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Early Paleozoic to Devonian multiple-accretionary model for the Qilian Shan, NW China

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A R T I C L E   I N F O

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A B S T R A C T

The Qilian Shan, located in the northern Tibetan Plateau of NW China, has an excellent record of early to middle Paleozoic subduction–accretion that resulted from convergence between the Alax and Qaidam blocks, but there is no consensus about its detailed tectonic history. This paper summarizes its tectonic divisions and discusses its tectonic evolution from the Cambrian to Devonian. The belt has the following tectonic divisions: In the far north the southern passive margin of the Alax block is juxtaposed against an early Cambrian to Ordovician, Marianan-type intra-oceanic arc (North Qilian). The North Qilian arc is separated from a Japanese-type arc (Central Qilian) to the south by a high-pressure metamorphic belt composed mostly of ophiolitic slices and oceanic crusts. The Central Qilian is bounded to the south by a wide mélange zone (South Qilian), consisting of ophiolitic slices and continental margin sequences. Farther to the south lies the Oulongbuluk microcontinent that is separated from the Qaidam block and farther south by an ultrahigh-pressure metamorphic belt. Tectonostratigraphic analysis, together with geochemical, geochronological, and geophysical data, indicates a complex evolution by subduction–accretion processes from the Cambrian to the Devonian before final amalgamation and docking to the northern Alax block. This model solves the long-lasting discussion on the polarity of subduction in Paleozoic time; this multiple subduction–accretion history sheds light on the continuity of Paleozoic sutures along the Qilian Shan and the nature of the Altyn Tagh fault, and thus contributes to an improved understanding of the tectonic architecture of Central Asia.

1. Introduction

The northern Tibetan Plateau occupies an important position as the northernmost orogenic collage of the Tethyan domain. In contrast to the style of Altaids to the north characterized by long-lived accretionary processes (Şengör et al., 1993; Jahn, 2001; Litvinovsky et al., 2002; Jahn et al., 2004; Xiao et al., 2003b, 2004a,b, 2006, in press, 2008a,b; Wu et al., 2007), the architecture of these Tethyan orogenic collages was long regarded as resulting from collisions between various continental terranes derived from the northern margin of Gondwana (Chang et al., 1986; Şengör, 1987; Dewey et al., 1988; Matte et al., 1996; Dilek and Moores, 1999; Tapponnier et al., 2001; Spurlin et al., 2005; Yin et al., 2008). However, the Qilian Shan in the northern Tibetan Plateau (Fig. 1) has a long history of crustal growth, accretion and collision from early to mid-Paleozoic, more comparable to that of accretionary orogenic belts to the west and north such as the Kunlun and Altaids (Şengör and Okurogullari, 1991; Şengör and Natal'in, 1996a,b; Mattern et al., 1996; Xiao et al., 1998, 2002a,b, 2003a, 2005; Pan et al., 2006; Aitchison et al., 2001; Arnaud et al., 2003). Therefore, the Qilian Shan provides the link between the dominantly collisional terranes to the south and the dominantly accretionary belts to the north and west.

The Qilian Shan (Figs. 1 and 2) is a classical mountain belt that formed by subduction- and collision-related processes that led to formation of island arcs, accretionary prisms, ophiolites, seamounts, and high-pressure and ultrahigh-pressure metamorphic rocks (Xiao et al., 1974, 1978; Wang and Liu, 1976; Li, 1979; Xu et al., 1994; Wu et al., 1993; Gehrels et al., 2003a,b; Smith et al., 1997; Smith, 2006; Smith and Yang, 2006; Song, 1997, 2006, 2007). However, much disagreement exists regarding the temporal and spatial framework of the Qilian Shan and about details of its tectonic history such as subduction polarity, younging direction of arcs and crustal growth, and collisional thrust polarity (Zhang and Xu, 1995; Feng, 1997; Song, 1997; Gehrels et al., 2003a,b; Wang et al., 2005). In particular, there is confusion about the location, nature, and ages of the sutures within the belt, and therefore

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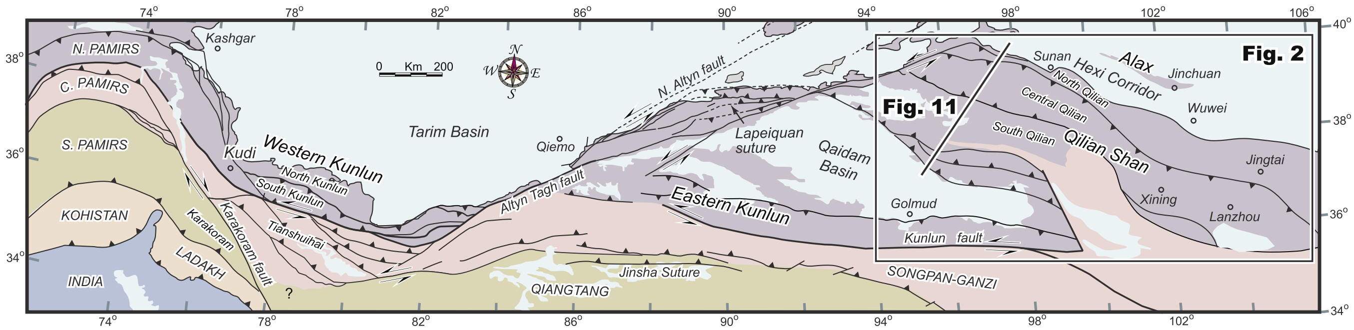

Fig. 1. Schematic tectonic map of the northern Tibetan Plateau and adjacent regions showing the position of the Qilian Shan (modified after Sobel and Arnaud, 1999; Arnaud et al., 2003; Xiao et al., 2003a, 2005; Cowgill et al., 2003; Gehrels et al., 2003a,b); Figs. 2 and 11 are marked.

