Structural evolution of zonal metamorphic sequences in the southern Chinese Altai and relationships to Permian transpressional tectonics in the Central Asian Orogenic Belt

Pengfei Li ^{1*}, Min Sun ¹, Gideon Rosenbaum ², Yingde Jiang ³, Keda Cai ⁴

¹ Department of Earth Sciences, The University of Hong Kong, Pokfulam Road, Hong Kong,
China

² School of Earth Sciences, The University of Queensland, Brisbane 4072, Queensland,
Australia

³ State Key Laboratory of Isotope Geochemistry, Guangzhou Institute of Geochemistry,
Chinese Academy of Sciences, Guangzhou 510640, China

⁴ Xinjiang Research Center for Mineral Resources, Xinjiang Institute of Ecology and
Geography, Chinese Academy of Sciences, Urumqi 830011, China

*Corresponding author: Department of Earth Sciences, The University of Hong Kong,

Pokfulam Road, Hong Kong, China. Email: pengfei@hku.hk; pengfeili2013@gmail.com

Abstract: The Chinese Altai in the Central Asian Orogenic Belt is characterized by the occurrence of kyanite- and andalusite-type metamorphic zones. However, the tectonic setting associated with these metamorphic zones is still debated. Here we present structural observations from the southern Chinese Altai (Aletai area), where a relict kyanite zone occurs within an andalusite-type metamorphic zonal sequence of sillimanite, andalusite-sillimanite, andalusite-staurolite, staurolite-garnet and biotite. We document two major phases of folding in this area. The earlier structures (D_1) developed synchronously with kyanite growth and are represented by an axial planar fabric of tight folds. D_1 fabric is mostly obliterated by later deformation, but is inferred to be penetrative as indicated by a profound intersection lineation (L_{21}). The second generation of deformation (D_2) is associated with superimposed F_2 folds and a dominant axial planar foliation (S_2) with ~NW-SE orientation. Microstructural observations show that D_2 structures are associated with the andalusite-type metamorphic series, which is characterized by an early- D_2 occurrence of sillimanite, staurolite-garnet and biotite zonal sequence overprinted by the late- D_2 growth of andalusite. Combining with previous metamorphic data, we consider that these two folding events (D_1 and D_2) correspond with the development of kyanite- and andalusite-type metamorphic zones, respectively, which records the burial and exhumation history of metamorphic rocks possibly in response to Devonian-Carboniferous accretion and Permian transpressional tectonics. The latter was associated with oblique convergence between the Chinese Altai and the intra-oceanic arc

system of the East/West Junggar.

Key words: Chinese Altai; Central Asian Orogenic Belt; Kyanite; Andalusite; transpressional tectonics; Irtysh Shear Zone

1. Introduction

Transpressional deformation is characterized by a combination of a strike-slip component and a shortening component orthogonal to the deformation zone (Harland, 1971; Dewey et al., 1998), and is a common deformation style in regions affected by oblique convergence (Sanderson and Marchini, 1984; Dewey et al., 1998; Little et al., 2002; Sarkarinejad et al., 2008; Fernández et al., 2013). It typically involves general shear (Sanderson and Marchini, 1984; Jones and Tanner, 1995), with the kinematic vorticity number used to quantify the relative contribution of simple shear relative to pure shear (e.g. Holcombe and Little, 2001; Xypolias and Koukouvelas, 2001; Iacopini et al., 2008; Frassi et al., 2009). The two end members of pure shear and simple shear deformation have vorticity numbers of 0 and 1, between which a range of vorticity number from 0 to 1 characterize the general shear deformation (e.g. Fossen et al., 1994). Whether transpressional deformation is close to end members of simple shear (wrench-dominant) or pure shear (contraction-dominant) depends on the convergence vector. Simple shear deformation dominates when the convergence angle

is less than 20° , whereas pure shear is dominant when the convergence angle is greater than 20° (Tikoff and Teyssier, 1994).

Transpressional deformation is particularly common in accretionary orogens (e.g. Johnston, 2001), where oblique convergence and accretion involves partitioning of deformation into contractional and transcurrent components (Harland, 1971; Teyssier et al., 1995; Dewey et al., 1998; Lin et al., 1998; Iacopini et al., 2008). Deformation partitioning along transpressional zones in accretionary orogens could lead to exhumation of lower crustal rocks through vertical extrusion and/or large-scale folding (Carosi and Palmeri, 2002; Schulmann et al., 2003; Goscombe et al., 2005; Frassi et al., 2009; Rolland et al., 2009; Carosi et al., 2012; Fernández et al., 2013).

The Central Asian Orogenic Belt (CAOB) is the largest Phanerozoic accretionary orogen in the world. The formation of this orogenic system involved episodes of accretion of island arcs, ophiolites, accretionary complexes, seamounts and micro-continental blocks along the convergent plate margin prior to the late Paleozoic to Mesozoic amalgamation of Siberian, Baltica and Tarim-North China cratons (Şengör et al., 1993; Khain et al., 2002; Xiao et al., 2003; Windley et al., 2007). The prolonged accretion and the subsequent amalgamation of continental blocks involved episodes of transpressional tectonics in response to oblique

convergence (e.g. Qu and Zhang, 1994; Choulet et al., 2012; Li et al., 2015a). Metamorphic zonal sequences have been reported in the CAO (Zhuang, 1994a, b; Polyansky et al., 2011; Burenjargal et al., 2014; Broussolle et al., 2015), but their relationship with oblique convergence is still poorly constrained.

Here we focus on the Chinese Altai in the central CAO (Fig. 1), which is characterized by the juxtaposition of kyanite-type, and andalusite-type metamorphic zones (Zhuang, 1994b; Wei et al., 2007). The kyanite-type metamorphic zones include a zonal sequence of biotite, garnet, staurolite, kyanite and sillimanite, whereas the andalusite-type zonal sequence is commonly represented by biotite, garnet-staurolite, staurolite-andalusite, andalusite-sillimanite, sillimanite and garnet-cordierite zones (Zhuang, 1994b; Wei et al., 2007; Jiang et al., 2015). The kyanite-type metamorphic series is commonly overprinted by the andalusite-type metamorphic zones (Wei et al., 2007; Jiang et al., 2015). Previous authors suggested that earlier kyanite-type metamorphic zones were associated with burial in response to an accretion event in the late Paleozoic (He et al., 1990; Wang et al., 2014b; Jiang et al., 2015). However, recent geochronological data indicate that the andalusite-type metamorphic zones developed during two distinct episodes, in the Middle Devonian and Permian, respectively (Wang et al., 2009; Jiang et al., 2010; Li et al., 2014; Tong et al., 2014a; Wang et al., 2014b; Jiang et al., 2015). The Devonian episode has been attributed either to

rifting (He et al., 1990), or to doming of partially molten lower crust in response to contractional deformation (Jiang et al., 2015), whereas the Permian episode was attributed to post-orogenic extension following the amalgamation of the Chinese Altai with the intraoceanic arc system of the East Junggar and the West Junggar (Fig. 1a) (Wang et al., 2009; Wang et al., 2014b). The time range for the Permian andalusite-type metamorphic zones overlaps with the development of the regional Irtysh Shear Zone (Laurent-Charvet et al., 2003; Buslov et al., 2004; Briggs et al., 2007; Liu et al., 2013; Li et al., 2015b), which is characterized by both sinistral and contractional deformation (Qu and Zhang, 1991; Qu and Zhang, 1994; Li et al., 2015a). This casts doubt on the suggestion that the Early Permian development of the andalusite-type metamorphic zones was associated with extensional tectonism (e.g. Wang et al., 2014b).

In this study, we present structural and microstructural observations from the southern Chinese Altai (SW of the Aletai city, Fig. 1a), where a relict kyanite zone is found within a Permian andalusite-type metamorphic zonal sequence (Zhuang, 1994a; Wei et al., 2007; Zheng et al., 2007; Wang et al., 2014b). We reconstruct the pressure-temperature-deformation (P-T-D) history via linking structural elements with metamorphic mineral assemblages, as well as combining with a previous metamorphic study (Wei et al., 2007). These results are discussed in the context of the Permian tectonic evolution in the southern Chinese Altai.

2. Geological setting

The Chinese Altai is a segment of the Altai-Mongolian Terrane, which extends from Russia and east Kazakhstan in the west, through northern Xinjiang of China to western Mongolia in the east. It is characterized by the development of a Paleozoic arc system along the margin of the Siberian Craton (Fig. 1a) (Windley et al., 2002; Long et al., 2010; Safonova, 2013; Xiao and Santosh, 2014). In the late Paleozoic, the Altai-Mongolian Terrane was amalgamated with the intraoceanic arc system of the East Junggar and the West Junggar along the Irtysh Shear Zone (Fig. 1a) (Qu and Zhang, 1994; Laurent-Charvet et al., 2003; Briggs et al., 2007; Xiao et al., 2008).

