Paleozoic tectonics of the southern Chinese Tianshan: Insights from structural, chronological and geochemical studies of the Heiyingshan ophiolitic mélange (NW China)

Bo Wanga,b,c⁎, Liangshu Shua, Michel Faurec, Bor-ming Jahnb,e, Dominique Cluzelc,d, Jacques Charvetc, Sun-lin Chunge, Sébastien Meffref

a State Key Laboratory for Mineral Deposits Research, School of Earth Sciences and Engineering, Nanjing University, 210093 Nanjing, China
b Institute of Earth Sciences, Academia Sinica, Taipei, 11529 Taiwan
c Institut des Sciences de la Terre d’Orléans, UMR CNRS 6113, Université d’Orléans, 1A rue de la Férolerie, 45071 Orleans, France
d Pole Pluridisciplinaire de la Matière et de l’Environnement, EA 3325, Université de la Nouvelle-Calédonie, 98851 Nouméa, New Caledonia
e Department of Geological Sciences, National Taiwan University, Taipei, 10617 Taiwan
f Centre of Excellence in Ore Deposits, University of Tasmania, Hobart Tasmania 7001, Australia

ABSTRACT

In the southern Chinese Tianshan, the southernmost part of the Central Asian Orogenic Belt (CAOB), widespread ophiolitic mélanges form distinct tectonic units that are crucial for understanding the formation of the CAOB. However, the timing of tectonic events and the subduction polarity are still in controversy. In order to better understand these geological problems, a comprehensive study was conducted on the Heiyingshan ophiolitic mélange in the SW Chinese Tianshan. Detailed structural analysis reveals that the ophiolitic mélange is tectonically underlain by sheared and weakly metamorphosed pre-Middle Devonian rocks, and unconformably over lain by non-metamorphic and undeformed lower Carboniferous (Serpukhovian) to Permian strata. The igneous assemblage of the mélange comprises OIB-like alkali basalt and andesite, N-MORB-like tholeiitic basalt, sheeted diabase dikes, cumulate gabbro and peridotite. Mafic rocks display supra-subduction signatures, and some bear evidence of contamination with the continental crust, suggesting a continental marginal (back-arc) basin setting. Zircons of a gabbro were dated at 392±5 Ma by the U–Pb LA-ICP-MS method. Famennian–Visean radiolarian microfossils were found in the siliceous matrix of the ophiolitic mélange. Mylonitic phyllite which displays northward-directed kinematic evidence yielded muscovite 40Ar/39Ar plateau ages of 359±2 Ma and 356±2 Ma. These new data, combined with previously published results, suggest that the mafic protoliths originally formed in a back-arc basin in the Chinese southern Tianshan during the late Silurian to Middle Devonian and were subsequently incorporated into the ophiolitic mélange and thrust northward during the Late Devonian to early Carboniferous. Opening of the back-arc basin was probably induced by south-dipping subduction of the Paleo-Tianshan Ocean in the early Paleozoic, and the Central Tianshan block was rifted away from the Tarim block. Closure of the back-arc basin in the early Carboniferous formed the South Tianshan Suture Zone and re-amalgamated the two blocks.

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1. Introduction

The Tianshan Belt, also known as “Tien Shan” in the literature, is the constituent of the southwestern part of the Central Asia Orogenic Belt (CAOB) (Fig. 1A) (e.g. Jahn et al., 2000; Jahn, 2004; Xiao et al., 2004; Kröner et al., 2007; Windley et al., 2007) or Altaids (Sengör et al., 1993; Sengör and Natal’in, 1996; Xiao et al., 2010). It is a key area for studying the tectonic evolution of the CAOB which is one of the world’s largest, most complex, and long-lasting accretionary orogens. Formation of the CAOB resulted from subduction and closure of multiple oceanic basins in the broad, SW Pacific-type Paleo-Asian Ocean (Khain et al., 2003) and subsequent amalgamation of various microcontinents, magmatic arcs and accretionary complexes between the Tarim-North China and Siberian cratons (e.g. Coleman, 1989; Shu et al., 2002; Charvet et al., 2007; Kröner et al., 2007; Windley et al., 2007).

Tectonic reconstruction of an accretionary orogen requires a good understanding of suture zones which generally contain ophiolitic mélanges. Whether suture zones of diverse ages represent the closure...
of a pre-existing "older" oceanic basin or, alternatively, marginal basins opened behind an older subduction complex, and eventually closed, is rarely considered. Actually, there is evidence for mafic rocks which are found in some mafic/ultramafic mélanges to have been formed in a supra-subduction setting (Hawkins, 2003; Metcalf and Shervais, 2008). Therefore, investigating the geochemical features of these oceanic rocks and the timing of accretion and subsequent closure of the basins provides necessary constraints for a genetic model.

In the southwestern Chinese Tianshan, several mélangé belts have been recognized (e.g., Xiao et al., 1990, 1992; Gao et al., 1998) (Fig. 1B), and studied for their petrological and geochemical characteristics, emplacement times and tectonic significance (Jiang and Li, 1990; Gao et al., 1995a; Tang et al., 1995; Wang et al., 1995b; Liu, 2001; Zhou et al., 2004; Dong et al., 2005, 2006; Yang et al., 2005a; Ma et al., 2006a; Charvet et al., 2007; Shu et al., 2007; Zhu, 2007). However, due to limited data and different interpretations it remains difficult to: (1) correlate them laterally; (2) establish the timing and kinematics of their tectonic emplacement; (3) reconstruct the geodynamic evolution of the southern Tianshan Belt. Consequently, two key issues related to the tectonics of the southern Chinese Tianshan are still in debate. The first one is the age of the high pressure metamorphism which was thought to be either late Paleozoic (e.g., Gao et al., 1998, 2009; Wang et al., 2010; Su et al., 2010) or, alternatively, Triassic (e.g., Zhang et al., 2007; Xiao et al., 2004, 2008). The second issue refers to the subduction polarity of the paleo-Tianshan Ocean. A north-dipping subduction was proposed by Windley et al. (1990), Xiao et al. (2004, 2008), Gao et al. (1998) and Gao and Klemm (2003); whereas south-dipping subduction is apparently supported by structural evidence (Charvet et al., 2007; Wang et al., 2008; Lin et al., 2009). A compromise of bi-directional subduction was suggested by Gao et al. (2009).

In order to place more constraints on the kinematics and age of this orogenic event, we have conducted a comprehensive study on the Heiyingshan ophiolitic mélange in the southern Chinese Tianshan (Figs. 1B and 2). The data set includes structural observations, dating of the ophiolitic blocks and matrix using zircon U–Pb, muscovite 40Ar/39Ar, and paleontological methods, as well as whole-rock and Sr–Nd isotope geochemistry of the magmatic rocks. These new data, and those of the literature, are then combined to discuss the geological significance of the ophiolitic mélange and the tectonic evolution of the southern Chinese Tianshan.

