Understanding and study perspectives on tectonic evolution and crustal structure of the Paleozoic Chinese Tianshan

Qingchen Wang, Liangshu S. Shu, Jacques Charvet, Michel Faure, Huadong Ma, Boris Natal'In, Jun Gao, Alfred Kroner, Wenjiao Xiao, Jinyi Liu, et al.

by Qingchen Wang[1,#], Liangshu Shu[2], Jacques Charvet[3], Michel Faure[3], Huadong Ma[4], Boris Natal'in[5], Jun Gao[1], Alfred Kroner[6, 7], Wenjiao Xiao[1], Jinyi Li[8], Brian Windley[9], Yan Chen[3], Richard Glen[10], Ping Jian[7], W. Zhang[7], Reimar Seltmann[11], Simon Wilde[12], Flavien Choulet[3], Bo Wan[1], Cameron Quinn[10], Yamirka Rojas-Agramonte[6, 7], Qinghua Shang[13], Wei Zhang[7], Bo Wang[2, 14], Wei Lin[1,]*

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[1] State Key Laboratory of Lithospheric Evolution, Institute of Geology and Geophysics, Chinese Academy of Sciences, Beijing, China
[2] State Key Laboratory for Mineral Deposits Research, Department of Earth Sciences, Nanjing University, Nanjing 210093, China
[3] Université d'Orléans, CNRS/INSU, Institut des Sciences de la Terre d'Orléans–UMR 6113 Campus Géosciences 1A, rue de la Férollerie, 45071 Orléans cedex 2, France
[4] National 305 Project Office, Urumqi, Xinjiang, 830000, China
[5] ITU, Maden Fakultesi, Jeoloji Muhendisligi Bolumu, Genel Jeoloji Anabilim Dali, Ayazaga, 34449, Istanbul, Turkey
[6] Institut für Geowissenschaften, Universität Mainz, 55099 Mainz, Germany
[7] SHRIMP Centre, CAGS, 26 Baiwanzhuang Road, 100037 Beijing, China
[8] Chinese Academy of Geological Sciences, Beijing, China
[9] University of Leicester, United Kingdom
[10] Geological Survey of NSW, NSW Department of Primary Industries, Australia
[11] Centre for Russian and Central EurAsian Mineral Studies (CERCAMS), Department of Mineralogy, Natural History Museum, Cromwell Road, London SW7 5BD, UK
[12] The Institute for Geoscience Research, Department of Applied Geology, Curtin University of Technology, GPO Box U1987, Perth 6845, Australia
[13] Institute of Vertebrate Paleontology and Paleoanthropology, Chinese Academy of Sciences, Beijing 100044
[14] Institute of Earth Sciences, Academia Sinica, Taipei, 11529 Taiwan
[#] Topo-Central-Asia (International Lithosphere Program); [*] Corresponding author. *E-mail: linwei@mail.iggcas.ac.cn*

The Chinese Tianshan Belt is one of the key regions for the understanding of tectonics of the Central Asian Orogenic Belt (CAOB). An international field excursion and workshop were organized to conduct a common observation and discussion on the tectonic evolution of the Chinese Tianshan. This report summarizes the main achievements, including acknowledged geological features, controversial and remaining scientific problems, and discussion of a tentative geodynamic model. Thus, it is helpful to clarify what has been done in the past, what should be improved and what needs to be done in the future and therefore to better understand the tectonics of the Chinese Tianshan Belt and the CAOB as well.

Introduction

The Tianshan range is an important part of the Central Asian Orogenic Belt (CAOB) that presents a typical example for accretion and collisional orogens. Its tectonic evolution is recently in hot debate and draws more and more attention of the international geological community. In order to promote scientific exchanges and make an effort to reach a common understanding of the Paleozoic geodynamic evolution of Tianshan and, therefore, of CAOB, a 7-day (Sept. 10 to 16, 2009) International Field Excursion across the Chinese Tianshan, southernmost part of the CAOB, was organized by the State Key Laboratory of Lithospheric Evolution (Chinese Academy of Sciences), State Key Laboratory for Mineral Deposits Research (Nanjing University), Institut des Sciences de la Terre d'Orléans (University of Orléans) and the Xinjiang 305 Project. The Excursion was initiated by International Lithosphere Program (ILP) CC-1/4 Project TOPO-CENTRAL-ASIA and ERAS (Task Force 1), as well as Chinese National 973 project (2009CB825008) and Paleo-environment research of NW China. Integrating previous and recent field observations and laboratory analyses, the purpose of this excursion was to recognize the key tectonic zones, their geometric, kinematics and temporal relationships in order to reach a common understanding on the Paleozoic evolution of the Tianshan belt and to review updated models of continental accretion of Central Asia. Field-based

Photograph of the Permian Baiyanggou olistostrome including Carboniferous limestone blocks with variable sizes, and Permian terrigenous matrix (cf. Day 1 for the situation and the explanation in details). From left to right, rear: Dr. P. Jian; W.J. Xiao; M. Faure; F. Choulet; A. Kroner; J. Charvet; B. Natal'in; R. Seltmann; R. Glen; B. Windley; C. Quinn; Q. Wang, H. Ma, L. Shu; Y. Chen; Y. Rojas-Agramonte; S. Wilde; front: B. Wan; B. Wang; W. Lin; W. Zhang

discussions of the Tianshan Belt helped the participants to place the geodynamic evolution of this range within the general framework of Central Asian geology. Twenty-two scientists from 8 countries have participated in this 7-day field excursion (Photograph).

After the excursion, a 2-day workshop (Sept. 17 to 18, 2009) was held in Urumqi. The workshop provided an opportunity for participants to present new research results dealing with the various aspects of the geology of Central Asia and related areas, to exchange ideas for elaborated syntheses on the Paleozoic evolution of the Central Asian Orogenic Belts, and to set seeds for future international cooperation.

The following text summarizes the main points of the discussion that allowed the international geological community to understand the main geological features of the Chinese Tianshan orogen. However, several controversial questions remain and should be considered as targets for future work.

Generally agreed features

On the basis of effective discussion on the published data and field group observations during the excursion and workshop, a general agreement on the Paleozoic geology of the Chinese Tianshan can be reached on several important issues.

Ophiolitic mélanges

Several ophiolitic mélange zones are exposed in the Tianshan Belt (Fig. 1). Some of these represent suture zones (i.e. ancient plate boundaries), whereas others are oceanic elements included in a siliceous muddy or terrigeneous matrix and transported as allochthons far away from the original sutures (e.g., Wang et al., 2010a and references therein). The interpretation of the Tianshan ophiolitic mélanges as representing three main sutures zones (i.e. disappeared oceans), which are, from South to North: (i) The South Tianshan, (ii) the Central Tianshan and (iii) the North Tianshan sutures zones was well constrained by stratigraphic, biostratigraphic, structural, geochemical, metamorphic and geochronologic data (e.g., Laurent-Charvet, 2001; Wang, 2006; Charvet et al., 2007; Wang et al., 2006, 2008, 2010a and Lin et al., 2009) and thus might be today accepted by the scientific community.

Continental blocks or microcontinents

Several continental blocks or microcontinents are involved in the orogen. They are from South to North; (i) the Precambrian Tarim block, (ii) the Central Tianshan block, (iii) the Kazakh-Yili-North Tianshan block. The latter was formed by the Pre-Silurian amalgamation of several entities with accretionary prisms, continental and intra-oceanic arcs, and fragments of Precambrian continental crust (Allen et al., 1993; Mikolaichuk et al., 1997; Burtman, 2006; Windley et al., 2007).

Continental magmatic arcs

Two continental magmatic arcs represented by volcanic (i.e. lava flows, volcanic breccias, and agglomerates), volcaniclastic and pyroclastic rocks, and calc-alkaline plutons (granodiorite, diorite, and gabbro) are recognized in the Chinese Tianshan. (i) The largest magmatic arc is widely developed in the Kazakh-Yili-North Tianshan block. Stratigraphic and isotopic dating indicates that the North Tianshan arc formed in Devonian and Carboniferous times. (ii) Volcanic and sedimentary elements of an Early Paleozoic (Ordovician-Early Devonian) arc are scattered in the northern part of the Central Tianshan block. Moreover, some of the early Paleozoic calc-alkaline granitic plutons that intrude the Central Tianshan block may represent the deep part of the same early Paleozoic arc. The Early Paleozoic arc was interpreted as resulting from the south-directed subduction under the northern margin of the Central Tianshan Block (Wang, 2006; Charvet et al., 2007; Wang et al., 2008, 2010a).

Permian dextral strike-slip faulting

Permian dextral strike-slip faulting is a major tectonic event (Laurent-Charvet et al., 2003) that induced several phenomena such as: (i) control of sedimentation in pull-apart and transtensional basins (Wartes et al., 2002; Shu et al., 2005, 2010; Wang et al., 2009),

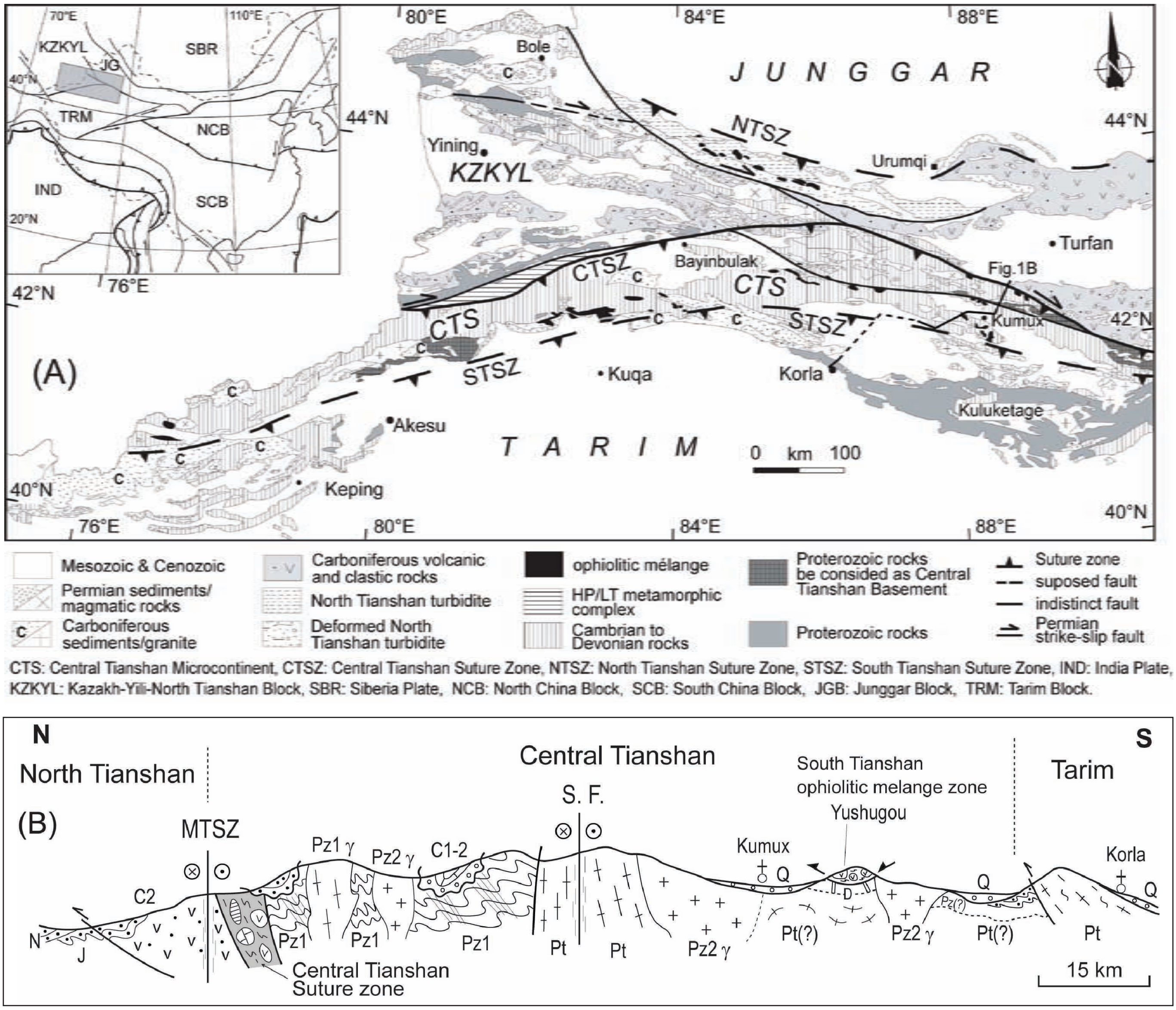

Figure 1. (A). Simplified geological map of the Chinese western Tianshan (modified from Wang et al., 2008; Lin et al., 2009). (B) Cross section of the Eastern Chinese Tianshan following the field excursion

(ii) development of alkaline magmatism (Yang et al., 1996, 2006; Wang et al., 2007d, 2009 and references therein), (iii) reworking of the ophiolitic mélange zones (Charvet et al., 2007, 2010; Wang et al., 2006, 2007c, 2010b), and (iv) fluid circulation and high thermal gradients responsible for ore deposits, retrogression of metamorphic rocks, and resetting of some radiometric ages (de Jong et al., 2009). The evolution of the Permian tectonic regime from transpression to transtension may also have produced a rather complex structural pattern (Laurent Charvet 2001; Wang Y. et al., 2008). In the Western Chinese Tianshan, two most important strike-slip faults are the Main Tianshan shear zone (MTSZ in Fig.1B) along the Central Tianshan Suture Zone (CTSZ in Fig.1A; Laurent-Charvet et al., 2002, 2003), several other ductile shear zones, characterized by subvertical foliation, horizontal stretching and mineral lineations, and dextral kinematic indicators, can be observed both in North and South Tianshan (Shu et al., 1999; Laurent-Charvet et al., 2002, 2003; Wang et al., 2006, 2007b, 2008, 2010b; Charvet et al., 2007; Lin et al., 2009).

Controversial points and remaining questions

In spite of the agreed features mentioned in the previous section, several points remain to be clarified. A non-exhaustive list is given below.

Suture locations

The Central Tianshan suture (CTSZ in Fig. 1A) separates the Kazakh-Yili-North Tianshan block to the North and the Central Tianshan block to the South. However, according to the different definition of Central Tianshan block, the ‘Nikolaev Line’ in Kyrgyzstan and Kazakhstan and the ‘North Nalati Fault’ in China was suggested as the suture zone between Kazakh-Yili-North Tianshan block and Central Tianshan block (Burtman, 1975; Gao et al., 2009; Qian et al., 2009 and references therein). More to the South, Atbashy–

Inyl'chek Fault in Kyrgyzstan and South Nalati-Qawabulak Fault in China were considered as the boundary and suture zone between Central Tianshan block and Tarim block (Gao et al., 2009).