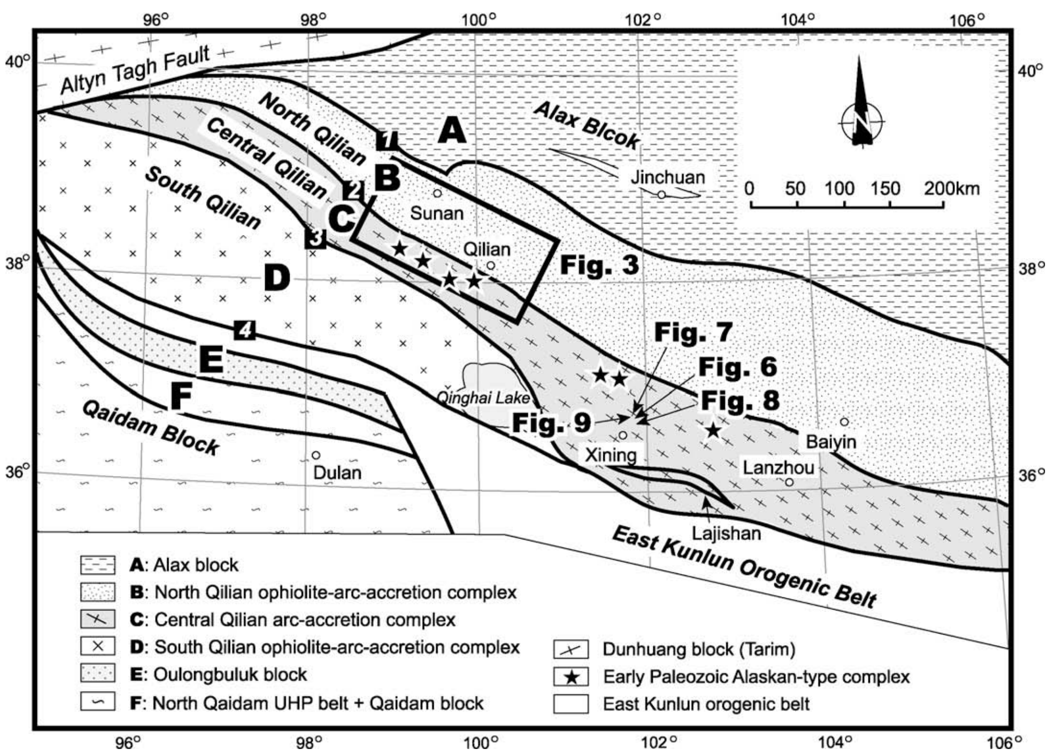

Fig. 2. Schematic tectonic division of the Qilian Shan (modified after Feng, 1997; Xu et al., 2006). Numbers in black boxes indicate major faults: 1-Lenglongling fault; 2-Heihe fault; 3-Nan Shan fault; 4-Tianjun fault. Figs. 3 and 6–9 are marked.

about their continuity to the east and west (Zhou and Graham, 1996; Yang, 1997; Sobel and Arnaud, 1999; Yuan et al., 2002, 2003; Yue et al., 2004).

The aim of this paper is to review the geological history of the Qilian Shan constrained by stratigraphic, geochemical, geochronological and geophysical data in order to understand its overall geodynamic evolution. We use these data to build a new tectonic model, and to discuss implications for the architecture and evolution of the northern Tibetan Plateau.

2. Tectonic background and regional geology

The Paleozoic Qilian Shan is divisible from north to south into the Alax block (Alashan, part of the North China craton, unit A in Fig. 2), North Qilian, Central Qilian and South Qilian (Fig. 3). Tectonically, the Qilian Shan is a wide orogenic collage on the northern margin of the Tibetan Plateau and adjacent areas including the convergent Qaidam block to the south (unit B in Fig. 2). To the east it merges with the East Kunlun orogenic belt that continues farther east as the Qinling–Dabie orogenic belt. To the west it is bounded by the Altyn Tagh fault, across which its continuation is uncertain: it may extend as the Altyn-West Kunlun-Pamirs (Li, 1979; Schwab et al., 2004; Wang and Liu, 1976), the Beishan-Tianshan (Zhou and Graham, 1996), or the Altyn–Central Tarim (Yin and Nie, 1996) (Fig. 1).

An important breakthrough in study of the Qilian Shan was the discovery of ophiolites, blueschists and ophiolitic mélanges in the North Qilian (Xiao et al., 1974, 1978; Wu et al., 1993; Wang and Liu, 1976). Since the discovery of high-pressure and ultrahigh-pressure metamorphic rocks along the northern Qaidam (Yang et al., 2002, 2006; Wu et al., 2002; Zhang et al., 2006; Shi et al., 2006; Yang and Powell, 2008), the northern Tibetan orogenic belts have become the focus of extensive research. However, some basic tectonic problems remain unsolved, in particular, the tectonic settings of many tectonic units.

In this paper, we summarize the geology of the Qilian Shan by describing, from north to south, the major tectonic units that are defined as A, B, C, D, E and F in Fig. 2.