2. Geological background

The Chinese Tianshan is the eastern segment of the Tianshan Belt that extends E–W for more than 2,500 km from China to Central Asian territories (Fig. 1C). It is divided into northern and southern ranges by the Kazakh–Yili and Tu–Ha basins (Fig. 1C). The southern Chinese Tianshan of this study refers to the mountain ranges situated between the Yining and Tarim Cenozoic basins (Fig. 1B). The Chinese Tianshan can be subdivided into five domains which are, from north to south: (1) the Yili–North Tianshan magmatic arc; (2) the high-pressure (HP) metamorphic belt; (3) the Central Tianshan Paleozoic succession and its Proterozoic substratum; (4) the southern Tianshan mélange zones and, (5) the northern Tarim margin.

2.1. Yili–North Tianshan magmatic arc

This domain corresponds to the Bogda–North Tianshan arc in the eastern Tianshan (Charvet et al., 2007), and the "Kazakh (northern Tien Shan)–Yili Plate" in Kazakhstan and Kyrgyzstan (Mikolaičuk et al., 1995; Konopelko et al., 2008; Gao et al., 2009). The magmatic arc comprises Late Devonian to Carboniferous shallow marine and terrigenous sedimentary rocks, calc-alkaline volcanic rocks (363–313 Ma) and I-type granites (370–308 Ma) (e.g., XBGMR, 1993;
Zhu et al., 2005, 2006a,b; Wang et al., 2006, 2007a,b; Xu et al., 2006; Gao et al., 2009). In addition, Silurian to Middle Devonian (436–398 Ma) and minor Ordovician (479–466 Ma) intrusive rocks occur along the Nalati Fault (Zhu et al., 2006c; Konopelko et al., 2008; Gao et al., 2009; Yang and Zhou, 2009).

In the Yili area, a Precambrian metamorphic complex occurs beneath the arc series and is composed of Neoproterozoic granite-gneiss, a series of Mesoproterozoic metasedimentary rocks, and a presumed Paleoproterozoic crystalline basement (e.g., XBGMR, 1993; Allen et al., 1993; Gao et al., 1998; Hu et al., 2006).

2.2. High-pressure (HP) metamorphic complex and associated ophiolitic rocks

A HP metamorphic belt is exposed to the south of the Nalati Fault (fault 1 in Fig. 1B). It consists of greenschist-, blueschist- and eclogite-facies rocks which were probably transformed from sea-floor deposits and basaltic rocks (Gao et al., 1995b, 1999; Ai et al., 2006). Isotopic ages of 415–343 Ma (phengite 40Ar/39Ar plateau and Sm–Nd isochron) were obtained for eclogite and blueschist (Dobretsov et al., 1987; Xiao et al., 1992; Gao et al., 1995b, 2000, 2006; Gao and Klemd, 2003), and the peak HP metamorphism was considered to have occurred at ~345 Ma (Gao and Klemd, 2003; Klemd et al., 2005). Recently, new ages of ~320 Ma (Su et al., 2010) and ~230 Ma (Zhang et al., 2007) (both on zircons from eclogite) were reported and considered as age of peak HP/UHP metamorphism. On the other hand, eclogites and blueschists from both Chinese and Kyrgyzstan Tianshan yielded ages of 331–302 Ma (recrystallized phengite 40Ar/39Ar plateau and Rb–Sr isochron) that were regarded as reflecting the timing of retrograde metamorphism during exhumation of the HP metamorphic rocks (Gao and Klemd, 2003; Stupakov et al., 2004; Klemd et al., 2005; Simonov et al., 2008; Wang et al., 2010).

Ophiolite relics occur sporadically within and closely along the HP metamorphic belt. The protoliths of mafic rocks from the ophiolites were generated in late Neoproterozoic to early Cambrian times. In the Dalubayi ophiolite (locality “d” in Fig. 1B), OIB-like gabbro and basalt were dated at 600±15 Ma and 590±11 Ma (zircon U–Pb), respectively (Yang et al., 2005a; Zhu, 2007). In Xiate (locality “x” in Fig. 1B), an age of 516±7 Ma was obtained for MORB-type basalt (zircon U–Pb SHRIMP) (Qian et al., 2009). Basaltic rocks of the Mishigou and
Gangou ophiolites (localities “m” and “g” in Fig. 1B) (Laurent-Charvet, 2001; Liu et al., 2005; Charvet et al., 2007) were metamorphosed at ca. 345 Ma (phengite $^{40}$Ar/$^{39}$Ar age; Liu and Qian, 2003).

2.3. Central Tianshan Paleozoic succession and Proterozoic substratum

This domain refers to the area located in the Hark Shan and extends eastward to the Erbin Shan and Baluntai areas (Fig. 1B; Wang et al., 2008). It is composed of a Proterozoic basement, an early Paleozoic platform and a deep water sedimentary cover, mid-Paleozoic arc-related intrusive rocks and unconformable Carboniferous platform sediments. The Hark Shan is mainly made up of Ordovician to Silurian marble, dolomite, crystalline limestone with interbedded breccia and clastic rocks (XBGMR, 1993; Wang et al., 1997; Zhou et al., 2001). Late Silurian to Devonian deformed turbidite, shallow-water to deep marine clastic rocks, carbonate and chert are observed in the south of the Kulehu area (locality “k” in Fig. 1B) (Zhou et al., 2001; Zhu, 2007). The Carboniferous series consists of unconformable deformed clastic rocks and limestone without volcanic rocks. An unconformity occurs between the Carboniferous and older rocks (XBGMR, 1993).

Arc-type intermediate to felsic volcanic and volcanoclastic rocks of mostly Ordovician–late Silurian age were recognized in this domain. In the Aheqi area (locality “a” in Fig. 1B), a calc-alkaline andesite yielded a $^{40}$Ar/$^{39}$Ar whole-rock isochron age of 427 ± 5 Ma (Gong et al., 2003). Immediately to the south of the HP metamorphic belt, a rhyolite was dated at ca. 396 Ma (zircon U–Pb age; Zhu, 2007). Ordovician to Silurian weakly deformed arc-type volcanic rocks occur in the south of the Nalati Pass and in the Mishigou area (localities “n” and “m” in Fig. 1B, respectively) (Ma et al., 2006b; Zhu, 2007).

