Structural and kinematic evolution of strike-slip shear zones around and in the Central Tianshan: Insights for eastward tectonic wedging in the southwest Central Asian Orogenic Belt

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ABSTRACT

In order to better understand the late Paleozoic tectonic evolution of the southwestern Central Asian Orogenic Belt (CAOB), we carried out structural and geochronological studies on the poorly investigated Xiaergou and Wulasitai shear zones around and in the Chinese Central Tianshan. The Xiaergou shear zone is the connecting segment between the North Tianshan Fault and Main Tianshan Shear Zone along the northern margin of the Yili - Central Tianshan blocks, it strikes NW-SE with a width of ~3–5 km and shows predominant dextral kinematics. Zircon U–Pb ages of pre- and syn-kinematic granitic dykes within the Xiaergou shear zone indicate that the dextral shearing was active at ~312-295 Ma. The Wulasitai shear zone is a high-strain belt occurring in the interior of the Central Tianshan block, it extends NW-SE for more than 40 km with variable widths of ~1–5 km, steep mylonitic foliations and sub-horizontal stretching lineation are well developed and various kinematic indicators suggest prevailing sinistral shearing. New biotite $^{40}\text{Ar}/^{39}\text{Ar}$ ages of two meta-sedimentary rocks, together with the published metamorphic zircon ages constrain the timing of the sinistral shearing at ~312-301 Ma. Our new results combined with the previous studies reveal that the dextral strike-slip shear zones framing the Central Tianshan formed almost simultaneously in the latest Carboniferous (~310 Ma) and lasted until the middle to late Permian. They resulted from the eastward tectonic wedging and relative rotations between continental blocks in the SW CAOB. The sinistral shearing of the Wulasitai shear zone within the Central Tianshan was likely generated due to differential eastward motions of the northern and southern parts of the Central Tianshan.

1. Introduction

Transcurrent tectonics generally refers to large strike-slip faulting system in which the displacement vector is parallel to the strike of fault due to plate motions on a sphere (Freund, 1974; Onstott and Hargraves, 1981; Beck, 1983; Sylvester, 1988). Transcurrent tectonics usually forms at plate boundaries by oblique plate convergence (Allen, 1965; Fossen et al., 1994; Dewey et al., 1998), and accretionary orogeny (Mann, 2007). It can also develop as a transfer zone in a rift setting or a fold-and-thrust belt (Wilson, 1965; Moore, 1979). As one important manifestation, strike-slip shear zones stand for a deep version of intracontinental transcurrent tectonics characterized by plastic deformation and a tabular to sheet-like, planar or curvilinear domains (Berthé et al., 1979; Ramsay, 1980; Fossen, 2010; Davis et al., 2011). Continental-scale strike-slip shear zones typically exhibit ductile deformation fabrics with steeply-dipping foliations (Davis et al., 1986; Tapponnier et al., 1990; Leloup et al., 1995; Cao and Neubauer, 2016; Zhang et al., 2017). As a prominent dynamic process occurring in continental crust, they delimit mechanical and rheological anomalies that tend to be reactivated or have distinct impact on structural evolution during
subsequent phases of tectonism (e.g., Daly et al., 1989; Holdsworth et al., 1997; Metelkin et al., 2010; Bercovici and Ricard, 2012). Thus, understanding the structural patterns and kinematics of strike-slip shear zones as well as their tectonic mechanisms is an important issue in continental dynamics research.

The Tianshan (Tien Shan) Orogen lies in the southernmost part of the Central Asian Orogenic Belt (CAOB), or the Altaiids, which is the largest Phanerozoic orogenic system on the world formed by progressive amalgamation of various microcontinents, island arcs, seamounts, oceanic plateaus, and accretionary complexes (Şengör et al., 1993; Jahn et al., 2000; Xiao et al., 2003; Windley et al., 2007; Wilhem et al., 2012). Following successive accretions to the northern margin of the Tarim Craton in late Paleozoic, the Tianshan Orogen and adjacent areas underwent large-scale transcurrent tectonics that greatly influenced the tectonic framework of the SW CAOB (Allen et al., 1995; Şengör and Natalin, 1996; Laurent-Charvet et al., 2002, 2003; Wang et al., 2007a, 2009, 2014; Li et al., 2015, 2020). Therefore, recognizing the styles of transcurrent deformation is crucial for deciphering the orogenic history and tectonic transition from convergent to intracontinental evolution of this giant belt.

One of the most remarkable features of the Tianshan Orogen is the occurrence of two large-scale ductile shear zones that are parallel to major ophiolitic sutures (i.e. the North Tianshan Fault-Main Tianshan Shear Zone and Nalati-Baluntai Fault, respectively) (Figs. 1 and 2). Numerous studies have suggested that these two shear zones resulted from Permian regional transpressional and/or transtensional tectonics, with evidence of both general dextral strike-slip shearing and folding induced by lateral displacements (Yin and Nie, 1996; Shu et al., 1999; Laurent-Charvet et al., 2002; 2003; Wang et al., 2008b; Wang et al., 2009; 2014; de Jong et al., 2009; Pirajno, 2010; Tang et al., 2011; Branquet et al., 2012; Cai et al., 2012). However, other authors proposed that pure shear strain related to N–S coaxial compressional tectonics was responsible for the formation of the Jueluotage shear zone (middle part of the Main Tianshan Shear Zone) and the Baluntai Fault, based on symmetrical structures observed (Xu et al., 2003; Yang et al., 2007). Thus, there is no consensus on the mechanism and geodynamic setting of their deformation so far. In addition to these large shear zones along boundaries between major continental units, several subordinate strike-slip faults were also reported within some continental blocks, in which mylonitic rocks are widespread (e.g., Xingdi Fault, Cai et al., 2012; Hulashan Fault, Lin et al., 2013; Wulasitai shear zone, Yang et al., 2004; He et al., 2018a). However, structural data are scarce from these high-strain shear zones. Meanwhile, it is also poorly understood how they were formed and responded to the complex accretionary and collisional orogenesis, and what their structural relationship is with large transcurrent tectonics marking the boundaries of tectonic units. Further investigation is therefore needed to obtain more information on the activity of these shear zones.

In this study, we investigated two contiguous strike-slip shear zones, namely, the Xiaergou and Wulasitai shear zones, which hitherto have been poorly studied. The former is a connecting part between the North Tianshan Fault and the Main Tianshan Shear Zone along the northern boundary of the Yili - Central Tianshan blocks, and the latter is a subordinate shear zone inside the Central Tianshan (Fig. 2; Yang et al., 2004; He et al., 2018a). The detailed structural, kinematic and geochronological data allow us to explore the possible formation mechanism of these strike-slip shear zones developed at different scales and opposite kinematic features under an overall consistent deformation regime. This study also places further constraints on the post-orogenic intracontinental evolution of the Tianshan Orogen, and provides new insights into the eastward wedging of tectonic units between the Tarim and Siberian blocks.