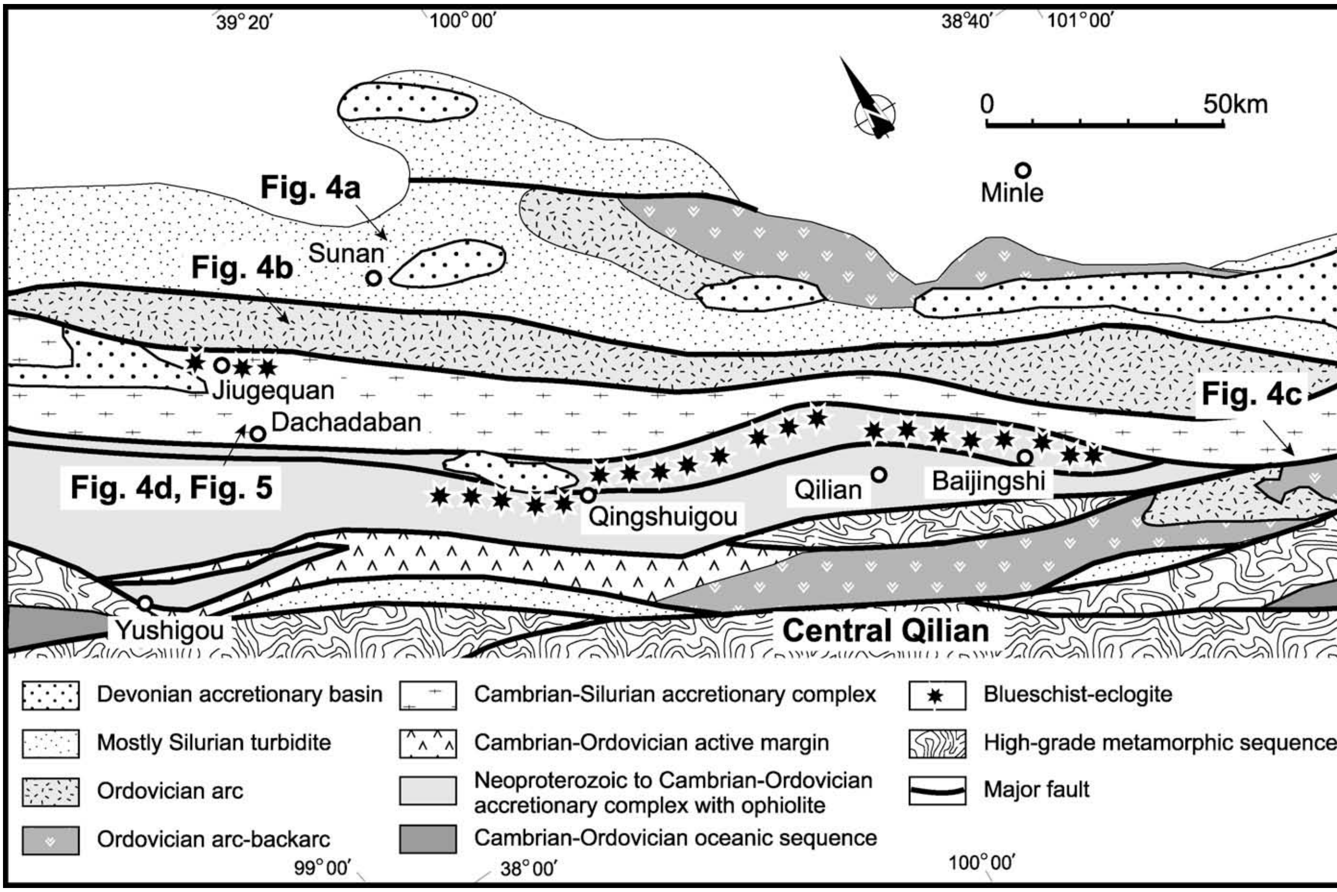

Fig. 3. Tectonic map of the Sunan-Qilian area showing imbricated accretionary sequences (modified after Zuo and Wu, 1997; Zuo et al., 2000; Song, 1996, 1997). See Fig. 2 for location. Figs. 4 and 5 are marked.

2.1. Southern Alax thrust belt (A)

The Alax block is considered to be the westernmost part of the North China craton. There is no evidence of Archean rocks, but Lu et al. (2002a,b) described early Proterozoic amphibolite-facies metamorphic rocks whose protoliths are clastic sediments, carbonates and minor mafic volcanic rocks. Prominent is the 812 ± 26 Ma Jinchuan ultramafic intrusion (Li et al., 2005), which hosts the third largest Ni–Cu deposit in the world. Lehmann et al. (2007) showed that the plume-derived intrusion was emplaced between gneisses and marbles in the southern Alax thrust belt on the southern margin of the North China craton. This thrust belt forms the northernmost tectonic component related to the Qilian Shan.

2.2. North Qilian arc-accretionary system (B)

Unit B (North Qilian) is characterized by arc volcanic rocks and high-pressure metamorphic rocks, and is the most extensively studied part of the orogen. Structural and petrochemical data reveal the following subunits from N to S: (1) an Ordovician to mid-Devonian Baiquanmen forearc accretionary complex that includes ophiolites and blueschists; (2) an Ordovician Dacha-Bianmagou arc with an intra-arc basin; (3) Ordovician to Silurian Qingshuigou accretionary complexes that include ophiolites, seamount fragments, turbidites, eclogites and blueschists; (4) the Yushugou ophiolite; and (5) several late Ordovician to Silurian-Early Devonian forearc basins that overlie accretionary complexes.

Petrochemical studies of volcanic rocks in the North Qilian indicate the presence of three main volcanic units: a mid-ocean ridge (MORB), oceanic island (alkaline OIB), and a calc-alkaline to tholeiitic island arc (Lai et al., 1997). In the northern and southern parts of the North Qilian, the Yushigou and Jiugequan ophiolites contain MOR basalts. Ocean island basalts mainly in the Laohushan area were interpreted by Zhang et al. (1995) and Lai et al. (1997) as components of a seamount. The Laohushan ophiolite contains pillow basalts, ophiolitic gabbros and serpentinized dunites, imbricated in a major thrust stack with red and green cherts, mafic mudstones and sandstones that represent a ridge-to-trench succession of ocean plate stratigraphy, which was finally emplaced into the accretionary wedge. Typical components of an accretionary wedge include thick turbidite (Fig. 4a), pillowed basalt, and chert (Fig. 4b, and c). Red radiolarian chert is common in the North Qilian (Fig. 4c). Island arc volcanic rocks are widely distributed in the North Qilian, and boninites are present in the North Qilian arc (Zhang and Xu, 1995; Zhang et al., 1996, 1997b, 1998). Backarc or arc-related basins were chemically defined (Xia et al., 2003). Basalts at Dacha Daban in the North Qilian contain well-preserved pillows (Fig. 4d), although some are strongly deformed. These island arc volcanic rocks generally become progressively younger from north to south (Zhang and Xu, 1995; Zhang et al., 1996, 1997b, 1998).

Most prominent are high-pressure metamorphic rocks mainly in subunit 3. Structural studies indicate that their general structure is dominated by south-verging thrusts (Xu et al., 1994, 1997, 2000, 2006) and that they underwent multiple periods of deformation (Zhang and Xu, 1995; Zhang et al., 1996, 1997a, 1998). $^{40}Ar/^{39}Ar$ ages on high-pressure metamorphism of the accretionary prisms range from 480 Ma to 410 Ma (Zhang and Xu, 1995; Zhang et al., 1996, 1997b, 1998). $^{40}Ar/^{39}Ar$ Plateau ages in the range of 454 ± 9–447 ± 4 Ma were obtained on phengites of the North Qilian