Another controversy is the recognition or not of suture zones in North and South Tianshan. Due to the strong Cenozoic tectonics, the South Tianshan suture (STSZ in Fig. 1A) was suggested to separate the Central Tianshan block to the North from the Tarim block to the South hidden below Mesozoic and Cenozoic formations. In the same way, the North Tianshan suture (NTSZ in Fig. 1A), lying between the Kazakh-Yili-North Tianshan and the Junggar blocks is a cryptic (Wang et al., 2006, 2008; Charvet et al., 2007; Lin et al., 2009).

Age of (U)HP metamorphism

On the basis of structural evidence, high or ultra-high pressure metamorphism occurred mainly in the westernmost part of the belt and should date back to the Devonian or early Carboniferous (pre-Visean) (Wang et al., 2010 and references therein). However, radiometric data obtained from high-pressure minerals such as phengite often indicate middle to late Carboniferous ages (e.g., Gao and Klemd, 2003; Klemd et al., 2005). Even Triassic metamorphic zircon ages have been obtained (Zhang et al., 2007). Although these rather young ages can be explained by fluid-assisted crystallization or thermal resetting (de Jong et al., 2009), there is a need to reassess the age of (U)HP metamorphism. The main issue is in the geodynamic interpretation of the various ages: do they reflect prograde metamorphism during subduction or are they related to retrogression, uplift and cooling?

Direction of subduction

There is a consensus on (1) microstructure of top-to-the-North kinematics developed in the early Paleozoic Central Tianshan suture (Gao et al., 1995; Lin et al., 2009; Wang et al., 2010), and (2) bulk south-verging structures occurring to the south of the Central Tianshan suture (Windley et al., 1990; Allen et al., 1993), but which one should be considered as the indicator for the syn-accretionary kinematics remains disputed, and therefore the subduction polarity is still controversial. The important factor is that south-verging structures are widespread in both Paleozoic and Mesozoic rocks. Sometimes, this similar structure could be observed in the Cenozoic rocks (Allen et al., 1999; Yin et al., 1998). This implies that the Tianshan belt was reactivated by post-orogenic polyphase tectonics (Yin et al., 1998; Lin et al., 2009; Wang et al., 2010a). Furthermore, if the early Paleozoic magmatic arc developed in the Central Tianshan block and the occurrence of the South Tianshan back-arc basin are rather well supported by data, the closing history of the latter has to be confirmed (Zhu et al., 2008; Wang et al., 2008, 2010a). In the case of the South Tianshan suture, arc is not well preserved (cf. next point). However, the contact between the South Tianshan mélange and its tectonic substratum is associated with top-to-the-North kinematic indicators, also implying south-directed subduction (Charvet et al., 2007; Lin et al., 2009; Wang et al., 2010a). Detailed studies in the future should focus on the Upper Carboniferous clastic rocks that are shown on 1:200 000 scale geological maps along the southern side of Tianshan (Fig. 1A). Some maps suggest that the terrigenous sequence may contain blocks of limestones with Tethyan fusulinids, cherts, and ultramafic rocks (Zhu et al., 2007). In this case, this series might represent an accretionary prism related to the subduction of south Tianshan back-arc basin lithosphere. Clearly, the stratigraphy, structural style and kinematics of these rocks require further study.

Active margin of Northern Tarim

A magmatic arc that may be related to south-directed subduction and closure of the South Tianshan back-arc basin cannot be clearly identified in the northern part of the Tarim block. This apparent indigence of magmatism may be explained as follows: (1) Closure of the young Devonian back-arc basin may have taken place with very few or without the formation of a magmatic arc. (2) The arc may have been obliterated by Meso-Cenozoic reworking (Wang et al., 2010a). Nevertheless, several lines of evidence suggest an existence of Devonian calc-alkaline plutons which have recently been documented to the north of Kuqa and Kuluketage areas (Zhu, 2007; Zhu et al., 2008; Fig. 1A). A geochemical and geochronological study of these granitic plutons would be an important target for future investigations in order to constrain the potential existence of a Devonian arc on the Northern Tarim margin that was generally interpreted as a continued passive margin during the whole Paleozoic (e.g., Carroll et al., 1995; Gao et al., 1998; Xiao et al., 2004).

Nature of the basement of the Junggar basin

The Junggar basin currently contains a ca. 10 km thick sedimentary sequence of Carboniferous to Cenozoic deposits, but the underlying rocks are unknown. Knowledge of the nature of the basement is of particular importance to understand the geodynamic process during the orogeny of the Tianshan belt. A trapped oceanic plate or early Paleozoic island arc were favored according to geochemical and isotopic data from the magmatic rocks around the Junggar basin (Chen et al., 2000; Carroll et al., 2001; Zheng et al., 2006). However, a continental basement underlying the Junggar basin is not ruled out according to geophysical data and results of drill holes (Wang et al., 2000; Wang et al, 2004; He et al., 2008, 2010; Ji et al., 2010). No matter how, an intermediate crust including fragments of early Paleozoic magmatic arcs may also account for the late Carboniferous tectonics of the Kazakh-Yili-North Tianshan blocks. Seismic surveys and deep drilling will provide important information to answer this question.

Existence of pre-Permian strike-slip faulting

Permian dextral strike-slip faults are well developed, but the question of the pre-Permian strike-slip faulting remains open. Such a tectonic pattern might accommodate oblique plate convergence or account for the splitting of magmatic arcs.

Pre-Cambrian and Early Paleozoic tectonics in the Kazakh-Yili-North Tianshan and in the Central Tianshan blocks

These continental blocks obtained their bulk architecture in the Devonian, Carboniferous, and Permian during the formation of the Tianshan orogeny (Charvet et al., 2007; Wang et al., 2008 and reference therein). However, the Kazakh-Yili-North Tianshan and the Central Tianshan blocks contain Early Paleozoic and Proterozoic rocks that obviously experienced earlier deformations (e.g., Gao et al., 2009; Xu et al. 2010). For instance, the Terskey and Yili Early Paleozoic sutures as well as paired magmatic arcs recognized in Kyrgyzstan and Kazakhstan may extend eastwards into the Yili-North Tianshan block (Qian et al., 2009). The recognition of such pre-Devonian features will provide guidelines for the identification of the Gondwana-derived or Siberia-derived microcontinents and paleogeographic correlations throughout the Central Asia Orogenic Belt.

Correlation and nomenclature of tectonic units

Since the level of knowledge throughout the CAOB varies from one segment to the other, the Chinese Tianshan may become a key area showing the typical lithological, magmatic, structural, and metamorphic elements that can then also be recognized in the other segments of the CAOB (such as Kazakhstan and Kyrgyzstan). More locally, there is a need for correlation and harmonization of unit names, such as "South Tianshan" or "Central Tianshan" that are commonly used with different meanings depending on places and authors (Xiao et al., 1992; Gao et al., 1995, 1998, 2009; Charvet et al., 2007, 2010).

Recognition of typical features of a collisional orogen and distinction between accretion-related and collision-related structures

Although continental subduction and collision have certainly played a major role in the evolution of the Tianshan orogen, several typical elements observed in other collisional belts such as the Himalaya, the Alps or the Variscan belts are not yet clearly recognized yet. Some of these lacking features are: (i) widespread crustal melting characterized by leucogranitic or peraluminous plutonism, (ii) syn- and post-orogenic collapse with ductile normal faults that induced the exhumation of the high-grade metamorphic rocks, (iii) foreland basins filled by terrigeneous rocks derived from the erosion of the rising orogen. Whether these elements are really missing or were not yet recognized in the Tianshan remains an open question.

Since both accretionary complexes and nappe structures are represented in the Tianshan belt, it would be important to be able to separate two structural styles, and evaluate, through thermo-barometric studies, the physical conditions of their development.

A tentative geodynamic model

In spite of the pending questions mentioned above and the debates which are still on-going on the mechanism and timing of the agglomeration of Central Asia, after a comprehensive analysis on the published data during last several decades in different aspects of structural geology, geochemistry, geochronology and geophysics, a review of some up-dated models was conducted mainly focusing on the subduction polarity and age of accretion/collision, and a preliminary geodynamic model for the evolution of the Chinese Tianshan can be proposed. Some controversial points related to the above-discussed questions need further testing by future multi-disciplinary research. In this tentative model, the Paleozoic evolution of the Chinese Tianshan can be separated into five main stages (Fig. 2).

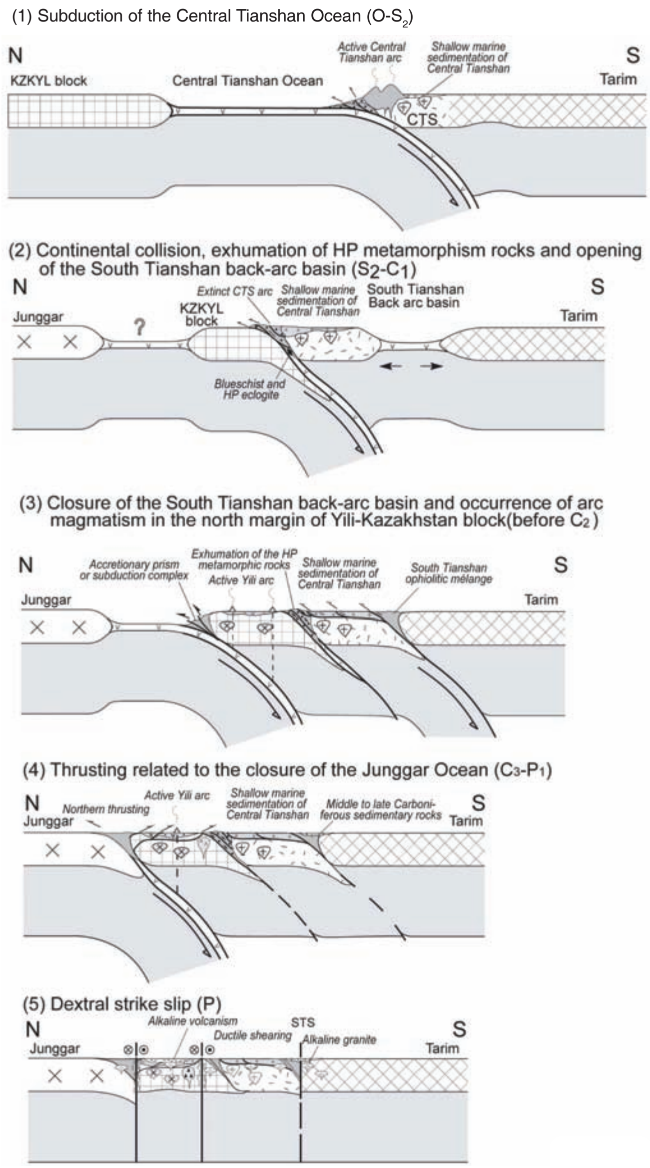

Figure 2. A tentative geodynamic model for the Paleozoic Chinese Tianshan (modified from Wang et al., 2008; Lin et al., 2009)

Early Paleozoic closure of the Central Tianshan Ocean

The Central Tianshan oceanic basin separating the Tarim and Kazakh-Yili-North Tianshan block began to close in the Ordovician. The closure was achieved by a south-directed subduction below the Tarim block. During Late Silurian-Middle Devonian, the northern margin of the Tarim block experienced extensional tectonism that was responsible for the formation of the South Tianshan back-arc basin.

Early Carboniferous collision between the Kazakh-Yili-North Tianshan and Central Tianshan blocks

This early collision in the evolution of the Tianshan orogen that can be called the "Eo-Tianshan phase" was responsible for the development of the high to ultra-high pressure metamorphism along the Central Tianshan suture. The collision followed oceanic lithosphere consumption and deep subduction and was coeval with top-to-the-North ductile shearing.

Late stage of Early Carboniferous closure of the South Tianshan back-arc basin, and formation of the North Tianshan magmatic arc

The continental collage formed by the welding of the Kazakh-Yili-North Tianshan and Central Tianshan blocks collided with the Tarim block and induced closure of the South Tianshan back-arc basin. Sedimentary rocks (chert, siliceous mudstone, limestone), remnants of the oceanic crust (pillow lava, diabase, gabbro), and the underlying mantle (serpentinized peridotite) of the South Tianshan back-arc basin mixed together with sedimentary rocks of the Tarim block, formed the South Tianshan ophiolitic melange. Presently, this unit crops out as klippes emplaced from South to North upon the Central Tianshan block. More to the north, high pressure eclogitic rocks that had formed along the Central Tianshan suture are retrogressed into greenschist facies conditions during their exhumation. Lastly, the northern boundary of the Kazakh-Yili-North Tianshan block became an active margin along which the North Tianshan accretionary complex, including the North Tianshan ophiolitic melange, and the North Tianshan magmatic arc developed.

Late Carboniferous tectonics in the Kazakh-Yili-North Tianshan block

Most of the tectonic activity was located in the Kazakh-Yili-North Tianshan block. The end of North Tianshan arc magmatism is interpreted as the consequence of subduction of the Junggar basement. In the Central Tianshan, late Carboniferous sedimentation is represented by shallow marine terrigeneous and carbonated rocks. Tectonically, South-directed thrusts and folds that developed in the Kazakh-Yili-North Tianshan and Central Tianshan blocks can be viewed as resulting from back-folding and thrusting due to the chocking of the north Tianshan subduction.

Permian dextral strike-slip faulting

The various tectonic elements, including magmatic arcs, continental blocks, and ophiolitic melanges, were already welded together at the end of the Carboniferous. In Permian times, all these units experienced major dextral wrenching parallel to the strike of the orogen. To the north, the Altai Fold Belt underwent sinistral strike-slip faulting. The two strike-slip systems accommodated an opposite motion of Tarim and Siberia as indicated by paleomagnetism. This strike-slip tectonics was accompanied by pull-apart basin opening and post-tectonic magmatism expressed by volcanic rocks and granitic plutons. The coeval emplacement of Permian calc-alkaline and alkaline suites is noteworthy in Tianshan, showing the influence of the mantle metasomatism during the Carboniferous subduction.

During the Mesozoic, deformation resumed, as documented by Triassic and Jurassic unconformities. But these tectonic events were purely intra-continental, like the Cenozoic event responding to the Asia-India collision.