2. Regional geology

2.1. Tectonic units in the Chinese Tianshan

The Tianshan Orogen stretches east-west for about 2500 km from eastern Xinjiang in NW China to central Uzbekistan (Fig. 1). This orogenic belt was built by multi-stage subduction of the Paleo-Asian oceanic plate and the subsequent welding between the Kazakhstan-Yili block and Tarim Craton during the Paleozoic (e.g., Allen et al., 1993; Gao et al., 1998; 2009; Charvet et al., 2007; 2011; Wang et al., 2008a,b; 2011; 2018a,b; Xiao et al., 2013), and was reactivated during the Meso-Cenozoic as a far-field response of Qiangtang-Lhasa and India-Asia collisions (e.g., Molnar and Tapponnier, 1975; Avouac et al., 1993; De Grave et al., 2007; Glorie and De Grave, 2016). The Chinese segment of the Tianshan Orogen is sandwiched between the Junggar and Tarim

Fig. 1. (A) Simplified tectonic divisions of East Asia showing the location of the Central Asian Orogenic Belt (CAOB), EEC, East European Craton; KZN, Kazakhstan; QQ, Qaidam-Qinling (modified after Şengör and others, 1993; Jahn et al., 2000). (B) Geological map of the SW CAOB, including major tectonic units and boundaries (after Windley et al., 2007; Choulet et al., 2011; Wang et al., 2012; Cao et al., 2017). Abbreviations correspond to: IKMT, Ishim-Kyrgyzstan Middle Tianshan; SKNT, Stepenyak-Kyrzyz North Tianshan; ACNT, Aktau-Chinese North Tianshan; NB, North Balkhash; BY, Balkhash-Yili; CY, Chu-Yili; BA, Baidaulet-Akbastau; BC, Boshchekul-Chingizia; JB, Junggar-Balkhash; ZTS, Zharma-Tarbagatay-Saur; KM, Karamay; JW, West Junggar; CNT, Chinese North Tianshan; CCT, Chinese Central Tianshan; BGD, Bogda; Bay, Bayinbuluk; Gul, Gulugou; KU, Kulehu; WW, Wuwamen. Numbers denote major faults: 1 = North Tianshan Fault (NTF), 2 = Main Tianshan Shear Zone (MTSZ), 3 = Nalati Fault (NF), 4 = Baluntai Fault (BF).
basins (Fig. 1B). According to the differences in basement nature and tectonic settings, the Chinese Tianshan is traditionally subdivided into four tectonic units separated by regional crustal-scale faults, namely, the North Tianshan, Yili Block, Central Tianshan and South Tianshan from north to south (Fig. 2; Xiao et al., 1992, 2004; Gao et al., 1998; Charvet et al., 2007).

The North Tianshan is an accretionary complex formed by the subduction and accretion of the Junggar - North Tianshan oceanic plate. It is composed of late Paleozoic sedimentary-volcanic sequences and magmatic intrusions, which occur in the Kazakhstan-Yili blocks to the west and around the Turpan-Hami (Tu-Ha) basin in the east. (e.g., Wang et al., 2006; Han et al., 2010; Zhang et al., 2016; Wali et al., 2018). The Yili Block represents the eastern part of the Kazakhstan microcontinent, and is a wedge-shaped area between the North and Central Tianshan blocks (Figs. 1B and 2), it consists of Meso-to Neoproterozoic basements, Paleozoic sedimentary cover and magmatic arc rocks that were generated mostly by the southward subduction of the Junggar oceanic plate (e.g., Gao et al., 1998, 2009; Hu et al., 2000; Charvet et al., 2007, 2011; Wang et al., 2007b, 2014a; Liu et al., 2014; Cao et al., 2017; Zhu et al., 2019a). Bordered by the Main Tianshan Shear Zone to the north and the Baluntai Fault to the south, the Central Tianshan refers to a ribbon-like domain extending from the Natali Range in the west to Xingxingxia areas in the east (Fig. 2), it consists of Precambrian metamorphic basement (e.g., Hu et al., 2000; He et al., 2014; 2015; 2018b; Gao et al., 2015; Wang et al., 2017), early Paleozoic magmatic arc sequences, late Paleozoic sedimentary strata and Paleozoic intrusions (e.g., Shi et al., 2007; Dong et al., 2011; Lei et al., 2011; Ma et al., 2014; Zhong et al., 2015). The South Tianshan is confined to the region between the Natali - Baluntai faults and the northern Tarim margin. This unit contains an early Paleozoic continental arc and late Paleozoic sedimentary cover, which were formed during the successive closure of the South Tianshan Ocean and several back-arc basins (e.g., Gao et al., 1998, 2009; Wang et al., 2010, 2011, 2018a,b; Jiang et al., 2014; Alexeiev et al., 2015; Han et al., 2016; Zhong et al., 2017, 2019).

2.2. Large-scale shear zones in the Chinese Tianshan

The main tectonic units described above contact each other by large-scale shear zones that extends roughly east-west and are sub-parallel to the ophiolite melange zones developed along the Bayingou - Mishigou - Gangou and Atbashi - Kekusu - Wuwamen areas (Fig. 2) (Wang et al., 2008a,b; Charvet et al., 2011).

The Main Tianshan Shear Zone (MTSZ) (Shu et al., 1999; Laurent-Charvet et al., 2002; Liu et al., 2020a,b) is the tectonic boundary between the North Tianshan and Central Tianshan and it stretches for over 700 km from Xiaergou-Gangou eastward to Weiya (Fig. 1B) (XIGMR, 2007). Along this shear zone, Precambrian schists and gneisses, Paleozoic granitoids and volcanics, as well as ophiolitic rocks were mylonitized and they generally exhibit sub-vertical mylonitic foliations with sub-horizontal stretching lineation (Shu et al., 1999, 2002; Laurent-Charvet et al., 2002, 2003; Li et al., 2020). Consistent asymmetric fabrics indicate a right-lateral strike-slip movement, with thrusting and/or normal faulting components, probably formed in transpressional and/or transtensional settings (Laurent-Charvet et al., 2003; Wang et al., 2008a,b; Yang et al., 2009; Li et al., 2020; Liu et al., 2020a,b). The North Tianshan Fault (NTF) is essentially the westward continuation of the MTSZ and it runs into Kazakhstan, separating the Yili block to the south from the Chinese North Tianshan to the north (Fig. 2). Kinematic features along the NTF also indicate a dextral ductile shearing (Zhou et al., 2001; Wang et al., 2006, 2009; de Jong et al., 2009; Yang et al., 2009; Zhu, 2011; Liu et al., 2020a,b).

The Natali Fault (NF) occurs along the Haerke-Nalati ranges in the South Tianshan (Fig. 1B), and is a large ductile shear zone ~5–15 km wide (e.g., Wang et al., 2010; Charvet et al., 2011; Han et al., 2011). It continues eastwards to merge with the NTF near the Bingdaban area (Figs. 1B and 2). This ductile shear zone was active mainly in the Permian and reworked the Carboniferous suture zone (Akeyazi-Kekusu ophiolite mélanges and high-pressure metamorphic belt) (Fig. 1B) formed by the subduction of the South Tianshan oceanic plate (e.g., Gao et al., 1998, 2009; Lin et al., 2009; Qian et al., 2009; Wang et al., 2009, 2010; Long et al., 2011; Xu et al., 2013; Zhong et al., 2017, 2019). Diverse mylonites, foliated meta-sedimentary rocks and gneissic granitoids are well exposed in this shear zone, and structural studies from the Kekusu high-pressure metamorphic belt and north of Bayinbulak (Fig. 1B) indicate dextral kinematics (YXGMR, 1993; Li and Liu, 1997; Wang et al., 2007c; 2010; Lin et al., 2009; Zhong et al., 2019).