The Chinese Altai is divided into four fault-bounded tectonic domains: Northern Altai Domain, Central Altai Domain, Qiongkuer Domain, and Southern Altai Domain (He et al., 1990; Windley et al., 2002; Cai et al., 2011a) (Fig. 1a). The Northern Altai Domain mainly includes Devonian to Carboniferous metavolcanic and metasedimentary rocks (Fig. 1a). It is separated by a normal fault from the Central Altai Domain, which is made of Cambrian to Ordovician meta-turbiditic/pyroclastic rocks (Habahe Group, Fig. 1a) that were interpreted to be an early Paleozoic accretionary wedge complex (e.g. Long et al., 2012). The Habahe Group is overlain by the Silurian metasedimentary rocks of the Kulumuti Group (Fig. 1a). In

the northwestern Chinese Altai, Late Ordovician to early Devonian metavolcanic rocks of the Dongxileke Formation and Devonian metasedimentary rocks of the Baihaba Formation locally occur above the Habahe Group (Fig. 1a) (Long et al., 2010; Wang et al., 2011). Farther south, rocks in the Qiongkuer Domain are characterized by Devonian metavolcanic rocks of the Kangbutiebao Formation and meta-sedimentary/volcanic sequence of the Altai Formation (Fig. 1a) (Windley et al., 2002; Chai et al., 2009). The Southern Altai Domain represents the southernmost tectonic domain in the Chinese Altai and is dominated by the Irtysh Complex, which is mainly exposed in the Fuyun area and is covered by Cenozoic sedimentary rocks farther west. Rocks of the Irtysh Complex are mainly represented by amphibolite-grade schists, para- and ortho-gneisses, amphibolites, and metacherts (Briggs et al., 2007; Xiao et al., 2009; Li et al., 2015a). These rocks were affected by sinistral deformation associated with the Irtysh Shear Zone that separated the East/West Junggar from the Chinese Altai (Fig. 1a).

A large volume of granitic rocks were emplaced in the Chinese Altai during two major phases of magmatism in the Devonian and the Permian, respectively (Wang et al., 2006; Yuan et al., 2007; Sun et al., 2008; Cai et al., 2011b; Liu et al., 2012; Tong et al., 2014b). The older granitoids are widely distributed throughout the Chinese Altai, and are normally represented by orthogneiss or granitic gneiss surrounded by zonal metamorphic sequence with

metamorphic grade decreasing away from the granitoids (Fig. 1b) (Zhuang, 1994b). In contrast, the Permian granitoids generally occur in the southern Chinese Altai and are predominantly undeformed (Fig. 1a). Mesozoic granitoids also occur in the Chinese Altai (Fig. 1a) and were interpreted to have been emplaced in an intraplate anorogenic setting (e.g. Wang et al., 2014a).

3. Structural observations

Structural mapping was conducted in the area to the southwest of Aletai city (Figs. 1 and 2, and Appendix A). Rocks in the study area belong to the Devonian Altai Formation of the Qiongkuer Domain (Cai et al., 2011a), and two lithostratigraphic units were recognized. The first unit is characterized by pelitic- semipsammitic schist with minor interlayered amphibolite, whereas the second unit is represented by quartzite and quartz-feldspar schist (Fig. 2). Gneissic two mica granites of the Taerlang Batholith (emplacement age of ~460-380 Ma, Wang et al., 2006; Yuan et al., 2007; Cai et al., 2011b) occur in the southwestern part of the study area, and is locally interlayered with the pelitic/semipsammitic schist (Figs. 2 and 4a). A series of metamorphic zones trending NW-SE was recognized in the study area, represented from SW to NE, by sillimanite, andalusite-sillimanite, andalusite-staurolite, staurolite-garnet and biotite zones. A relict kyanite zone locally occurs within the andalusite-staurolite zone (Fig. 2) (Wei et al., 2007). In the kyanite zone, quartz

kyanite/andalusite veins are common with bluish kyanite surrounded by brown-pink andalusite (Fig. 4b), indicating a later growth of andalusite (Wei et al., 2007).

3.1. Primary structures

Bedding (S_0) in the study area is locally recognized, and is generally defined by compositional layering intersecting the dominant cleavage (S_2) at variable angles (Fig. 4c, d). Bedding is steeply dipping and shows variable strike orientations that define a poorly constrained β -axis of $67\text{-}144^\circ$ (Figs. 2 and 3a).

3.2. First phase of folding (D_1)

S_1 foliation is recognized only in a low strain area (Fig. 2). It overprints the bedding (S_0 , Fig. 4d), and is transposed by S_2 foliation (Fig. 4d, e). S_1 is steeply dipping with variable orientations corresponding to F_2 folds with β -axis of $67\text{-}165^\circ$ (Fig. 3b). This β -axis is similar to the β -axis of $67\text{-}144^\circ$ calculated from the orientations of S_0 (Section 3.1), indicating that S_0 had been transposed towards parallelism with S_1 , and together with S_1 was folded by F_2 . Microstructurally, S_1 is normally defined by preferred alignments of biotite, muscovite and quartz/feldspar-rich layers. Within the relict kyanite zone (Fig. 2), S_1 is generally transposed to be parallel to S_2 . Locally, S_1 fabric is manifested by quartz inclusion trails within kyanite porphyroblasts, which are generally continuous with the external S_1 foliation and show

curved geometry close to the rim of the porphyroblast (Fig. 4f). Furthermore, it is recognized that the quartz inclusions are smaller in comparison to the quartz grains in the matrix (Fig. 4f), and this is likely indicating continuous growth of quartz grains along the external S_1 after the formation of the kyanite. These microstructural relationships suggest syn- D_1 growth of kyanite, thus defining an E4-type porphyroblast according to the classification by Passchier and Trouw (1996).

3.3. Second phase of folding (D_2)

S_2 foliation is the dominant fabric in the study area (Fig. 2). It is normally steeply dipping to the southwest (Fig. 3c), and parallel to the axial plane of F_2 upright folds. Outcrop-scale F_2 folds are common and affect earlier planar features, including pegmatite veins, S_1 foliation, and bedding (Figs. 4g, h and 5a). An F_1/F_2 fold interference pattern is recognized within the andalusite-staurolite and sillimanite zones in both outcrop and map scales (Figs. 5a, c and 6).

An L_{21} intersection lineation (Fig. 5b) is recognized in both metasedimentary rocks and gneissic granitoids, and predominantly plunges to the south (Fig. 3d). The intersection lineation between S_2 and S_0 (L_{20}) is locally recognized and is roughly parallel to L_{21} (Fig. 3d, e), indicating at least local parallelism of S_0 and S_1 before D_2 deformation.

Microstructurally, S_2 is defined by preferred alignment of micas and sillimanites (Fig. 5d-f), and is recognized as inclusion trails within staurolite and andalusite porphyroblasts. These inclusion trails are found in the garnet-staurolite, andalusite-staurolite and andalusite-sillimanite zones, as well as in the relict kyanite zone. Two types of staurolites were recognized within the garnet-staurolite and andalusite-staurolite (kyanite) zones. Most staurolite porphyroblasts contain an internal fabric that continues to the external S_2 foliation with a slight deflection (Fig. 5g). However, some staurolite porphyroblasts show an internal fabric of crenulated S_1 , which becomes tighter in the rim of the porphyroblast and in the matrix (Figs. 5h and 7a). These microstructures indicate syn- S_2 staurolite growth. Garnet porphyroblasts in the garnet-staurolite, andalusite-staurolite and andalusite-sillimanite zones contain inclusions of quartz and mica commonly without preferred orientations (Fig. 7b). This observation, together with evidence for a deflection of the external S_2 fabric around the porphyroblasts (Fig. 7b), indicate that garnet growth occurred prior to D_2 or at the early stage of D_2 deformation. Andalusite porphyroblasts within andalusite-staurolite and andalusite-sillimanite zones, as well as the relict kyanite zone, contain an internal fabric that is continuous with the external S_2 (Fig. 7c, e). This microstructural relationship, together with the observation that external S_2 wraps around andalusite porphyroblasts (Fig. 7e and Appendix B), indicate that the growth of andalusites occurred during D_2 deformation, which

is consistent with the spatial occurrence of andalusite along a zone parallel to D_2 structures as mapped by Zhuang (1994a), Wei et al. (2007) and this study (Fig. 2).