Early-middle Paleozoic I-type granitoids are widely distributed in this domain. They include granodiorite of the Bayinbulak area (447 ± 1 Ma), granites north of Kulehu (dated at 426–425 Ma by the multigrain zircon U–Pb TIMS method; Xu et al., 2006), gabbro and granodiorite between Mishigou and Yushugou (dated at 428–394 Ma by the zircon U–Pb, SHRIMP and TIMS methods; Hopson et al., 1989; Shi et al., 2007; Xu et al., 2006; Yang and Wang, 2006; Yang et al., 2006) (Fig. 1B).

Moreover, A-type granites (470–420 Ma, zircon U–Pb ages) were recognized in this domain; the occurrence of such granites suggests that an extensional regime probably existed during the middle Ordovician to late Silurian (Han et al., 2004). To the north of Kumux, Late Devonian granites (368–361 Ma, zircon U–Pb SHRIMP) show geochemical and isotopic features indicative of a syn-collisional tectonic setting (Shi et al., 2007). In the Kumux and Wuwumen areas (Fig. 1B), late Carboniferous granites (327–297 Ma, zircon U–Pb TIMS) formed in a post-collisional setting (Xu et al., 2006; Zhu et al., 2008a).

The Proterozoic rocks are mainly exposed in the Baluntai area (Fig. 1B) where zircons from an orthogneiss were dated at ~700 Ma by the SHRIMP U–Pb method (Yang et al., 2006; Zhu and Song, 2006). In addition, to the north of Kulehu (Figs. 1B, and 2) zircons from a Neoproterozoic pegmatite were dated at ~931 Ma by the U–Pb method (Xinjiang Bureau of 305 Project, unpublished data). The occurrence of acritarch Brocholaminaria nigrita in a limestone and a whole-rock Rb–Sr isochron age of 606 ± 4 Ma on a quartz-schist suggest a probable Proterozoic age for the migmatite, marble and metasediments (Wang et al., 1995a,b, 1996). These Precambrian rocks are comparable to rocks of the same age in the Tarim block (Hu et al., 2006; Lu et al., 2008), but they are now separated by the southern Tianshan ophiolitic mélangé zones (Fig. 1B; cf. below).

Recent detrital zircon ages and paleocurrent data of Devonian clastic rocks from the Biediele area (locality “b” in Fig. 1B) suggests that a large population of Early Devonian detrital zircons (~415 Ma) originated from the Tarim Block (Luo et al., 2010) which was thus connected with the Central Tianshan at that time. This domain is therefore interpreted as an early Paleozoic continental magmatic arc of the Central Tianshan (Charvet et al., 2007; Wang et al., 2008) rather than a passive margin of northern Tarim (e.g. Chen et al., 1999; Carroll et al., 2001). The basement of this continental arc probably formed one single domain with the northern margin of Tarim (Charvet et al., 2007; Wang et al., 2008).

2.4. Southern Tianshan ophiolitic mélangé zones

To the south, 70–100 km away from the HP metamorphic belt, several ophiolitic mélangé zones occur discontinuously in the areas of Aheqi, Heiyingshan, Serikeya, Kulehu, Wuwumen, Yushugou and Tonghuashan (localities “a”, “h”, “s”, “k”, “w”, “y” and “t” in Fig. 1B, respectively). Near Aheqi, mafic lavas with geochemical affinity of P-MORB yielded a Sm–Nd whole-rock isochron age of 392 ± 15 Ma (Xu et al., 2003). In the Kulehu mélangé, an N-MORB pillowed basalt was dated at 425 ± 8 Ma (zircon U–Pb SHRIMP; Long et al., 2006), and a quartz schist gave a biotite $^{40}$Ar/$^{39}$Ar plateau age of 370 ± 5 Ma which was interpreted as the time of shearing of the highly deformed matrix of the mélangé (Cai et al., 1996). The mélangé was later subject to a thermal overprint at 259 ± 3 Ma (biotite $^{40}$Ar/$^{39}$Ar age at a temperature of 260–300 °C) (Cai et al., 1996). A mylonitic quartzite which is tectonically overlain by the mélangé was metamorphosed at 386 ± 1 Ma (muscovite $^{40}$Ar/$^{39}$Ar plateau age; Li et al., 2004).

In Yushugou, a cumulate gabbro yielded a U–Pb zircon age of 378 ± 6 Ma (Jiang and Li, 1990; Jiang et al., 2000); a granulite–facies metabasalt (Shu et al., 1996, 2004) yielded zircon U–Pb SHRIMP ages of 392–390 Ma (Zhou et al., 2004), and Ca-amphibole $^{40}$Ar/$^{39}$Ar plateau ages of 368–360 Ma (Wang et al., 2003). In the Wuwumen mélangé, tholeiitic basalts have geochemical features of N-MORB (Dong et al., 2005). In the Tonghuashan mélangé, a gabbro was considered to have formed at 420 ± 14 Ma (amphibole K–Ar age) (Zhang and Wu, 1985); blueschist-facies metamorphic rocks (Gao et al., 1993) yielded a glaucophane $^{40}$Ar/$^{39}$Ar age of ca. 360 Ma (Liu and Qian, 2003).

Middle Devonian (Givetian) to early Carboniferous (Tournaisian or Visean) radiolarian and conodont microfossils were found in abundance in cherts of the Kulehu and Heiyingshan mélanges (Gao et al., 1998; Liu, 2001; Zhu, 2007). Early-Middle Devonian radiolarian fossils were also identified in chert blocks in the Tonghuashan mélangé (Gao et al., 1998).

An apparent inconsistency exists between magmatic (U–Pb on zircon) and fossil ages on one hand, and Ar–Ar ages on the other. But still, the magmatic and fossil ages constrain the timing of formation of “oceanic” rocks (mid-Silurian to Early Carboniferous) which are included in the ophiolitic mélangé, and the Ar–Ar ages mostly date either the age of metamorphism during a HP gradient in the Late Devonian to Early Carboniferous and otherwise, later thermal overprint in Permian times.

In addition, according to a recently compiled geological map of the Khan Tengri Massif, southern Kyrgyz Tianshan (Mikolaiuchik and Buchroithner, 2008), early Paleozoic serpentinite, peridotite and gabbro are accompanied with middle Silurian–Carboniferous (?) basalt, spilite, chert, shale and siltstone. However, their structure, age and geochemical significance remain unknown in international literatures.