The Baluntai Fault (BF) stands for the boundary between the Central Tianshan to the northeast and the South Tianshan to the southwest (Alexeiev et al., 2015; Wang et al., 2018a,b; Zhong et al., 2019). It extends from the north of Bayinbulak, nearly parallel to the NTF - MTSZ, to the Sangshuyuanzi area to the east (Figs. 1B and 2) (XIGMR, 2007). Foliated schists and gneisses, mylonitic rocks and ductilely deformed granitoids are widely distributed along the BF, which also partially reworked the Wuwamen - Gulougu ophiolite mélanges (Fig. 2) (YXGMR, 1993; Yang et al., 2004; Deng et al., 2006; Wang et al., 2014; Wang et al., 2018a,b). Localized coaxial pure strain was described in the south of Baluntai regions and was considered as the result of N-S compression (Yang et al., 2007); however, most structural investigations
from the Sangshuyuanzi, Baluntai areas and their eastward continuation demonstrated dextral strike-slip shearing (Laurent-Charvet et al., 2003; Wang et al., 2008b; Wang et al., 2009; Xu et al., 2011; Cai et al., 2012; Zhong et al., 2015; Li et al., 2020).

3. Overall geometry, structures and kinematics of the Xiaergou and Wulasitai shear zones

Our structural investigations were conducted along several sections crossing the Xiaergou and Wulasitai shear zones around and within the Central Tianshan (Figs. 2–10). In the following sections, we present the main lithological units in the two shear zones and their structural and kinematic features.

3.1. Xiaergou Shear Zone

As the eastern part of the NTF, the Xiaergou Shear Zone (XSZ) is a ~NW-SE trending mylonitic belt with a width of ~3–5 km, and was locally reworked or truncated by brittle reverse and/or left-lateral strike-slip faults (Figs. 2 and 3). Due to difficult physical conditions our field observations were limited to a 5-km-long section mainly along its strike near the Xiaergou village (Figs. 3B and 4).

Fig. 3. (A) Google Earth© Satellite image of the Xiaergou shear zone (XSZ). (B) Geological map of the XSZ (after 1:200,000 geological map of Houxia by XBGMR, 1977a).
3.1.1. Lithological units

Silurian to Devonian marine sequences were affected by the ductile deformation along the XSZ. Silurian meta-sediments belong to the middle Ahebulake Group and consist of marbles, greywackes, schists, phyllites and calcareous sandstones with interlayered tuff. Devonian sequences are represented by the middle Tiangeer Group that is dominated by basaltic tuffs, tuffaceous sandstones and marbles (XBGMR, 1993). Both groups are in contact with each other along a steep N-dipping reverse fault (Figs. 3 and 4).

Early Paleozoic granodiorites and late Paleozoic granites are well exposed within and across the shear zone (Figs. 3B and 4). The late Paleozoic granites were dated at ~370-337 Ma (zircon U–Pb ages) and were interpreted to be related to the subduction of the North Tianshan oceanic plate and the collision between the Central and North Tianshan (including Tu-Ha basin) during the early Carboniferous (Ma et al., 2014; Yin et al., 2017). In addition, numerous undeformed granitic and diabase dykes of unknown ages intruded into Silurian-Devonian meta-sedimentary and volcanic rocks as well as the Paleozoic plutons (Figs. 3 and 4).

3.1.2. Structures and kinematics

Except for the undeformed granitic and diabase dykes intruding the XSZ, all other lithological units mentioned above underwent intensive ductile shearing, showing well-defined ~ E-W or ~ ENE-WSW-striking steep (40°–78°) mylonitic foliations (S1) associated with pervasive stretching lineation (L1) gently plunging (<40°) to E/NE or W/SW. 

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Fig. 4. (A) Structural map of the studied domain of the Xiaergou shear zone (XSZ) (see Fig. 3 for location) (after 1:200,000 geological map of Houxia by XBGMR, 1977a), showing field structural data and sampling locations. (B) Stereonet plots (equal area lower hemisphere) of beddings (S0 poles), mylonitic foliations (S1 poles) and stretching lineation (L1) in the XSZ. (C) Cross-section across the XSZ showing the sample numbers and locations.
The strikes of S1 foliations and the plunges of L1 lineation are sub-parallel to the overall strike of the shear zone. The mylonitic foliations and stretching lineation are usually defined by elongated quartz and feldspar ribbons and mica aggregates (Figs. 5 and 6). In the Silurian-Devonian metasedimentary rocks, the S1 is predominantly dipping to the ~N-NNE with variable dip angles ranging from 42° to 76°, and is parallel to the locally preserved S0 bedding planes (Fig. 4A–B). The K-feldspar porphyroclasts are elongated and oriented parallel to the shearing foliations. In addition, mylonitic felsic dykes intruding the marbles and schists also exhibit steep foliations and sub-horizontal mineral stretching lineation, which are defined by a preferred orientation of elongated feldspar and quartz grains (Figs. 4C and 5D). Leuco-granitic dykes and their host granitic pluton both display ~ NE-SW-striking mylonitic foliations with ~ENE/WSW plunging lineation (Fig. 4A–B and 5A), which are oblique to the general strike of the shear zone, probably due to localized rotation related to the NE-striking brittle reverse fault (Fig. 4A).

Disjunctive cleavage in granodiorites shows a general strike of 160°, sub-parallel to the shear zone; and shear bands suggest a dextral sense of shearing (Fig. 5E). In highly deformed marbles, sheath folds and A-type folds were well preserved, whose hinges are parallel to the stretching lineation; on the X-Z plane (perpendicular to foliation and parallel to lineation), the asymmetric fold shapes present a dextral shearing (Fig. 5F). S-C fabrics can be recognized in marbles as well, the S-foliation is represented by elongated calcite veins, and a dextral sense of movement is also indicated (Fig. 5G). It is worth noting that sinistral shearing was also occasionally preserved, as revealed by asymmetric quartz lens in a small-scale greenschist outcrop (Fig. 5H). Under microscope, mylonitic granitoids and tuffaceous sandstones contain plenty of kinematic indicators, such as S–C fabrics, feldspar bookshelf texture, sigmoid asymmetric feldspar porphyroclasts and mica pressure shadows showing a principal dextral sense of shearing (Fig. 6A–D), sinistral kinematics was only locally developed and is associated with dextral kinematics (Fig. 6E–F).

3.2. Wulasitai Shear Zone

The Wulasitai shear zone (WSZ) is a remarkable subordinate high-strain deformation zone occurring within the Central Tianshan, it extends NW-SE, nearly parallel to the NTF and BF, for more than 40 km with variable widths of ~1–5 km (Figs. 2 and 7). This high-strain mylonitic belt merged westwards into the NF, and it is covered eastwards by strongly weathered granites, vegetation and glacier (Fig. 2), it is possible that the WSZ connects the MTSZ in the Yuergou area (XIGMR, 2007).

3.2.1. Lithological units

A variety of rocks are well exposed along the WSZ and were significantly deformed by ductile shearing, they mainly include Proterozoic paragneiss, early Paleozoic sedimentary rocks and granodiorites, and late Paleozoic granites (Fig. 7B; XBGMR, 1993).

Proterozoic paragneiss occur north of the Wulasitai village (Fig. 7B)
and were previously assigned to the Paleoproterozoic Xingxingxia Group (XBGMR, 1993; XIGMR, 2007). However, recent zircon U–Pb dating indicated that some of these meta-sedimentary rocks were likely deposited in the early Devonian to late Carboniferous (Shu et al., 2013; Wang et al., 2018). Early Paleozoic meta-sedimentary rocks dominantly comprise paragneiss, marbles, greenschists, deformed quartz sandstones and greywackes, they were considered as Silurian in age, but some of them were recently constrained as Devonian (He et al., 2018a).