A later phase of folding was locally recognized. It deflects S_2 fabric, and is normally represented by gentle kink folds with a steep axial plane trending to the north (Fig. 7d).

4. Discussion

4.1. P-T-D reconstruction

Our field mapping and microstructural analysis show that D_1 is locally preserved in a low strain area, but this deformational phase likely affected the whole study area as indicated by the occurrence of pervasive L_{21} . The spatial distribution of D_1 metamorphic zones is unclear.

In the relict kyanite zone, D_1 foliation is commonly defined by preferred alignment of biotite and muscovite, and is characterized by the coeval growth of kyanite porphyroblasts (Fig. 8).

Pseudosection modelling from a garnet kyanite mica schist in the relict kyanite zone yielded a P-T range of 615-650°C and 6-10 kbar with a progressive P-T increase during the growth of garnet (Wei et al., 2007), which together with the syn- D_1 growth of kyanite, indicates a prograde metamorphism during D_1 . Relict D_1 mineral assemblages defining the S_1 fabric were also recognized in other metamorphic zones, but the metamorphic history of these S_1 mineral assemblages is not well constrained.

D₂ foliation is the dominant fabric throughout the study area, and is coeval with the development of the andalusite-type metamorphic zones (i.e., the regional metamorphic zonal sequence: biotite, garnet-staurolite, andalusite-staurolite, andalusite-sillimanite, and sillimanite zones, Fig. 2) as indicated by syn-D₂ growth of biotite, staurolite, andalusite and sillimanite (Section 3.3 and Fig. 8). This is supported by the pseudosection modeling of Wei et al. (2007), which showed that rocks in andalusite-sillimanite and sillimanite zones were subjected to a different temperature gradient (28-32 °C/km) in comparison to syn-D₁ mineral assemblages within the kyanite zone (21-26 °C/km). Given the different P-T field of syn-D₂ andalusite from sillimanite and staurolite, we interpret that D₂ may have involved retrograde metamorphism with an earlier occurrence of sillimanite, staurolite-garnet and biotite zones, which were overprinted by growth of andalusite during a later stage of D₂ to form andalusite-staurolite and andalusite-sillimanite zones. The implication of this interpretation is the fast exhumation of metamorphic rocks during D₂ from the stability field of staurolite to the andalusite field (Wei et al., 2007).

Overall, the available data show that the formation of kyanite- and andalusite-type metamorphic zones corresponds to two phases of folding (D₁ and D₂). The syn-D₁ prograde metamorphism, together with the syn-D₂ retrograde metamorphism, represent a cycle of

burial and exhumation (Fig. 9) (Wei et al., 2007).

4.2. Tectonic setting of kyanite- and andalusite-type metamorphic zones in the southern Chinese Altai

Our results show that the occurrence of ~NW-SE andalusite-type metamorphic zones in the Qiongkuer Domain (Fig. 2) was controlled by the second deformation event (D_2). This deformation and associated metamorphism occurred in the Permian, based on metamorphic zircons from a sillimanite schist that yielded an age at ~299 Ma (Fig. 2; Wang et al., 2014b), and metamorphic monazites from the andalusite-sillimanite zone that yielded a Th-U-total Pb isochron age of 262 ± 10 Ma (Zheng et al., 2007). This time range is consistent with 295-277 Ma metamorphic zircon ages and ~270 Ma $^{40}\text{Ar}/^{39}\text{Ar}$ amphibole age from the garnet-cordierite zone to the south of the study area (Fig. 1b) (Wang et al., 2009; Tong et al., 2014a; Li et al., 2015b). The garnet-cordierite zone, representing a higher grade metamorphic zone, was interpreted to be part of andalusite-type metamorphic zonal sequence in the southern Chinese Altai (Figs. 1b and 9) (Wei et al., 2007). Based on all these considerations, we conclude that the syn- D_2 andalusite-type metamorphic zones were likely developed within a time range of ~299-262 Ma, and were subjected to a regional uplift event at ~270 Ma as constrained by the cooling of the garnet-cordierite zone through the amphibole closure temperature.

The timing of formation of the syn-D₂ andalusite-type metamorphic zones, at ~299-262 Ma, overlaps with the development of the sinistral Irtysh Shear Zone to the south of the study area (Fig. 1), which has been constrained to be ~290-252 Ma by ⁴⁰Ar/³⁹Ar thermochronological data and granitic dykes that cut the shear zone (Laurent-Charvet et al., 2003; Buslov et al., 2004; Briggs et al., 2007; Zhang et al., 2012). This shear zone is a major boundary between the peri-Siberian orogenic system (i.e. Chinese Altai) and the Kazakhstan-South Mongolia orogenic system (i.e. West Junggar and East Junggar, Fig. 1a) (Şengör et al., 1993; Şengör and Natal'in, 1996), and is characterized, in the Chinese segment, by sinistral-reverse shearing and ~NE-SW shortening (Qu and Zhang, 1991; Zhang and Zheng, 1993; Qu and Zhang, 1994; Li et al., 2015a). The Irtysh Shear Zone to the south of the map area is concealed under younger sedimentary rocks, but is well exposed in the Fuyun area (Fig. 1a). A structural analysis in this area has shown a series of ~NW-SE kilometer-scale upright folds, which are bounded by ~NW-SE sinistral mylonite zones with stretching lineations that shallowly plunge to the southeast (Fig. 10a) (Li et al., 2015a). The combined folding and sinistral-reverse shearing structures have been interpreted to result from a phase of transpressional deformation in response to oblique convergence between the Chinese Altai and the East/West Junggar (Li et al., 2015a). The oblique convergence commonly results in partitioning of strain between transcurrent and contractional components across deformation

zones (e.g. Jones and Tanner, 1995; Dewey et al., 1998; Díaz-Azpiroz et al., 2014). In the southern Chinese Altai, structural styles are characterized by discrete mylonite zones and in-between folded zones (Fig. 10). The parallelism between mylonitic fabric and fold axial plane suggests that transpressional strain has been partitioned into a simple shear component in the mylonite zones and a pure shear component in the fold zones (Tikoff and Teyssier, 1994; Dewey et al., 1998; Schulmann et al., 2003). Such high degree of strike-slip partitioning is similar to the San Andreas fault system in central California, which is characterized by a low convergence angle ($\sim 5^\circ$) and 95-100% strike-slip partitioning along discrete faults (Tikoff and Teyssier, 1994; Teyssier et al., 1995; Teyssier and Tikoff, 1998; Argus and Gordon, 2001). Accordingly, we interpret that the convergence angle during the development of the Irtysh Shear Zone was possibly less than 20° , which corresponds to a convergence orientation from $\sim$ WNW-ESE to $\sim$ NW-SE. Based on strain modelling by Tikoff and Teyssier (1994), such a low convergence angle ($<20^\circ$) could efficiently partitioned the strike-slip component into discrete slip planes.

The presence of $\sim$ NW-SE upright folds in the Qiongkuer Domain and the Irtysh Shear Zone (Figs. 1a and 10) strongly suggests that both domains were subjected to the same $\sim$ NE-SW shortening event related to sinistral transpression (Qu and Zhang, 1991; Qu and Zhang, 1994; Li et al., 2015a). This interpretation is supported by $^{40}\text{Ar}/^{39}\text{Ar}$ step-heating ages of

amphiboles, which indicate that rapid uplift and/or cooling occurred in the Permian both in the Irtysh Shear Zone and in the Qiongkuer Domain (Li et al., 2015b). In our study area, the transpressional deformation is represented by the development of ~NW-SE upright folds and associated axial planar fabric (D₂). During this deformation event, the metamorphic pressure decreased to the stability field of andalusite in all metamorphic zones (Fig. 9). We suggest that this decrease in metamorphic pressure resulted from heterogeneous exhumation during D₂ that eventually led to the juxtaposition of metamorphic rocks from different crustal levels. On a larger scale, the study area is located in the southern limb of a synclinorium structure (Fig. 1a) (Qu, 1991). This synclinorium structure is characterized by an increase of metamorphic grade away from the core of the synclinorium, thus forming zonal metamorphic sequences in the southern limb (our map area) and the northern limb of the structure (Fig. 1b). In both limbs, the timing of metamorphism is constrained to the Permian, based on monazite Th-U-total Pb isochron ages (Zheng et al., 2005; Zheng et al., 2007). The axial plane of the synclinorium, which is striking ~NW-SE and is steeply dipping (Qu, 1991), is compatible with D₂ structures in our study area. Therefore, we consider that the development of S₂ axial planar fabric and the formation of the andalusite-type metamorphic zones in the study area (Fig. 2) were linked with large-scale folding associated with the development of the transpressional Irtysh Shear Zone during the oblique convergence between the Chinese Altai and the East/West Junggar (Qu and Zhang, 1994). The transpressional deformation was

partitioned into wrench- and contraction-dominant domains, and generated large-scale synclinorium in Qiongkuer Domain, which allows progressive increase of metamorphic grade away from the core of the synclinorium and could have been responsible for the juxtaposition of metamorphic rocks from distinct structural levels (Fig. 10b). Similar exhumation processes along transpressional zones have been reported in other ancient orogenic belts (e.g. the Variscan orogenic belt, Carosi and Palmeri, 2002; Carosi et al., 2012) and also in modern wrench tectonic environments (e.g. the Alpine Fault, Little et al., 2005). Furthermore, transpression-related exhumation is commonly accompanied by a rapid uplift and erosion that facilitates upward flow of material (e.g. Little et al., 2005; Giorgis et al., 2009). It is thus likely that the ~270 Ma regional uplift event in the southern Chinese Altai (Li et al., 2015b) was linked to the exhumation in response to D₂ transpressional deformation.