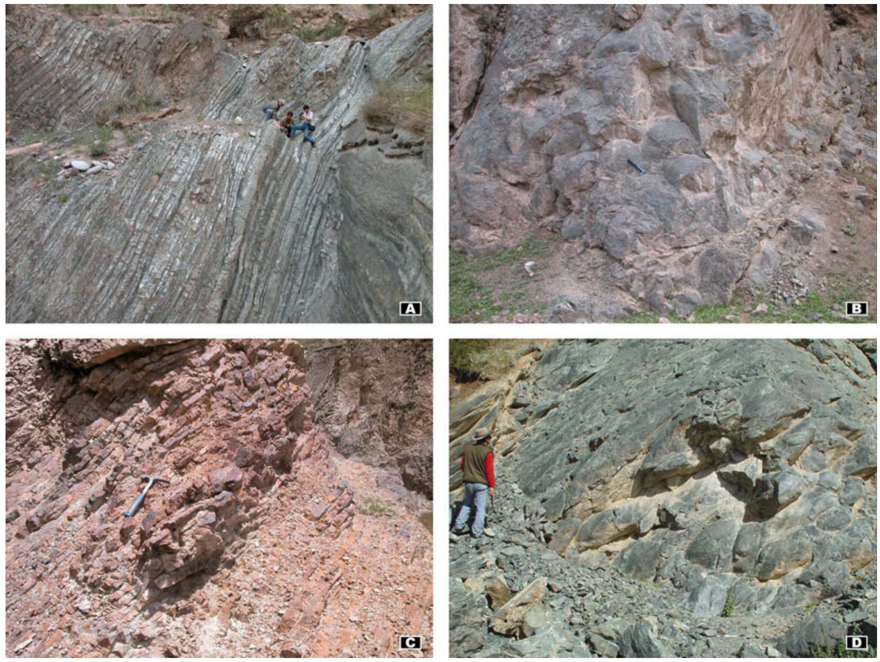

Fig. 4. (A) Steeply dipping greenish turbidite, north of Sunan. Scientists for scale. Looking east. (B) Pillow basalt, north of Jiugequan. Hammer is 37 cm. Looking east. (C) Red radiolarian chert, east of Baijingshi. Hammer is 37 cm. Looking west. (D) Well-preserved pillows in boninitic basalt at Dachadaban. Scientist for scale. Looking west. See Fig. 3 for location (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.).

Shan (Liu, 2000; Liu et al., 2006). A blueschist from the Jiugequan area has a younger $^{40}Ar/^{39}Ar$ age of ca. 360 Ma (Zuo and Wu, 1997; Zuo et al., 2000), but more precise ages of this high-pressure metamorphism are needed.

The southward younging of the accretionary prisms and arc volcanic rocks indicates that subunit 3 has a northward subduction polarity and that the subducting slab retreated southward (Xu et al., 1994, 1997, 2000, 2006). The spatial distribution of the arcs, accretionary complexes and forearc basins suggests, however, different subduction systems.

At Dacha Daban, an unconformity separates ophiolites below and Devonian forearc sediments above (Fig. 5). Recent sedimentary research on Silurian to Devonian forearc sediments in this belt indicates that subduction–accretion processes lasted until the Devonian (Yan et al., 2007).

We conclude that unit B in the North Qilian contains intra-oceanic and subduction-generated rocks, as well as accretionary prisms and exhumed high-pressure rocks. More structural and field-based evidence is required to unravel the history of the obviously complex multiple subduction and accretion events.

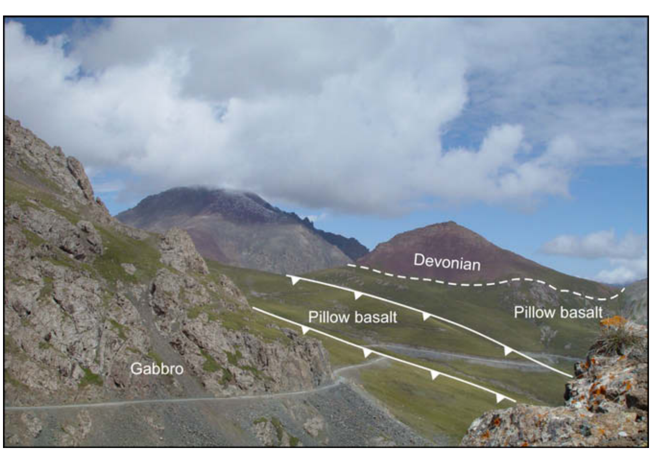

Fig. 5. Photo showing an unconformity between imbricated ophiolite sequences below and Devonian forearc sediments above at Dachadaban. The imbricated ophiolite sequences here are mainly represented by pillow basalt (with a boninitic geochemical signature), which is overthrust by gabbro (in the foreground) on moderately south-dipping thrusts. Looking north. See Fig. 3 for location.

2.3. Central Qilian arc-accretionary system (C)

High-grade metamorphic rocks in the Central Qilian are mainly mica schist ± garnet ± kyanite, biotite gneiss, quartzite, marble and minor graphite mica schist (Lu et al., 2002b). These rocks have been thought to be Proterozoic in age, because mylonitic granitic rocks have a single U–Pb zircon age of 917 ± 12 Ma (Guo and Li, 1999; Guo et al., 2000). The high-grade rocks are unconformably overlain by unmetamorphosed to low-grade metamorphic clastic sediments, sericite schist, siltstone, slate and carbonate (Lu et al., 2002b). A sedimentary cover of Cambrian to lower Silurian carbonate and clastic rocks is unconformably overlain by upper Devonian conglomerates (Lu et al., 2002b).

However, Wang and Liu (1976) reported metamorphic ages of 420–442 Ma from imbricated granitic gneiss and garnet–biotite gneiss, although no details of these age data were given. Also radiolarian fossils and conodonts of Silurian age occur in cherts within a low-grade mélange (Yan et al., unpublished data); this might imply that the imbrication process was later than Silurian (Wang and Liu, 1976). At present, it seems more likely that most of the rocks in the Central Qilian formed and accreted in the early-mid Paleozoic.

The high-grade metamorphic rocks are mainly characterized by imbricate thrusts and duplexes, but they have not been described in detail. Low-grade rocks contain coherent strata and incoherent mélanges in which metabasalts contain well-preserved pillows (Fig. 6) and block-in-matrix and imbricate structures (Fig. 7). Asymmetrical structures in mylonites indicate southward thrusting (Fig. 8) and dextral strike-slip (Fig. 9). These strike-slip faults have $^{40}Ar/^{39}Ar$ and single U–Pb evaporation ages of 410–394 Ma

Fig. 6. Deformed pillows in metabasalts in the Central Qilian block, north of Xining. Some pillows have chilled margins. The main pillows are 30–60 cm long. The cliff is roughly 4 m high. Looking east. See Fig. 2 for location.

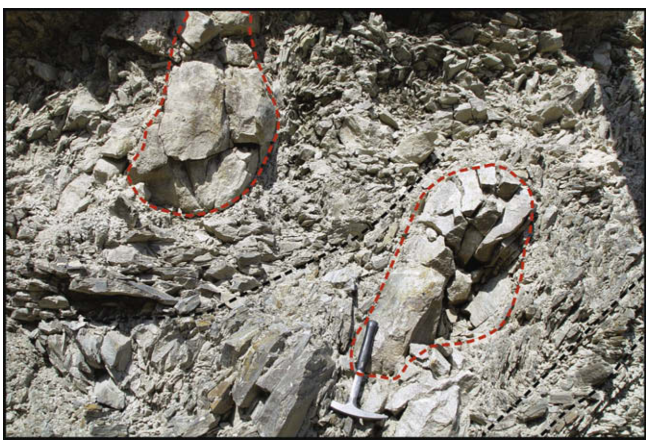

Fig. 7. Block-in-matrix structure in an accretionary mélange in the Central Qilian block. Dashed lines outline blocks of sandstone in a matrix of thin-bedded sandstone. Hammer is 37 cm. Looking east. See Fig. 2 for location.