Paleozoic plutonic rocks along the WSZ include early Paleozoic granodiorites and late Paleozoic granites intruding the “Proterozoic” and “Silurian” meta-sedimentary rocks (Fig. 7B). Migmatites are frequently associated with the granodiorites and can also be observed in the meta-sandstones. Some late Paleozoic granites exposed along the WSZ were dated at ~354-332 Ma (He et al., 2018a).

These ductilely deformed and metamorphosed sedimentary rocks are unconformably covered by undeformed and gently tilted Jurassic sandstones (Fig. 7B).

3.2.2. Structures and kinematics

Along the WSZ, ~E-W or ~NW-SE-striking, diversely S/SW- or N/NE-dipping mylonitic foliations (S1) and associated mineral stretching lineation (L1) are well developed in most lithological units (Figs. 8 and 9A-E). The dip angles of foliations vary from 30° to 80°, and the plunging angles of lineation are 3°–40° (Fig. 8). In general, the steeper foliations bearing shallower lineation occur along the straight segment, and gentle foliations with nearly down-dip lineation are mostly observed at the turning segment of the WSZ (Figs. 7 and 8). Silurian meta-greywackes underwent intensive ductile deformation displaying steep mylonitic foliations and gentle stretching lineation (Fig. 9A). Some paragneiss and phyllites show gently south-dipping foliations and sub-horizontal stretching lineation defined by elongated ribbons of felsic melts, and coeval sub-S-N crenulation cleavages (L1′) represented by hinges of microfolds full of mica and sericite (Fig. 9B–C). In migmatites, foliation-parallel leucocratic veins reflect a low-degree partial melting, elongated K-feldspar and quartz ribbons in the leucosome indicate a syn-kinematic transport of melts (Fig. 9B). The granitic rocks were also ductilely deformed showing mylonitic foliations and ~E-W-trending stretching lineation characterized by elongated feldspar and quartz ribbons and oriented micas (Fig. 9D–E).

Overall bending geometry suggests that localized transpressional deformation affected the WSZ. For example, along a ~NE-SW profile across the bending segment of the WSZ, folded and duplicated quartz veins occur in mylonitic granites with the axial planes parallel to the S1 foliation, asymmetric folds and shear bands indicate a top-to-the-southwest shearing (Fig. 9F). Moreover, strike-slip motions along the WSZ were well recorded by a series of apparent kinematic indicators. At the field scale, asymmetric intrafolial microfolds in the meta-rhyolites (Fig. 9G), shear bands in the meta-sandstones (Fig. 9H), and fractured...
and offset felsic veins in the mylonitic granites (Fig. 9I) suggest a sinistral shearing along the strike of the shear zone. In addition, microscopic textures such as the sigmoid biotite mica fishes (Fig. 10A), shear bands and pressure shadows composed of mica around K-feldspar porphyroclasts (Fig. 10D–E), S-C fabrics and \( \sigma \)-type feldspar porphyroclasts (Fig. 10D–E) consistently demonstrate a sinistral sense of shear. However, dextral motion is also indicated by sigmoid quartz and feldspar porphyroclasts (Fig. 10F) that are occasionally visible in few samples showing predominantly sinistral shearing.

4. Temperature conditions of the ductile deformation

Quartz is one of the most sensitive minerals during plastic deformation. In a shear zone, quartz can be deformed via different mechanisms under various temperature conditions. Previous studies established relationships between deformation mechanisms and physical conditions based on naturally and experimentally deformed rocks, e.g., types of quartz dynamic recrystallization and corresponding temperatures, are widely applied in studies of shear zones (e.g., Hirth et al.,...
Here we estimated deformation temperatures of these two shear zones according to the criteria for quartz dynamic recrystallization proposed by Stipp et al. (2002a). The studied samples were collected from the axial parts of the shear zones (Figs. 4 and 8) so that they may reflect the peak conditions of ductile shearing. In order to avoid possible large uncertainty brought by the sampling effect, at least two samples were taken from each sampling site for thin section observation. Detailed microstructural descriptions and temperature estimations are given in supplementary Table S1.

Our observations suggest that the sub-grain rotation is the dominant mechanism of quartz dynamic recrystallization in both the XSZ and WSZ (Fig. 11; Table S1). In a number of samples, numerous new small grains produced by both bulging and sub-grain rotation mechanisms occur around the original quartz grains, revealing a typical core-mantle structure (Fig. 11A, B and D), and the elongated quartz ribbons parallel to main foliations reflect intensive dislocation creep deformation (Fig. 11C, E and F). Grain boundary migration recrystallization appears more frequently in the XSZ (Fig. 11C), indicating a higher temperature condition compared to the WSZ. Generally, deformation temperatures in the XSZ are estimated as ~460–510 °C, slightly higher than the temperature conditions of the WSZ (~450–485 °C) (Fig. 12; Table S1). In addition, feldspar only displays bulging recrystallization and no clear evidence for sub-grain rotation was identified in both shear zones, suggesting a maximum temperature threshold of ~550–600 °C for ductile shearing. It is noted that the estimated temperatures here only refer to the pervasive dextral shearing of the XSZ and sinistral shearing of the WSZ. Meanwhile, sinistral kinematics within the XSZ and dextral kinematics along the WSZ are only locally preserved as described before, their corresponding deformation temperatures are thus difficult to be determined without efficient indicators.

5. Geochronology

In order to constrain the timing of ductile deformation, new isotopic data were obtained by zircon LA-ICP-MS U–Pb and biotite 40Ar/39Ar dating. Sample locations are marked on Figs. 4 and 8, analytical procedures are described in Appendix, and analytical data are provided in supplementary Tables S2 and S3.

5.1. Zircon U–Pb ages for pre- and syn-kinematic granitic dykes in the Xiaergou Shear Zone

Pre- and syn-kinematic plutons develop along the XSZ. The syn-kinematic ones were emplaced during the ductile shearing, some occur as migmatitic veins due to in situ partial melting of the host rocks and some injected from deep-seated magma via foliations or faults (Hutton, 1988; Pitcher, 1997; Pirajno, 2010; Wang et al., 2014b). One distinct character of syn-kinematic dykes is that their distributions are only limited within the shear zone. This situation differs from that of the pre-kinematic dykes, which are distributed not only within but also outside the shear zone and they usually crosscut the shear zone or...
lithological boundaries (Searle, 2006; Rolland et al., 2009; Cao et al., 2011; Liu et al., 2020a). From the XSZ, one sample of pre-kinematic granite dyke and another of syn-kinematic dyke intruding the Silurian marbles and late Paleozoic granites (~370-337 Ma; Ma et al., 2014; Yin et al., 2017) (Fig. 4), were dated using the zircon LA-ICP-MS U–Pb method.

Sample 44-B was taken from a granitic dyke of ~1m wide (Fig. 13 A), which displays sharp contact with the host rocks. Both the dyke and its host rocks show similar deformation fabrics, i.e., steeply N-dipping mylonitic foliations and shallowly plunging lineation, indicating a strike-slip shearing, and a pre-kinematic emplacement of the granite dyke. The sample mainly contains K-feldspar and quartz with minor biotite and muscovite (Fig. 13 B). The zircon grains from this sample are commonly euhedral and 100–150 μm in length, their CL (Cathodoluminescence) images generally show well-developed concentric oscillatory zoning (Fig. 13 C). A total of fifteen analyses were carried out on twelve zircons, showing Th/U ratios of 0.4–0.8 (Table S2), indicating a magmatic origin according to the descriptions of Corfu et al. (2003). Therein, 12 out of 15 analyses yielded a concordant age of 311.9 ± 2.4 Ma (MSWD = 0.21; Fig. 13 D), including two analyses on the modified rims (Nos. 1 and 14; Fig. 13 C), while the unmodified parts of these two zircons yielded older 206Pb/238U ages of ~342 Ma and ~331 Ma (Fig. 13D), comparable to the ages of the host granites, from which these two zircons were likely derived. One additional zircon yielded much older age of ~431 Ma, and it is probably inherited.