The origin of high thermal gradient during D₂ is enigmatic. Some authors suggested that it was associated with the development of a Permian mantle plume (Tong et al., 2014a; Zhang et al., 2014; Yang et al., 2015). Alternatively, Wang et al. (2009; 2014b) attributed the Permian high thermal gradient in the southern Chinese Altai to post/syn-orogenic extension. We note, however, that such a geodynamic setting is likely to result in a flat-lying syn-metamorphic fabric (e.g. Argles et al., 1999), which is not observed in the map area.

The geodynamic setting of the syn-D₁ kyanite-type metamorphic zones remains unresolved, and the timing of deformation is still poorly constrained. The deformation fabric (S₁) associated with the development of the kyanite zone in the study area affects middle Devonian rocks of the Altai Formation, placing a post-middle Devonian time constraint on the formation of the kyanite-type metamorphic zones. We speculate that a Middle Devonian to Carboniferous crustal-thickening event (D₁) was responsible for burial and the formation of the kyanite-type metamorphic zones.

Kyanite- and andalusite-type metamorphic zones are recognized also in the central Chinese Altai and in western Mongolia, where the formation of the kyanite-type metamorphic zones was attributed to a middle to late Paleozoic burial event (Burenjargal et al., 2014; Jiang et al., 2015; Nakano et al., 2015). In contrast, the andalusite-type zonal sequence was proposed to develop simultaneously with the intrusion of Devonian to Carboniferous granitoids, and was interpreted to result from vertical extrusion of molten rocks in response to a contractional doming event in the Devonian to Carboniferous (Broussolle et al., 2015; Jiang et al., 2015). This mechanism is distinct from the Permian development of the andalusite-type metamorphic zones in the southern Chinese Altai, which was fundamentally controlled by regional scale transpression. In the southwestern Chinese Altai (west of the Chonghuer area, Fig. 1), juxtaposition of metamorphic rocks from different structural levels was recognized

and attributed to superimposed folding with later ~NW-SE folds possibly related to the development of the Irtysh Shear Zone (Zhang et al., 2015), consistently with the observations from our map area.

5. Conclusions

Our results indicate that deformation in the southern Chinese Altai involved two episodes of folding (D_1 and D_2), which are recorded in two types of metamorphic zones (kyanite- and andalusite-types). D_1 is locally recognized with steeply dipping fabric and associated tight folds, and was coeval with the formation of the kyanite-type metamorphic zones. The foliation associated with D_2 is the dominant fabric in the study area and is steeply dipping to SW. Microstructural observations show that D_2 was simultaneous with the development of andalusite-type metamorphic series, which is characterized by the earlier occurrence of sillimanite, staurolite-garnet and biotite zonal sequence overprinted by the growth of andalusite. Combining with results from previous metamorphic studies, we interpret that D_1 and D_2 were responsible for the burial and exhumation of metamorphic rocks, respectively, corresponding to the formation of kyanite- and andalusite-type metamorphic zones. The timing of D_2 deformation is constrained to the Permian, during which D_2 -related exhumation processes were most likely associated with transpressional deformation along the Irtysh Shear Zone.

Acknowledgements: This study was financially supported by the Major Basic Research Project of the Ministry of Science and Technology of China (Grant: 2014CB448000 and 2014CB440801), Hong Kong Research Grant Council (HKU705311P and HKU704712P), National Science Foundation of China (41273048), HKU CRCG grants and a HKU small grant (201309176226). The manuscript benefited from constructive comments by Rodolfo Carosi, an anonymous reviewer and Guest Editor Manuel Díaz-Azpiroz. We thank Rod Holcombe for his comments and discussion about the structural interpretation, Zihe Bao and Yang Yu for their assistance in the field, and Karel Schulmann for the discussion on Altai geology. Chunjing Wei and Wei Wang are acknowledged for providing the location information of their dated samples (Fig. 2). Yingde Jiang acknowledges the 100 Talents Program of the Chinese Academy of Sciences. This work is a contribution of the Joint Laboratory of Chemical Geodynamics between HKU and CAS (Guangzhou Institute of Geochemistry), IGCP 592 and PROCORE France/Hong Kong Joint Research Scheme.

References:

- Amante, C., Eakins, B.W., 2009. ETOPO1 1 arc-minute global relief model: procedures, data sources and analysis. NOAA Technical Memorandum NESDIS NGDC-24.
- Argles, T., Platt, J., Waters, D., 1999. Attenuation and excision of a crustal section during extensional exhumation: the Carratraca Massif, Betic Cordillera, southern Spain. *J. Geol. Soc.* 156, 149-162.
- Argus, D.F., Gordon, R.G., 2001. Present tectonic motion across the Coast Ranges and San Andreas fault system in central California. *Geol. Soc. Am. Bull.* 113, 1580-1592.
- Briggs, S.M., Yin, A., Manning, C.E., Chen, Z.-L., Wang, X.-F., Grove, M., 2007. Late Paleozoic tectonic history of the Ertix Fault in the Chinese Altai and its implications for the development of the Central Asian Orogenic System. *Geol. Soc. Am. Bull.* 119, 944-960.
- Briggs, S.M., Yin, A., Manning, C.E., Chen, Z.-L., Wang, X.-F., 2009. Tectonic development of the southern Chinese Altai Range as determined by structural geology, thermobarometry, $^{40}\text{Ar}/^{39}\text{Ar}$ thermochronology, and Th/Pb ion-microprobe monazite geochronology. *Geol. Soc. Am. Bull.* 121, 1381-1393.
- Broussolle, A., Štípská, P., Lehmann, J., Schulmann, K., Hacker, B., Holder, R., Kylander-Clark, A., Hanzl, P., Racek, M., Hasalová, P., 2015. P-T-t-D record of crustal-scale horizontal flow and magma assisted doming in the SW Mongolian Altai. *J.*

Metamorph. Geol. 33, 359-383.

Burenjargal, U., Okamoto, A., Kuwatani, T., Sakata, S., Hirata, T., Tsuchiya, N., 2014.

Thermal evolution of the Tseel terrane, SW Mongolia and its relation to granitoid intrusions in the Central Asian Orogenic Belt. *J. Metamorph. Geol.* 32, 765-790.

Buslov, M.M., Watanabe, T., Fujiwara, Y., Iwata, K., Smirnova, L.V., Safonova, I.Y.,

Semakov, N.N., Kiryanova, A.P., 2004. Late Paleozoic faults of the Altai region, Central Asia: tectonic pattern and model of formation. *J. Asian Earth Sci.* 23, 655-671.

Cai, K., Sun, M., Yuan, C., Long, X., Xiao, W., 2011a. Geological framework and Paleozoic

tectonic history of the Chinese Altai, NW China: a review. *Russian Geology and Geophysics* 52, 1619-1633.

Cai, K., Sun, M., Yuan, C., Zhao, G., Xiao, W., Long, X., Wu, F., 2011b. Prolonged

magmatism, juvenile nature and tectonic evolution of the Chinese Altai, NW China: Evidence from zircon U–Pb and Hf isotopic study of Paleozoic granitoids. *J. Asian Earth Sci.* 42, 949-968.

Carosi, R., Palmeri, R., 2002. Orogen-parallel tectonic transport in the Variscan belt of

northeastern Sardinia (Italy): implications for the exhumation of medium-pressure metamorphic rocks. *Geol. Mag.* 139, 497-511.

