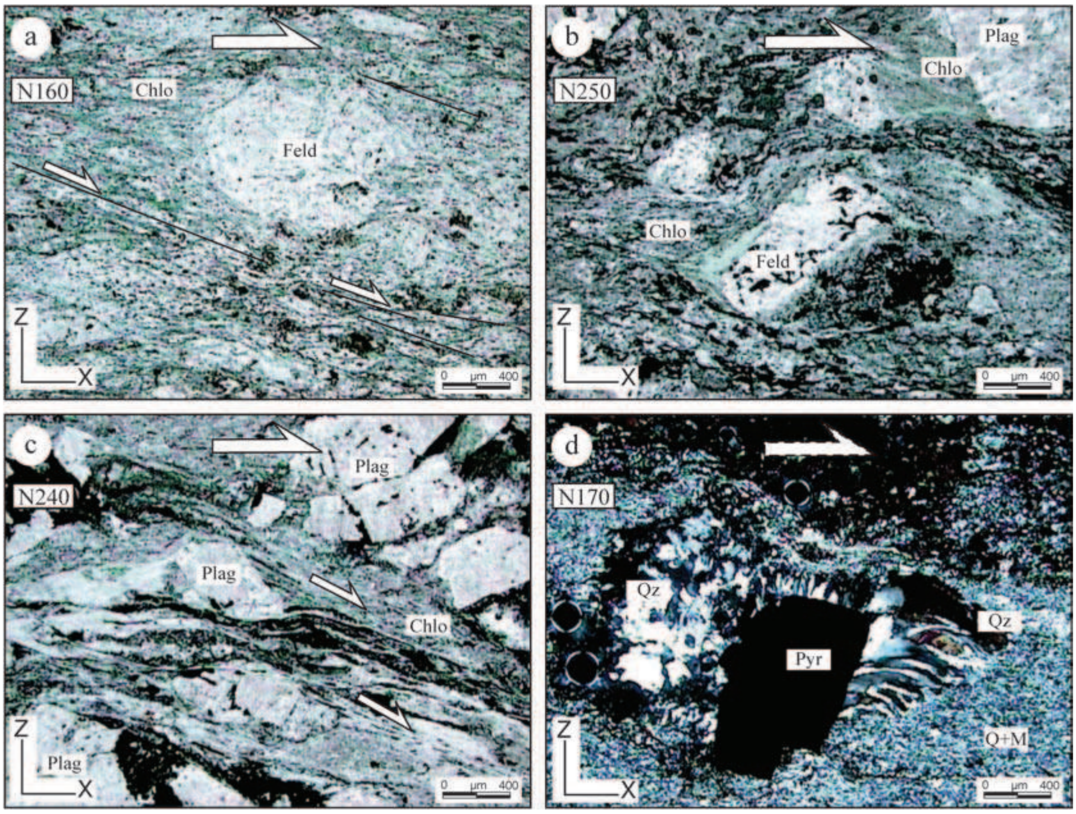

Figure 7 Photomicrographs showing examples of north-verging deformation in the Ordovician volcanics and Mishigou mélange, Mishigou area. a: Chloritized feldspar porphyroclast in a graywacke, top-to-the-N340 shearing, PPL; b: Feldspar clast with chlorite asymmetric pressure shadows in an andesitic tuff, top-to-the-N70 shearing, PPL; c: Shear-bands with chlorite and oxides in a tuff, top-to-the-N60 shearing, PPL; d: Quartz fringes around a pyrite grain in a micro-sandstone, top-to-the-N350 deformation, CPL. Feld.: feldspar; Chlo: chlorite; Qz: quartz; Oxi: oxides; Plag: plagioclase; Pyr: pyrite; Q+M: quartz-mica matrix.