Sample 49-C was collected from another granitic dyke intruding the Silurian marbles and tuffaceous sandstones (Fig. 4). The dyke is ~1–1.5 m wide and shows boudinage structure and well-developed mylonitic foliations and stretching lineation (Fig. 13E), consistent with those of the host rocks. Generally parallel contact between the dyke and its host rocks to the main mylonitic foliations, and high-strain superplastic creep (Fig. 13 F), i.e., high-temperature syn-magmatic deformation, indicate a syn-kinematic emplacement of the dyke. The sample is fine-grained and consists of feldspar, quartz and fine-grained muscovite (Fig. 13 F). Subhedral zircon crystals from this sample have length/width ratios of 2.5:1–1:1 with variable long axes of 50–200 μm (Fig. 13 G). Sixteen zircons were dated, concordant and consistent results were obtained from nine zircons with typical oscillatory zoning, indicative of an igneous origin together with their relatively high Th/U ratios (0.14–1.25) (Fig. 13 G; Table S2); these nine analyses yielded a weighted mean 206Pb/238U age of 294.6 ± 3.7 Ma (MSWD = 1.6; Fig. 13 H), which is interpreted to represent the crystallization age of this syn-kinematic dyke. Five zircon grains yielded older ages ranging from ~332 Ma to ~1476 Ma, indicating derivation from older crustal rocks. Two additional analyses show high degrees of discordance (>10%) (Nos. 12 and 15; Table S2) of which the meaning is still unclear.

5.2. Biotite 40Ar/39Ar ages for meta-sedimentary rocks in the Wulasitai Shear Zone

Biotite 40Ar/39Ar dating was performed on two samples from meta-sedimentary rocks of the Silurian Ahebulake Group in the WSZ, both
samples were collected from the axial part of the shear zone (Fig. 8B) and were subjected to intensive ductile shearing. Sample 01-B is a paragneiss and mainly composed of quartz, feldspar and biotite (Fig. 14A). Preferred orientation of biotite assemblages and quartz ribbons define foliations and lineation, and quartz shows undulose extinction and subgrain rotation dynamic recrystallization (Fig. 14A). Sample 02-B is a meta-sandstone mainly containing quartz, plagioclase, K-feldspar and biotite (Fig. 14B). Despite sporadic distribution, elongation of fine-grained biotites assigned along the main foliations and lineation and filled in between the granular quartz and feldspar grains, which also show undulose extinction, bulging dynamic recrystallization, and sometimes grain boundary migration recrystallization or even probable superplastic creep as indicated by equidimensional quartz grains with relatively straight grain boundaries (Fig. 14B). Overall oblique orientation and sigmoidal shape of biotite aggregates indicate a sinistral sense of shearing (Fig. 14A–B).

The $^{40}$Ar/$^{39}$Ar dating results of biotites from the meta-sedimentary rocks are plotted in Fig. 14C–F, all ages are laser step-heating ages, and errors are quoted at the 1σ level. The age spectrum of biotite sample 01-B of a paragneiss are somewhat scattered, without a clear trend through the degassing steps. Apart from the initial steps, the other analyses yielded apparent ages ranging from 295 to 306 Ma (Table S3), a Total-Gas Age (TGA) of 300.3 ± 2.5 Ma and a weighted mean age (WMA) of 300.5 ± 1.6 Ma (MSWD = 3.7; ~100% of $^{39}$ArK released) are calculated (Fig. 14C). For the biotite sample 02-B from a meta-sandstone, most analyses yielded generally consistent apparent ages (298–310 Ma) except one step that shows a much younger apparent age probably due to extremely low $^{39}$Ar released (Table S3). The TGA and WMA of this sample are calculated at 303.0 ± 2.5 Ma and 303.4 ± 1.3 Ma (MSWD = 1.7; ~100% of $^{39}$ArK), respectively (Fig. 14D).

6. Discussion

6.1. Kinematic significance of the Xiaergou and Wulasitai shear zones

According to the general geometry of the Xiaergou shear zone (XSZ), this structure forms the connecting segment between the North Tianshan Fault (NTF) and Main Tianshan Shear Zone (MTSZ) (Figs. 1 and 2). Based on our structural observations and kinematic analysis of prevalent macro- and micro-kinematic characteristics, the XSZ is dominated by a simple dextral shearing. This is in agreement with previous investigations along both the NTF and MTSZ (Shu et al., 1999; Laurent-Charvet et al., 2002, 2003; Wang et al., 2006, 2009; de Jong et al., 2009; Li et al., 2020). At the same time, sinistral shearing is only locally recognized along the XSZ. In the field, it only occurs in the greenschist from one observation site (Fig. 5H); in a few thin sections (samples 45-A and 52-B; Table S1), it was locally preserved along with the dominant dextral kinematics (Fig. 6E–F).

The Wulasitai shear zone (WSZ) was previously reported by Yang et al. (2004) near the Wulasitai village, and He et al. (2018a) traced this
shear zone far westward and proposed that it can separate the Central Tianshan into northern and southern parts (Fig. 2). Based on our field and microscopic investigations, the WSZ geometrically is a bending strike-slip shear zone and is kinematically dominated by sinistral shearing (Figs. 7B and 8), meanwhile, very limited dextral shearing can be distinguished in thin section (sample 06-B; Table S1) to be associated with the dominant sinistral kinematics (Fig. 10). In addition, at the bends and stepovers of the WSZ, a component of top-to-the-southwest shearing is also associated with the general sinistral kinematics (Fig. 9F), and most likely resulted from strain partitioning due to transpression at the stepovers along the bending WSZ (Fig. 7), as commonly recognized in most bending strike-slip shear zones (e.g., Cunningham and Mann, 2007).

Therefore, both the XSZ and WSZ are characterized by a co-existence of opposite kinematic features. Four possibilities might potentially explain co-occurrence of these opposite kinematics within an identical shear zone: (1) strain localization along shear zone, (2) strain partitioning between conjugate structures, (3) low differential stress or coaxial shortening perpendicular to the shear zone, or (4) multi-stage deformation events. However, how and when these possible earlier deformations are the reasons for the opposite kinematics in the XSZ and WSZ because kinematic senses remain consistent when the shear directions (foliations) change.

In addition, the general sub-E-W stretching lineation and consistently low plunging (Figs. 4 and 8) in both the XSZ and WSZ indicate simple shear instead of pure shear or dominant coaxial contraction. Slight variations in lineation plunging directions and angles are the effects of bending of the shear zone and localized strain partitioning for the case of the WSZ, and the influence of localized fabrics rotation related to later reworking by reverse faults for the XSZ. Moreover, development of sheath folds and A-type folds in the XSZ (Fig. 5) and syn-kinematic granites in the WSZ (Fig. 9) also indicate quite high strain rate in both shear zones, and the possibility of low differential stress can be ruled out.

Considering that sinistral shearing is very locally preserved in the overwhelming dextral kinematics of the XSZ, and that locally recognized dextral shearing is observed only in a sample with predominant sinistral motions from the WSZ, it is most likely that these opposite kinematics in both shear zones formed in different stages of ductile deformation. In a multi-stage deformation belt like the Tianshan Orogen, the most pervasive structures should be the result of the most intensive and younger deformation events, and the fabrics formed in earlier deformation stage(s) could be rarely preserved due to later strong overprinting and replacement. Thus, it is reasonable to suggest that the occasionally observed sinistral kinematics in the XSZ and dextral kinematics in the WSZ might represent locally preserved fabrics of earlier deformation events. However, how and when these possible earlier structures were formed is still not clear, and localized development of coeval but opposite kinematics could not be completely excluded, thus, further investigations are needed in future.