Fig. 8. Asymmetrical structure in a mylonite in the Central Qilian indicating southward thrusting. Coin for scale. Looking east. See Fig. 2 for location.

(Qi, 2003). These structural relations suggest that the accretionary prism underwent complicated deformation including oblique shear and thrusting probably during accretion, but detailed high-resolution isotopic data, such as SHRIMP zircon ages, are needed to constrain the timing. Along the main ridge of the Central Qilian block several Alaska-type, zoned mafic complexes have geological and geochemical features that indicate an origin related to subduction towards the south (Zhang et al., 1997c,d).

Fig. 9. Asymmetrical structure in mylonite in the Central Qilian showing horizontal dextral strike-slip motion. Coin for scale. Looking down on a horizontal outcrop. See Fig. 2 for location.

At Lajishan an elongated zone of ophiolitic mélange with chert and ultramafic and mafic rocks crops out (Fig. 2). All these ophiolitic sequences or mélanges are thought to be Ordovician in age (Qiu et al., 1998; Zuo et al., 2000).

In summary, we suggest that the Central Qilian is a section of a Japanese-type orogen that contains a possible late Proterozoic slab, an early Paleozoic magmatic arc, and an accretionary prism.

2.4. South Qilian arc-accretionary system (D)

The South Qilian unit D is mainly composed of Cambrian to Ordovician marine sediments and oceanic crustal fragments (Pan et al., 2002), and lava flows, pyroclastic rocks and abyssal and bathyal deposits (Xu et al., 2006). Well-developed middle Ordovician arc volcanic rocks comprise spilite, pillow basalt, volcaniclastic rocks and andesitic porphyry, which are imbricated with chert and minor carbonate; these rocks are unconformably overlain by upper Devonian conglomerates (Lu et al., 2002b; Zhao et al., 2004). Silurian flysch sediments are tightly folded and cleaved, and intruded by late Caledonian granites (Xu et al., 2006).

The South Qilian was defined by Pan et al. (2002) as an arc-accretionary system.

2.5. Oulongbuluk block (E)

The Oulongbuluk block of unit E consists of high-grade metamorphic rocks interpreted as part of a continental fragment (Pan et al., 2002). The oldest rocks are granitic gneisses containing enclaves of amphibolite and migmatite (Lu et al., 2002b). Granitic gneiss and amphibolite have single zircon evaporation ages of 2412 ± 14 Ma and 2366 ± 10 Ma, respectively (Lu et al., 2002a). These rocks are considered to form the basement of the Oulongbuluk block.

In tectonic contact with these oldest rocks is a supracrustal sequence composed of quartzite, garnet–sillimanite-bearing quartz schist, mica schist, amphibolite, and minor granulite, the protoliths of which were mainly clastic and volcaniclastic rocks. A second sequence is composed of carbonaceous sericite schist, calc-schist, carbonaceous marble and phyllite, all tectonicially intercalated with marble; isotopic ages have not been measured for these rocks (Lu et al., 2002b). However, they are overlain unconformably by a cover sequence, the basal rocks of which are basalts that have a single zircon evaporation age of 738 ± 28 Ma, indicating that the underlying supracrustal basement might be as young as middle Neoproterozoic in age (Lu et al., 2002b). The Oulongbuluk block has a well-developed Neoproterozoic to Ordovician sedimentary cover that is unconformably overlain by upper Devonian conglomerates (Lu et al., 2002b).

2.6. North Qaidam UHP belt (F)

Unit F of the North Qaidam collisional system is the southernmost part of the Qilian Shan; it occupies the collision zone between the Qaidam and Oulongbuluk blocks (Gao et al., 1999; Yin et al., 2001; Yang et al., 2001a, 2002; Manning et al., 2001; Wu et al., 2002; Gehrels et al., 2003b). The oldest rocks of the Qaidam block are high-grade gneisses, quartzites and marbles (Lu et al., 2002a,b).

In the northern part of unit F, three main volcanic environments are defined by petrochemical data: mid-ocean ridge (tholeiitic series), oceanic island (seamount) (alkaline series), and island arc (calc-alkaline and tholeiitic series) (Lai et al., 1996; Shi et al., 2004, 2006). A U–Pb zircon age (LA-ICPMS) of 514.2 ± 8.5 Ma from the island arc volcanic rocks (Shi et al., 2004, 2006) implies that subduction started in the late Cambrian.

The plutonic part of the arc is represented by a suite of I-type monzodiorite, quartz monzodiorite, granodiorite, and monzogranite of calc- alkaline affinity (Wu et al., 2000, 2001, 2002). The age of this arc is envisioned as late Cambrian to Ordovician (Xu et al., 2006) or Silurian (Pan et al., 2002).

The southern part of unit F is characterized by garnet mica schist ± quartz, muscovite quartzite, marble, garnet amphibolite, and garnet peridotite, all of which have undergone ultrahigh-pressure metamorphism (Lu et al., 2002a,b; Yang et al., 1998, 2001a,b, 2002; Mattinson et al., 2006; Yang and Powell, 2008). Eclogites occur as lenses in garnet–muscovite gneiss (Lu et al., 2002a,b) that contains zircons with coesite inclusions, indicating that the rocks have been subducted to a depth of more than 100 km (Xu et al., 2006; Yang et al., 2001b). Yang and Powell (2008) found that the original assemblages of the garnet peridotites in the northern Qaidam UHP belt were hydrothermally altered by seawater-derived fluids. This is reasonable in the context of the tectonic evolution of the orogenic belt, involving an oceanic basin in the early Palaeozoic (Yang and Powell, 2008).

The juxtaposition of the island arcs and the occurrence of the ultrahigh-pressure metamorphic rocks have been interpreted to be the result of northward deep subduction of the Qaidam block beneath the northerly tectonic units either in the early Paleozoic (Yang et al., 2000, 2001a, 2002) or early–middle Paleozoic (Song et al., 2003a,b, 2006).