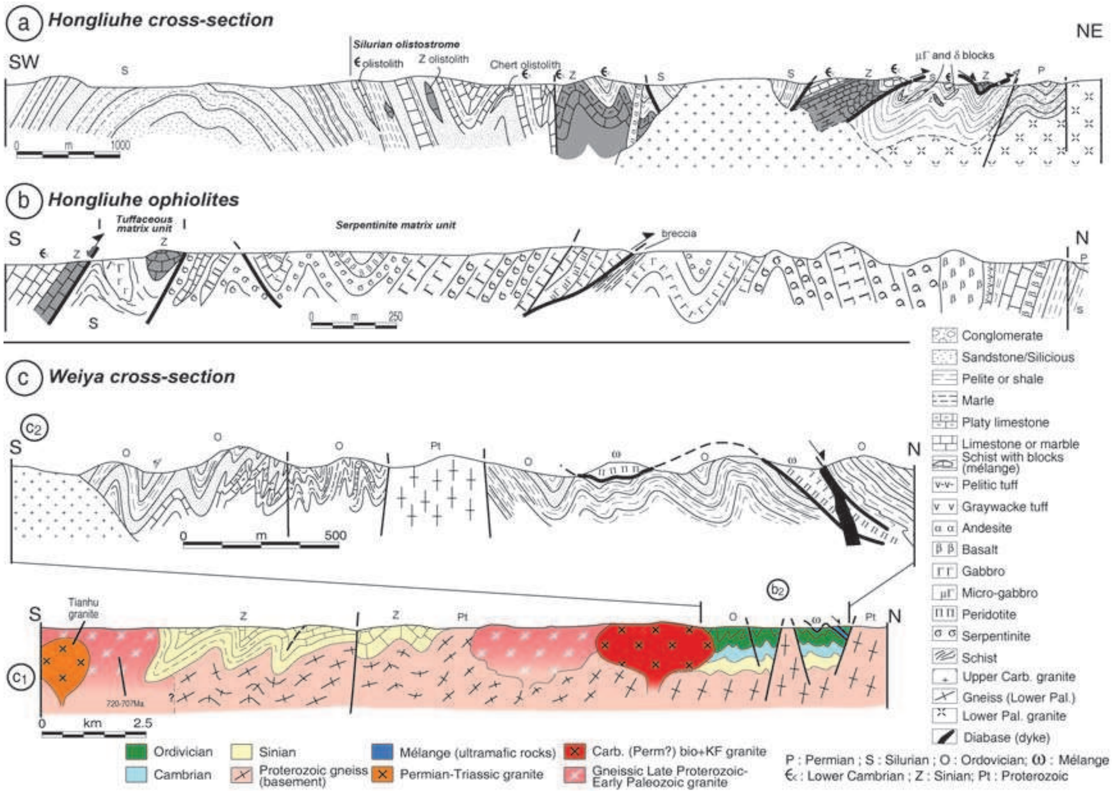

Figure 8 Cross-sections of Hongliuhe-Weiya area (location on Figure 1).

Mishigou section, located about 30 km SW of Toksun (Figure 6). NTS is not visible there.

Outline of the section

At the southern end, the unconformity of Lower Carboniferous conglomerate above the Silurian flysch is very clear; the basal conglomerate contains pebbles of basalt, tuff, chert, sandstone, schistose pelite (initial cleavage disposed randomly in the conglomeratic bed). The flysch, cropping out over 3 km, is Lower Silurian (Che et al., 1993, 1994). The basal bed over the Ordovician volcanics is a reddish conglomerate, including pebbles and boulders of red chert, tuff, basalt and andesite in a greywacke matrix. Within 50 cm, the overlying layers grade progressively through microconglomerate to fine-grained sansdtone.

The Ordovician volcanic formation (Che et al., 1994) is made of tuff, sandstone, and greywacke alternating with basalt and andesite. The basalt is represented by deformed pillows and massive flows several meters thick. Andesite, and minor dacite, abundant in the middle of the section, also show deformed pillows or massive, frequently prismatic, flows. In thin section, feldspar phenocrysts are surrounded by tails of chlorite. The geochemical signature suggests calc-alkaline and low-K tholeiite series (Laurent-Charvet, 2001).