6.2. Timing of strike-slip ductile shearing around and in the Central Tianshan

Along the MTSZ, the northern boundary of the Central Tianshan, mica $^{40}$Ar/$^{39}$Ar ages of 290–242 Ma were obtained from the Gangou, Mishigou and Hongyuntan areas (Shu et al., 2002; Laurent-Charvet et al., 2003; Cai et al., 2012), together with a muscovite $^{40}$Ar/$^{39}$Ar plateau age of 309.7 ± 2.2 Ma for a mylonite from Mishigou (Xu et al., 2011), it is suggested the dextral shearing along the MTSZ occurred during the late Carboniferous to Early Triassic. Along the NTF, the westward continuation of the MTSZ, the age of dextral ductile shearing was constrained between ~270 and ~245 Ma by mica $^{40}$Ar/$^{39}$Ar dating on mylonitic slates and foliated granites in the Du-Ku and Bingdaban areas (Laurent-Charvet et al., 2003; de Jong et al., 2009; Yang et al., 2003). In addition, sinistral ductile shearing was also reported along the Baluntai Fault (or Southern Central Tianshan Fault) and considered as the result of clockwise rotation of Tarim with respect to Central Tianshan (Deng et al., 2006) or resulting from Devonian oblique convergence (Li et al., 2020). Some authors also proposed that the ductile shearing along the Central and North Tianshan formed under coaxial pure shear related to the NE-SW contraction induced by convergence between the Tarim and Central Tianshan blocks (e.g., Xu et al., 2003; Yang et al., 2007).

In the cases of the XSZ and WSZ, strain partitioning mostly occurred along the bending segment of the WSZ as the top-to-the-SW shearing and changes of shear directions can be observed there (Figs. 7, 9 and 10F). Shear directions also dramatically change in the XSZ but only in the overlapping segments between the overall NW-SE-striking ductile shear zone and the NE-SW-trending brittle strike-slip reverse faults (Fig. 4A). The latter cut across lithological boundaries and the mylonitic foliations of the shear zone, without any associated ductile deformation. They are not conjugate (subordinate) shear zones coeval to the NW-SE main shear zone, but rather posterior brittle faults. Local rotation related to these brittle reverse faults could be partially responsible for the changes of shear directions along the XSZ shear zone. Even though, strain partitioning and strain localization are unlikely the reasons for the opposite kinematics in the XSZ and WSZ because kinematic senses remain consistent when the shear directions (foliations) change.

Considering that sinistral shearing is very locally preserved in the overwhelming dextral kinematics of the XSZ, and that locally recognized dextral shearing is observed only in a sample with predominant sinistral motions from the WSZ, it is most likely that these opposite kinematics in both shear zones formed in different stages of ductile deformation. In a multi-stage deformation belt like the Tianshan Orogen, the most pervasive structures should be the result of the most intensive and younger deformation events, and the fabrics formed in earlier deformation stage(s) could be rarely preserved due to later strong overprinting and replacement. Thus, it is reasonable to suggest that the occasionally observed sinistral kinematics in the XSZ and dextral kinematics in the WSZ might represent locally preserved fabrics of earlier deformation events. However, how and when these possible earlier structures were formed is still not clear, and localized development of coeval but opposite kinematics could not be completely excluded, thus, further investigations are needed in future.

Fig. 12. Plots of estimated temperatures v.s. latitudes of sampling sites for the dextrally deformed samples along the Xiaergou (A) and Wulasitai (B) shear zones. Ranges of quartz recrystallization temperatures are based on Stipp et al. (2002a). Abbreviations: BLG, bulging; SGR, sub-grain rotation; GBM, grain boundary migration.

$^{40}$Ar/$^{39}$Ar ages of 290–242 Ma were obtained from the Gangou, Mishigou and Hongyuntan areas (Shu et al., 2002; Laurent-Charvet et al., 2003; Cai et al., 2012), together with a muscovite $^{40}$Ar/$^{39}$Ar plateau age of 309.7 ± 2.2 Ma for a mylonite from Mishigou (Xu et al., 2011), it is suggested the dextral shearing along the MTSZ occurred during the late Carboniferous to Early Triassic. Along the NTF, the westward continuation of the MTSZ, the age of dextral ductile shearing was constrained between ~270 and ~245 Ma by mica $^{40}$Ar/$^{39}$Ar dating on mylonitic slates and foliated granites in the Du-Ku and Bingdaban areas (Laurent-Charvet et al., 2003; de Jong et al., 2009; Yang et al., 2003).
In this study, pre- and syn-kinematic granitic dykes in the XSZ yielded zircon U–Pb ages of 311.9 ± 2.4 Ma (Figs. 13D) and 294.6 ± 3.7 Ma (Fig. 13H), approximately overlapping the oldest mica $^{40}$Ar/$^{39}$Ar ages from the MTSZ and NTF. Taking into account that (1) igneous origins of the dated concordant zircons and both pre- and syn-kinematic features of the granite dykes, and (2) the estimated deformation temperatures (450–550 °C) are lower than crystallization temperature of igneous zircons and closure temperature of zircon U–Pb system (>700 °C; Cherniak and Watson, 2003), but higher than the closure temperatures

Fig. 13. (A and E) Field occurrences and (B and F) photomicrographs of the sampled pre- and syn-tectonic granitic dykes in the Xiaergou shear zone. (C and G) CL images of the analyzed zircons from the granitic samples. (D and H) Concordia diagrams of U–Pb analytical results and mean age plots (insets).
of biotite and muscovite argon system (365 ± 35 to 425 ± 70 °C; Harrison et al., 1985, 2009; McDougall and Harrison, 1999; Sciborksi et al., 2015), we consider the new zircon U–Pb ages (312–295 Ma) of the pre-
and syn-kinematic granite dykes as the maximum age, i.e. the initiation
timing of the ductile dextral shearing along the XSZ, and previously
published mica $^{40}$Ar/$^{39}$Ar ages (290-242 Ma) for the MTMSZ and NTF as the
cooling ages of the ductile dextral shearing. It is worth noting that
dextral shearing all along the NTF-XSZ-NTSZ could have been active
diachronously along different segments. The timing of earlier sinistral
deformation along the WSZ cannot at this point be reliably constrained
with the available data.

The WSZ represents a localized high strain belt inside the Central
Tianshan (Fig. 2). Within the WSZ, our new biotite $^{40}$Ar/$^{39}$Ar ages of
301–304 Ma were obtained from meta-sedimentary rocks showing
sinistral kinematic fabrics (Fig. 10A–C). As the estimated deformation
temperatures (>450 °C) of the WSZ are higher than the closure tem-
perature of biotite argon system (335 ± 50 °C), we therefore regard the
newly acquired $^{40}$Ar/$^{39}$Ar ages as the cooling ages of the sinistral
deformation along the WSZ. Moreover, metamorphic zircons from a
mylonitic greywacke of the Silurian Ahebulake Group within the WSZ
yielded a mean age of ~312 Ma (He et al., 2018a). Thus, we infer that the
sinistral shear of the WSZ likely took place during 312–301 Ma. As to
the dextral deformation, its timing and regional context are however
difficult to be constrained.