2.5. Northern Tarim

This domain corresponds proximately to the regions located to the south of the southern Tianshan mélangé zones (Fig. 1). The Paleozoic rocks of this domain are distinct from those of the Central Tianshan in lithologic and tectono-metamorphic features although their basement rocks are similar (Wang et al., 2008). To the southwest of Akesu and southeast of Korla (Fig. 1B), late Cambrian to Middle Devonian strata are composed of non-metamorphic, gently folded marine carbonate and
Devonian arc-type volcanic rocks are developed in the northern
ear the Akesu area (XBGMR, 1993; Liou et al., 1996). Near Korla, gabbro, diorite, quartz diorite and granite
also show calc-alkaline geochemical features; the granite yielded a zircon U–Pb SHRIMP), granodiorite and monzonite display the features of active margin magmatism (Zhu et al., 2008b). More to the south, late Devonian arc-type volcanic rocks are developed in the northern Kukalteka area (Fig. 1B) (Ma et al., 2002).

In the Kyrgyz southern Tianshan, within early Paleozoic thick sedimentary succession (Biske, 1996), Cambro–Ordovician basalt, andesite, lava breccia, tuff and Middle Ordovician diorite, granodiorite and granite occur to the south of the Abashi HP metamorphic belt (Mikolaichuk and Buchroithner, 2008). More to the south, late Silurian Neoproterozoic carbonate and Precambric blueschists crop out in the Akesu area (XBGMR, 1993; Liou et al., 1996).

continental sandstone, unconformably overlain by late Paleozoic to Mesozoic rocks (e.g. XBGMR, 1993; Carroll et al., 1995, 2001). The basement is composed of Archean to Proterozoic amphibolite and orthogneiss, which occur in the Kukalteka area (e.g., Hu et al., 2006; Lu et al., 2008). Neoproterozoic carbonate and Precambrian blueschists crop out in the Akesu area (XBGMR, 1993; Liou et al., 1996).

The south of Serikeya and Kulehu (Fig. 1B), Late Devonian calc-
alkaline diorite (382 ± 6 Ma, zircon U–Pb SHRIMP), granodiorite and monzonite display the features of active margin magmatism (Zhu et al., 2008b). Near Korla, gabbro, diorite, quartz diorite and granite also show calc-alkaline geochemical features; the granite yielded a zircon U–Pb age of 363 ± 2 Ma (Jiang et al., 2001). Moreover, Late Devonian arc-type volcanic rocks are developed in the northern Kukalteka area (Fig. 1B) (Ma et al., 2002).

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serpentinitized, and Cr-spinel has a vermicular habit surrounded by magnetite or set in neoblasts (Fig. 5A). Harzburgite consists of olivine (>70%), orthopyroxene (~25%) and Cr-spinel (<5%). Lherzolite contains olivine (~70%), orthopyroxene (15–20%), clinopyroxene (5–10%), amphibole (<5%) and spinel (<5%). Secondary carbonate is well developed in all ultramafic rocks.

Fig. 3. Field photographs of the Heiyingshan ophiolitic mélangé: (A) pillow lava, (B) sheeted diabase (dike) surrounded by serpentinized peridotite, (C) sheared serpentinite with calcite veins, (D) limestone (“L”) olistoliths, (E) pebbly mudstone, (F) folded calcareous turbidite with disrupted beds corresponding to the matrix of the mélangé, (G) blocks of chert and limestone (“L”) included in the sheared muddy matrix, fibrous quartz or calcite pressure shadows crystallized around sigmoid limestone clasts indicating top-to-the north sense of shear, (H) Devonian foliated marble corresponding to the tectonic substratum (i.e. autochthonous lower unit) underlying the mélangé, the flat slaty cleavage dips to the northwest.
Gabbro is often coarse-grained and locally shows a cumulate texture (Fig. 5B). Main minerals include plagioclase (~60%), clinopyroxene (~30%), amphibole (~5%) and minor olivine (<5%). Diabase is composed of calcic plagioclase, clinopyroxene and Fe/Ti-oxide. Clinopyroxene is partially replaced by chlorite and/or epidote.

Basalt occurs as massive flows or as pillow lava. The size of pillow varies from 20 to 50 cm in diameter (Fig. 3A). Some basalt and basaltic andesite display a porphyritic texture defined by matrix (~50%) and embedded phenocrysts (~30–40%) of clinopyroxene, plagioclase, and subordinate olivine and hornblende. The matrix shows a glass-rich hyalopilitic texture that is characteristic of a sub-crystalline groundmass made up of microcrystals of plagioclase, pyroxene and glass (Fig. 5C). In some cases volcanic rocks also show an aphyritic texture consisting of plagioclase, pyroxene and oxide (Fig. 5D). Most volcanic rocks were subjected to different degrees of alteration, showing replacement of pyroxene by chlorite, epidote and Fe/Ti oxide (Fig. 5C and D), and plagioclase by calcite.

5. Sampling and analytical methods for geochronology and geochemistry

A cumulate gabbro (sample 499-11) was collected from the Heiyingshan ophiolitic mélangé (GPS: N42°13.34′, E82°13.37′). Zircon grains were extracted by crushing, sieving, heavy liquids and magnetic separation, and finally by handpicking under a binocular microscope. Zircons are euhedral, colorless and without fracture. U–Pb dating was carried out at the Radiochronology Laboratory of the Centre of Excellence in Ore Deposits, University of Tasmania, Australia, using a Hewlett Packard HP 4500 quadrupole Inductively Coupled Plasma Mass Spectrometer fitted with a 213 nm NewWave Merchantek UP213.
Nd-YAG Laser. Detailed analytical technique was described by Meffre et al. (2004).

Metapelites (samples 437 and 438-1) were collected from the mylonitic matrix of the mélange (GPS: N42° 14.09′, E82° 12.52′). Fine-grained muscovite was handpicked under a binocular microscope from the ~0.3 mm-size fraction of crushed rock, following thorough ultrasonic rinsing in distilled water. 40Ar/39Ar step-heating of muscovite was conducted at the Institute of Geology, Chinese Academy of Geological Sciences (IG-CAGS, Beijing). The description of analytical technique and procedures can be found in Chen and Liu (2002).

Four siliceous mudstone samples (506-1, 506-2, 511 and 512) were collected from the matrix of the mélange (GPS: N42° 12.68′, E82° 13.66′) and were analyzed for microfossils at the Nanjing Institute of Geology and Paleontology, Chinese Academy of Sciences (NIGP-CAS).

Two peridotites, one cumulate gabbro, six basalts and one andesite were analyzed for whole-rock chemical compositions. Major elements were determined by X-ray fluorescence (XRF) at the Modern Analysis Center, Nanjing University, following procedures described by Couture et al. (1993). Rare earth and other trace elements were analyzed in the State Key Laboratory for Mineral Deposits Research of Nanjing University using a HR-ICP-MS (Finnigan Element II). The analytical technique was described by Gao et al. (2003). A duplication of REE and trace element abundances of the maﬁc–andesitic rocks and sample 499-3 were performed by an ICP-MS method at the Department of Geological Sciences, National Taiwan University (Taipei), using an Agilent 7500s quadrupole ICP-MS. Details of the analytical procedures may be found in Yang et al. (2005b). Analytical errors are 0.5–3% for major elements and 0.7–5% for most REE and trace elements.