Appendix

Guidebook for the International Geological Excursion in the Paleozoic Chinese Tianshan (Sept. 10 to 16, 2009)

Bo Wang[1], Wei Lin[2], Jacques Charvet[3], Michel Faure[3], Lianshu Shu[1] and Domique Cluzel[4]

[1] State Key Laboratory for Mineral Deposits Research, Department of Earth Sciences, Nanjing University, Nanjing 210093, China
[2] State Key Laboratory of Lithospheric Evolution, Institute of Geology and Geophysics, Chinese Academy of Sciences, Beijing, China
E-mail: linwei@mail.iggcas.ac.cn
[3] Université d'Orléans, CNRS/INSU, Institut des Sciences de la Terre d'Orléans–UMR 6113 Campus Géosciences 1A, rue de la Férollerie, 45071 Orléans cedex 2, France
[4] Pole Pluridisciplinaire de la Matière et de l'Environnement, Université de la Nouvelle-Calédonie, 98851 Nouméa, New Caledonia

PART I: A GEOLOGICAL OUTLINE

Introduction

The Tianshan Belt is a major orogenic domain within the Central Asian Orogenic Belt (CAOB) (e.g. Jahn et al. 2000, 2004; Jahn 2004; Xiao et al. 2004; Kröner et al. 2007; Windley et al. 2007) or Altaid orogenic collage (Sengör et al. 1993; Sengör and Natal'in 1996). It is bounded by the Kazakhstan microcontinent to the northwest, the Junggar basin to the northeast, and the Tarim basin to the south (Coleman 1989; Xiao et al. 1992; Konopelko et al. 2007; Kröner et al. 2008 and references therein, Fig.1). It extends east-west for over 2500 km and exhibits the highest relief in Central Asia. The present topography is due to Tertiary Asia-India collision (Tapponnier et al. 1986; Nelson et al. 1987; Avouac et al. 1993; Sobel and Dumitru 1997). In addition, Cenozoic tectonism is responsible for the recent northward underthrusting of Tarim below the South Chinese Tianshan, and for the southward underthrusting of Junggar below the North Tianshan (Windley et al. 1990; Avouac et al. 1993; Hendrix et al. 1994; Burchfiel et al. 1999; Allen et al. 1999; Li et al. 2009). From the Neoproterozoic to late Paleozoic, accretion of several continental blocks, island arcs and accretionary complexes to the southern margin

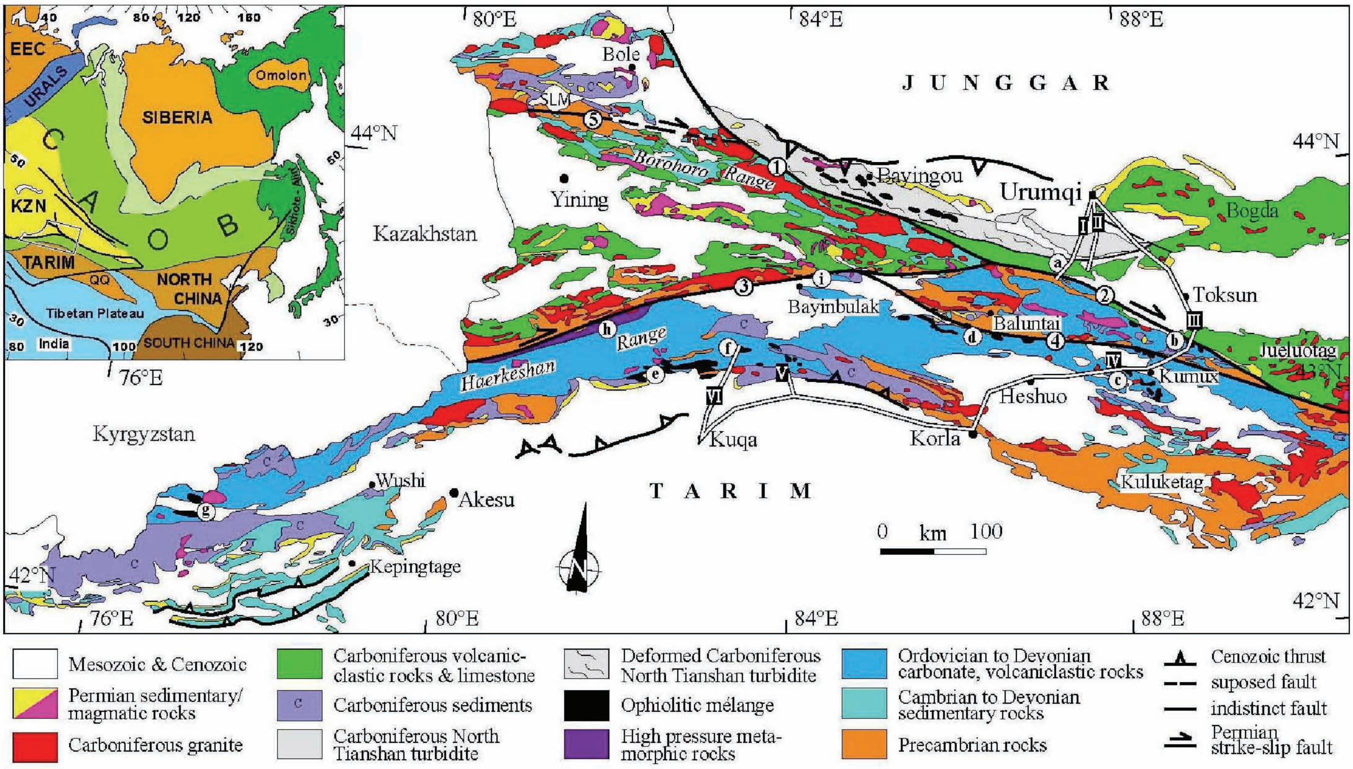

Figure 1. Geological map of the Chinese western Tianshan belt (modified after Wang et al., 2008). Numbers in circle refer to the main faults: 1-North Tianshan fault (NTF); 2-Main Tianshan shear zone (MTSZ); 3-Qingbulak-Nalati fault (QNF); 4-Sangshuyuanzi fault; 5-Jinghe fault. Letters correspond to localities cited in the text: a. Houxia; b. Gangou-Mishigou; c. Yushugou; d. Guluogou-Wuwamen; e. Heiyingshan; f. Kulehu; g. Aheqi; h. Kekesu; i. Nalati. Roman numbers stand for the excursion sections: I-Houxia section; II-Aiweiergou section; III-Gangou section; IV-Yushugou section; V-Cedaya section; VI-Duku road section. Inset shows location of the Tianshan Belt in Central Asia (modified from Jahn, 2004). Abbreviations: CAOB: Central Asian Orogenic Belt; EEC: Eastern European Craton; KZN: Kazakhstan; QQ: Qaidam-Qinling.

of Eurasia formed the CAOB, within which the Tianshan Belt resulted from amalgamation of the Tarim, Junggar and Kazakh-Yili-North Tianshan blocks and intervening microcontinents (Wang et al. 1994; Gao et al. 1998; Chen et al. 1999; Charvet et al. 2007; Wang et al. 2008; Windley et al. 2007).

According to previous works (e.g. Windley et al. 1990; Allen et al. 1993; Gao et al. 1998; Chen et al. 1999), several ophiolitic belts were used to define an Early Paleozoic South Tianshan Suture (STSS, corresponding to faults 3 and 4 in Fig. 1) and a Late Paleozoic North Tianshan suture (NTSS, corresponding to faults 1 and 2 in Fig. 1), dividing the Chinese Tianshan belt into North Tianshan, Central Tianshan and South Tianshan zones. In the literature, there is often confusion between a suture zone that represents a plate boundary and a strike-slip fault that reworked the plate boundaries during Permian, i.e. after accretion and collision.

The tectonic evolution of this complex orogen remains controversial, and numerous geodynamic models have been proposed during the last two decades. According to Coleman (1989), the Tianshan resulted from the closure of an oceanic basin during the early Paleozoic. Ma et al. (1993) suggested that the southern Tianshan evolved from a back-arc basin that formed by southward subduction of the Paleo-Junggar Oceanic lithosphere, whereas Cao et al. (1992) considered that the southern Tianshan represents oceanic crust thrust to the south upon the Tarim Block during the late Paleozoic. According to Windley et al. (1990) and Allen et al. (1993), north-directed subduction occurred in the eastern Chinese Tianshan along the STSS during the late Devonian-early Carboniferous, whereas south-directed subduction occurred in the late Carboniferous-early Permian along the NTSS. In the western Tianshan, Gao et al. (1995, 1998) proposed a north-directed subduction along the southern Tianshan suture zone. According to Chen et al. (1999), the southern Tianshan originated from the closure of an early Paleozoic ocean located between Tarim and the Central Tianshan and subsequent late Paleozoic oblique collision. More recently, Charvet et al. (2007), Wang et al. (2008), and Lin et al. (2009) argued that the Paleozoic Chinese Tianshan is a polyphase orogenic belt formed by the closure of three oceanic basins that separated four continental blocks, namely from north to south, Junggar, Yili-North Tianshan, Central Tianshan, and Tarim. The three subduction systems were not coeval, but all directed to the south. In the following discussion, the main tectonic units are presented from the north to south.

The Yili-North Tianshan Domain

The North Tianshan accretionary prism

In the North Tianshan, two lithotectonic units can be identified, namely a Carboniferous turbidite and an ophiolitic mélange well exposed at Bayingou (Wang et al. 2006; Fig. 1). The turbidites are developed in an area of 300-km long and 20-km wide and consist of sandstone and black argillite alternations. Sandstone presents typical Bouma sequences and the thickness of sandstone beds varies from a few centimeters to 1 meter (XJBGMR 1993; Wang et al. 2006).

Terrigenous, siliceous and calc-alkaline magmatic clasts were observed in sandstone and conglomerates, and deep-water ichnofossils indicate that the turbidites were deposited in a fore-arc deep-sea environment (Wang et al. 2006). The southern part of the turbidite, along the NTF, exhibits a subvertical slaty cleavage with a subhorizontal mineral-stretching lineation. Kinematic observations indicate a dextral ductile shearing related to the NTF (Fig. 1). Biotite in slates yields a $^{40}Ar/^{39}Ar$ age of 275-245 Ma indicating the time of the dextral shearing (de Jong et al. 2009). This Permian age is consistent with that of the Main Tianshan shear zone (Fig. 1; Shu et al., 1999; Laurent-Charvet et al. 2002, 2003; Wang Y. et al. 2008).

The Bayingou ophiolitic mélange is discontinuously developed in a 250 km long and 5~15-km wide area and crops out within the turbidite. It consists of serpentinized peridotite, gabbro, diabase, basalt, chert, plagiogranite and rare limestone blocks enclosed in a sheared matrix made of black or red mudstone and light-yellow-green greywacke. Famennian-Visean microfossils have been found in cherts (Xiao et al. 1992; Li and Du 1994), and zircon U-Pb ICPMS or SHRIMP ages of 344-325 Ma are obtained from Bayingou gabbro and plagiogranite (Xu et al. 2005, 2006a), both indicate late Devonian to late Early-Carboniferous ages for the ophiolitic rocks. Petrological and geochemical studies show that the mafic rocks were formed in an oceanic basin (Wu et al. 1989; Xiao et al. 1992; Li and Du 1994). Structural analysis indicates that both blocks and matrix were deformed by north-directed shearing (Wang et al. 2006). Recent SHRIMP zircon U-Pb dating on the A-type granite that intrudes the North Tianshan suture yielded an age of 316±3 Ma, suggesting that the subduction and accretion events in North Tianshan terminated in Late Carboniferous (Han et al. 2010).

The Yili-North Tianshan Late Paleozoic magmatic arc

In the western part, this unit is mainly composed of Carboniferous limestone and sandstone associated with andesite, rhyolite, trachyte, tuff and minor basalt (Fig. 1; XJBGMR 1993). Synchronous plutons of gabbro, granodiorite, tonalite, K-granite, pegmatite and aplite dykes are well developed. The Carboniferous rocks are lithologically similar throughout the Yili area (Fig. 1). Trace elements geochemistry and isotopic studies indicate that the magmatic rocks are calc-alkaline in composition and were generated in an active continental margin (Chen et al. 2000a; Zhu et al. 2005, 2006; Wang et al. 2007b). Zircon U-Pb dating of the magmatic rocks (SHRIMP/ICPMS) yield 363-300 Ma ages indicating that these arc-type rocks formed during Late Devonian to latest Carboniferous (Zhu et al. 2005; Xu et al. 2006a; Wang et al. 2006; Zhai et al. 2006; Gao et al. 2008). To the west of Urumqi, the magmatic arc is almost undeformed except locally along the Qingbulak-Nalati fault where dextral ductile shearing occurred around 270-250 Ma (Yin and Nie 1996; Zhou et al. 2001).

To the east of Urumqi, greywackes, red porphyritic andesite, basalt, and limestone are developed in the Bogdashan. It corresponds to the eastern extension of the North Tianshan arc. This unit is deformed by hundred-meters scale upright or north-verging folds and north directed reverse faults, but it disappears beneath the unconformably overlying Upper Jurassic coarse sandstones and conglomerates that can be observed along the Houxia and Toksun-Kumux sections (Fig. 1) and other parallel N-S sections more to the east (Charvet et al. 2007). The volcanic rocks of the North Tianshan arc are often associated with Mid-Carboniferous tightly folded meter-scale beds of grey and brown fossiliferous limestone and sandstone with minor red pelite, assigned to the Lower Carboniferous (Ma et al. 1997; Shu et al. 2000; Laurent-Charvet 2001; Xiao et al. 2004; Charvet et al. 2007). Granitic rocks are also developed in these areas and formed during the late Devonian to Carboniferous (383-310 Ma, zircon U-Pb ages) (Yang et al. 1996, 2000; Ma et al. 1997; Qin et al. 2000, 2002; Li et al. 2003). The basement of the Bogda arc is not exposed and remains unknown.

The Yili-North Tianshan basement

The Yili-North Tianshan magmatic arc is situated above a Proterozoic basement and an Early Paleozoic sedimentary cover. The basement rocks crop out along the boundaries of the Yili Block (Fig. 1). The Meso- to Neoproterozoic carbonates and clastic rocks of the Jixian and Qingbaikou formations are developed in the north of the Borohoro range and to the south of Yining. Neoproterozoic red sandstone and minor "tillite" (XJBGMR 1993; Gao et al. 1998; Xia et al. 2002) are exposed to the south of Sailimu Lake (Fig. 1). Precambrian amphibolite facies metamorphic rocks mainly crop out in the Bingdaban-Baluntai area, south of Urumqi. They were also recognized at Nalati Pass, north of Bayinbuluk, and to the north of the Haerke Mountains (Fig. 1), where orthogneiss yield zircon U-Pb ages at 882 and 709 Ma (Chen et al. 2000b, 2000c). The early Paleozoic strata are mainly Cambrian and Ordovician chert and carbonates occurring in the Borohoro range, the northern margin of the Yili Block (Fig. 1).