Carosi, R., Montomoli, C., Tiepolo, M., Frassi, C., 2012. Geochronological constraints on

post-collisional shear zones in the Variscides of Sardinia (Italy). *Terra Nova* 24,

42-51.

Chai, F., Mao, J., Dong, L., Yang, F., Liu, F., Geng, X., Zhang, Z., 2009. Geochronology of metarhyolites from the Kangbutiebao Formation in the Kelang basin, Altay Mountains, Xinjiang: Implications for the tectonic evolution and metallogeny. *Gondwana Res.* 16, 189-200.

Choulet, F., Faure, M., Cluzel, D., Chen, Y., Lin, W., Wang, B., 2012. From oblique accretion to transpression in the evolution of the Altaid collage: New insights from West Junggar, northwestern China. *Gondwana Res.* 21, 530-547.

Díaz-Azpiroz, M., Barcos, L., Balanyá, J.C., Fernández, C., Expósito, I., Czeck, D.M., 2014. Applying a general triclinic transpression model to highly partitioned brittle-ductile shear zones: A case study from the Torcal de Antequera massif, external Betics, southern Spain. *J. Struct. Geol.* 68, Part B, 316-336.

Dewey, J.F., Holdsworth, R.E., Strachan, R.A., 1998. Transpression and transtension zones. *Geol. Soc. Spec. Publ.* 135, 1-14.

Fernández, C., Czeck, D.M., Díaz-Azpiroz, M., 2013. Testing the model of oblique transpression with oblique extrusion in two natural cases: Steps and consequences. *J. Struct. Geol.* 54, 85-102.

Fossen, H., Tikoff, B., Teyssier, C., 1994. Strain modeling of transpressional and transtensional deformation. *Norsk Geologisk Tidsskrift* 74, 134-145.

- Frassi, C., Carosi, R., Montomoli, C., Law, R.D., 2009. Kinematics and vorticity of flow associated with post-collisional oblique transpression in the Variscan Inner Zone of northern Sardinia (Italy). *J. Struct. Geol.* 31, 1458-1471.
- Giorgis, S., Tong, J., Sirianni, R., 2009. Constraining neotectonic orogenesis using an isostatically compensated model of transpression. *J. Struct. Geol.* 31, 1074-1083.
- Goscombe, B., Gray, D., Hand, M., 2005. Extrusional Tectonics in the Core of a Transpressional Orogen; the Kaoko Belt, Namibia. *J. Petrol.* 46, 1203-1241.
- Harland, W., 1971. Tectonic transpression in Caledonian Spitsbergen. *Geol. Mag.* 108, 27-41.
- He, G., Han, B., Yue, Y., Wang, J., 1990. Tectonic division and crustal evolution of Altay orogenic belt in China. *Geoscience of Xinjiang* 2, 9-20 (In Chinese with the English abstract).
- Holcombe, R.J., Little, T.A., 2001. A sensitive vorticity gauge using rotated porphyroblasts, and its application to rocks adjacent to the Alpine Fault, New Zealand. *J. Struct. Geol.* 23, 979-989.
- Iacopini, D., Carosi, R., Montomoli, C., Passchier, C., 2008. Strain analysis and vorticity of flow in the Northern Sardinian Variscan Belt: Recognition of a partitioned oblique deformation event. *Tectonophysics* 446, 77-96.
- Jiang, Y., Sun, M., Zhao, G., Yuan, C., Xiao, W., Xia, X., Long, X., Wu, F., 2010. The ~ 390 Ma high-T metamorphic event in the Chinese Altai: A consequence of

- ridge-subduction? *American Journal of Science* 310, 1421-1452.
- Jiang, Y., Štípská, P., Sun, M., Schulmann, K., Zhang, J., Wu, Q.H., Long, X., Yuan, C., Racek, M., Zhao, G., Xiao, W., 2015. Juxtaposition of Barrovian and migmatite domains in the Chinese Altai: a result of crustal thickening followed by doming of partially molten lower crust. *J. Metamorph. Geol.* 33, 45-70.
- Johnston, S.T., 2001. The great Alaskan terrane wreck: Reconciliation of paleomagnetic and geological data in the northern Cordillera. *Earth Planet. Sci. Lett.* 193, 259-272.
- Jones, R., Tanner, P.W., 1995. Strain partitioning in transpression zones. *J. Struct. Geol.* 17, 793-802.
- Khain, E., Bibikova, E., Kröner, A., Zhuravlev, D., Sklyarov, E., Fedotova, A., Kravchenko-Berezhnoy, I., 2002. The most ancient ophiolite of the Central Asian fold belt: U–Pb and Pb–Pb zircon ages for the Dunzhugur Complex, Eastern Sayan, Siberia, and geodynamic implications. *Earth Planet. Sci. Lett.* 199, 311-325.
- Laurent-Charvet, S., Charvet, J., Monié, P., Shu, L., 2003. Late Paleozoic strike-slip shear zones in eastern Central Asia (NW China): New structural and geochronological data. *Tectonics* 22, doi:10.1029/2001TC901047.
- Li, P., Sun, M., Rosenbaum, G., Cai, K., Yu, Y., 2015a. Structural evolution of the Irtysh Shear Zone (northwestern China) and implications for the amalgamation of arc systems in the Central Asian Orogenic Belt. *J. Struct. Geol.* 80, 142-156.

- Li, P., Yuan, C., Sun, M., Long, X., Cai, K., 2015b. Thermochronological constraints on the late Paleozoic tectonic evolution of the southern Chinese Altai. *J. Asian Earth Sci.*, in press.
- Li, Z., Yang, X., Li, Y., Santosh, M., Chen, H., Xiao, W., 2014. Late Paleozoic tectono–metamorphic evolution of the Altai segment of the Central Asian Orogenic Belt: Constraints from metamorphic P–T pseudosection and zircon U–Pb dating of ultra-high-temperature granulite. *Lithos* 204, 83-96.
- Lin, S., Jiang, D., Williams, P.F., 1998. Transpression (or transtension) zones of triclinic symmetry: natural example and theoretical modelling. *Geol. Soc. Spec. Publ.* 135, 41-57.
- Little, T.A., Holcombe, R.J., Ilg, B.R., 2002. Kinematics of oblique collision and ramping inferred from microstructures and strain in middle crustal rocks, central Southern Alps, New Zealand. *J. Struct. Geol.* 24, 219-239.
- Little, T.A., Cox, S., Vry, J.K., Batt, G., 2005. Variations in exhumation level and uplift rate along the oblique-slip Alpine fault, central Southern Alps, New Zealand. *Geol. Soc. Am. Bull.* 117, 707-723.
- Liu, F., Wang, Z., Lin, W., Chen, K., Jiang, L., Wang, Q., 2013. Structure deformation and tectonic significance of Erqis fault zone in the southern margin of Chinese Altay. *Acta Petrologica Sinica* 29, 1811-1824.

- Liu, W., Liu, X., Xiao, W., 2012. Massive granitoid production without massive continental-crust growth in the Chinese Altay: Insight into the source rock of granitoids using integrated zircon U-Pb age, Hf-Nd-Sr isotopes and geochemistry. *American Journal of Science* 312, 629-684.
- Long, X., Yuan, C., Sun, M., Xiao, W., Zhao, G., Wang, Y., Cai, K., Xia, X., Xie, L., 2010. Detrital zircon ages and Hf isotopes of the early Paleozoic flysch sequence in the Chinese Altai, NW China: new constraints on depositional age, provenance and tectonic evolution. *Tectonophysics* 480, 213-231.
- Long, X., Yuan, C., Sun, M., Xiao, W., Wang, Y., Cai, K., Jiang, Y., 2012. Geochemistry and Nd isotopic composition of the Early Paleozoic flysch sequence in the Chinese Altai, Central Asia: Evidence for a northward-derived mafic source and insight into Nd model ages in accretionary orogen. *Gondwana Res.* 22, 554-566.
- Nakano, N., Osanai, Y., Owada, M., Satish-Kumar, M., Adachi, T., Jargalan, S., Yoshimoto, A., Syeryekhan, K., Boldbaatar, C.H., 2015. Multiple growth of garnet, sillimanite/kyanite and monazite during amphibolite-facies metamorphism: implications for the P-T and tectonic evolution of the western Altai Range, Mongolia. *J. Metamorph. Geol.* 33, 937-958.
- Passchier, C.W., Trouw, R.A., 1996. *Microtectonics*. Springer, Berlin, page 160.
- Polyansky, O., Sukhorukov, V., Travin, A., Alekhin, I., Yudin, D., 2011. Tectonic