3. Geophysical data and other constraints

Units A, B, C, D, E, and F are mutually separated by suture zones now mostly expressed as major faults (Xu et al., 1999, 2006); stratigraphic and structural data that demonstrate the relationships among them are shown in Fig. 10. The interpreted geophysical section of these units across the Qilian Shan shown in Fig. 11 contains these data that confirm the relationships between the Alax block and the lithosphere of the northern Tibetan Plateau (Gao et al., 1999; Chen et al., 1999; Yin and Harrison, 2000; Tapponnier et al., 2001).

In spite of the major strike-slip faults in East-Central China (Tapponnier et al., 1990, 2001; Arnaud et al., 2003), the principal far-field effect of the India–Asia collision in the Qilian Shan was the formation of northward-verging thrusts (Dewey et al., 1988), associated with the subduction of the Alax block beneath the Qilian Range that gave rise to N–S shortening of some 300 km (Gao et al., 1999; Chen et al., 1999; Yin and Harrison, 2000; Tapponnier et al., 2001). Before this shortening (Fig. 11), the southern margin of the Alax block would have extended much farther to the south. Nevertheless, the present distribution of tectonic units A, B, C, D, E and F still represents the essential Paleozoic paleogeography that forms the basis of our tectonic analysis below.

In addition to the above relations, we note the following important information: (1) the totally different distribution of the North China craton and the North and Central Qilian based on geological and isotopic studies (Smith et al., 2000); (2) early to end-Devonian metamorphic ages (400–360 Ma) of the blueschists of the accretionary complex in North Qilian (Wu et al., 1993; Zuo and Wu, 1997; Zhang et al., 1997a); (3) a southwestward decrease across the Qilian Shan of detrital zircon ages from ca. 490–480 Ma in the northeast to ca. 440–430 Ma in the southwest, which matches well a similar younging of U–Pb ages of granitoid plutons across the belt and a concomitant northeastward increase of magmatic ages from ~440 to 406 Ma (Cowgill et al., 2003; Gehrels et al., 2003a); (4) the northern Qaidam UHP rocks experienced peak metamorphism at 440–423 Ma, during which continental collision between Qaidam and Oulongbuluk blocks and deep subduction of the northern Qaidam continental crust might have taken place (Yang et al., 2001a, 2002, 2006; Song et al., 2004, 2006); and (5) northern Qaidam UHP rocks were exhumed at 423–400 Ma (Yang et al., 2001a, 2002, 2006; Song et al., 2004, 2006).

4. Tectonic evolution

Taking into account all the above data, we interpret the Paleozoic tectonic evolution of the Qilian Shan as follows. In the late Cambrian to early Silurian (Figs.10 and 12A) the Yushugou oceanic lithosphere was doubly subducted: northwards beneath a Marianan-type intra-oceanic subduction system (North Qilian), and southwards beneath a Japan-type intra-oceanic subduction system (Central Qilian). At the same time, the ocean north of the Qaidam block was subducted northwards beneath the Oulongbuluk block that was connected with the Central Qilian by the South Qilian ocean. In the early to mid-Silurian (Fig. 12B), the North Qilian intra-oceanic subduction system collided with the Central Qilian, which had amalgamated with the Oulongbuluk block to form a composite arc associated with double subduction of oceanic lithosphere. The Qaidam block collided with the central composite arc and was deeply subducted beneath the central composite arc, giving rise to formation of UHP metamorphic rocks (Fig. 12B). In the late Silurian to Devonian (Fig. 12C), the UHP metamorphic rocks were exhumed into the North Qaidam block, while subduction of the ocean to the south of the North China craton continued with northward migration of magmatism. In the late Devonian (Fig. 12D), the entire Qilian orogenic collage was accreted to the North China craton, terminating the intervening ocean. During this orogenic process, large-scale syn- and post-accretionary strike-slip faulting occurred along the Qilian Shan suture zones (Xu et al., 1994, 2006).

5. Discussion

5.1. Significance for subduction polarities

The above tectonic model solves the long-standing controversy regarding Paleozoic subduction polarity and formation of the northern Tibetan Plateau. Nearly all previous investigations were only concerned with single or two-way of subduction events. For example, in the North Qilian block northward subduction of the