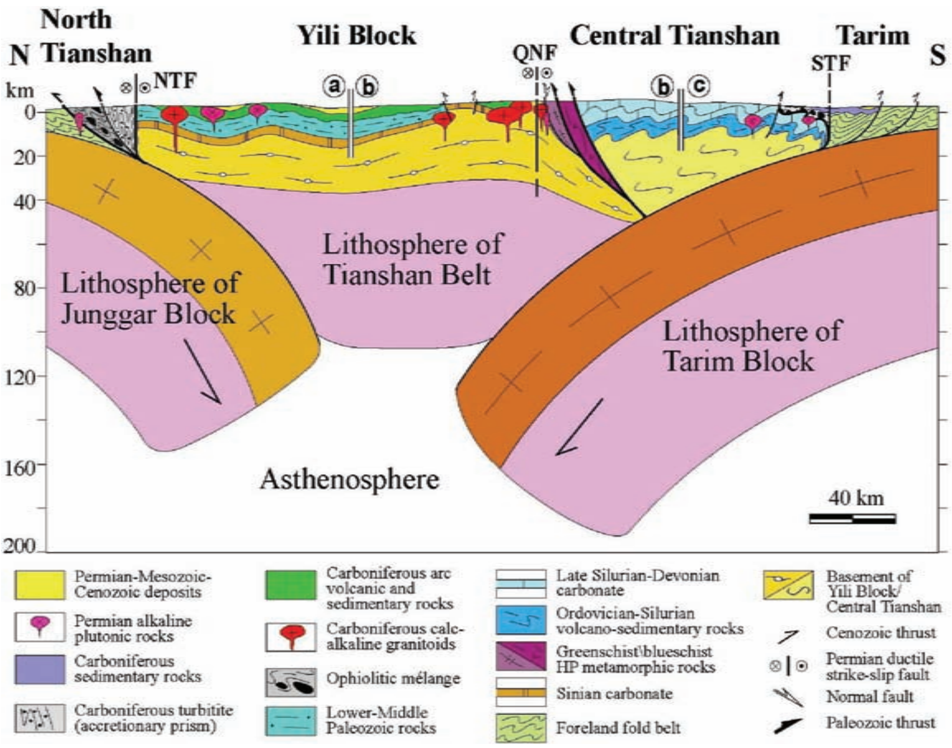

Figure 2. Interpretative cross section of the Yili Block and its boundaries (from Wang et al., 2008).

The Precambrian basement of the Yili triangular area was generally considered as a microcontinent corresponding to the western part of the Yili-Central Tianshan Plate (e.g. Xiao et al. 1992; Allen et al. 1993; Gao et al. 1998; Zhang et al. 2007), whereas, it was regarded as the "North Tien Shan-Ili Plate" in Kazakhstan and Kyrgyzstan (Mikolaichuk et al. 1995; Konopelko et al. 2007). Recent studies also suggest that the Yili Block is distinct from the Central Tianshan (Charvet et al., 2007; Wang et al. 2007c, 2008; Gao et al. 2009; Qian et al. 2009). However, an ambiguity exists regarding the definition of the "Yili Block" and its boundary with the Central Tianshan. The main characteristic of this block is the presence of a series of an Upper Paleozoic (Late Devonian- Carboniferous) pile of sedimentary rocks and abundant arc volcanic and plutonic rocks, while the Central Tianshan is characterized by the occurrence of Early Paleozoic arc-type magmatic rocks and late Paleozoic sedimentary and post-collisional plutonic rocks (e.g. XJBGMR 1993; Xu et al. 2006a; Wang et al. 2008; Gao et al., 2009).

(U)HP metamorphic belt and related ophiolites along the southern margin of the Yili-North Tianshan Block

The SW Chinese Tianshan (U)HP/LT metamorphic belt

The SW Chinese Tianshan (U)HP/LT metamorphic belt mainly consists of blueschist- and greenschist-facies mafic and metapelitic rocks. Silurian marble lenses and slices of ultramafic rocks represent exotic blocks included in a mélange that is interpreted as an accretionary wedge on the southern side of the Kazakh-Yili-North Tianshan Block (Gao et al. 1999). According to previous tectonic studies, the (U)HP metamorphic rocks formed during the subduction of oceanic lithosphere of the Tianshan Paleo-ocean beneath the Kazakh-Yili-North Tianshan (Gao et al. 1995, 1998, 2000, 2006; Volkova and Budanov 1999; Gao and Klemd 2003; Klemd et al. 2005; Zhang et al. 2007). Protoliths are MORB and OIB basalts, mafic volcaniclastic rocks, and deep-sea sediments representing an oceanic crust (Gao et al. 1995; Gao and Klemd 2003). This metamorphic complex extends southwestward to Kyrgyzstan and Tajikistan (Dobretsov et al. 1987; Tagiri et al. 1995; Volkova and Budanov 1999). Kinematic analyses of these (U)HP metamorphic rocks and the underlying gneiss indicate top-to-the-north shearing (Gao et al. 1995; Wang et al. 2007a, 2010; Lin et al. 2009). This northward shearing was firstly interpreted as resulting from the exhumation of HP metamorphic rocks (Gao et al. 1995). However, the south dipping foliation and the kinematic consistency in the HP metamorphic rocks better fit with the interpretation of northward thrusting of oceanic rocks upon the Yili continental basement (Lin et al. 2009; Wang et al., 2010). Radiometric ages of greenschists and blueschists reveal an important retrogression that occurred around 310 Ma (Gao and Klemd 2003; Klemd et al. 2005; Wang et al. 2010). Despite the formation of an Ordovician-Devonian magmatic arc due to subduction of oceanic lithosphere (Laurent-Charvet 2001; Ma et al., 2006; Charvet et al., 2007), isotopic ages for blueschists and eclogites from the HP metamorphic complex cluster closely around 340-320 Ma (Xiao et al. 1992; Gao et al. 1995; Gao and Klemd 2003; Wang et al., 2010)

The Gangou ophiolitic mélange

Along the Toksun-Kumux transect, between the gneissic granites of Central Tianshan and the NTS Carboniferous andesites, a mélange zone composed of several fault-bounded units is exposed. The first unit consists of a clastic and tuffaceous series, similar to the Ordovician flysch but highly schistose (S_1 110S70); the second unit is a mélange including various altered mafic and ultramafic rocks, cherts, and limestone blocks in a tuffaceous matrix. This ophiolitic mélange (Allen et al. 1993; Ma et al. 1997; Laurent-Charvet 2001; Guo et al. 2002; Shu et al. 2002, 2004) is a part of the accretionary prism associated with the closure of the "Tianshan Paleo-ocean" by southward subduction beneath the Central Tianshan (Laurent-Charvet 2001; Charvet et al. 2001, 2004, 2007; Guo et al. 2002; Shu et al. 2002, 2003; Zhou et al. 2004; Wang et al. 2008). The formation age of this mélange is likely Devonian, as constrained by the presence of Silurian fossils in the limestone blocks. Furthermore, Middle to Late Devonian plutons intrudes the mélange and a Lower Carboniferous unconformity overlies the rocks affected by the first deformation. (XJBGMR 1993; Zhu et al. 2002; Shi et al. 2007). An early slaty cleavage, bearing a rarely preserved stretching lineation trending N280-250, is frequently overprinted by a steep fabric linked with a strike-slip motion, especially near the contacts with granite. The contact between the mélange zone and North Tianshan Carboniferous volcanics rocks is underlined by a ductile-brittle zone, with sigma-type kinematic criteria indicating a top-to-the-north motion (Charvet et al. 2007).

The Central Tianshan microcontinent succession and arc magmatism

To the south of the (U)HP metamorphic belt, the Haerkeshan Range is made of a Paleozoic succession of carbonates, sandstones and mudstones that was considered as the passive margin of the Tarim plate (Windley et al. 1990; Allen et al. 1993; Carroll et al. 1995, 2001; Wang et al. 1994; Zhou et al. 2001) or a late Permian to Triassic accretionary complex (Xiao et al. 2008). However, subduction-related granitoids dated at 446-395 Ma by TIMS U-Pb occur south of Gangou-Mishigou (Xu et al. 2006b), north of Kumux (Hopson et al. 1989), north of Baluntai (Yang et al. 2006) and north of Kulehu areas (Fig. 1). Furthermore, early Paleozoic granitic gneisses (Yang et al. 2007) as well as Ordovician-Silurian arc-type volcanic and volcaniclastic rocks are observed in the Bayinbuluk and south of Gangou-Mishigou areas (XJBGMR 1993; Laurent-Charvet 2001; Ma et al. 2006; Charvet et al. 2007).

These Early Paleozoic magmatic and sedimentary rocks stand for the Central Tianshan arc that develops above a Precambrian basement (Wang et al. 2008). The basement rocks exposed in the southernmost part of the Haerkeshan range mainly consist of gneissic granite that formed during 707-931 Ma (zircon U-Pb; Chen et al. 2000b; Zhu 2007). A high ASI value, high LILE and LREE contents, high $^{87}Sr/^{86}Sr$ initial ratios (0.7076~0.7096) and very low $\varepsilon_{Nd}(T)$ values (-4.4~-7.7) all indicate that this gneissic granite was derived from an ancient continental basement with Nd mean crustal residence ages of 1.7-1.9 Ga and a long history prior to partial melting (Chen et al. 2000b). Similar granitic gneisses occur also to the north of Kumux and Baluntai areas (Fig. 1). In addition, quartz-schist and marble are exposed and were considered as belonging to the Precambrian basement (Wang et al. 1996).

South of Bayinbuluk or north of Kumux, weakly deformed and unmetamorphosed Early to Middle Carboniferous conglomerate, sandstone and limestone unconformably overlie Early Paleozoic rocks and pre-Carboniferous granitic plutons (Hu et al. 1986, Wang et al.

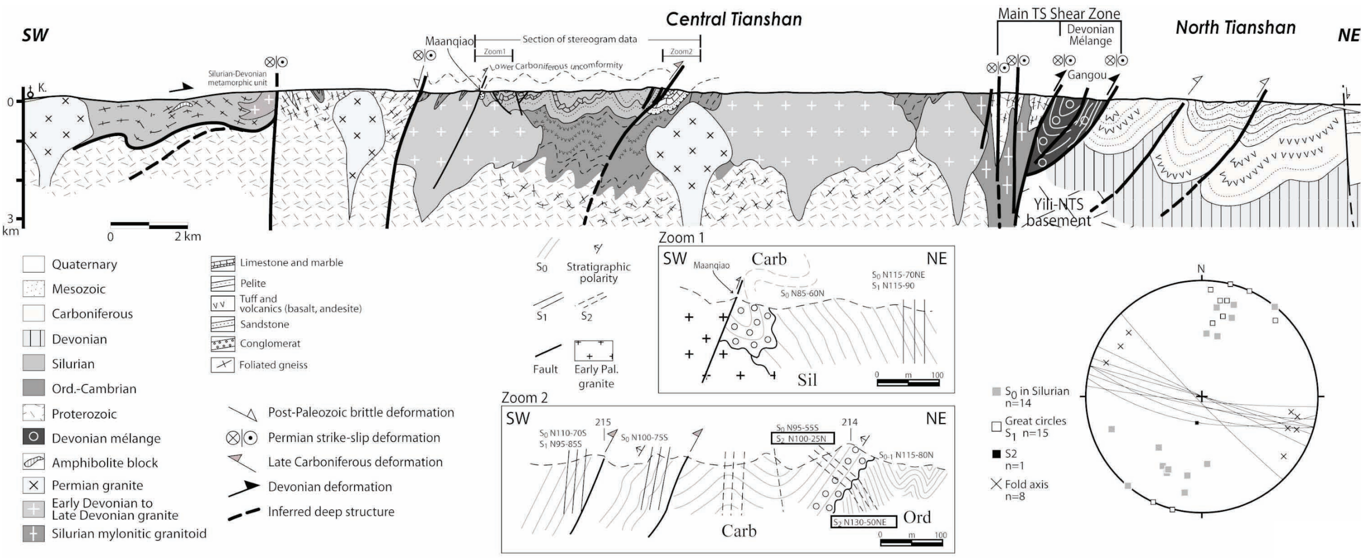

Figure 3. Synthetic cross-section of Central and North Tianshan along the Kumux-Toksun transect (from Charvet et al. 2007).

1994; Zhou et al. 2001; Yang et al. 2006; Charvet et al. 2007; Wang et al. 2008; Fig. 1). Late Devonian to Carboniferous post-collisional granites are also noticed in these areas (Xu et al. 2006a).

The South Tianshan ophiolitic mélange

In the Southern ranges that form the highest relief of the Tianshan orogen, from Korla to the Kyrgyz border (Fig. 1), the Paleozoic series that represents the cover of the Central Tianshan microcontinent is tectonically overlain by numerous klippes of ophiolitic mélange, such as in Yushugou, Guluogou-Wuwamen, Kulehu, Heiyingshan or Aheqi (Fig. 1). These melanges are composed of serpentinized ultramafic rocks, gabbros, (pillow) basalts, mafic volcanic-clastic rocks, sheeted dyke, chert or siliceous mudstone, limestone and rare high-pressure rocks enclosed in a sheared matrix (Gao et al. 1998; Shu et al. 2002; Charvet et al. 2007; Wang et al. 2008). The geochemical features of the mafic rocks suggest a back-arc basin setting (Ma et al. 1993, 2006; Dong et al. 2005; Long et al. 2006; Zhu 2007). These ophiolite and ophiolitic mélanges were initially assumed to be rooted to the north and emplaced from north to south, onto the Tarim passive margin, after a phase of northward subduction (Windley et al. 1990; Allen et al. 1993; Gao et al. 1998; Xiao et al. 2004; Chen et al. 1999). However, structural studies of the mélange and its tectonic substratum from the Yushugou, Kulehu, and Aheqi areas indicate a top-to-the-north ductile shearing (Shu et al. 2002; Li et al. 2004; Charvet et al. 2007; Wang et al. 2008). Therefore, these ophiolitic rocks were considered to be originated from the south Tianshan back-arc basin that separated the Central Tianshan microcontinent from the northern margin of Tarim (Charvet et al. 2007; Wang et al. 2008; Lin et al. 2009). The flat-lying foliation and thrust contact are often deformed by south verging folds and high angle thrust faults (Li et al. 2004), but this folding is at least partly due to a Meso-Cenozoic event, since Permian sandstone is affected by the folding (Wang et al. 2008).