The Ordovician is in contact, along a south-dipping fault, with the mélange and divided into two units. The southern portion is intruded by a granite. At the northern edge of the pluton, relics of a sheeted dyke complex occur among the reworked blocks and include altered doleritic basalt, and marble in a tuffaceous matrix. A south-dipping thrust, outlined by marble lenses, marks the contact with the northern unit containing blocks of limestone, chert, gabbro, ultramafics in a greenschist matrix. As already stated, despite the presence of Ordovician-Silurian fossils in the blocks, the age of this mélange is Devonian.

Structures and microstructures

The Silurian flysch, in which S0 is easily seen, is affected by folds, the average trend of which is N90. The flysch is usually normal, sometimes overturned toward the north (Figure 6b). A spaced fan-shaped cleavage corresponds to the axial planes; it is weaker and refracted in the sandstone beds. To the north, the schistosity becomes

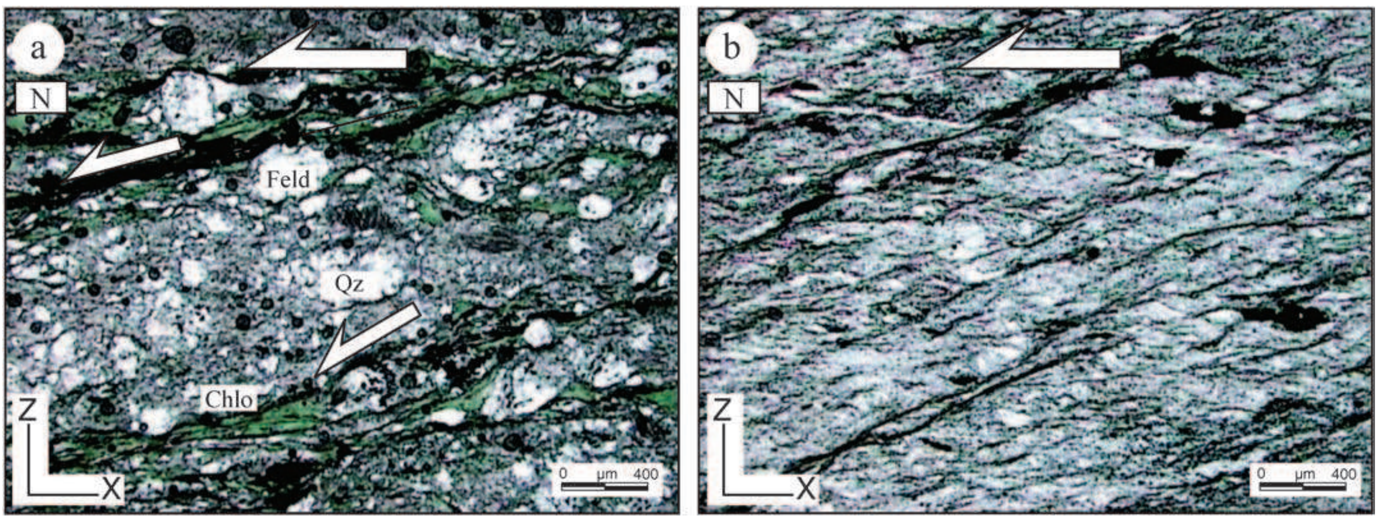

Figure 9 Photomicrographs showing kinematic criteria in Hongliuhe-Weiya area; a: Chlorite shear-bands in a Silurian tuffaceous sandstone, near the thrust plane of the Sinian klippe of section 8a, Hongliuhe area, PPL; b: Shear-bands in an Ordovician sandstone, southern end of section 8c2, Weiya area, PPL.