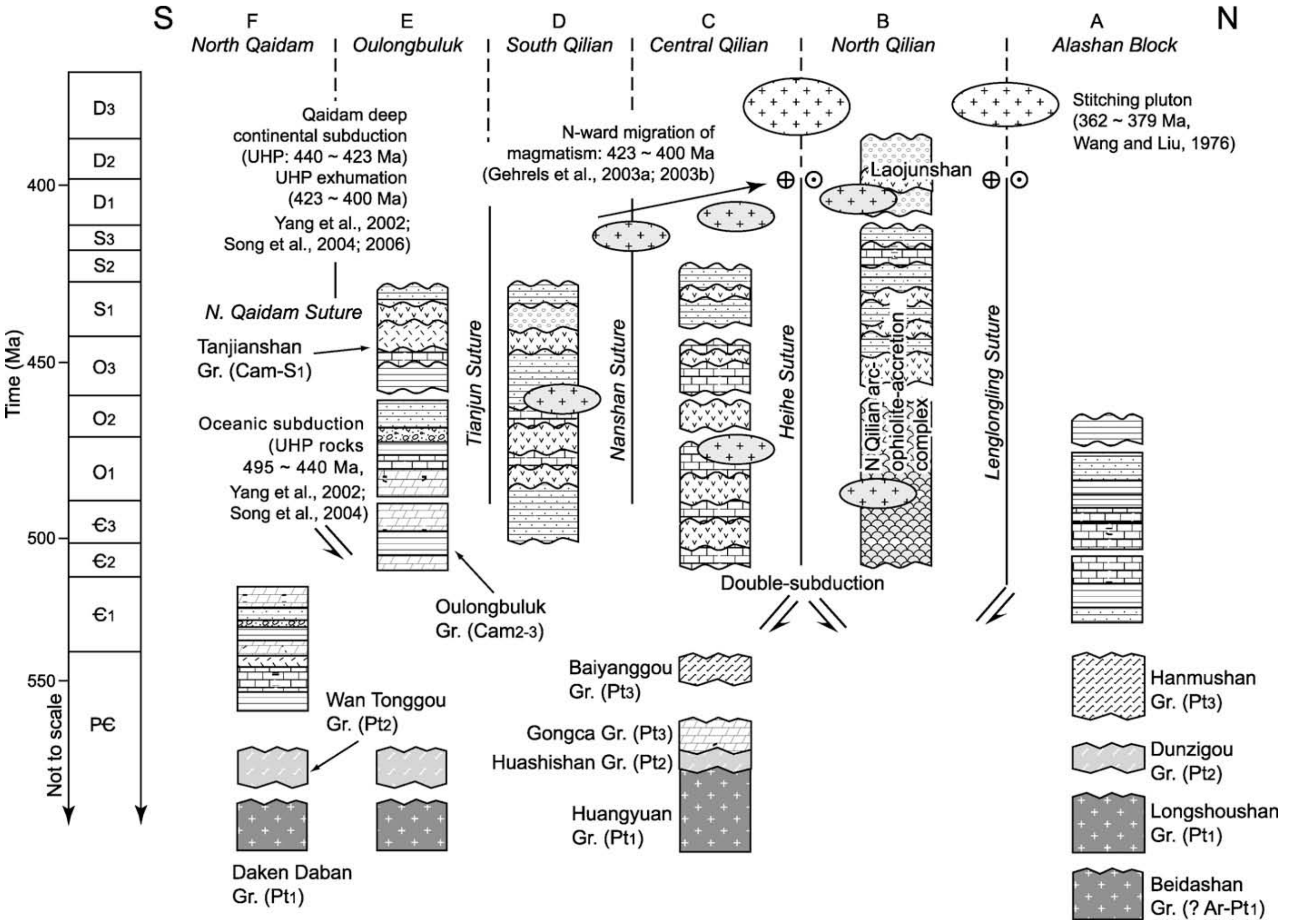

Fig. 10. Time-correlated stratigraphic columns for the 6 tectonic units (A, B, C, D, E, and F as in Fig. 2) of the Qilian Shan, indicating directions of subduction, key events and references. Cam-Cambrian, Gr-Group, Pt-Proterozoic, Ar-Archean.

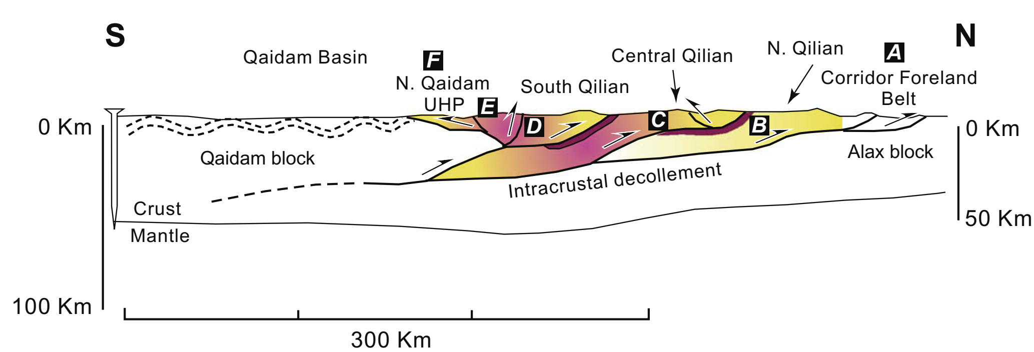

Fig. 11. Reinterpretation of the geophysical section of the Qilian Shan showing the deep relationships between the 6 tectonic units (A, B, C, D, E, and F as in Fig. 2) of the Qilian Shan (modified after Chen et al., 1999; Gao et al., 1999).

North Qilian oceanic plate (between the North and Central Qilian) took place beneath the North Qilian arc (Xu et al., 1994, 1997, 2000, 2006), verified by the southward migration of arc volcanism and the southward younging of the accretionary prism (Zhang and Xu, 1995; Zhang et al., 1996, 1997b, 1998). However, the Alax block (North China craton) and its cover sequence were underthrust southward beneath the coherent Qilian arc at a low angle (Yin and Harrison, 2000). A mélange, at least a few kilometers thick (Yin and Harrison, 2000) underlies the contact zone between the Paleozoic arc and the subducted shelf sequence and its forearc basins (Yan et al., 2007). Concerning the relationship between the North Qilian oceanic plate and the Central Qilian, southward subduction took place beneath the Central Qilian arc as verified by presence of the Alaska-type complexes (Zhang et al., 1997c,d).

For the whole Qilian Shan, Yang et al. (2002, 2006) and Song et al. (2006) used petrological, chemical and geochronological data to propose various models, but in which there was only a single northward subduction event between the Alax and the Qaidam blocks, with the North Qilian high-pressure metamorphic belt representing the oceanic subduction stage and the Qaidam ultrahigh-