The mélanges have been initially assigned to the Silurian (XJBGMR 1993). However, middle Devonian to Early Carboniferous radiolarians in chert olistoliths (Tang et al. 1995; Gao et al. 1998; Liu 2001; Shu et al. 2007; Zhu 2007) argue for a latest Devonian to earliest Carboniferous age, as it is unconformably overlain by an early Carboniferous conglomerate. Recent radiometric dating confirms this assumption. A gabbroic block from Heiyingshan and a diabase from Kulehu (Fig. 1) yield a zircon U-Pb LA-ICPMS age of 392 ± 5 Ma and SHRIMP age of 425±8 Ma, respectively (Long et al. 2006; Wang et al. in review). In the Kumux area, the granulite block of the Yushugou ophiolitic mélange yields zircon U-Pb SHRIMP ages of 390-392 Ma (Zhou et al. 2004). Therefore, the oceanic lithosphere was, at least partly, created during the Early Devonian and introduced

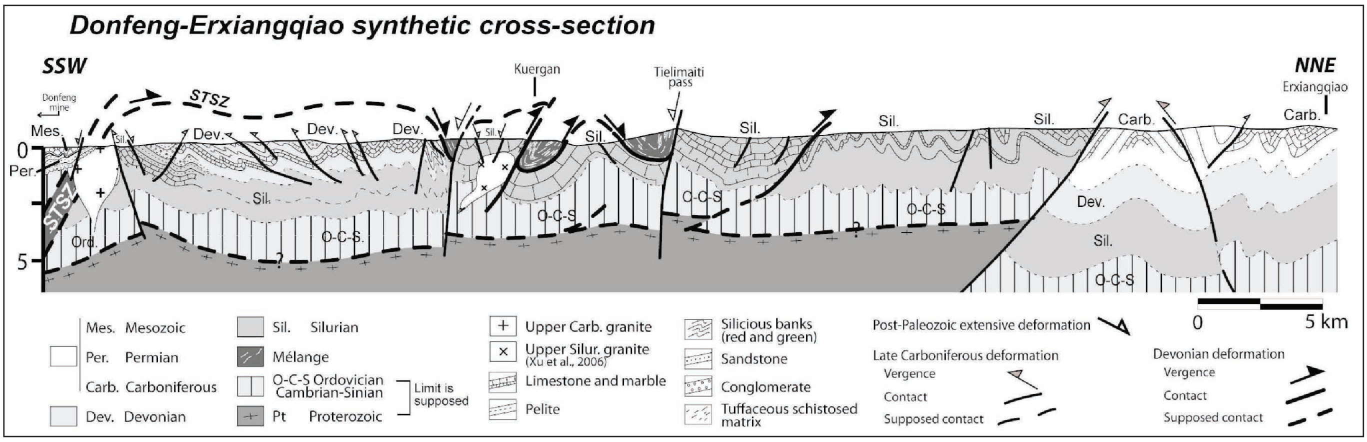

Figure 4. Synthetic cross-section along the Duku road (from Charvet et al. 2007)

into the mélange together with HP metamorphic rocks (Liu and Qian 2003) around the Devonian-Carboniferous boundary.

The Northern margin of the Tarim block

The southernmost unit involved in the orogeny of the Tianshan belt corresponds to the northern edge of the Tarim block, exposed in Kuruktag, Korla and Kepingtag. The Tarim block consists of variably deformed and metamorphosed rocks of Archean, Proterozoic to Early Paleozoic ages (XJBGMR 1993; Hu et al. 2000, 2006; Bykadorov et al. 2003; Lu et al. 2008). It has mainly been interpreted as a cratonic block although some different ideas existed (Hsu 1988, 1989). The basement is characterized by Achaean high-grade TTG gneiss and amphibolite and Proterozoic granitic gneiss, which have Nd model ages (TDM) ranging from 3.2 to 2.2 Ga (Hu et al., 2000). Neoproterozoic blueschist of ca. 800 Ma age is recognized near Aksu (Nakajima et al., 1991; Liou et al., 1996). Late Neoproterozoic to Ordovician platform sedimentary rocks including limestone and shale form the lower part of the sedimentary cover (Carroll et al., 1995, 2001). The Late Neoproterozoic and Cambrian series may contain intercalations of rift-related volcanic rocks (Xia et al., 2004) and bimodal igneous rocks dated at 820-800 Ma on zircon by LA-ICPMS U-Pb method (Deng et al., 2008). The Silurian overlies the older rocks with a slight unconformity (Carroll et al., 1995), and begins with a conglomerate and includes several polygenetic conglomeratic layers in a flysch-like series. It grades into an olistostrome, with huge olistoliths, to the south of Hongliuhe in Eastern Tianshan, indicating a period of instability (Charvet et al., 2007). Upper Devonian-Lower Carboniferous arc-related plutonic rocks occur at the northern edge of Tarim (Jiang et al., 2001; Zhu et al., 2008), indicating that it acted as an active margin at that time, after being the passive margin of the back-arc basin that separated the Tarim block from the Central Tianshan block during the Silurian-Devonian. Close to the South Tianshan ophiolitic melange, late Carboniferous to early Permian fluvial and marine deposits overlie Sinian to Devonian rocks with an angular unconformity (Carroll et al., 1995; Wang et al., 2008). The Lower Permian strata contain rift-related volcanic and volcaniclastic rocks dated at 275-280 Ma (^{40}Ar/^{39}Ar ages on feldspar and U-Pb ages on zircon) and are in turn unconformably overlain by Upper Permian detrital series (Carroll et al., 1995; Chen et al., 1999; Liu et al., 2004).

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PART II: FIELD DESCRIPTIONS

Day 1. Baiyanggou section (Southern Bogda): Early Permian rift

This short section presents a series of magmatic and sedimentary rocks: Carboniferous limestone olistoliths, Permian volcanic breccia, pillow basalt, deep water chert, flysch and mafic dykes (Fig. 6).

Stop 1-1: *43°38.368'N and 87°58.150'E, Milestone 10-11*

Intrusive contact between the gabbro dykes and the host Early Permian flysch.

Stop 1-2: *43°40.922'N and 88°03.129'E, 200 m North of a limestone*

Boundary between Permian pillow basalt and the overlying sediments (siliceous mudstone and siltstone).

Stop 1-3: *43°41.081'N and 88°02.950'E, 100 m further north*

Contact between the pillow lava and the underlying flysch-like greywacke, tuff and volcanic breccia. Alkaline rhyolite was interlayered in the volcanic breccia and was dated at 294±5 Ma (zircon U-Pb; Shu et al., 2005).

Stop 1-4: *43°41.154'N and 88°02.902'E*

Olistostrome made of olistoliths of Carboniferous limestone with variable size and tuff matrix. The olistostrome is intruded by alkaline gabbroic dykes of 297±5 Ma (zircon U-Pb, Shu et al., 2010).

The Baiyanggou section is interpreted as an Early Permian rift-sequence, which might have been deposited in a rift basin formed after the late Carboniferous tectonics.

Hougou section: North Tianshan accretionary complex overlain by Early Permian terrigeneous and volcanic rocks

SE of Urumqi, on the road subparallel to the G312 highway, starting from the Dabancheng Ancient Town, the Hougou section exposes Carboniferous schistose mudstone, olistostrome and broken formation, Carboniferous granite, Early Permian continental sedimentary rocks, volcanic and volcano-sedimentary rocks. An Early Permian unconformity upon the Carboniferous rocks can be observed.

Stop 1-5: *43°18.628'N and 88°21.182'E, between milestones 93 km and 94 km of the Road G314, close to a bridge of the highway G312.*

Carboniferous olistostrome made of blocks of limestone, chert and volcanics, and muddy matrix. Well developed cleavage and quartz veins indicate sub-N-S shortening. Initial bedding is difficult to distinguish.

Stop 1-6: *43°15.953'N and 88°21.580'E, between milestones 99 and 100 km of the Road G314.*

Broken formation composed of red siliceous mudstone, greenish chert and siliceous tuff, with black matrix of mudstone. The olistostrome and broken formation correspond to the Carboniferous fore-arc accretionary prism of the North Tianshan.

Stop 1-7 (optional): *43°11.894'N and 88°28.209'E, at 112.8 km of the Road G314.*

Carboniferous greyish medium to coarse-grained granite intrudes Carboniferous tuff, in which contact metamorphism occurred. Thin pink granitic dikes in turn intrude the grayish granite.

Stop 1-8: *43°11.705'N and 88°28.359'E, between milestones 113 and 114 km of the Road G314.*

Unconformable contact between Carboniferous (tuff and granite) and Early Permian. Northern side is the Carboniferous siliceous tuffs, southern side is Early Permian red-yellowish conglomerate with big pebbles of volcanics, chert, mudstone and granite. Rhyolitic and andesitic rocks are interlayered in the conglomerate. The present contact zone and bedding of Permian are sub-vertical.

Further south, interlayers of conglomerate, sandstone and rhyolite or rhyolitic tuff occur regularly, occurrence of tuff breccia and conglomerate with huge volcanic fragments suggests sedimentation very close to the erupting center. Basic dikes intrude in the Permian rocks.

Stop 1-9 (optional): *43°09.717'N and 88°29.262'E, between milestones 117 and 118 km of the Road G314.*

Early Permian fluviatile coloured conglomerate, and red sandstone showing sedimentary rythms. On the western side of highway G312,

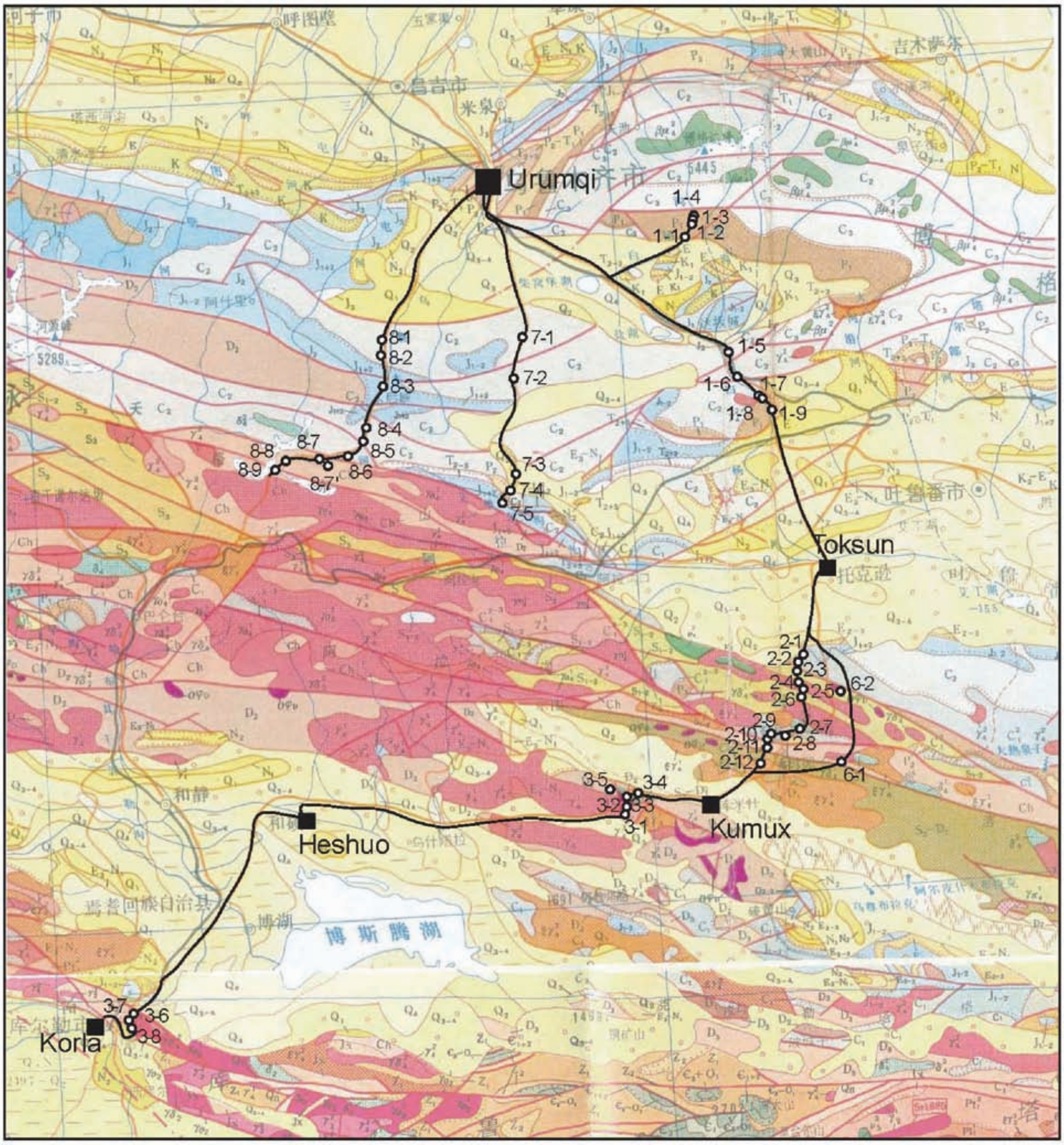

Figure 5. Geological map and the circuit for Days 1, 2, 3, 6, 7 and 8.

the panorama shows Early Permian rocks unconformably overlain by Late Triassic and Jurassic rocks.

Day 2. Gangou section: Early Paleozoic ophiolitic mélange, arc magmatic rocks and Late Paleozoic unconformity - Suture zone between Central Tianshan and Yili-North Tianshan blocks

South of Toksun, along Highway G314 (direction Toksun to Kumux, i.e., North to South), this section exposes the North Tianshan volcanic arc, Gangou ophiolitic mélange, Ordovician to Silurian schistose volcanic and volcaniclastic rocks, Early Paleozoic arc-type granitoids, the Carboniferous unconformity, and Proterozoic metamorphic basement rocks (Figs. 5 & 7).

Stop 2-1: *42°35.340'N and 88°32.758'E, Milestone 184-185, at the parking near 184.5th km of the new road*

Tuff and volcanic rocks of Early Carboniferous age, basalt and red andesite. These rocks are considered as the north Tianshan arc formed by the southward subduction of the North Tianshan oceanic basin beneath the Yili-North Tianshan block during the Late Paleozoic (Charvet et al. 2007).