Sr and Nd isotopic compositions were determined for the basaltic rocks and andesite using a 7-collector Finnigan MAT-262 mass spectrometer at the Institute of Earth Sciences, Academia Sinica (Taipei). Procedures of chemical separation and analysis were described by Jahn et al. (2009).

6. Age constraints

6.1. Zircon U–Pb age of gabbro

The analytical results of the gabbro sample 499–11 are presented in Table 1 and the isotopic ratios are plotted in a Tera-Wasserburg diagram (Fig. 6). Although cathodoluminescence images were not available, the analyzed zircons can be considered as a magmatic origin on the basis of their euhedral shape and Th/U ratios (N0.1; Table 1) (Vavra et al., 1996). Apparent 206Pb/238U ages are more concordant than 207Pb/206U ages and were therefore used to calculate a mean 206Pb/238U age of 392±5 Ma (MSWD=1.8) from nine analyses that are consistent within errors. This age is interpreted as the crystallization age of the gabbro. Two additional grains give older ages of 419±4 Ma and 434±6 Ma, and the significances of these two ages are not clear.

6.2. 40Ar/39Ar ages of mylonitic metapelite

The 40Ar/39Ar dating results are shown in Table 2 and are further illustrated in Fig. 7. The errors represent 2 sigma deviation for plateau ages. For sample 437, eight steps from 500 °C to 1200 °C with 96.9% of 39Ar release yielded a well deﬁned plateau age of 359±2 Ma (MSWD=0.45). For sample 438-1, a plateau age of 356±2 Ma (MSWD=0.77) is deﬁned by five contiguous steps from 900 °C to 1300 °C with 87.3% of 39Ar release. The two 40Ar/39Ar ages are consistent and hence are interpreted as the age of recrystallization of muscovite during the mylonitization.
6.3. Biostratigraphic constraints on matrix of mélange

The Heiyingshan ophiolitic mélangé was previously assigned to the upper Silurian to Lower Devonian Aertengkesi Formation on the basis of corals, brachiopods, gastropods and crinoid fossils found in blocks of limestone and sandstone (XBGMR, 1983). However, the ages of these blocks are often older than the mélange, and the age of the mélange could be constrained by the matrix. In our samples of siliceous mudstone, derived from a radiolarian chert to the northeast of Heiyingshan (Fig. 2A), representative radiolarian species and their occurrence assemblages of Famennian and Visean ages, respectively. Representative radiolarian species and their occurrence epochs are shown in Fig. 8. This age constraint is consistent with that derived from a radiolarian chert to the northeast of Heiyingshan (Fig. 2A) (Liu, 2001). Thus, early Carboniferous (Visean) represents the upper limit for the formation age of the mélange.

7. Geochemical and isotopic compositions of the magmatic rocks

7.1. Major elements

The gabbro has a moderately high Mg# value (0.84) and high abundances of Al2O3 (19.4%) and CaO (10.2%), consistent with its cumulate origin. The basaltic rocks can be subdivided into two groups: tholeiitic and alkali basalt (Fig. 9). The tholeiitic basalts (samples 499-3, 499-6 and pillow basalt sample 499-8) have relatively low contents of K2O (2.0%) and alkali basalt (Fig. 9). The tholeiitic basalts (samples 499-3, 499-6 and 499-8) have relatively low contents of K2O (2.0%). The alkali basalt has a higher Mg# value (0.72) and lower Al2O3 content than normal calc-alkaline (Table 3; Wilson, 1989).

7.2. REE and trace elements

The peridotites are typically rich in Ni and Cr, and depleted in REE and high field strength (HFS) elements compared to the primitive mantle (~0.1 × PM) (Sun and McDonough, 1989) (Table 3). The gabbro is also poor in HFS elements and REE (2× CI abundances), a feature consistent with its cumulate character. The REE pattern has a slightly negative slope and displays a strong positive Eu anomaly (Eu/Eu* = 1.8), which is likely due to plagioclase accumulation. In multi-element variation diagrams, the negative anomalies in Nb, Ta, Zr, Hf, Th and Y, are mostly “immobile” during alteration, and this is supported by their consistent compositions within subgroup (Table 3; Fig. 10). Therefore, only “immobile” incompatible trace elements and REE are considered in the following discussion on petrogenesis and tectonic setting of these magmatic rocks.

Table 1

<table>
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<tr>
<th>Analyses</th>
<th>U (ppm)</th>
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<th>Pb (ppm)</th>
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<th>Apparent ages in Ma</th>
<th>Disc. (%)</th>
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<td>11</td>
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Note: Analyses done at the School of Earth Sciences, University of Tasmania (Australia).

⁎ Disc. (%) denotes percentage of discordance.
lower in total REE abundance (Fig. 10A). In multi-element variation diagrams (Fig. 10B), weak depletion in Nb, Ta and Zr, Hf and positive Eu anomalies (EuN/Eu*=1.0) can be observed. These features are distinct from those of the typical N-MORB (Fig. 10B).

The alkali basalts display LREE-enriched patterns (LaN/SmN =3.3–3.4, LaN/YbN =8.6–8.9) (Table 3) which are similar to that of OIB, but HREE are less fractionated (Fig. 10C). In the multi-element variation diagram (Fig. 10D) the alkali basalts demonstrate a pronounced depletion in Nb and Ta as compared to typical OIB. Note that both the tholeiitic and alkali basalts have relatively high Th contents (Fig. 10), the significance of which will be discussed later.

The andesite has REE and multi-element variation patterns similar to the alkali basalts. A negative Eu anomaly indicates a fractionated character (Fig. 10C and D). However, its lower total REE abundance than the alkali basalts in spite of a higher SiO2 content suggests that the andesite is unlikely to be genetically related to the alkali basalts.

7.3. Sr and Nd isotopic compositions

Sr and Nd isotopic data are reported in Table 4. Initial εNd(t) values were calculated using the age of the gabbro (~395 Ma), assuming that it is more or less contemporaneous with the extrusive rocks. The tholeiitic basalts have εNd(395) values ranging from +7.2 to +10.7. Their high initial Sr isotopic data (0.7070–0.7084) are probably related to incorporation of radiogenic Sr during alteration (Jahn et al., 1980; Fig. 11). In contrast, the alkali basalts show negative εNd(395) values (~3.7 to ~3.9), but their initial Sr isotopic data (0.7073 to 0.7075) are similar to those of the tholeiites, and this feature may also have resulted from alteration. The andesite sample has an εNd(395) of ~4.7 and εNd(395) =0.7064.