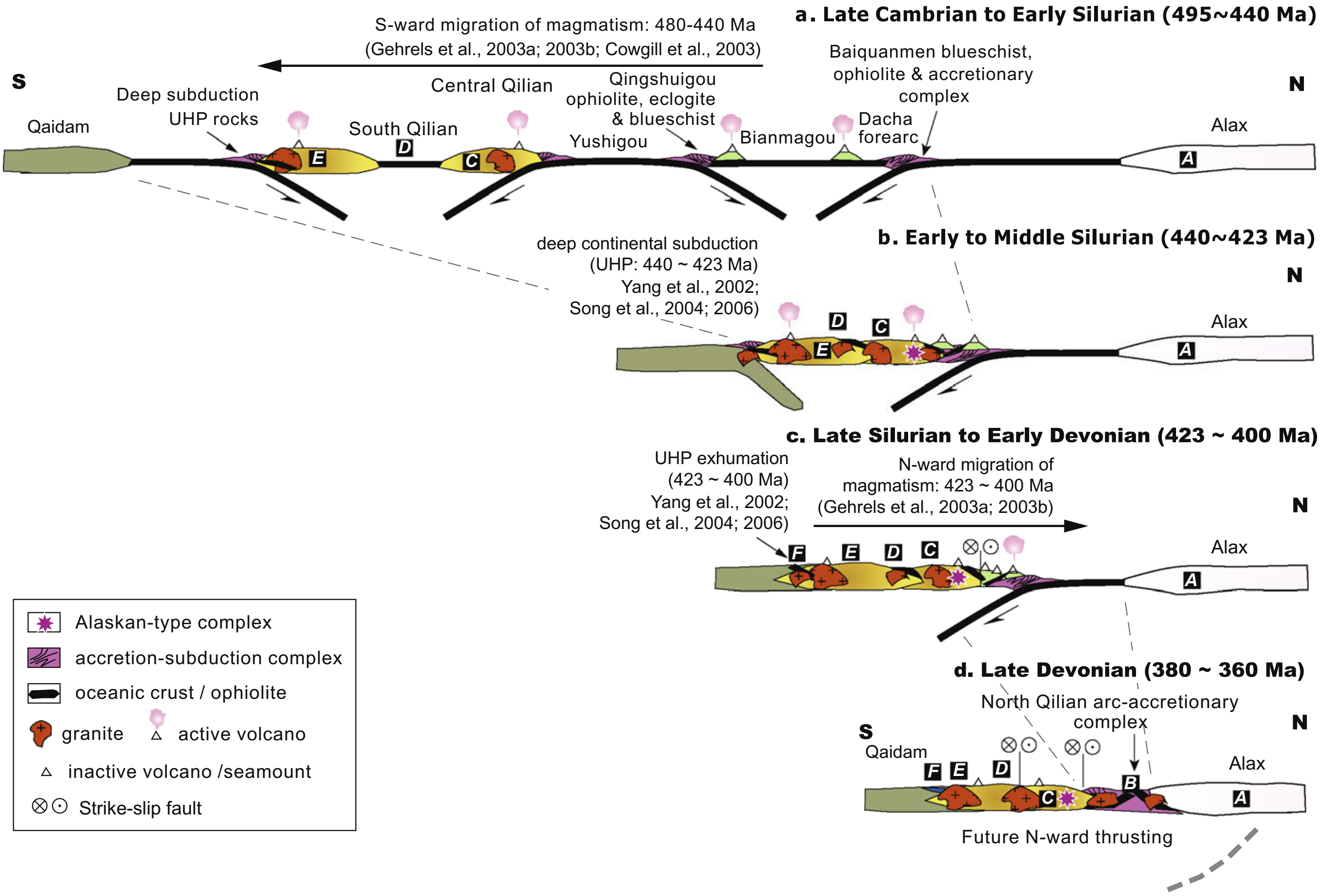

Fig. 12. Schematic cross-sections illustrating the tectonic evolution of the Qilian Shan.

pressure metamorphic belt the continental deep subduction stage, a typical Himalayan-type collisional orogen (Song et al., 2006). However, as this tectonic review demonstrates (see Figs. 10 and 12), several important tectonic units between the northern Qaidam ultrahigh-pressure metamorphic belt and the North Qilian arc are missing, for instance the Central Qilian arc, the South Qilian ocean basin and the Oulongbuluk block, and the ophiolites between them.

Accordingly, to us the data indicate that the Qilian Shan was created by many subduction events with different polarities. A multiple subduction system scenario reconciles the problematic subduction polarity, not well accounted for by previous models. Our model thus can solve the long-lived discussion regarding the Paleozoic polarity of subduction.

5.2. Significance for tectonic architecture

Our model also shed lights on the controversy about the western extension of the Qilian Shan along the northern Tibetan Plateau (Zhou and Graham, 1996; Yang, 1997). Zhou and Graham (1996) suggested that the Beishan–East Tianshan belt is a possible extension of the Qilian belt, but Yin and Nie (1996) proposed the Central Tarim as the possible western extension. However, the Qilian belt instead could also be connected with the Altyn (Gehrels et al., 2003a,b) and further westward with the West Kunlun (Sobel and Arnaud, 1999; Sobel et al., 2001; Cowgill et al., 2003). From recent tectonic studies in the West and East Kunlun (Sobel and Arnaud, 1999; Sobel et al., 2001; Cowgill et al., 2003, Xiao et al., 1998, 2002a,b 2003a, 2005), we conclude that, due to the position of the Qaidam block, the Qilian Shan is the most complicated in the northern Tibetan Plateau.

Plate reconstructions show that the Tarim and North China microcontinents were located near Gondwana in the early to middle Paleozoic (Fortey and Cocks, 2003). The Tarim block finally collided with the Southern Altaids to the north in the late Permian to early Triassic (Xiao et al., 2004a,b, 2006, in press, 2008a,b), while the North China craton, to which the Qaidam block had already been accreted by the late Paleozoic, was amalgamated to southern Siberia in the early Triassic to the Jurassic (Şengör et al., 1993; Şengör and Natal'in, 1996a,b). Therefore it would be reasonable to define the Tarim block separately from the Qaidam block, at least before the early Mesozoic when the North China craton amalgamated with the Southern Altaids. This leads us to the conclusion that the Qilian belt formed an independent orogenic collage in the Paleozoic that was later connected with the West Kunlun by transform or accretionary tectonics, and which now lies somewhere along the Altyn Tagh fault zone. Thus, understanding of the multiple subduction and accretion processes in the Qilian Shan, together with recent advances in knowledge of the Altyn Tagh fault (Yang, 1997; Yue and Liou, 1999; Yue et al., 2001, 2003, 2004) contributes considerably to the tectonic architecture of Central Asia.

Orogenic belts have been mainly classified into two end-members: accretionary and collisional (Windley, 1993, 1995) though other versions exist (Şengör and Okurogullari, 1991; Şengör and Natal'in, 1996a,b). In the case of the northern Tibetan Plateau, accretionary and collisional tectonics co-existed simultaneously, that is, coeval accretionary and collisional processes contributed significantly to its growth and continental architecture. Furthermore, accretionary orogens have a long history and make a substantial contribution to crustal growth (Windley, 1995; Tagami and Hasebe, 1999; Holbrook et al., 1999; Polat et al., 2005). Therefore, the role of accretionary processes in the continental growth of the Tibetan Plateau should be re-evaluated and constrained by more field mapping and isotopic studies (Kapp et al., 2000; Kapp et al., 2003a,b; Yin and Harrison, 2000; Yuan et al., 2002, 2003).

Multiple subduction systems have broad implications for a better understanding of orogens throughout the world. In the case of the northern Tibetan Plateau, we emphasize that the Qilian Shan was created by many subduction events with different polarities. The double and multiple subduction systems envisaged in this model are comparable to those of the Inner Mongolian part of the southern Altaids (Xiao et al., 2004a,b), the Bismarck-Solomon region (Petterson et al., 1999; Hall and Spakman, 2002; Hall, 2002; Mann and Taira, 2004; Phinney et al., 2004), the Molucca Sea between East Sulawesi and Halmahera arcs in Indonesian (Bader et al., 1999) including parts of the Philippines (Bader et al., 1999; Hall and Spakman, 2002; Hall, 2002; Yumul et al., 2003; Pubellier et al., 2004), and the early Eocene arc–continent collision reconstructed from the Kamchatka Orogenic Belt, NE Russia (Konstantinovskaia, 2000, 2001).

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