Stop 2-2: *42°32.673'N and 88°31.836'E, Milestone 191, by a small bridge*

Highly deformed Early Carboniferous volcano-sedimentary rocks related to the Main Tianshan Shear Zone. Steeply south-dipping foliation, subhorizontal lineation and asymmetric clasts in the mylonitized tuff indicate a dextral shearing. This shear zone separates

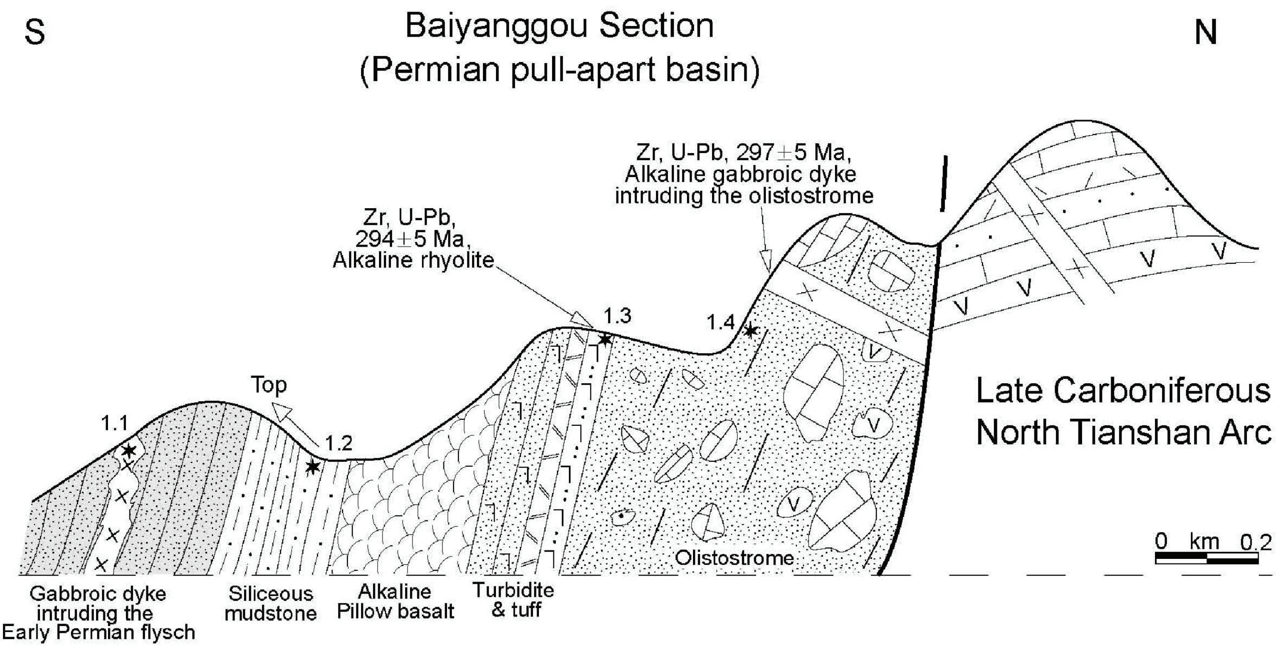

Figure 6. Cross section of Baiyanggou, south of Bogda Mountain.

the Early Carboniferous arc volcanic rocks to the north from the Gangou ophiolitic mélange and Early Paleozoic volcanic arc series to the south.

Stop 2-3: *42°32.238'N and 88°31.872'E, Milestone 192-193, by a bridge near the 192.6th km*

Gangou ophiolitic mélange consists of blocks of metatuff, greenstone, chert, and the matrix made of greywacke. The mélange zone of ca. 30 m wide strikes SEE-ward (N120). Reddish granite intrudes in the mélange zone.

Stop 2-4: *42°31.406' N and 88°31.761' E, Milestone 194*

Orthogneiss derived from a porphyritic K-granite dated at 428 ± 10 Ma by U-Pb method on zircon (Shi et al. 2007). Mylonitic zones with subvertical foliation and a low angle stretching lineation exhibit a dextral sense of shear. The orthogneiss is intruded by undeformed doleritic dykes on unknown age. This plutonic body is interpreted as related to a Silurian magmatic arc, and the ductile deformation is due to the Permian strike-slip tectonics.

Stop 2-5: *42°30.840' N and 88°31.098' E, Milestone 196*

Slightly oriented fine-grained granite with xenoliths. Developing a visible contact metamorphism in the host-rock of Ordovician-Silurian meta-volcanoclastic rocks, this undeformed post-tectonic granite is dated at 368±9 Ma (Shi et al. 2007).

Stop 2-6: *42°28.500' N and 88°31.462' E, Milestone 201.7 km*

Schistose Silurian mafic volcanoclastic rocks belonging to the Central Tianshan arc. A contact metamorphism with andalusite can be also observed. This rock is also exposed at the 200.6th km (GPS: 42°29.104' N and 88°31.741' E).

Stop 2-7: *42°23.835' N and 88°31.285' E, Milestone 212.4 km of the new road*

Unconformity of Early Carboniferous conglomerate above the Ordovician metatuffs. Early Carboniferous conglomerate is overlain conformably by crinoidal limestone of Early to Middle Carboniferous. Both formations are affected by a S_2 cleavage, associated with south verging folds.

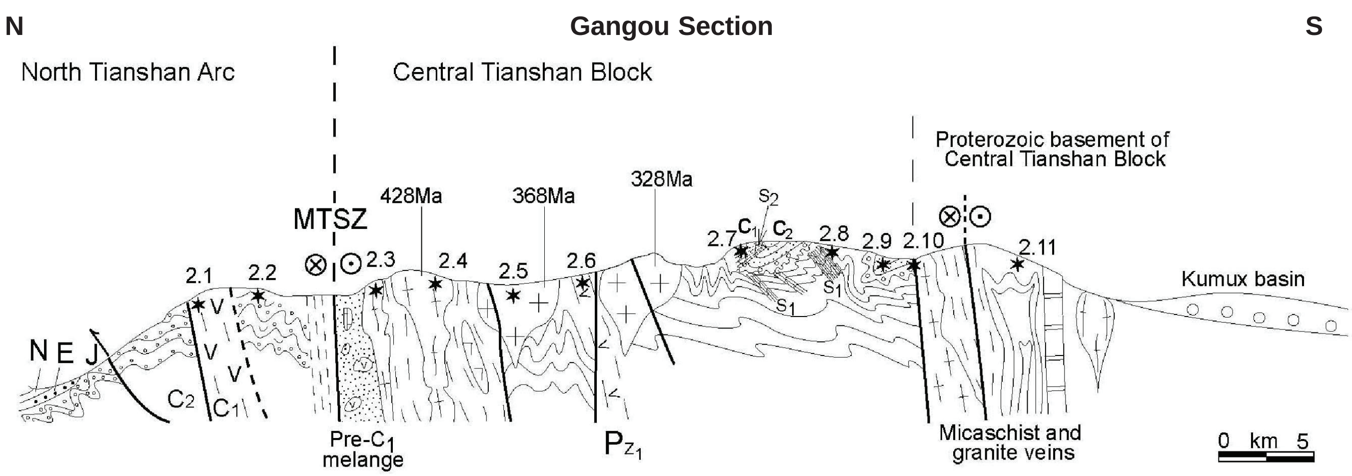

Figure 7. Schematic cross section of the Gangou-Kumux transect.

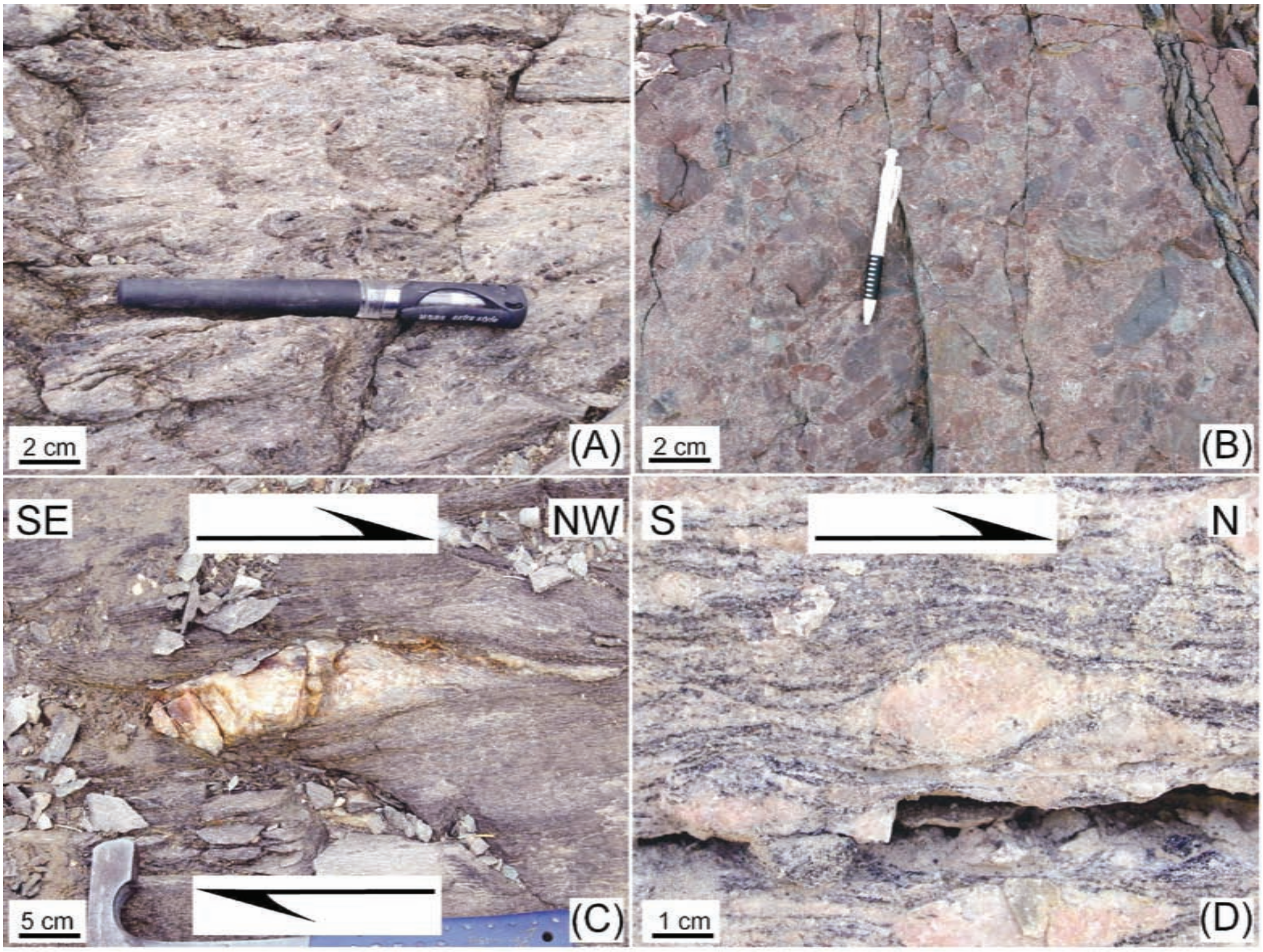

Figure 8. Field pictures related to the cross section between Toksun and Kumux. A. Garnet micaschist which is considered as the Proterozoic basement of Central Tianshan; B. Conglomerate of Early Carboniferous (Ma'Anqiao group); C. Quartz vein, which indicated dextral sense of shear, was considered as the Proterozoic basement of Central Tianshan; D. Augen gneiss indicating top-to-the-North sense of shear.

Stop 2-8: *42°22.479' N and 88°28.618' E, Milestone 217.4th km of the new road*

Silurian limestone and flysch, asymmetric tight folds and flat-lying shear zone indicate a north-directed movement.

Stop 2-9: *42°22.101' N and 88°27.975' E, at Ma'anqiao, Milestone 218.7th km*

Overturned Lower Carboniferous non-schistosed red conglomerate (C_1 Ma'anqiao group) overlying Silurian fossiliferous flysch affected by a south-dipping cleavage. Granite pebbles are common in the conglomerate.

Stop 2-10 (optional): *42°21.342'N and 88°26.796'E, Milestone 220-221 of the new road*

Fault contact between Proterozoic gneiss and Lower Paleozoic (Ordovician?) schists. The supposed basement rocks of the Central Tianshan are highly deformed by the Sangshuyuanzi Fault showing N120-striking vertical foliation and sub-horizontal lineation, kinematic criteria indicate a dextral sense of shear. Nevertheless, the orthogneiss near the Marble Mine which shows asymmetrical augen K-feldspar, sigma-type quartz and S-C composite foliation, indicates a sinistral sense of shear (foliation 120NE75; lineation 110/10).

Stop 2-11: *42°19.610' N and 88°24.803' E, near Sangshuyuanzi, milestone 227*

Mylonitic marble and biotite garnet micaschist, paragneiss of Xingxingxia Group considered as the Proterozoic basement of Central Tianshan. These rocks exhibit a vertical foliation and a subhorizontal mineral and stretching lineation. The related ductile deformation indicates a dextral sense of shear, corresponding to the eastward extension of the Nalati Fault. Hornblende, biotite and K-feldspar yield $^{40}Ar/^{39}Ar$ ages around 350 Ma and 260 Ma, respectively (Yin and Nie 1996). Centimeter-scale blue hydrothermal kyanite develops close to granite-pegmatite veins. Monazite U-Th-Pb dating on the kyanite-staurolite -garnet-bearing schist of Xingxingxia group yield an age of ~343 Ma that is interpreted as a mixture of older age at ca. 355 Ma and younger age of ca. 323 Ma, which could be related with a HP metamorphism and subsequent retrogression, respectively; Much younger age of 282±9 Ma was also well defined and considered as related to shear deformation (Li et al., 2008).

Stop 2-12 (optional): *42°16'57"N and 88°21.08"E, Milestone 232.8th km of the new road, on the west of the road (This site is now inaccessible because of the wire fence)*

Mylonitic syn-kinematic K-granite with subhorizontal stretching

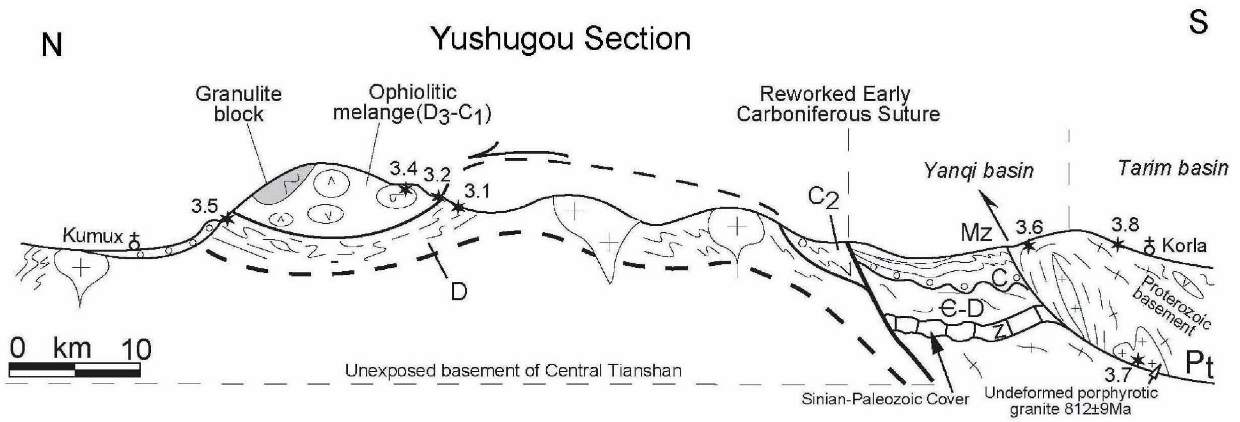

Figure 9. Schematic cross section of theYushugou ophiolitic mélange zone.

lineation. Sigmoidal K-feldspar shows dextral sense of shear. K-granite was dated at 254 ± 4 Ma by zircon U-Pb ICPMS method (Wang et al. 2009).

Day 3. Yushugou section: Pre-Carboniferous ophiolite, granulite-facies meta-mafic rocks, top-to-the-north kinematics, Tarim basement

To the west of Kumux Town along the highway G314, the South Tianshan ophiolitic zone crops out in the Yushugou area where serpentinized peridotite and granulite can be observed (Fig. 9). The Yushugou ophiolitic body and the neighboring ones, such as the Tonghuashan-Liuhuangshan mafic and ultramafic bodies are considered as the ophiolitic mélanges of the Chinese South Tianshan (Ma et al., 1993; Guo et al., 1993; Charvet et al., 2007).