Fig. 7. 40Ar/39Ar age spectra of muscovites from mylonitic matrix of the Heiyingshan melange.
in relation to the tectonic evolution of the region. The north-dipping subduction model was proposed (Windley et al., 1990; Allen et al., 1993; Gao et al., 1998; Chen et al., 1999; Zhou et al., 2001) mainly based on (1) a well documented large-scale south-vergent fold-and-thrust system both in the Kyrgyz Tianshan (Biske, 1996; Biske and Seltmann, 2010) and in Chinese southern Tianshan (Allen et al., 1993), (2) arc magmatism in the Yili–Kazakhstan block and in Kyrgyzstan Central Tianshan, and (3) thick Paleozoic sedimentary succession in the northern part of the Tarim basin, interpreted as a passive margin (Chen et al., 1999; Carroll et al., 2001). On the contrary, a south-directed subduction was suggested (Charvet et al., 2007; Wang et al., 2008; Gao et al., 2009) on the basis of (1) northward ductile deformation in high-grade metamorphic rocks and ophiolitic mélangé zones in the southern Chinese Tianshan (Charvet et al., 2007; Lin et al., 2009; Wang et al., 2010), and (2) arc-type magmatic rocks in the southern Tianshan and northern Tarim (Jiang et al., 2001; Ma et al., 2002; Zhu et al., 2008b).

This controversy is a result of (i) a long-lasting confusion on the location of suture zones, (ii) recognition or not of arc-type magmatism, and therefore opposite interpretations of an active margin or a passive margin in the northern Tarim block, and (iii) different interpretation that either north-directed ductile deformation or south-vergent thrusting corresponds to the Paleozoic accretion. In the following, previously published data and new results of this study are synthesized to better understand above-mentioned problems and to discuss the tectonics of the southern Chinese Tianshan.

8.1. Occurrence of a back-arc basin in the southern Chinese Tianshan

The ultramafic and mafic rocks in the Heiyingshan mélangé are tectonically associated with chert and limestone, forming a dismembered ophiolite suite. However, the mafic rocks may have originated from different sources on the basis of the geochemical composition of “immobile” incompatible trace elements and Nd isotope that were not modified by secondary alteration. The tholeiitic basalts have N-MORB REE patterns, trace element abundances, and positive εNd(T) values close to that of present-day depleted mantle. They also show trace element ratios (Zr/Nb = 24–46, Zr/Hf = 29–31 and Nb/Ta = 13–14; Table 3) similar to N-MORB (~30, ~36 and 6–14, respectively; Rollinson, 1993), and plot in the field of N-MORB in the Nb–Zr–Y diagram (Meschede, 1986; Fig. 12A). Therefore, they were most probably produced from a depleted mantle source.

Taking into account the occurrence of pillow lava and abyssal chert in the mélangé, the ophiolitic suite is likely to represent an oceanic crust. The associated dunite, harzburgite and minor lherzolite may thus be remnants of the oceanic lower crust and upper mantle. Some ultramafic rocks could have been generated by a relatively high degree of partial melting and fractionation of the upper mantle (Bodinier and Godard, 2004).

The low content of incompatible elements in the tholeiitic basalts is consistent with a depleted mantle source or, alternatively, may be due to a high degree of hydrous melting. This is corroborated by the weak Nb and Ta (and Ti) negative anomalies (Fig. 10B), indicating that the source...
contained Nb–Ta retaining refractory minerals (ilmenite and pargasitic amphibole) which are generally present in metasomatised (e.g. hydrous) mantle sources. Such features are frequently related to a supra-subduction setting where the residual depleted mantle was metasomatized by slab-derived fluids (Hawkins, 2003; Kim et al., 2003).

In addition, a high Th content in the tholeiitic basalts may indicate an effect of contamination by continental crust. Thus, the tholeiitic basalts were likely generated during the early stage of continental back-arc basin opening rather than in a fore arc basin (Wilson, 1989; Metcalf and Shervais, 2008; Fig. 12B). Although no isotopic data are

### Table 3

<table>
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<tr>
<th>Samples</th>
<th>Andesite</th>
<th>Alkali basalts</th>
<th>Tholeiitic basalts</th>
<th>Gabbro</th>
<th>Peridotites</th>
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<td>499-9</td>
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<td>99.7</td>
<td>99.7</td>
<td>99.4</td>
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</tbody>
</table>

Notes: REE and trace elements of gabbro and peridotites and all major elements were analyzed at Nanjing University; the REE and trace elements of the andesite of basalts were analyzed at National Taiwan University.

* Mg# = MgO/(MgO + 0.505 × (Fe₂O₃ × 0.9 + FeO)) assuming that FeO equals to 90% of total Fe-oxide.
* Eu* = (SmN × GdN)¹/²; N: normalized to chondrites (Sun and McDonough, 1989).
* n: normalized to primitive mantle (Sun and McDonough, 1989).
available for the gabbro due to its low Nd content, this rocks shows a geochemical affinity to E-MORB (Fig. 12A), suggesting that it probably formed during a later stage of back-arc spreading (Fig. 12B).

In contrast, the alkali basalts and andesite have negative εNd(t) values, indicating that they contain either an enriched mantle or continental component (Rollinson, 1993). Their Nd depleted mantle model ages and fractionation factors (Table 4) as well as REE signatures preferably suggest significant crustal contamination by continental crust (Fig. 11). The OIB-like geochemical features (Fig. 10C and D) suggest that the alkali basalts and andesite were produced in a within-pllate setting (Fig. 12A). However, the negative Nb and Ta anomalies of the alkali basalts and andesite were probably produced by slab-derived fluids, hence implying the formation of these rocks in a supra-subduction environment. Therefore, we suggest that a continental back-arc rift could be the most likely tectonic setting for the alkali basalts and andesite which were generated during the very early stages of the opening of the continental back-arc basin.

The andesite, if compared to the alkali basalts, has geochemical characteristics closer to OIB (Fig. 10C and D). Such OIB-like andesite with a subtle arc signature is analogous to andesites from the Ryukyu arc of SW Japan (Shinjo, 1999) and basaltic andesites in northern Taiwan (Wang et al., 2002). Both were formed in modern back-arc basin settings.