Along the Baluntai Fault (BF), southern boundary of the Central
Tianshan, granitic mylonites from the Baluntai, Kumishiand eastward
vicinities were dated at 311-248 Ma by
Tianshan, granitic mylonites from the Baluntai, Kumishiand eastward
vicinities were dated at 311-248 Ma by
the Baluntai-Wuwamen-Kumishi section (Yin and Nie, 1996;
Laurent-Charvet et al., 2003; Wang et al., 2009; 2018a,b; Tang et al.,
2011; Xu et al., 2011; Cai et al., 2012; Wang et al., 2014; Zhong et al.,
2015; Li et al., 2020). Thus, the dextral ductile shearing along the BF
occurred during the latest Carboniferous to the end of Permian, and are
hence comparable to the age span of the dextral shearing along the
MTSZ-NTF. In addition, within and outside of the BF and in the MTSZ,
sinizral shearing and N–S contractional deformation were previously
suggested to occur at ~399-393 Ma and ~358-356 Ma, respectively
(Allen et al., 1993; Deng et al., 2006; Yang et al., 2007; Li et al., 2020),
prior to the dextral ductile shearing. Thus, the locally preserved sinistral
kinematics recognized in the WSZ could be probably related also to this
Devonian to early Carboniferous stage.

Farther westwards, the Nalati Fault (NF) also underwent
dextral ductile deformation, which was dated by (1) mica $^{40}$Ar/$^{39}$Ar plateau
ages of ~285-252 Ma in mylonites (Zhou et al., 2001; Wang et al.,
2007c; de Jong et al., 2009), (2) 277 ± 3 Ma zircon U–Pb age for a
syn-kinematic intrusion in the Kekesu area (Wang et al., 2009), and (3)
~307 Ma to ~255 Ma metamorphic zircon U–Pb ages for strongly
foliated early Paleozoic sandstones in the southern Nalati Range (Zhong
et al., 2019). Therefore, the dextral ductile shearing along the NF took
place from the late Carboniferous to end Permian, synchronous with the
BF.

6.3. Implications for late Paleozoic eastward tectonic wedging in SW
CAOB

Strike-slip faults developed in the entire CAOB and played an
important role in building this large accretionary and collisional
orogenic system (e.g., Sengör et al., 1993; Allen et al., 1993, 1995;
Choulet et al., 2011; Li et al., 2017, 2018). There are different hypoth-
eses concerning the formation mechanism and tectonic significance of
these orogen-scale strike-slip shear zones. Many strike-slip faults sub-
parallel to the orogens were considered to have formed during oblique
subduction, duplicating and juxtaposing different fragments of the same
arc, and shifting the magmatic front and overall geometry of orogens to
form the oroclinal architecture of the Kazakhstan, SW CAOB (Şengör et al., 1993; Şengör and Natal’in, 1996, 2014). Alternatively, a growing number of recent studies showed that the magmatic arcs in the SW CAOB were formed by multi-stage subduction of various oceanic basins within the Paleo-Asian Ocean domain (e.g., Windley et al., 2007; Xiao et al., 2003; 2004; Wilhem et al., 2012), and that the orogen-parallel strike-slip faults more likely resulted from intra-continental tectonism after the Carboniferous oblique collision between the Siberian and Tarim cratons (Allen et al., 1993, 1995; Yin and Nie, 1996; Shu et al., 1999; Buslov et al., 2004; Wang et al., 2009; Pirajno, 2010).

In this context, Laurent-Charvet et al. (2002, 2003) and Cai et al. (2012) emphasized the anticlockwise rotation of the Junggar block during the early Permian, which resulted in dextral shearing along the NTF - MTSZ and sinistral transpression of the Irtysk Shear Zone (ISZ) (e.g., Glorie et al., 2012). Li et al. (2015) suggested that such coeval dextral and sinistral shearing was controlled by the lateral migration of various units within the CAOB. Wang et al. (2008b) proposed that series of dextral strike-slip shearing were results of post-orogenic eastward extrusion of the CAOB between the Siberian and Tarim Cratons. Similar eastward extrusion tectonics was also documented by paleomagnetic studies (Wang et al., 2007a; Choulet et al., 2011; Zhu et al., 2018, 2019b) suggesting that relative motions among the Kazakhstan-Yili, Junggar, Tu-Ha, Tarim and Siberia blocks during the late Carboniferous to Permian were characterized by significant anticlockwise rotations and accommodated by lateral displacement along major strike-slip faults (Wang et al., 2007a). The coeval horizontal displacements up to hundreds of kilometers along the large-scale shear zones (sinistral Irtysk and dextral NF-BF) favor an eastward tectonic wedging of Junggar-Yili-Central Tianshan in between the Siberia and Tarim blocks (Wang et al., 2007a).

Reliable geological and paleomagnetic data indicate that the Tian- shan Orogen was formed by consumption of the Junggar-North Tian- shan Ocean at ~310 Ma (e.g., Han et al., 2010) and by welding of the Kazakhstan-Yili terrane with Tarim at ~320-310 Ma owing to the closure of the South Tianshan Ocean (e.g., Charvet et al., 2011; Wang et al., 2018b) and associated back-arc oceanic basins (Wang et al., 2011, 2018a,b). As mentioned above, although sinistral strike-slip kinematics recognized along the BF and MTSZ possibly resulted from the Devonian to early Carboniferous oblique subduction (Li et al., 2020), the more explicit and pervasive ductile strike-slip shearing around and within the Central Tianshan initiated almost simultaneously at 312-310 Ma, and lasted until the end of Permian, except along the WSZ. Despite uncertainties on the timing and genesis of the locally preserved (and possible earlier) dextral kinematics in the WSZ, we suggest that the latest Carboniferous to Permian (312-242 Ma) dextral strike-slip shearing along the MTSZ and BF, and the latest Carboniferous (312-301 Ma) sinistral strike-slip shearing along the WSZ occurred in post-orogenic intra-continental setting.

Combined with previous structural and paleomagnetic studies, our new results further confirm that the previously welded Yili - Central Tianshan - Junggar blocks simultaneously moved eastwards and wedged in between the Siberian and Tarim cratons (Fig. 15A). This eastward wedging was accommodated by synchronous dextral strike-slip shearing along the NF and BF, and then by the sinistral strike-slip shearing along the ISZ since ~284 Ma (Li et al., 2015). The dextral ductile strike-slip shearing along the NTF - MTSZ could be the result of differential eastward displacement rates of Junggar relative to the Yili - Central Tianshan blocks. Similarly, the sinistral WSZ probably resulted from relatively lower displacement velocity of the northern part of the Central Tianshan (north of the WSZ) with respect to its southern part (south of the WSZ), likely due to the backstop effect of the Tu-Ha terrane (Fig. 15B). Meanwhile, it is noteworthy that the movement along the ISZ during earliest Permian was not well constrained due to lack of reliable geochronological data (e.g., Hu et al., 2020). This interpretation could be tested with further kinematic and paleomagnetic studies to quantitatively assess the relative movement (rotation) rates between different tectonic units. Finally, the eastward tectonic wedging of the Kazakhstan-Yili, Central Tianshan and Junggar blocks was most likely triggered by the sub-E-W convergent orogenesis of the late Paleozoic Uralides related to the collision between the Baltic and Siberia blocks (e.g., Biske and Seltmann, 2010; Ivanov et al., 2013).