Stop 3-1: *42°14.001'N and 87°55.026'E, west side of a bridge at the crossing with the poor road going to an asbestos mine*

Devonian meta-flysch with marble blocks. NE-dipping foliation and NE-plunging lineation are well developed, intrafolial asymmetric tight folds and numerous kinematic criteria indicating a top-to-the-north shearing along a N10-N40 lineation.

Stop 3-2: *42°14.264'N 87°55.161'E, ca.350 m to the north of stop 4-1*

Basal contact of the ophiolitic mélange with the highly deformed Silurian-Devonian flysch, the mélange is composed of blocks of serpentinite, gabbro, basalt, chert and marble. In the matrix of the mélange, greywacke and pelitic rocks were ductilely deformed with a north-dipping foliation and N30-50 striking lineation. In the XZ section, S-C fabrics, sigmoidal clasts and drag-folds show a top-to-the-north sense of shear.

Stop 3-3 *(optional)*: *just before exit the Yushugou near the stop 4-4*

Contact between the granulite unit and the ophiolitic mélange unit. Blocks of basalt and gabbro developed in serpentinite matrix.

Stop 3-4: *42°15.879'N and 87°54.918'E, at the NE side of the exit of the Yushugou valley*

Coarse-grained mafic granulite enclosed in a serpentinite matrix. The protolith of the granulite is considered as a mafic rock (Shu et al. 2004; Zhou et al. 2004). Granulite yielded zircon U-Pb SHRIMP ages of 390±11 Ma and 392±7 Ma (Zhou et al. 2004), and Ca-amphibole from the granulite yielded $^{40}Ar/^{39}Ar$ ages of 368±5 Ma and 360 ± 10 Ma, and grt+pl+ilm+WR Sm-Nd isochron age of 310± 10 Ma (Wang et al. 2003). Zircon U-Pb ages were interpreted by Zhou et al.(2004) as the time of peak metamorphism under granulite-facies, but Wang RS et al. (2003) considered the amphibole $^{40}Ar/^{39}Ar$ ages at 370-360 as the peak metamorphism, and the Sm-Nd age of 310 Ma as the retrogression.

Stop 3-5 (optional): *Milestone 280 of the old road (this site is now along the new highway and there is no parking)*

Roof pendant of the mélange within a granite body supposed to be Carboniferous or Permian in age, with contact metamorphism.

Stop 3-5': *42°15.926'N and 87°53.570'E, at the 274.2th km of the new highway (no parking)*

Early Carboniferous highly deformed meta-flysch with boudinaged quartz veins, intrafolial tight folds. The foliation trends N160E and contains a N45E striking stretching lineation. Asymmetric kinematic indicators show a top-to-the-NE shearing.

The second part of this day deals with the basement of the Tarim Block exposed along the Highway north of Korla

Stop 3-6: *41°48.654'N and 86°14.816'E, at the 6.77km*

Retrogressed biotite amphibolite with folded and foliated granitic veins. The amphibolite foliation is oriented N80 S50 contains a N160E mineral lineation. The granitic veins yield zircons dated at 2.8 Ga, 1.9 Ga, 1 Ga, and 0.8 Ga (Deng et al., 2008).

Stop 3-7: *41°48.068 and 86°13.927at the 678th km*

Biotite micaschist with nearly parallel granitic veins. The 120E S60 foliation is cross-cut by magmatically oriented porphyritic granite with biotite clots and K-feldspar megacrysts. This plutonic rock yield zircons dated at 812 ± 9 Ma by LA-ICPMS method (Shu et al., unpublished data).

Stop 3-8: *41°47.546 and 86°13.616 at the 680th km*

Garnet amphibolite, marble, garnet-biotite micaschist, quartzite, and calc-silicate. The foliation is still dipping southward (N90 S80). The metamorphic series is intruded by 1 to 5m-thick garnet-biotite granitoids veins. Locally, meter-sized boudins of garnet amphibolite can be observed.

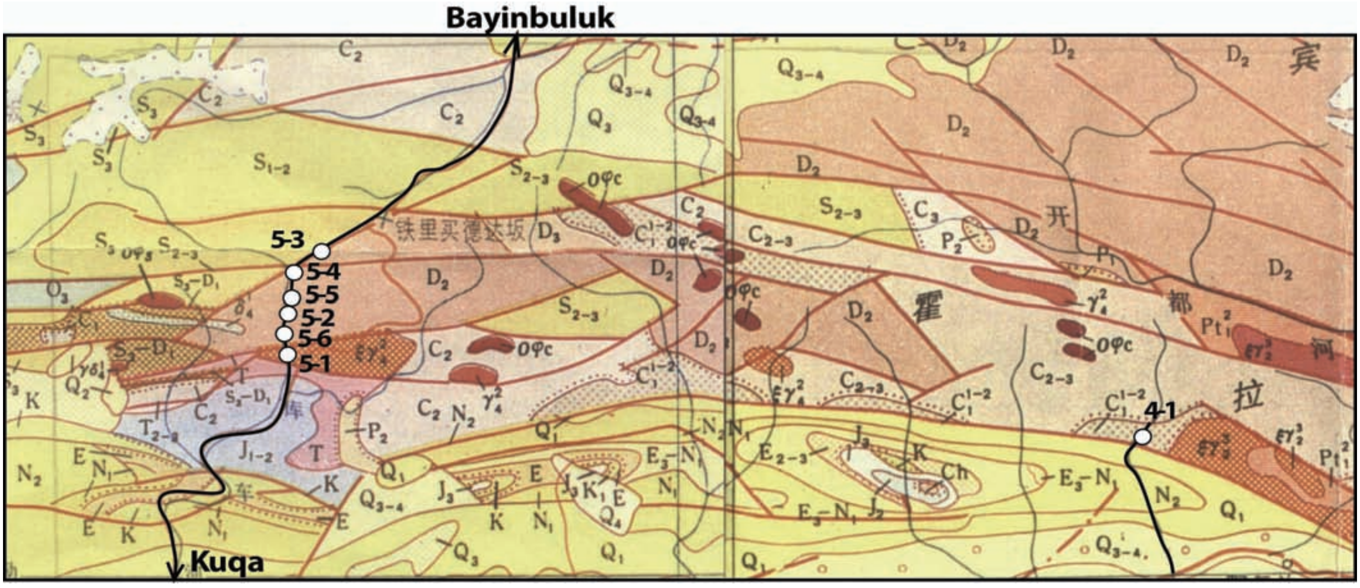

Figure 10. Geological map and the circuit for Days 4 and 5 in the central part of South Chinese Tianshan.

Day 4. Cedaya section: Carboniferous limestone of Northern Tarim

Stop 4: *North of Highway G314, between Korla and Kuqa.*

In this section, we shall observe a coarse-grained sandstone and mudstone formation with limestone layers containing coral fossils of Carboniferous age. This series is considered as a mass flow supplied from the northern part of the Tarim block.

Day 5. Du-Ku road section: Pre-C_2 ophiolitic mélange, sedimentary cover of the Central Tianshan block, and polyphase deformation

North of Kuqa city, road G217, along the banks of the Kuqa River. This section allows us to observe the sedimentary cover of the Central Tianshan block, and the South Tianshan ophiolitic mélange overthrust to the north (Fig. 12).

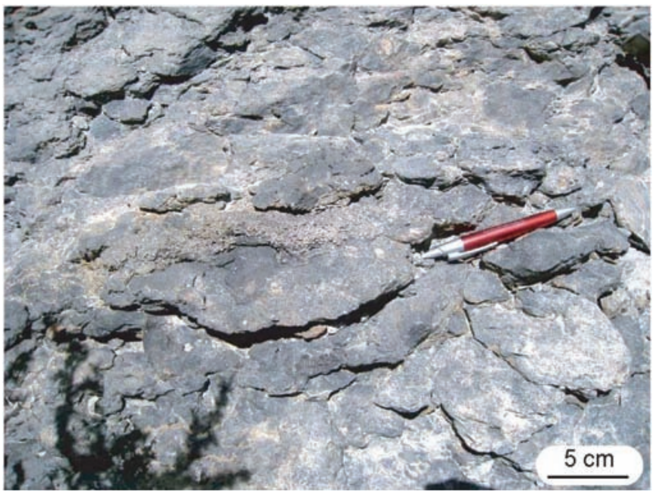

Figure 11. Terrigeneous formation with limestone layers containing Carboniferous coral.

Stop 5-1: *42°17'28"N and 83°16'39"E, near Milestone 985 of Road G217. Immediately north of the Shengli coal mine and Triassic red sediments*

Diorite, granodiorite and red granite intrude mica-quartz schist of unknown age. Red granite includes diorite enclaves. Diorite pluton yielded zircon U-Pb SHRIMP age of 387±8 Ma (Zhu et al. 2008). Since these granitoids show arc geochemical affinities (Zhu et al. 2008), they are interpreted as the magmatic arc formed upon the northern margin of the Tarim Block. On the road, the arc-type granitoids are in fault contact with Upper Permian conglomerate, but an unconformity is also recognized nearby. Pebbles of granitic rocks, chert, sandstone and basalt can be identified in the Upper Permian conglomerate.

Stop 5-2: *42°23'54"N and 83°16'21"E, Milestone 968 of Road G217*

Contact between the Early-Middle Devonian limestone and the schistose sandstone, which forms the matrix of the Kulehu melange. North-vergent folds and faults develop in the limestone overthrusting to the north above the schist. At Milestone 967, the andalusite-bearing micaschist yielded a muscovite $^{40}Ar/^{39}Ar$ plateau age of 368±1 Ma (Li et al. 2004).

Stop 5-3: *Kulehu ophiolitic mélange with various rock types*

1 *At 42°26'46"N and 83°15'59"E, Milestone 959, south of the Dalaoba ("Big dragon lake").* Pillow lava blocks included in the limestone and schistose matrix;
2 *At 42°25'50"N and 83°15'29"E, near Milestone 963.1,* sheared calcareous flysch and limestone (sometime marble) with disrupted bedding showing north-vergent folds;
3 *At 42°26'24"N and 83°15'38"E, around Milestone 961.8,* radiolarian chert and siliceous mudstone with remarkable cleavage indicating north-directed shearing. Late Devonian to Early Carboniferous radiolarians were found from the chert (Tang et al. 1995; Gao et al. 1998; Zhu 2007);
4 *At 42°26'29"N and 83°15'49"E, around Milestone 963.1,* block of basalts and gabbro that have geochemical features of N-MORB,

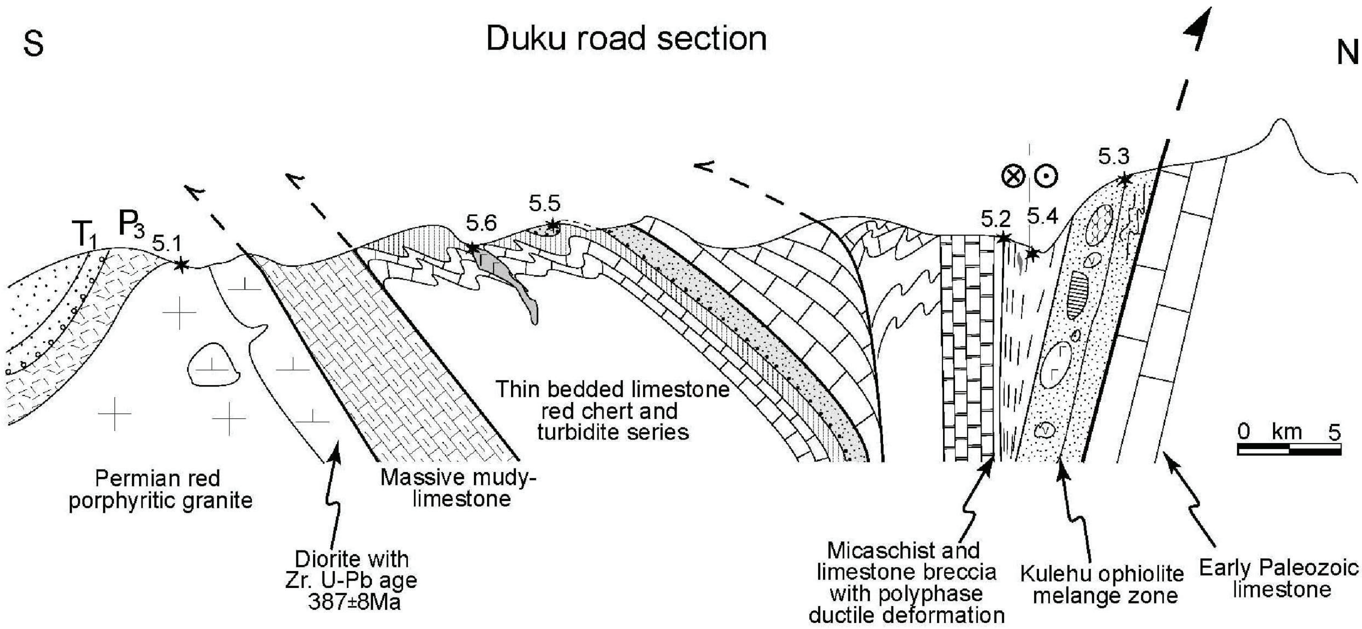

Figure 12. Schematic cross section of the southern segment of the Du-Ku Road.

gabbro yielded zircon SHRIMP U-Pb age of 425 ± 8 Ma (Long et al. 2006).

The Kulehu ophiolitic mélange is interpreted as a north-directed klippe overlying the limestone-red chert series. This mélange exhibits the same lithological and structural features than the Yushugou mélange klippe. Both are considered as parts of the South Tianshan mélange that tectonically overlies the central Tianshan Block.

Stop 5-4: *42°25.911'N and 83°14.969'E, South of Korgan village*

Andalusite-cordierite micaschist showing a well developed subvertical foliation and subhorizontal lineation. These metamorphic minerals and planar-linear structural fabric are related to the Permian dextral strike-slip shearing. An early, steeply dipping, (N-S striking) stretching lineation can also be observed in some places. To the south, recrystallized Silurian limestone, with locally limestone breccia, exhibits also a steeply dipping stretching lineation. This ductile deformation is related to the emplacement of the Kulehu mélange klippe.

Stop 5-5: *42°22.770'N and 83°15.877'E*

Turbidite with alternations of coarse- to medium-grained sandstone and mudstone, disrupted sandstone beds, intraformational conglomerate. Load casts at the base of sandstone beds indicate that this north-dipping series is overturned. Bedding-cleavage relationships show that the series is deformed by south-verging folds.

Stop 5-6: *42°22.568'N and 83°15.959'E*

Diabase intruding in thin-bedded red cherts.