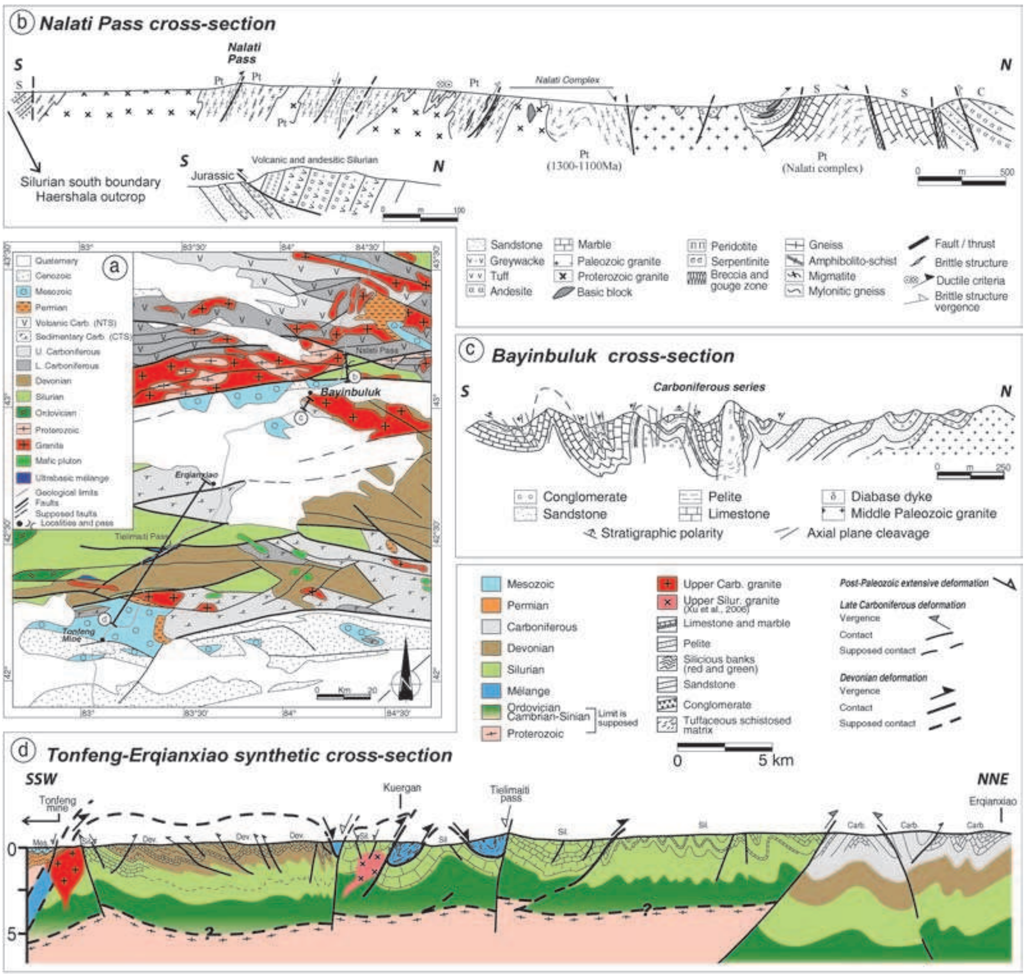

Figure 10 Geological map and cross-sections of Bayinbuluk area, West Tianshan; a: Geological map and location of sections; b: Cross-section through Nalati Pass, showing the Proterozoic basement and Lower Paleozoic volcaniclastics; c: Cross-section of the sedimentary Carboniferous near Bayinbuluk; d: Tonfeng-Erqianxiao synthetic crustal-scale cross-section.

more and more penetrative and parallel to S0. S0-1 is well developed in the Ordovician and the mélange, usually dipping south. At the slightly disconformable Ordovician-Silurian boundary, S0-1 cross-cuts both formations and the conglomerate; there is no difference in the deformation history of both formations.

The Ordovician rocks are affected by ductile shearing. S1 bears a N170-N240 stretching lineation (Figure 6a), accompanied by numerous kinematic criteria showing a top-to-the-north shear sense (Figure 7), in a greenschist facies environment. Marbles within the mélange are well lineated with a texture indicating N340-directed shearing at low to medium temperatures (~200°C) (Laurent-Charvet, 2001).