- interpretation of the thermochronological data and PT-conditions of rock metamorphism in the Bodonchin zonal complex (Mongolian Altay). *Russian Geology and Geophysics* 52, 991-1006.
- Qu, G., 1991. Deformational structure of tectonic division of the Altaides, Xinjiang. *Geoscience of Xinjiang* 3, 132-144 (in Chinese with the English abstract).
- Qu, G., Zhang, J., 1991. Irtys structural zone. *Geoscience of Xinjiang* 3, 115-131 (in Chinese with the English abstract).
- Qu, G., Zhang, J., 1994. Oblique thrust systems in the Altay orogen, China. *Journal of Southeast Asian Earth Sciences* 9, 277-287.
- Rolland, Y., Corsini, M., Demoux, A., 2009. Metamorphic and structural evolution of the Maures-Tanneron massif (SE Variscan chain): evidence of doming along a transpressional margin. *Bulletin de la Société Géologique de France* 180, 217-230.
- Safonova, I., 2013. The Russian-Kazakh Altai orogen: An overview and main debatable issues. *Geoscience Frontiers*, 537-552.
- Sanderson, D.J., Marchini, W., 1984. Transpression. *J. Struct. Geol.* 6, 449-458.
- Sarkarinejad, K., Faghih, A., Grasemann, B., 2008. Transpressional deformations within the Sanandaj–Sirjan metamorphic belt (Zagros Mountains, Iran). *J. Struct. Geol.* 30, 818-826.
- Schulmann, K., Thompson, A.B., Lexa, O., Ježek, J., 2003. Strain distribution and fabric

- development modeled in active and ancient transpressive zones. *J. Geophys. Res.* 108, 2023, doi: 2010.1029/2001JB000632.
- Şengör, A.M.C., Natal'in, B.A., Burtman, V.S., 1993. Evolution of the Altaid tectonic collage and Palaeozoic crustal growth in Eurasia. *Nature* 364, 299-307.
- Şengör, A.M.C., Natal'in, B.A., 1996. Turkic-type orogeny and its role in the making of the continental crust. *Annual Review of Earth and Planetary Sciences* 24, 263-337.
- Sun, M., Yuan, C., Xiao, W., Long, X., Xia, X., Zhao, G., Lin, S., Wu, F., Kröner, A., 2008. Zircon U–Pb and Hf isotopic study of gneissic rocks from the Chinese Altai: progressive accretionary history in the early to middle Palaeozoic. *Chem. Geol.* 247, 352-383.
- Teyssier, C., Tikoff, B., Markley, M., 1995. Oblique plate motion and continental tectonics. *Geology* 23, 447-450.
- Teyssier, C., Tikoff, B., 1998. Strike-slip partitioned transpression of the San Andreas fault system: a lithospheric-scale approach. *Geol. Soc. Spec. Publ.* 135, 143-158.
- Tikoff, B., Teyssier, C., 1994. Strain modeling of displacement-field partitioning in transpressional orogens. *J. Struct. Geol.* 16, 1575-1588.
- Tong, L., Xu, Y.G., Cawood, P.A., Zhou, X., Chen, Y., Liu, Z., 2014a. Anticlockwise P-T evolution at ~280 Ma recorded from ultrahigh-temperature metapelitic granulite in the Chinese Altai orogenic belt, a possible link with the Tarim mantle plume? *J. Asian*

Earth Sci. 94, 1-11.

Tong, Y., Wang, T., Jahn, B.M., Sun, M., Hong, D.W., Gao, J.F., 2014b. Post-accretionary permian granitoids in the Chinese Altai orogen: Geochronology, petrogenesis and tectonic implications. *American Journal of Science* 314, 80-109.

Wang, T., Hong, D.W., Jahn, B.M., Tong, Y., Wang, Y.B., Han, B.F., Wang, X.X., 2006. Timing, petrogenesis, and setting of Paleozoic synorogenic intrusions from the Altai Mountains, Northwest China: implications for the tectonic evolution of an accretionary orogen. *The Journal of Geology* 114, 735-751.

Wang, T., Jahn, B.-m., Kovach, V.P., Tong, Y., Wilde, S.A., Hong, D.-w., Li, S., Salnikova, E.B., 2014a. Mesozoic intraplate granitic magmatism in the Altai accretionary orogen, NW China: Implications for the orogenic architecture and crustal growth. *American Journal of Science* 314, 1-42.

Wang, W., Wei, C., Wang, T., Lou, Y., Chu, H., 2009. Confirmation of pelitic granulite in the Altai orogen and its geological significance. *Chin Sci Bull.* 54, 2543-2548.

Wang, W., Wei, C., Zhang, Y., Chu, H., Zhao, Y., Liu, X., 2014b. Age and origin of sillimanite schist from the Chinese Altai metamorphic belt: implications for late Palaeozoic tectonic evolution of the Central Asian Orogenic Belt. *Int. Geol. Rev.* 56, 224-236.

Wang, Y., Yuan, C., Long, X., Sun, M., Xiao, W., Zhao, G., Cai, K., Jiang, Y., 2011. Geochemistry, zircon U–Pb ages and Hf isotopes of the Paleozoic volcanic rocks in

- the northwestern Chinese Altai: Petrogenesis and tectonic implications. *J. Asian Earth Sci.* 42, 969-985.
- Wei, C., Clarke, G., Tian, W., Qiu, L., 2007. Transition of metamorphic series from the Kyanite- to andalusite-types in the Altai orogen, Xinjiang, China: Evidence from petrography and calculated KMnFMASH and KFMASH phase relations. *Lithos* 96, 353-374.
- Windley, B.F., Kröner, A., Guo, J., Qu, G., Li, Y., Zhang, C., 2002. Neoproterozoic to Paleozoic Geology of the Altai Orogen, NW China: New Zircon Age Data and Tectonic Evolution. *The Journal of Geology* 110, 719-737.
- Windley, B.F., Alexeiev, D., Xiao, W., Kroner, A., Badarch, G., 2007. Tectonic models for accretion of the Central Asian Orogenic Belt. *J. Geol. Soc.* 164, 31-47.
- Xiao, W., Windley, B.F., Hao, J., Zhai, M., 2003. Accretion leading to collision and the Permian Solonker suture, Inner Mongolia, China: Termination of the central Asian orogenic belt. *Tectonics* 22, 1069.
- Xiao, W., Han, C., Yuan, C., Sun, M., Lin, S., Chen, H., Li, Z., Li, J., Sun, S., 2008. Middle Cambrian to Permian subduction-related accretionary orogenesis of Northern Xinjiang, NW China: implications for the tectonic evolution of central Asia. *J. Asian Earth Sci.* 32, 102-117.
- Xiao, W., Windley, B., Yuan, C., Sun, M., Han, C., Lin, S., Chen, H., Yan, Q., Liu, D., Qin, K.,

- Li, J., Sun, S., 2009. Paleozoic multiple subduction-accretion processes of the southern Altaids. *American Journal of Science* 309, 221-270.
- Xiao, W., Santosh, M., 2014. The western Central Asian Orogenic Belt: A window to accretionary orogenesis and continental growth. *Gondwana Res.* 25, 1429–1444.
- Xypolias, P., Koukouvelas, I., 2001. Kinematic vorticity and strain rate patterns associated with ductile extrusion in the Chelmos Shear Zone (External Hellenides, Greece). *Tectonophysics* 338, 59-77.
- Yang, T., Li, J., Liang, M., Wang, Y., 2015. Early Permian mantle–crust interaction in the south-central Altaids: High-temperature metamorphism, crustal partial melting, and mantle-derived magmatism. *Gondwana Res.* 28, 371-390.
- Yuan, C., Sun, M., Xiao, W., Li, X., Chen, H., Lin, S., Xia, X., Long, X., 2007. Accretionary orogenesis of the Chinese Altai: insights from Paleozoic granitoids. *Chem. Geol.* 242, 22-39.
- Zhang, C.L., Santosh, M., Zou, H.B., Xu, Y.G., Zhou, G., Dong, Y.G., Ding, R.F., Wang, H.Y., 2012. Revisiting the “Irtish tectonic belt”: Implications for the Paleozoic tectonic evolution of the Altai orogen. *J. Asian Earth Sci.* 52, 117-133.
- Zhang, C.L., Zou, H.B., Yao, C.Y., Dong, Y.G., 2014. Origin of Permian gabbroic intrusions in the southern margin of the Altai Orogenic belt: A possible link to the Permian Tarim mantle plume? *Lithos* 204, 112–124.