Day 6. Basement of Central Tianshan and Gangou ophiolitic mélange, north of Kumux

Stop 6-1: *42°178.705'N and 88°28.556'E, on the G314 highway from Kumux to Toksun (South to North)*

Augen orthogneiss and biotite-muscovite micaschists. The mean foliation trends N145E. A N-S to NW-SE striking mineral and stretching lineation can be observed on this foliation. Kinematic indicators such as asymmetric augen or sigma-type porphyroclasts systems show a top-to-the-N shearing. Muscovite yields poorly defined $^{40}Ar/^{39}Ar$ ages of 390-360 Ma (Deng et al., 2006). The foliation and lineation are refolded by upright folds.

These metamorphic rocks are interpreted as the Proterozoic basement of the Central Tianshan Block, but the ductile deformation likely developed during the northward emplacement of the South Tianshan mélange (cf. the Yushugou klippe cropping out several kilometers Southward). The post- folial upward folding post dates the South Tianshan mélange emplacement.

Stop 6-2: *42°29.634' N and 88°39.440' E along the road G314 from Kumux to Toksun, exit the main road from the 189.6th km and run to the west for 4.7 km*

Gangou ophiolitic mélange: blocks of serpentinite, rodingite, chert within a matrix made of schistose tuff and greywacke. The ophiolitic mélange is intruded by SE-trending K-rich granitic dykes. This mélange is equivalent to that observed a few kilometres to the west, at stop 2-3. Due to the intense shearing related to the Permian strike-slip faulting, the mélange matrix is undated. However, it is likely of pre-Visean age as, at Mishigou, the same mélange is unconformably covered by Visean conglomerate.

Day 7. Aiwergou section: Carboniferous olistostrome of North Tianshan, Permian alluvial sedimentary rocks and Triassic unconformity

South of Urumqi, along the Road S103, this section is sub-parallel to the Houxia section. But the chaotic sedimentary rocks interpreted as deposited in an accretionary complex are better developed. We shall observe Carboniferous pebbly mudstones, olistostrome with chert or siliceous mudstone blocks. These rocks are interpreted as trench-fill sediments formed in the accretionary prism related to a south-directed subduction in front of the North Tianshan arc.

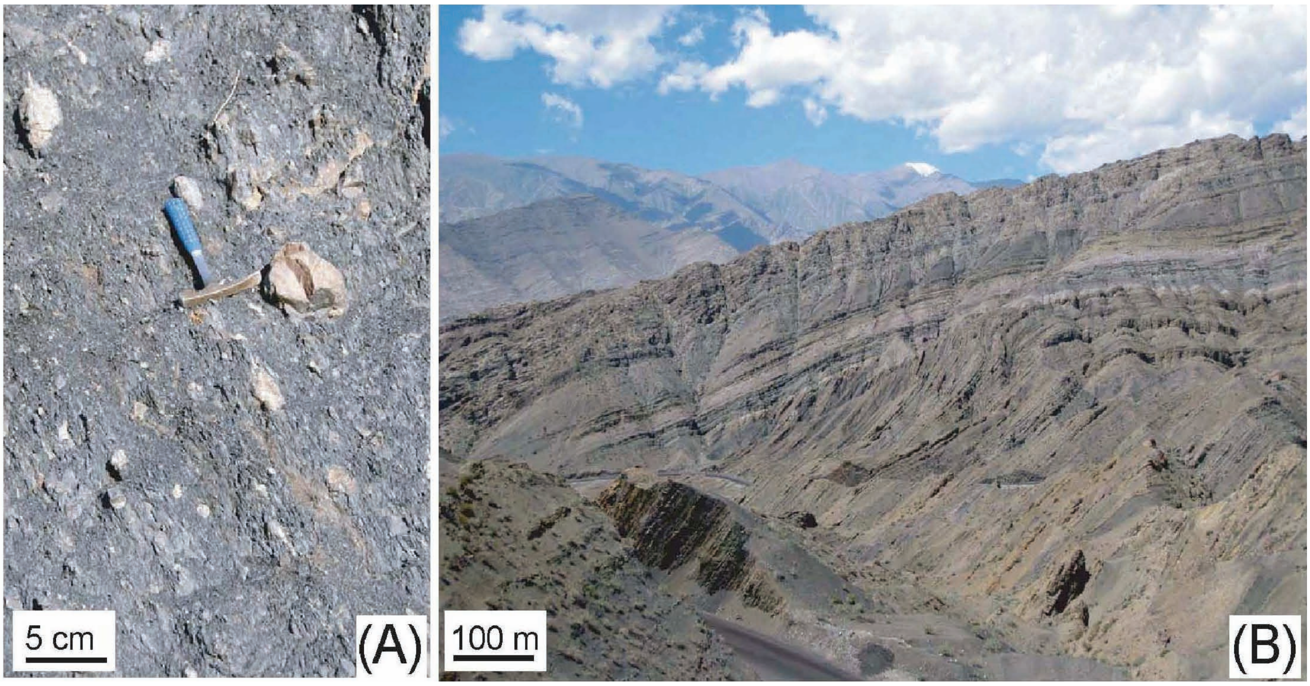

Figure 13. Field pictures of the outcrops observed in Aiwergou section.A. Pebbly mudstone with C_2 age; B. Late Triassic terrigeneous rocks unconformably overlying on the Late Permian rocks

Stop 7-1: *43°18.839'N and 87°38.008'E, near Milestone 43*

Pebbly mudstone with black matrix enclosing centimeter to plurimeter blocks of sandstone, pyroclastite, chert and limestone (Fig. 13A). The pervasive slaty cleavage is oriented N110E N65.

Stop 7-2: *Milestone 50 of the Road S103*

Block-in-matrix series with siliceous mudstone, chert, limestone olistoliths within the mudstone matrix.

Stop 7-3: *Panorama Aiwergou, Road Z401 Milestone 2*

View of subvertical Late Permian conglomerates overlie by Late Triassic terrigeneous rocks. In the southern background, Jurassic sandstone and mudstone overly the Late Triassic beds. The southernmost mountains are formed by Carboniferous volcanic rocks belonging to the North Tianshan arc (Figs. 13B, 14).

Stop 7-4: *in the curve of Road Z401, Milestone 6*

The unconformity of Late Permian sandstone and conglomerate with pebbles of granite, andesite, rhyolite, quartz upon the Carboniferous rocks cannot be directly observed there. The Late Permian rocks are deformed by folds with steeply plunging axes. This folding event took place before the deposition of Early Triassic conglomerates.

Stop 7-5: *43°00.894'N and 87°33.571'E*

Late Triassic sandstone and conglomerate containing pebbles of quartz, volcanic rocks and sandstone. The base of the conglomerate exhibits erosional channels. These fluvial deposits unconformably overlie folded Permian sandstone and black carbonaceous mudstone with plant remains. The Late Permian, Triassic and Jurassic terrigeneous deposits or volcanic rocks that unconformably cover the Carboniferous-Early Permian arc rocks are continental formations.

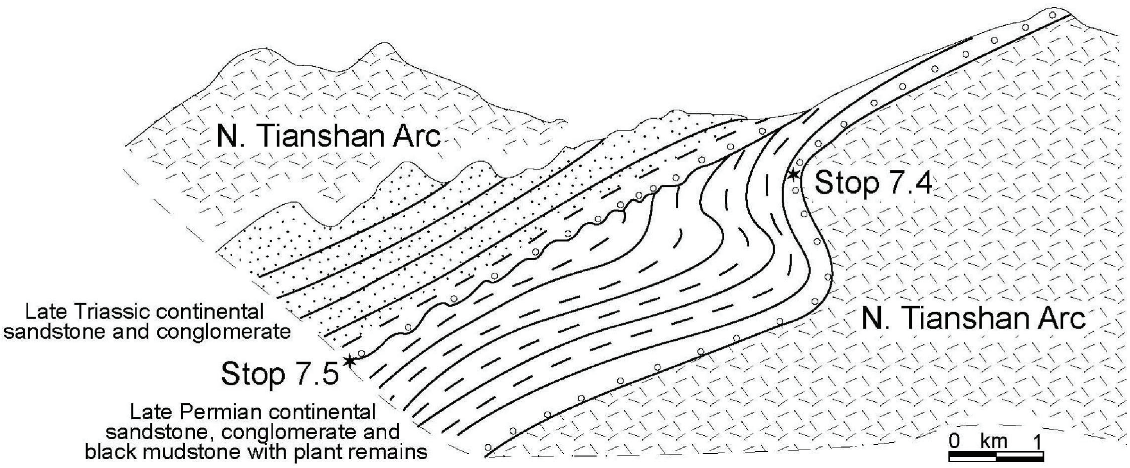

Figure 14. Schematic cross section of the Aiwergou section.

Together with some other lines of evidence found in the Southwestern Chinese Tianshan such as Late Permian radiolarian fossils (Li et al. 2002, 2005), UHP eclogite yielding a Late Triassic age (Zhang et al. 2007) and Permian Alaskan-type granite, the Late Triassic unconformity led Xiao et al. (2008, 2009) to conclude that the northward subduction between Tarim and Yili blocks was completed in the Triassic. However, due to its continental sedimentary environment, this unconformity might be also interpreted as a sedimentary response of a post-collisional tectonic event.

Day 8 (not done). Urumqi-Houxia-Bingdaban section

In this section along the Road G216, we shall observe the Carboniferous-Early Permian sedimentary rocks of the North Tianshan active margin (andesitic-rhyolitic rocks dated at 272±4 Ma using zircon U-Pb SHRIMP method by Yang et al. 2006, turbidites, chert or siliceous mudstone and pebbly mudstone). North of the Bingdaban pass (Fig. 5), augen gneiss, foliated, or even mylonitic, metavolcano-sedimentary rocks with dextral kinematic can be observed as well.

Stop 8-1: *43° 22.429'N and 87°12.426'E, between milestones 737 and 738*

Black mudstone, laminated siliceous mudstone and discontinuous sandstone beds. The bedding (S_0) is folded by upright folds. En echelon tension gashes indicate a south directed faulting.

Stop 8-2: *43° 21.955'N and 87° 12.108'E, after the bridge*.

Subvertical turbidite. Graded bedding and cross lamination show both top-to-the north and top-to-the-south polarity. These sedimentological features argue for tight upright folds.

Stop 8-3: *Immediately north of Houxia, between milestones 744 and 745*

View of the flat-lying unconformity of Jurassic over Carboniferous, and open folds.

Stop 8-4 *(optional): 43° 07.983'N and 87° 04.633'E*

Carboniferous limestone series indicates by vertical bedding S_0. The present contact with the volcanic series is tectonic, but this limestone may be stratigraphically associated with the volcanics. The series is very similar to the sequence of the Yili arc.

Stop 8-5: *43°07.367'N and 87°03801'E*

Red mudstone and andesitic lava of Late Carboniferous age. This site has been studied for paleomagnetic studies (Wang et al., 2007b).

Stop 8-6: *43°07.13'N and 87°03.044'E, south of the "Red May" bridge, milestone 774*

Fine grained diorite with skarn xenoliths. The diorite is locally mylonitic with steeply south-dipping foliation.

Stop 8-7: *43°06.88'N and 87°01.009'E*

Subvertical mudstone-phyllite with a well marked subhorizontal mineral and stretching lineation. In thin section sheared andalusite can be observed and indicates dextral shearing. This site corresponds to the North Tianshan Fault (NTF, Wang et al. 2006) and the Main Tianshan shear zone (MTSZ, Laurent-Charvet et al. 2003). Whole-rock $^{40}Ar/^{39}Ar$ dating of mylonitic phyllite yielded ages of 275-263 Ma (de Jong et al. 2009).

Figure 15. Porphyritic granite deformed by Permian dextral shearing at Bingdaban (Stop 8.8).

Stop 8-7' (optional): *43°06.88'N and 87°00.482'E, eastern side of the river*

Mylonitic mica-quartz schist with steep foliation and subhorizontal stretching lineation. These rocks are the most deformed ones in the shear zone.

Stop 8-8: *43° 05.951'N and 86°50.306'E, in the curves in front of the glacier, Milestone 798*

Augen gneiss with dextral kinematic indicators. The protolith is a porphyritic granodiorite dated at 442 ± 4 Ma by SHRIMP method on zircon with inherited zircons of up to ~1788 Ma (Zhu and Song 2006). But Yang et al. (2008) interpret this augen gneiss as the basement of North Tianshan according to their new zircon U-Pb geochronological date of 956±11 Ma.

Stop 8-9: *Bingdaban (elevation 4280 m)*

Landscape on the North Tianshan range. This domain is a Carboniferous magmatic arc due to a southward subduction of the North Tianshan Oceanic basin. The arc has been afterward sheared by dextral wrenching along the MTSZ during the Permian (Laurent-Charvet et al., 2002, 2003).

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Qingchen Wang is currently the Secretary-General of the China National Committee for SCL/ILP, and the Chairman of the International Lithosphere Program project TOPO-CENTRAL-ASIA (CC-1/4). He got his Ph.D. from, Chinese Academy of Sciences in 1985. He majors in petrology and tectonics, and studies geodynamics of orogenic belts and sedimentary basins.

Liangshu Shu *is Professor of structural geology at Nanjing University, China. His major interests are geo-tectonics and structural geology, especially the deformation and evolution of crustal rocks. Since 1980's, he has been studying plate tectonics and the geodynamic evolution of the orogenic belt in the Jiangnan,Cathaysia and Tianshan areas.*

Jacques Charvet *is emeritus Professor at Orléans University. He received his Doctor's degree from Lille University in 1978. His main scientific interest is on tectonics and geodynamics, mountain building, and ore deposits. After field studies in various areas: Dinarides, Pyrénées, and South Iberian Pyrite Belt in Europe; western Cordillera in North America; Brazilian Espinhaço Belt in South America; SW Japan. He concentrated his research on the geology of China during the last two decades.*

Michel Faure *is professor of structural geology and tectonics in Orléans University. His scientific work is dedicated to the geodynamic evolution of mountain belts. He investigates the tectonic setting of metamorphic and magmatic roots of orogens from lithospheric convergence to collision, exhumation of High Pressure and Ultra-High Pressure tectonic units and crustal melting.*

Bo Wang *is associate professor at Nanjing University (China). He received his Ph.D. degrees on structural geology from Nanjing University and on geodynamics from Orléans University (France), respectively. His research interests are on the tectonic evolution of the Tianshan Belt and recently on other mountain belts of the Central Asia.*

Wei Lin *is Professor of structural geology at the Institute of Geology and Geophysics, Chinese Academy of Sciences. He obtained his PhD. degree in Orleans University (France). In recent years, his research interest focuses on the structural analysis, tectonic evolution and geodynamics of the Paleoproterozoic belts in the North China craton and the South China block, the HP and UHP orogenic belt of Central China and the Mesozoic to Cenozoic lithosphere thinning in the North China Craton.*