At the Carboniferous-Silurian contact, a north dipping spaced cleavage S2 affects both series (Figure 6b). It differs from S1 and does not correspond to the axial planes of Silurian folds. However it is locally visible in the Ordovician, where it marks the axial planes of microfolds, kink-bands, with both north and south apparent vergences. Thus, as in the previous section, a post-Carboniferous deformation, sometimes south-verging, is recognized.

Lastly, several sub-vertical shear zones show a sub-horizontal lineation on a N120 trending schistosity, associated with dextral strike-slip evidence.

Summary

The transect of Kumux-Toksun area, including Mishigou, shows: 1) a pre-Carboniferous north-verging tectonic event responsible for the emplacement of the South Tianshan ophiolites, in a southern suture zone, thrusting of an Ordovician-Lower Devonian island arc, emplacement of the Gangou-Mishigou ophiolitic mélange, marking a second, northern, suture; 2) post-Carboniferous folding, south-verging in the southern half of the area, likely older than the Permian unconformity; 3) a Permian dextral strike-slip shearing.

Hongliuhe-Weiya area

This area is located at the eastern end of Tianshan belt, straddling the boundary between Gansu and Xinjiang provinces (Figure 1). Three sections provide additional information on the STS and CTS (Figure 8).

Outline of sections

South Tianshan Suture Zone: Hongliuhe. The first detailed section crosses the Silurian olistostromes of northern Tarim margin up to the subduction-related Hongliuhe granite, yielding a zircon U-Pb age of 441.4 ± 1.6 Ma (Li et al., 2001), and the Permian molasse (Figure 8a). In the south, the Silurian greenish-grey sandstones and polygenetic microconglomerates are non-schistose. To the north, the Silurian grades into a flysch-like alternation of sandstone and pelite, with tuffaceous layers and greywacke beds, and becomes schistose. A cleavage develops in folds and pelites are tranformed into slates, whereas the cleavage remains weaker in the sandstone beds. A low-greenschist facies metamorphism affects the rocks.

The Silurian comprises sandy limestone intercalations; they yield brachiopods about 17 km along strike to the west of the section. Laterally, this flyschoid matrix includes olistoliths of Sinian reddish chert-bearing marble, Lower Cambrian black chert and sandstone, and Middle Cambrian limestone. Microgabbro, dolerite, and andesite dykes are locally associated with these blocks. Along the section, the Silurian is in fault contact with such a Sinian marble and, beyond another fault, the olistostrome bears a thrust sheet of Sinian and Cambrian folds and a Sinian klippe. The entire unit is intruded by a Late Carboniferous granite (Ma et al., 1997). At the northern end, Permian molasse appears, juxtaposed against the Silurian along a late brittle fault. The Permian, regionally, becomes coarser northward, suggesting a northern source for various clasts that include: granite, chert, sandstone, schist.

Figure 8b gives an idea of the content and geometry of the Hongliuhe ophiolitic complex, cropping out in an E-W trending unit about 2 km wide. Like near Kumux, it comprises two types of mélange: one with a tuffaceous matrix, reworking blocks of gabbro, basalt, together with Sinian marble; and one with a serpentinite matrix including ophiolitic fragments such as: peridotite, pyroxenite, gabbro, dolerite, basalt, and some red or grey chert.