7. Conclusions

(1) The Xiaergou shear zone along the northern boundary of the Central Tianshan is the connecting segment between the North Tianshan Fault and Main Tianshan Shear Zone. Large-scale and sample-scale structural and kinematic analyses indicate principally ductile dextral strike-slip shearing with locally preserved sinistral kinematics. The timing of dextral ductile shearing is dated at ~312-295 Ma by U-Pb dating of zircons from pre- and syn-kinematic granitic dykes.

(2) The Wulasitai shear zone is generally a WNW-ESE-trending high-strain belt developing in the interior of the Central Tianshan. Geometric, structural and kinematic analyses suggest predominantly sinistral strike-slip shearing associated with top-to-the-SW thrusting at the NW-SE bending segment of the shear zone, and dextral kinematics is locally preserved. Biotite 40Ar/39Ar and metamorphic zircon U-Pb ages of meta-sedimentary rocks constrain the timing of the sinistral motion at ~312-301 Ma.
(3) New structural and geochronological data from the Xiaergou and Wulasitai shear zones together with the regional geological and paleomagnetic data suggest that the latest Carboniferous to Permian ductile strike-slip shear zones in the Tianshan Orogen, SW CAOB, formed in a post-orogenic intra-continental setting, and likely resulted from the eastward tectonic wedging of the Kazakhstan-Yili, Central Tianshan, Junggar blocks in between the Siberia and Tarim cratons.

Credit authorship contribution statement

Zhiyuan He: Conceptualization, Field Investigation, Methodology, Writing - original draft. Bo Wang: Conceptualization, Field Investigation, Methodology, Writing - review & editing. Supervision. Xinghua Ni: Field Investigation, Methodology, Writing - review & editing. Johan De Grave: Writing - review & editing, Co-supervision. Stéphane Scaillet: Methodology, Writing - review & editing. Yan Chen: Field Investigation, Writing - review & editing. Jiashuo Liu: Field Investigation, Writing - review & editing. Xin Zhu: Methodology, Writing - review & editing.

Declarations of competing interest

The authors declare that they are not aware of any competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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Appendix A. Supplementary data

Supplementary data to this article can be found online at https://doi.org/10.1016/j.jsg.2021.104279.

Appendix. Analytical methods

A.1. Zircon U–Pb dating

Zircon grains from the samples 44-B and 49-C were concentrated via heavy liquids and magnetic separation techniques, and then handpicked under a binocular microscope. Selected colorless zircons were mounted in epoxy resins and polished to approximately half-section before being estimated. Selected colorless zircons were handpicked under a binocular microscope. Zircon standard Mud Tank with an intercept age of 732 ± 5 Ma (Black and Gulson, 1979). Samples were analyzed in runs of 15 analyses including 5 analyses on standard zircons and 10 analyses on samples of unknown ages. All analyses were carried out using a beam with a 32 μm diameter and a repetition rate of 5 Hz.

U–Th–Pb isotopic ratios and ages were calculated from the raw signal data using the software package GLITTER. Correction for common Pb was performed via the EXCEL program ComPbCorr#3_15G (Anderson, 2002). U–Pb Concordia diagrams and probability density curves of ages were conducted using ISOPLOT 3.0 (Ludwig, 2003). Uncertainties are quoted at 1σ for individual analyses and at 2σ for mean ages.

A.2. Biotite 40Ar/39Ar dating

Single grains of biotite were carefully handpicked under a binocular microscope from 0.3 to 2.0 mm size fractions of crushed rock samples 01-B and 02-B. The biotite grains were then cleaned in distilled water and acetone before being weighed into Al foil envelopes for irradiation.

After neutron irradiation for 10 h in the CLICIT Cd-lined slot of the Corvallis Nuclear Reactor (Oregon State University, United States) along with the Fish Canyon Tuff sanidine standard (FCT 28.126 ± 0.019 Ma at 2σ) (Phillips et al., 2017), 40Ar/39Ar analyses were performed using a high-resolution Helix SFT mass spectrometer outfitted to a home-built CO2-laser based extraction system featuring ultra-low argon blanks. Detailed operating conditions can be found in Corti et al. (2019). Ages and isotopes ratios are plotted and tabulated at ± 1σ and were calculated according to Scaillet (2000). Weighted mean ages (WMA) are calculated by inverse-variance weighting of the steps pooled in the weighted mean. Total-Gas ages (TGA) are calculated by summing all fractions released and by quadratically propagating the attached errors. Pooled age errors include procedural errors, and decay constants and isotope abundance errors.

References

Alexeiev, D.V., Biske, Y.S., Wang, B., Djenchuraeva, A.V., Getman, O.F., Aristov, V.A., Kroner, A., Liu, H.S., Zhong, L.L., 2015. Tectono-stratigraphic framework and Paleozoic evolution of the Chinese South Tianshan. Geotectonics 49, 93–122.
Allen, C.R., 1965. Transcurrent faults in continental areas. Philos. Trans. Roy. Soc. A 258, 82–89.
Allen, M.B., Şengör, A.M.C., Natalin, B.A., 1995. Junggar, Turfan and Alalol basins as late Paleozoic to early Triassic extensional structures in a sinistral shear zone in the Altai orogenic collage, central-Asia. J. Geol. Soc. 152, 327–338.
Allen, M.B., Windley, B.F., Zhang, C., 1993. Paleozoic collisional tectonics and magmatism of the Chinese tien shan, central Asia. Tectonophysics 220, 89–115.
Anderson, T., 2002. Correction of common Pb in U-Pb analyses that do not report 206Pb/204Pb ratios. Chem. Geol. 192, 59–79.
Avouac, J.P., Tapponnier, P., Bai, P., You, H., Wang, G., 1993. Active thrusting and folding along the northern tien shan, and late Cenozoic rotation of the Tarim relative to the Junggar and Kazakhstan. J. Geophys. Res. 98, 6755-6804.
Beck, M.E., 1983. On the mechanism of tectonic transport in zones of oblique subduction. Tectonophysics 93, 1–11.
Bercovici, D., Ricard, Y., 2012. Mechanisms for the generation of plate tectonics by two-phase crustal damage and pinning. Phys. Earth Planet. In. 202–203, 27–55.
Berthé, D., Choukroune, P., Jegozou, P., 1979. Orthogneiss, mylonite and non-coaxial deformation of granites: the example of the Shear zones and mylonites South Armorican Shear Zone. J. Struct. Geol. 1, 51–42.
Biske, Y.S., Selimann, R., 2010. Paleozoic tien-shan as a transitional region between the urals and Turkestan oceans. Gondwana Res. 17 (2–3), 602–613.
Black, L.P., Gulson, B.L., 1978. The age of the Mud Tank carbonatite, Strangways range, northern Territory. Bureau of mineral Resources, J. Aust. Geol. Geophys. 3, 227-232.
Branquet, Y., Gumiaux, C., Sizaret, S., Barbanson, L., Wang, B., Cluzel, D., Li, G.R., 2002. A high-resolution Helix SFT mass spectrometer outfitted to a home-built CO2-laser based extraction system featuring ultra-low argon blanks. Detailed operating conditions can be found in Corti et al. (2019). Ages and isotopes ratios are plotted and tabulated at ± 1σ and were calculated according to Scaillet (2000). Weighted mean ages (WMA) are calculated by inverse-variance weighting of the steps pooled in the weighted mean. Total-Gas ages (TGA) are calculated by summing all fractions released and by quadratically propagating the attached errors. Pooled age errors include procedural errors, and decay constants and isotope abundance errors.

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Cao, S.Y., Neubauer, F., 2016. Deep crustal expressions of exhumed strike-slip fault systems: shear zone initiation on rheological boundaries. Earth Sci. Rev. 162, 155–176.