Zhang, J., Zheng, Y., 1993. A Thrust-wrench Model for the Altay Orogenic Belt. *Acta*

Scientiarum Naturalum Universitatis Pekinesis 29, 745-753 (in Chinese with the

English abstract).

Zhang, J., Sun, M., Schulmann, K., Zhao, G., Wu, Q., Jiang, Y., Guy, A., Wang, Y., 2015.

Distinct deformational history of two contrasting tectonic domains in the Chinese

Altai: their significance in understanding accretionary orogenic process. *J. Struct.*

Geol. 73, 64-82.

Zheng, C.Q., Xu, X.C., Enami, M., Kato, T., 2005. Monazite ages and geological

implications of andalusite- sillimanite type metamorphic belt in Aletai, Xinjiang.

Global Geology 24, 236-242 (In Chinese with the English abstract).

Zheng, C.Q., Kato, T., Enami, M., Xu, X.C., 2007. CHIME monazite ages of metasediments

from the Altai orogen in northwestern China: Devonian and Permian ages of

metamorphism and their significance. *Island Arc* 16, 598-604.

Zhuang, Y.X., 1994a. Tectonothermal evolution in space and time and orogenic process of

Altaide, China. Jilin Scientific and Technical Press, Changchun, China, 402 pp (In

Chinese).

Zhuang, Y.X., 1994b. The pressure-temperature-space-time (PTSt) evolution of

metamorphism and development mechanism of the thermal-structural-gneiss domes in

the Chinese Altaids. *Acta Geologica Sinica* 68, 35-47 (In Chinese with the English

abstract).

Figure caption

Fig. 1. (a) Simplified geological map of the Chinese Altai after Windley et al. (2002), Cai et al. (2011a) and Li et al. (2015a). The interpreted transect in the Aletai area is based on Qu (1991) and our observations, while the transect across the Irtysh Shear Zone in the Fuyun area is after Qu and Zhang (1991; 1994), Laurent-Charvet et al. (2003) and Li et al. (2015a). Inset figure shows the location of the Chinese Altai and major tectonic units in the CAOB. The topographic image is from Amante and Eakins (2009). E: East Junggar; W: West Junggar. (b) Simplified metamorphic map of the Chinese Altai showing distribution of metamorphic zones after Zhuang (1994b) and Jiang et al. (2010). Chronological data are after Zheng et al. (2005; 2007), Briggs et al. (2007; 2009), Wang et al. (2009; 2014b), Li et al. (2014) and Li et al. (2015b).

Fig. 2. Structural map of the study area. Inset figure in the southeastern corner shows the metamorphic zonal sequence of the study area based on Wei et al. (2007) and our observations. Note that the garnet and staurolite zones proposed by Wei et al. (2007) are here merged into the garnet-staurolite zone. The U-Pb age of metamorphic zircons is from Wang et al. (2014b). Throughout this paper, L20 represents the intersection lineation between S_2 and S_0 , and L21 is the intersection lineation between S_2 and S_1 . Sill: sillimanite; and: andalusite; ky: kyanite; st: staurolite; g: garnet; bi: biotite; mu: muscovite.

Fig. 3. Stereographic projection of structural elements in the map area (lower hemisphere, equal area). See the abbreviation of structural elements in the text and the caption of Fig. 2.

Fig. 4. (a) Interlayered occurrence of semipsammitic schist and gneissic granitoids with a penetrative S_2 ; (b) Bluish kyanite is surrounded by pinkish andalusite within a quartz kyanite/andalusite vein in the relict kyanite zone; (c) A composition band (S_0) with a high angle to the regional dominant fabric (S_2); (d) S_0 is folded with an axial plane sub-parallel to the dominant fabric (S_2). Note that S_1 is also locally recognized with an acute angle relative to S_2 ; (e) Overprinting relationship between S_2 and S_1 ; (f) Inclusion patterns in a kyanite porphyroblast showing curved geometry close to the rim of the porphyroblast. This observation, together with coarser quartz grains along the external S_1 in comparison with quartz inclusions, indicates a syn- S_1 kyanite growth (also see the explanation in the text); (g) A local F_2 fold overprinting S_1 in the andalusite-staurolite zone. (h) F_2 folds defined by a pegmatite vein. See Fig. 2 for mineral abbreviations.

Fig. 5. (a) Refolded fold within the sillimanite zone; (b) Intersection lineation (L_{21}) in a andalusite sillimanite mica schist (andalusite-sillimanite zone); (c) Fold interference patterns within the andalusite-staurolite zone (Google earth image, see also Fig. 6); (d-e) S_2 is defined by the preferred alignment of micas in a gneissic granitoid and a mica schist, respectively; (f)

Preferred alignment of micas and sillimanites defining S_2 in a sillimanite mica schist; (g)

Curved inclusion patterns in a staurolite mica schist indicating syn- S_2 staurolite growth; (h)

Syn- D_2 growth of staurolite in a garnet staurolite mica schist. Crenulated inclusion patterns within staurolites are continuous with the fabric outside the porphyroblasts, and some micas in the matrix are transposed to be parallel to S_2 . For mineral abbreviations see Fig. 2.

Fig. 6. Structural map showing the fold interference pattern of F_2 and F_1 (see location in Fig. 2). Lithological contacts are based on the satellite image (Fig. 5c) and our observations.

Fig. 7. (a) S_2 crenulations within a staurolite porphyroblast from a staurolite-kyanite-mica schist. The occurrence of tighter folds (left side) in the rim of the staurolite porphyroblast indicates syn- D_2 growth of staurolite; (b) A garnet-staurolite-mica schist with deflected S_2 foliation around the garnet. The quartz inclusions of the garnet do not define an internal foliation, which together with the deflection of external S_2 fabric, indicates that the garnet grew at an early stage of D_2 or prior to D_2 ; (c) S_2 continues from the matrix to the internal andalusite without obvious deflection; (d) D_3 kink folds overprinting S_2 fabric; (e) Deflection of external S_2 around an andalusite porphyroblast. The wrapping of S_2 around the andalusite indicates that the andalusite growth occurred during D_2 deformation. For mineral abbreviations see Fig. 2

Fig. 8. Schematic diagram with relative age relationships between deformation (D_1 and D_2) and metamorphic mineral assemblages in each metamorphic zone. The solid line with arrow indicates syn-deformation mineral growth, whereas the solid line without arrows shows the occurrence of minerals with uncertain relationship with deformation. Dash line illustrates inferred growth of minerals during deformation. For mineral abbreviation see Fig. 2.

Fig. 9. (a) P-T paths or peak P-T conditions of samples from each metamorphic zone. Solid lines show inferred P-T evolution paths from pseudosection modelling, whereas ellipsoid represents peak P-T conditions (Wei et al., 2007). The prograde metamorphism of a garnet-kyanite-mica schist from the kyanite zone (Wei et al., 2007) is correlated to D_1 based on the syn- D_1 growth of kyanite, while the retrograde P-T path of samples from andalusite-sillimanite and sillimanite zones (Wei et al., 2007) corresponds to D_2 based on the syn- D_2 growth of sillimanite and andalusite. Note that samples from biotite, garnet-staurolite, and andalusite-staurolite zones yielded peak P-T conditions with uncertain relationships with D_1 and D_2 . ky: a garnet-kyanite-mica schist from the kyanite zone; bi: a biotite schist from the biotite zone; g: a garnet-mica schist from the garnet-staurolite zone; st: a garnet-staurolite-mica schist from the garnet-staurolite zone; st-and: a staurolite-andalusite-mica schist from the andalusite-staurolite zone; and-sill: an

andalusite-sillimanite-mica schist from the andalusite-sillimanite zone; sill: a sillimanite-biotite gneiss from the sillimanite zone; g-cd: a garnet-feldspar gneiss from the garnet-cordierite zone (Fig. 1b).

Fig. 10. (a) Block diagram showing the geometry of the Irtysh Shear Zone and the Qiongkuer Domain in the Fuyun area (based on Qu and Zhang, 1991; Qu and Zhang, 1994; Li et al., 2015a); (b) Schematic block diagram highlighting the relationships between syn-D₂ development of the andalusite-type metamorphic zones and transpressional deformation. The geometry of the Irtysh Shear Zone to the south of the map area is concealed under Cenozoic rocks and is inferred from observations in the Fuyun area (Fig. 10a). Note progressive increasing exhumation during large-scale D₂ folding from the sillimanite zone, through the andalusite-sillimanite, andalusite-staurolite and garnet-staurolite zone, to biotite zone. The timing of the Irtysh Shear Zone is based on ⁴⁰Ar/³⁹Ar ages and the intrusion age of granitic dykes that cut the Irtysh Shear Zone (Laurent-Charvet et al., 2003; Buslov et al., 2004; Briggs et al., 2007; Zhang et al., 2012; Li et al., 2015a). Zircon, monazite and ⁴⁰Ar/³⁹Ar ages for the zonal metamorphic series are from Zheng et al. (2005; 2007), Wang et al. (2009; 2014b), Tong et al. (2014a) and Li et al. (2015b). For mineral abbreviation see Fig. 2.