The peculiarity of this section is the presence, to the south of the ophiolitic mélange, of: i) an olistostrome, assigned to Silurian (XBGMR, 1993), reworking olistoliths exclusively derived from

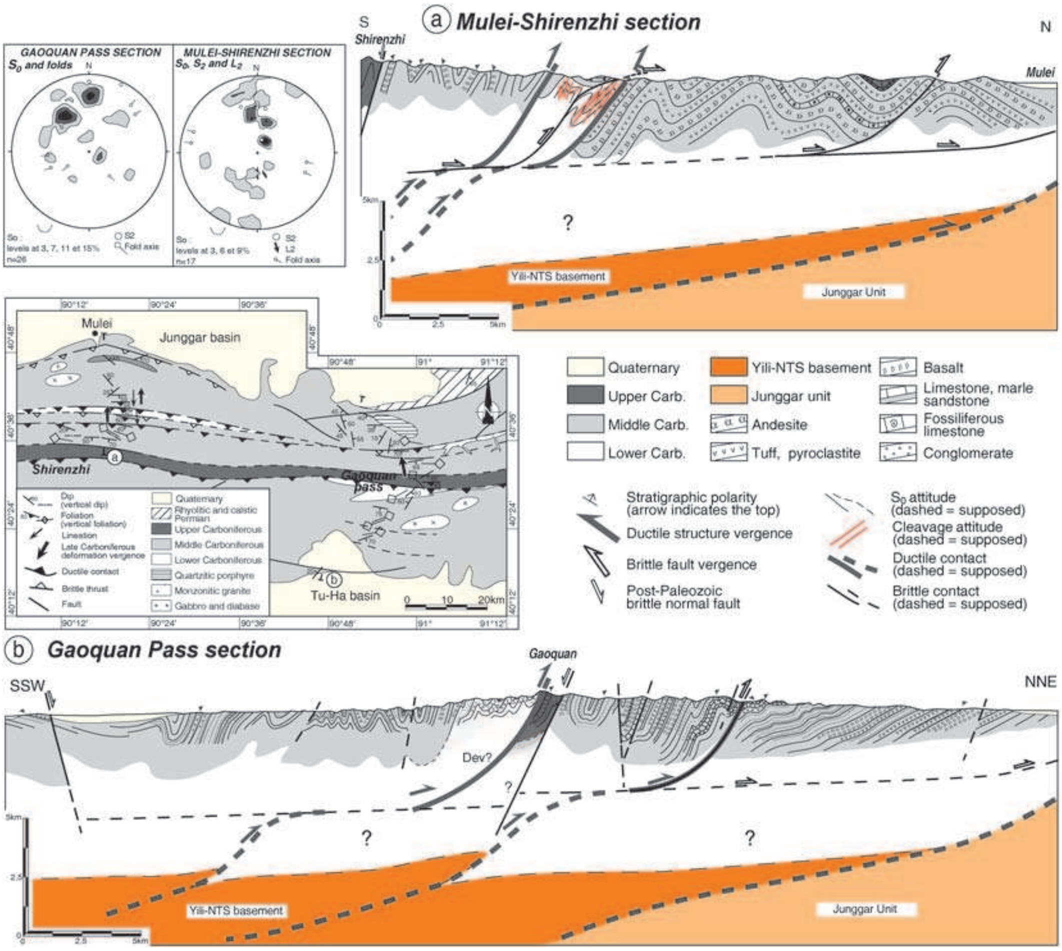

Figure 11 Geological map, structural data, and cross-sections of Bogda arc, interpreted at depth; a: Mulei-Shirenzi section; b: Gaoquan Pass section.

Tarim sequence; ii) a granitic body suggesting a subduction beneath Tarim plate at Late Ordovician time (Li et al., 2001).

Weiya. This area is located on a composite pluton, the central part of which is dated at 250 ± 8 Ma and 246 ± 6 Ma, by the 40Ar/39Ar method on biotite (Hu and Zhang, 1995), and yields zircon SHRIMP ages ranging from 246 ± 6 Ma to 233 ± 8 Ma (Zhang et al., 2005). This pluton crosscuts older E-W trending granitic bodies, assigned an Early Paleozoic (Shu et al., 2004) or Proterozoic age (Zhang et al., 2005). The granite host rocks mainly consist of Proterozoic basement: gneiss, orthogneiss, amphibolite, schist, and marble (Figure 8c1). To the west of Weiya batholith, it includes tectonic slices of granulite, yielding a Sm-Nd inner isochron age of 538 ± 24 Ma, considered to be the time of peak metamorphism, and $^{40}Ar/^{39}Ar$ ages on amphibole of 432 ± 1 Ma (plateau) and 435 ± 2 Ma (isochron), considered to be the time of retrograde metamorphism (Shu et al., 2004), linked with a tectonothermal event coeval with granitoid emplacement around 435–440 Ma (Hopson et al., 1989; Li et al., 2001).