8.2. Two distinct suture zones in the southern Chinese Tianshan

The geochemical and isotopic features of the Heiyingshan tholeiitic basalts are comparable with those of mafic rocks from adjacent ophiolitic mélanges zones. At Wuwumen (Fig. 1B), the source of N-MORB-like tholeiitic basalts was interpreted to have been metasomatized by slab-derived fluids (Dong et al., 2005), and their high primitive-mantle-normalized Th/Nb ratios (1.4–5.9) suggest significant crustal contamination (Saunders et al., 1992). At the Kulehu and Serikeya localities (Fig. 1B), N-MORB-type tholeiite and E-MORB-like alkali basalt were interpreted to be derived from mantle sources with involvement of sea-floor sediments and the subcontinental lithosphere (Gao et al. 1995a; Tang et al., 1995; Long et al. 2006; Ma et al. 2006a). The ophiolitic rocks in the Yushugou and Tonghuashan mélanges (Fig. 1B) were also considered to have formed in a back-arc basin (Ma et al., 1990; Shu et al., 2004; Charvet et al., 2007).

The gabbro in the Heiyingshan ophiolite (392 ± 5 Ma) was emplaced contemporaneously with the gabbro and granulite-facies meta-mafic rocks in the Yushugou ophiolite (392–378 Ma; Jiang et al., 2000; Zhou et al., 2004). These ages are comparable with that of the basalt from the Kulehu ophiolite (425 Ma; Long et al., 2006). In addition, Late Devonian to early Carboniferous radiolarian-bearing siliceous muddy matrix of the Heiyingshan mélange may be correlated with the Middle Devonian–early Carboniferous radiolarian-beraring cherts in the Kulehu and Tonghuashan mélanges (Gao et al., 1998; Liu, 2001; Zhu, 2007).

Structural analyses show that the ophiolitic mélanges in Heiyingshan and adjacent Kulehu, Yushugou and Tonghuashan (Shu et al., 1996; Charvet et al., 2007) tectonically overlie a metamorphosed substratum, in which kinematic indicators of top-to-the-north ductile shearing suggest that the ophiolitic mélanges were transported from south to north. Our muscovite ⁴⁰Ar/³⁹Ar dates (359–356 Ma) for mylonitized pelites from the Heiyingshan mélange are consistent with the age of deformation and metamorphism (370–360 Ma) in the Kulehu, Yushugou and Tonghuashan ophiolitic mélanges and their tectonic substrata (Cai et al., 1996; Liu and Qian, 2003; Wang et al., 2003; Li et al., 2004).

In summary, the Heiyingshan ophiolitic mélange is comparable to those in the Kulehu, Serikeya, Wuwumen, Yushugou-Tonghuashan and Aheqi areas in terms of: (1) geochemical affinity and geodynamic setting of mafic rocks; (2) ages of the ophiolitic rocks; (3) timing and kinematics of tectonic emplacement. Therefore, linearly distributed ophiolitic mélange zones in the southern Chinese Tianshan (Fig. 1B) likely represent remnants of one single suture related to the South Tianshan back-arc basin.

Some authors (e.g., Windley et al., 1990; Gao et al., 1998) regarded these ophiolitic mélange zones as tectonic klippen transported southward over ca. 100 km from the HP metamorphic belt and the associated ophiolitic mélange zone located farther north (Fig. 1B; see Sections 2.2 and 2.4). Therefore, the HP metamorphic complex and all ophiolitic mélanges within the southern Chinese Tianshan were considered to represent one single suture zone rooted along the Nalati Fault (Fig. 1B). However, this interpretation is not supported by this study and other recent research for the following reasons: (a) kinematic features of the above-mentioned ophiolitic mélange zones (Shu et al., 1996; Charvet et al., 2007; this study) consistently indicate northward emplacement rather than tectonic klippen transported southward; (b) T-MORB, OIB and seamount protoliths of the HP metamorphic rocks and the Xiate-Dalubayi ophiolites show no supra-subduction signature nor continental contamination (Gao et al., 1995b; Qian et al., 2007, 2009; Simonov et al., 2008) and thus probably formed in a larger oceanic basin different from the South Tianshan continental back-arc basin; (c) the ages of the mafic rocks in the Xiate-Dalubayi ophiolites (600–516 Ma) are ca. 90–140 Ma older than those of the ophiolitic rocks (425–378 Ma) in Heiyingshan, Kulehu and Yushugou areas; therefore, they most likely belong to a separate (and older) oceanic crust.
Consequently, at least two suture zones can be distinguished in the southern Chinese Tianshan, namely, a Central Tianshan Suture to the north along the HP metamorphic belt and a South Tianshan Suture to the south in Heiyingshan–Kulehu, extending eastwards to Wuwamen and Yushugou and westwards to the Biediele and Aheqi areas (Fig. 1B; Charvet et al., 2007; Wang et al., 2008). Westward extension of the Central Tianshan Suture was considered to be separated into two different suture zones (Qian et al., 2007, 2009; Gao et al., 2009): (1) a northern one related with the Terskey Ocean that was probably closed in the Early Ordovician, resulting in the amalgamation of the Kyrgyz Central Tianshan and the Kazakhstan–Yili blocks (Mikolaichuk et al., 1997; Burtman, 2006), and (2) a southern one corresponding to the Atbashi–Inylchek zone that probably resulted from closure of the Turkestan Ocean (Paleo-Tianshan Ocean in China) (Burtman, 2006; Biske and Seltmann, 2010). The equivalent of the South Tianshan Suture in Kyrgyzstan is not clear since the age and geochemical affinities of the ultramafic–mafic assemblages in the southern Kyrgyz Tianshan (Mikolaichuk and Buchroithner, 2008) are not available in international literatures yet.

8.3. An active northern margin of the Tarim craton

The northern Tarim craton has generally been considered as a passive margin characterized by Cambrian–Ordovician carbonate rocks. However, recent studies have suggested that the Tarim craton was an active margin. The northern margin of the Tarim craton is marked by the presence of a thick sedimentary sequence, which is interpreted as a passive margin sedimentary wedge. However, the presence of ophiolite complexes and other oceanic features, such as spreading centers and fracture zones, indicates that the northern margin of the Tarim craton was an active margin. These features suggest that the Tarim craton was an active margin during the Early Paleozoic, and that it was subducted beneath the Cathaysia block in the Late Paleozoic.

Table 4

<table>
<thead>
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<th>Sr (ppm)</th>
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<th>87Sr/86Sm</th>
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Note: Analyses done at the Institute of Earth Sciences, Academia Sinica (Taipei).  
Ages are given assuming that the volcanic rocks are synchronously with the gabbro that is dated at 392 ± 5 Ma.

1 Sm/Nd (fractionation factor) = [(144Sm/144Nd)sample / (144Sm/144Nd)chondrite] – 1.  
2 εNd (single-stage model age) = (1/λ) ln([143Nd/144Nd]sample / [143Nd/144Nd]chondrite) – 1, where s stands for sample, λ = 0.000035 Ga – 1 is the decay constant of 147Sm.