Figure 1

Fig. 1 (see the caption in the following page)

Fig. 1. (a) Simplified geological map of the Chinese Altai after Windley et al. (2002), Cai et al. (2011a) and Li et al. (2015a). The interpreted transect in the Aletai area is based on Qu (1991) and our observations, while the transect across the Irtysh Shear Zone in the Fuyun area is after Qu and Zhang (1991; 1994), Laurent-Charvet et al. (2003) and Li et al. (2015a). Inset figure shows the location of the Chinese Altai and major tectonic units in the CAO. The topographic image is from Amante and Eakins (2009). E: East Junggar; W: West Junggar. (b) Simplified metamorphic map of the Chinese Altai showing distribution of metamorphic zones after Zhuang (1994b) and Jiang et al. (2010). Chronological data are after Zheng et al. (2005; 2007), Briggs et al. (2007; 2009), Wang et al. (2009; 2014b), Li et al. (2014) and Li et al. (2015b).

Figure 2

Fig. 2. Structural map of the study area. Inset figure in the southeastern corner shows the metamorphic zonal sequence of the study area based on Wei et al. (2007) and our observations. Note that the garnet and staurolite zones proposed by Wei et al. (2007) are here merged into the garnet-staurolite zone. The U-Pb age of metamorphic zircons is from Wang et al. (2014b). Throughout this paper, L20 represents the intersection lineation between S2 and S0, and L21 is the intersection lineation between S2 and S1. Sill: sillimanite; and: andalusite; ky: kyanite; st: staurolite; g: garnet; bi: biotite; mu: muscovite.

Figure 3

Fig. 3. Stereographic projection of structural elements in the map area (lower hemisphere, equal area). See the abbreviation of structural elements in the text and the caption of Fig. 2.

Figure 4

Fig. 4. (a) Interlayered occurrence of semipsammitic schist and gneissic granitoids with a penetrative S2; (b) Bluish kyanite is surrounded by pinkish andalusite within a quartz kyanite/andalusite vein in the relict kyanite zone; (c) A composition band (S0) with a high angle to the regional dominant fabric (S2); (d) S0 is folded with an axial plane sub-parallel to the dominant fabric (S2). Note that S1 is also locally recognized with an acute angle relative to S2; (e) Overprinting relationship between S2 and S1; (f) Inclusion patterns in a kyanite porphyroblast showing curved geometry close to the rim of the porphyroblast. This observation, together with coarser quartz grains along the external S1 in comparison with quartz inclusions, indicates a syn-S1 kyanite growth (also see the explanation in the text); (g) A local F2 fold overprinting S1 in the andalusite-staurolite zone. (h) F2 folds defined by a pegmatite vein. See Fig. 2 for mineral abbreviations.

Figure 5

Fig. 5. (a) Refolded fold within the sillimanite zone; (b) Intersection lineation (L21) in a andalusite sillimanite mica schist (andalusite-sillimanite zone); (c) Fold interference patterns within the andalusite-staurolite zone (Google earth image, see also Fig. 6); (d-e) S2 is defined by the preferred alignment of micas in a gneissic granitoid and a mica schist, respectively; (f) Preferred alignment of micas and sillimanites defining S2 in a sillimanite mica schist; (g) Curved inclusion patterns in a staurolite mica schist indicating syn-S2 staurolite growth; (h) Syn-D2 growth of staurolite in a garnet staurolite mica schist. Crenulated inclusion patterns within staurolites are continuous with the fabric outside the porphyroblasts, and some micas in the matrix are transposed to be parallel to S2. For mineral abbreviations see Fig. 2.

Figure 6

Fig. 6. Structural map showing the fold interference pattern of F2 and F1 (see location in Fig. 2). Lithological contacts are based on the satellite image (Fig. 5c) and our observations.

Figure 7

Fig. 7. (a) S2 crenulations within a staurolite porphyroblast from a staurolite-kyanite-mica schist. The occurrence of tighter folds (left side) in the rim of the staurolite porphyroblast indicates syn-D2 growth of staurolite; (b) A garnet-staurolite-mica schist with deflected S2 foliation around the garnet. The quartz inclusions of the garnet do not define an internal foliation, which together with the deflection of external S2 fabric, indicates that the garnet grew at an early stage of D2 or prior to D2; (c) S2 continues from the matrix to the internal andalusite without obvious deflection; (d) D3 kink folds overprinting S2 fabric; (e) Deflection of external S2 around an andalusite porphyroblast. The wrapping of S2 around the andalusite indicates that the andalusite growth occurred during D2 deformation. For mineral abbreviations see Fig. 2

Figure 8

	D1	D2	D2			
	ky zone	bi zone	g-st zone	and-st zone	and-sill zone	sill zone
mu	→→→→→	→→→→→	→→→→→	→→→→→	→→→→→	→→→→→
bi	→→→→→	→→→→→	→→→→→	→→→→→	→→→→→	→→→→→
g	-----→→→→→		→→→→→	→→→→→	→→→→→	→→→→→
st	-----→→→→→		→→→→→	→→→→→		
ky	→→→→→					
sill					→→→→→	→→→→→
and		→→→→→		→→→→→	→→→→→	

Fig. 8. Schematic diagram with relative age relationships between deformation (D1 and D2) and metamorphic mineral assemblages in each metamorphic zone. The solid line with arrow indicates syn-deformation mineral growth, whereas the solid line without arrows shows the occurrence of minerals with uncertain relationship with deformation. Dash line illustrates inferred growth of minerals during deformation. For mineral abbreviation see Fig. 2.

Figure 9

Fig. 9. (a) P-T paths or peak P-T conditions of samples from each metamorphic zone. Solid lines show inferred P-T evolution paths from pseudosection modelling, whereas ellipsoid represents peak P-T conditions (Wei et al., 2007). The prograde metamorphism of a garnet-kyanite-mica schist from the kyanite zone (Wei et al., 2007) is correlated to D1 based on the syn-D1 growth of kyanite, while the retrograde P-T path of samples from andalusite-sillimanite and sillimanite zones (Wei et al., 2007) corresponds to D2 based on the syn-D2 growth of sillimanite and andalusite. Note that samples from biotite, garnet-staurolite, and andalusite-staurolite zones yielded peak P-T conditions with uncertain relationships with D1 and D2. ky: a garnet-kyanite-mica schist from the kyanite zone; bi: a biotite schist from the biotite zone; g: a garnet-mica schist from the garnet-staurolite zone; st: a garnet-staurolite-mica schist from the garnet-staurolite zone; st-and: a staurolite-andalusite-mica schist from the andalusite-staurolite zone; and-sill: an andalusite-sillimanite-mica schist from the andalusite-sillimanite zone; sill: a sillimanite-biotite gneiss from the sillimanite zone; g-cd: a garnet-feldspar gneiss from the garnet-cordierite zone (Fig. 1b).

Figure 10

Fig. 10. (a) Block diagram showing the geometry of the Irtysh Shear Zone and the Qiongkuer Domain in the Fuyun area (based on Qu and Zhang, 1991; Qu and Zhang, 1994; Li et al., 2015a); (b) Schematic block diagram highlighting the relationships between syn-D2 development of the andalusite-type metamorphic zones and transpressional deformation. The geometry of the Irtysh Shear Zone to the south of the map area is concealed under Cenozoic rocks and is inferred from observations in the Fuyun area (Fig. 10a). Note progressive increasing exhumation during D2 macroscopic folding from the sillimanite zone, through the andalusite-sillimanite, andalusite-staurolite and garnet-staurolite zone, to biotite zone. The timing of the Irtysh Shear Zone is based on $^{40}\text{Ar}/^{39}\text{Ar}$ ages and the intrusion age of granitic dykes that cut the Irtysh Shear Zone (Laurent-Charvet et al., 2003; Buslov et al., 2004; Briggs et al., 2007; Zhang et al., 2012; Li et al., 2015a). Zircon, monazite and $^{40}\text{Ar}/^{39}\text{Ar}$ ages for the zonal metamorphic series are from Zheng et al. (2005; 2007), Wang et al. (2009; 2014b), Tong et al. (2014a) and Li et al. (2015b). For mineral abbreviation see Fig. 2.