Two stages of ductile deformation, firstly at conditions under which pyroxene and garnet deform ductilely, and then in feldspar-quartz mylonite, indicate a top-to-the-north shear movement (Shu et al. 1996, 2004). These structures, as well as later dextral strike-slip shearing recorded in gneiss and schists, are cut by the Weiya granite, which constrains the upper time limit for wrenching. The Weiya granite partly seals and hides the MTSZ, its northern border being in intrusive contact with the NTS volcanics.

To the east of Weiya, a narrow strip of Ordovician-Silurian volcaniclastic and flysch formation and ophiolitic mélange is preserved (Figure 8c2). The Ordovician is composed of sandstone, pelite and tuff, almost devoid of volcanic flows, except a 200 m thick rhyolite. A slice of ophiolitic rocks including: peridotite, olivine pyroxenite, gabbro, and doleritic dykes, is thrust over the schists and itself overthrust by flysch.

Structures

In the area, cleavage subparallel to S0 (S0-1) trends between N80 and N120, dipping N or S, often steeply. Two stretching lineations can be recognized; one (L1) is steep, trending about N-S. In thin section, kinematic criteria show, in the XZ plane, a top-to-the-north shearing in the matrix of Hongliuhe mélange (e.g. Figure 9a) as well as in the Weiya section (e.g. Figure 9b).

When the stratigraphic polarity is clear, the folds of different scales show also a northern vergence. Microfolds in the flysch overthrusting the Weiya peridotite also indicate northward movement.

At CTS boundaries and in some shear zones within Proterozoic or granite, another gently dipping E-W trending lineation is linked with the dextral strike-slip motion. The Permian molasse is affected by reverse faults (Figure 8a) but also folded and locally schistose with a southward vergence.

Conclusions

In the easternmost Tianshan the elements seen in Kumux-Toksun section, indicating a pre-Carboniferous northward folding and thrusting, are also observed. The CTSZ is poorly exposed, often hidden by granites. The STSZ is better exposed and reveals ophiolitic mélange overthrust and bounded to the south by an olistrostrome containing exclusively Tarim-derived olistoliths. Therefore, the Hongliuhe ophiolitic mélange marks the root of this ophiolitic domain, the scar of the South Tianshan ocean.

An outlook on West Tianshan: Bayinbuluk transect

STS and CTS are widely exposed in the Bayinbuluk area, between the Mesozoic-Cenozoic formations to the south and the Yili-NTS Carboniferous arc volcanics, bounded by the Nalati Fault, to the north (Figure 10). We will briefly discuss information from three cross-sections.

Presentation of sections

North of Bayinbuluk basin, in the Nalati Pass section (Figure 1, 10b) the CTS arc andesitic tuffs and volcanic breccias assigned here to the Silurian (XBGMR, 1993), overthrusting the Jurassic to the south, at Haershala, are in fault contact to the north with the Proterozoic basement. Nalati complex is composed of migmatite, para and orthogneiss, amphibolite, frequently mylonitized granite. Radiometric data from orthogneiss (Wang et al., 1994) give ages of 1.3 ± 0.2 Ga (zircon U/Pb) and 1.1 ± 0.125 Ga (Sm-Nd whole rock). Beyond a slice of green metatuffs, assigned to the Silurian, and intruded by a chloritized granite, the Proterozoic basement reappears with gneiss and highly deformed bluish siliceous marble. Its contact with green-