Fig. 10. Chondrite-normalized REE patterns and primitive mantle-normalized multi-element variation diagrams for tholeiitic basalts (A and B) and alkali basalts (C and D) in the Heiyingshan mélangé. Normalization values for Condrite and primitive mantle, and data source for reference lines of average N-MORB and OIB are from Sun and McDonough (1989).
Fig. 11. εNd(395 Ma) vs. ISr(t) diagram for volcanic rocks of the Heiyingshan ophiolitic mélangé, T (395 Ma) is the age of the volcanic rocks supposed to be contemporaneous with the dated gabbro. Reference fields for MORB and OIB are after Zindler and Hart (1986).

Fig. 12. Discrimination diagrams for the tectonic setting of magmatic rocks from the Heiyingshan ophiolitic mélangé: (A) Zr/4 – Nb*2 – Y diagram after Meschede (1986), (B) Th/Yb vs. Nb/Yb diagram after Metcalf and Shervais (2008).
of Paleozoic and older lithotectonic complexes had been changed due to deep denudation and plantation during Mesozoic times. Hence, although post-orogenic wrench faults (e.g., Nikolaev Line) and Cenozoic mega-thrusts may have partially inherited the Paleozoic accretionary structures (Makarov et al., 2010), they cannot be considered to act as boundaries between two continental blocks (Mikolaichuk et al., 1995; Wang et al., 2010).

In addition, south-vergent fold-and-thrust structures occurring extensively in the southern Tianshan should be prudently used in reconstructing the polarity of oceanic subduction because (i) these structures occur both in the Paleozoic rocks and in Mesozoic-Tertiary rocks and show a deformation style of imbricate fold-and-thrust belt (Lu et al., 1994; Biske, 1996; Allen et al., 1999; Biske and Seltmann, 2010) which is similar to thin-skinned structure generated in middle to upper crustal level, and therefore cannot be distinguished from the Cenozoic deformation (e.g., Hendrix et al., 1994); (2) some south-vergent structures might be Paleozoic, but they often overprint earlier ductile structures (foliation, lineation and top-to-the-north shear kinematics), and thus, they most likely reflect back-thrusting during a later stage of accretion and collisional orogeny. Therefore, in a multi-stage orogenic belt like the Tianshan, large-scale brittle–ductile south-vergent thrusting and folding in southern Tianshan and northern Tarim could be related to late- or post-orogenic deformation and/or secondary reactivation during Cenozoic intracontinental shortening.

Whereas, the north-vergent structures were preserved exclusively in medium to high-grade rocks that formed a highly deformed autochthonous substratum of ophiolitic relics (Gao et al., 1995a; Charvet et al., 2007; Wang et al., 2008, 2010; Lin et al., 2009). These ductile structures indicate an intense deformation occurred in deeper

![Fig. 13. Simplified tectonic model for the Paleozoic evolution of the southern Chinese Tianshan (modified from Wang et al., 2008) (see discussion for details).]
crustal level mostly likely during subduction. Thus, although in small-scale and extensively overprinted by south-vertic geotypes, the ductile north-directed deformation is significant enough to suggest a north-vertic accretionary complex.

8.5. Subduction polarity of the paleo-Tianshan Ocean and Paleozone tectonics of the southern Chinese Tianshan

On the basis of the above discussion, a south-directed subduction of the Paleo-Tianshan Oceanic lithosphere below the Central Tianshan–northern Tarim seems more likely than northward subduction beneath the Yili–Kazakhstan microcontinent. In this interpretation, arc magmatism in the Chinese Yili–North Tianshan has been considered as a result of south-directed subduction of the North Tianshan oceanic lithosphere (Allen et al., 1993; Charvet et al., 2007; Wang et al., 2008) or, alternatively, as a consequence of bi-directional subduction of the Paleo-Tianshan Ocean (Gao et al., 2009).

The Chinese Central Tianshan, located between the Central Tianshan and South Tianshan sutures, constitutes the northern part of the Tarim craton upon which a magmatic arc developed during the Ordovician to Mid-Silurian. Arc magmatism was probably occurred due to south-dipping subduction of the Paleo-Tianshan Oceanic crust that separated the Kazakhstan–Yili block to the North from the Central Tianshan–Tarim block to the south (Charvet et al., 2007; Wang et al., 2008; Gao et al., 2009). After a period of active margin magmatism, back-arc extension occurred in the Middle Ordovician–Mid Silurian to produce A-type granites (Han et al., 2004) and OIB-like alkali basalt and andesite (this study) (Fig. 13A). Subsequently, active-margin magmatism temporarily ceased, and a back-arc basin formed since ~425 Ma (Fig. 13B). The opening of the back-arc basin tilted the early Paleozone Central Tianshan continental arc away from the Tarim block.

In the Middle Devonian, oceanic crust of the South Tianshan back-arc basin subducted beneath the Tarim block, generating calc–alkaline magmatism along the northern Tarim margin (Jiang et al., 2001; Ma et al., 2002; Zhu et al., 2008b) (Fig. 13C). Closure of the South Tianshan Ocean was closed, and collision between the Kazakhstan–Yili block and the Central Tianshan–Tarim assemblage occurred during the Late Devonian to early Carboniferous (e.g., Gao and Klemd, 2003; Wang et al., 2010; Fig. 13D).

9. Conclusions

The Heiyingshan mélangé is composed of dismembered ophiolitic rocks and sediments. The petrographic and geochemical data suggest that gabbro, peridotite and N-MORB-like basalts were derived from depleted mantle, whereas OIB-like basalts and andesite were contaminated by continental crust. The volcanic rocks probably originated in a supra-subduction environment and were variably modified by slab-derived fluids and continental material. The alkali basalts and andesite were produced during back-arc rifting, and tholeiitic basalt, gabbro and peridotite were formed in the South Tianshan back-arc basin initiated along the northern active margin of the Tarim Block.

Our zircon U–Pb age for the gabbro as well as biostratigraphic data, combined with previously published results, suggest that the South Tianshan back-arc basin formed during the late Silurian to Middle Devonian (425–378 Ma) and existed up to the early Carboniferous (Visean). Field observations, muscovite 40Ar/39Ar dating on mylonitic pelites from the mélange, and previously dated arc magmatism all indicate that the back-arc basin began to close in the Middle-Late Devonian and was consumed in the early Carboniferous (368–356 Ma). The ophiolitic mélanges were emplaced from south to north and thereafter over lain, unconformably, by Serpukhovian-age sediments.

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References


