Carboniferous back-arc extension in the southern Yili-Central Tianshan Block and its significance to the formation of the Kazakhstan Orocline: insights from the Wusun Mountain volcanic belt

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Received: 16 March 2021 / Accepted: 10 September 2021 / Published online: 8 November 2021
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Abstract
In Central Asia, the Carboniferous is a crucial period in the formation of the Tianshan Belt and associated bending of the Kazakhstan tectonic collage. In order to reveal Carboniferous magmatic events of the region and their tectonic implications, we conducted field investigations, zircon U–Pb dating, whole-rock geochemical and Sr–Nd isotopic studies on the Early Carboniferous Dahalajunshan Formation and Late Carboniferous Yishijilike Formation volcanic rocks of the Wusun Mountain Range (southern Yili-Central Tianshan Block). Volcanic rocks of the Dahalajunshan Formation consist of calc-alkaline basalt, andesite and dacite, yielding new zircon U–Pb ages of ~ 350 Ma. They have positive whole-rock εNd(t) values (+0.5 to +1.6). In contrast, the Yishijilike Formation volcanic rocks dominantly comprise alkaline and calc-alkaline bimodal suites that erupted at ~ 337 Ma to 313 Ma and have higher whole-rock εNd(t) values (+2.3 to +4.3). These two episodes of Carboniferous magmatism were correlated with partial melting of depleted mantle that metasomatized by slab-derived fluids. The late Carboniferous Wusun Mountain magmatic belt shows characteristics of a back-arc system that evolved due to trench retreat relative to the southern margin of the Yili-Central Tianshan Block. This mechanism induced an extensional regime with gradually depleting magma sources. The asymmetric retreat of the paleo-subduction zones of the South Tian-shan Ocean and Junggar Ocean relative to the Yili-Central Tianshan Block was hence a vital driving force for the bending of the Kazakhstan Orocline.

Keywords Accretionary orogen · Back-arc extension · Western Chinese Tianshan · Yili-Central Tianshan Block · Kazakhstan Orocline

Introduction
Accretionary orogens form at intraoceanic and active continental margins due to the subduction of oceanic plates (Cawood et al. 2009). These orogens are commonly affected by oroclinal bending, accretion of magmatic arcs, back-arcs, ophiolitic mélanges and continental fragments (Cawood et al. 2009, 2011; Johnston 2004; Van der Voo 2004). Based on the rates and dips of the subducting plates, accretionary orogens can be grouped into advancing and retreating types. Advancing accretionary orogens form when convergence of the overriding plate advances more rapidly compared to the subducting plate. This results in compressional forces in the overriding plate. Consequently, advancing orogens generally have thickened crust, develop retro-arc fold-and-thrust belts, and are associated with magmatic rocks derived from enriched magma sources. In contrast, retreating orogens form when the rate of trench retreat progresses faster than convergence of the overriding plate. Retreating orogens can thus be associated with an extensional state, thinner crust, and induce arc break-up or arc-back-arc extensional systems (Collins 2002; Collins et al. 2011; Cawood et al. 2009; Kemp et al. 2009). Back-arc extension is hence generally

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related to retreating orogens and shows a distinctive geological process that records complicated behaviors of the subducted oceanic lithosphere, asthenosphere and upper overriding plate, such as the changing of the oceanic plate’s dip, asthenospheric upwelling and/or trench retreat or slab roll-back (Heuret and Lallemand 2005; Pearce and Stern 2006; Schellart and Lister 2004). In some cases, the asthenospheric upwelling may lead to distinct melting sources (e.g., depleted MORB mantle, subcontinental mantle, and subduction component-enriched lithospheric mantle) and produce significant magmatic activity (Gribble et al. 1996, 1998; Ishizuka et al. 2010; Pearce et al. 2005; Shinjo et al. 1999; Shinjo and Kato 2000; Stern et al. 1990). Large-scale magmatic activity makes the back-arc lithosphere thinner, hotter and weaker; therefore, the back-arc region is easy to extend by the force developed at plate boundaries and may result in ensuing mobile belts (Hyndman and Currie 2011; Hyndman et al. 2005). In addition, the trench retreat or slab roll-back can cause curvature of the subduction zone to form an orocline with diverse geometries (Schellart et al. 2002, 2007). Thus, identifying back-arc extension, understanding its magmatic activity and tectonic evolution can help explain the type of the accretionary orogeny that might develop. It can also provide insights into crust-mantle interaction, lithospheric structure and oroclinal bending (Cawood et al. 2009, 2011; Pearce et al. 2005; Schellart et al. 2007; Stern et al. 2003; Wilhem et al. 2012; Xiao et al. 2018). The Central Asian Orogenic Belt (CAOB) is one of the largest accretionary orogens in the world. It is situated between the Siberian Craton to the north and the North China-Tarim Cratons to the south (Fig. 1a; Şengör et al. 1993; Windley et al. 2007; Xiao et al. 2004). The western CAOB is characterized by the horseshoe-shaped Kazakhstan Orocline. Its formation had a significant effect on the architecture of the CAOB (Fig. 1b). The main parts of the Kazakhstan Orocline comprise the so-called central Devonian Volcanic Belt (DVB) and the internal Balkhash–Yili arc (Fig. 1b, c; Bazhenov et al. 2012). The Tianshan Belt is located in the internal Balkhash–Yili arc, and its formation was associated with the consumption of two major oceanic plates (i.e. the Junggar Ocean and the South Tianshan Ocean; Charvet et al. 2007, 2011; Gao et al. 1998, 2009a; Han et al. 2011; Wang et al. 2008; Xiao et al. 2013). Formation of the ancestral Tianshan also had a genetic link with the bending of the Kazakhstan Orocline (Abrajevitch et al. 2008; Li et al. 2017a, 2018; Yi et al. 2015). The closure of the Junggar and South Tianshan Oceans caused the amalgamation of diverse island arcs, seamounts, accretionary prisms and micro-continents, and ended up with the docking of the Junggar Plate to the north and the Tarim Craton to the south (Charvet et al. 2007, 2011; Gao et al. 1998, 2009a; Han et al. 2011; Wang et al. 2008; Xiao et al. 2013). The asymmetric slab roll-back of the Junggar oceanic plate drove the first-stage formation of the Kazakhstan Orocline during the Late Devonian to Early Carboniferous (Li et al. 2017a, 2018). The subduction of the South Tianshan oceanic plate during the Late Devonian to Early Carboniferous was almost contemporaneous with the timing of the first-stage bending of the Kazakhstan Orocline (Gao et al. 2009a; Han et al. 2015; Han and Zhao 2018; Huang et al. 2020; Jiang et al. 2014; Li et al. 2017a, 2018; Long et al. 2011; Xia et al. 2014). However, the subduction evolution of the South Tianshan oceanic plate is still poorly understood. Complex subduction and accretion processes took place during the aforementioned period, producing massive Late Paleozoic magmatism in the western Chinese Tianshan, which is well recorded in a series of widespread Carboniferous volcanic rocks (XBGMR 1993). Previous studies suggested that they were formed in an intracontinental rift setting (Xia et al. 2012; Xia and Li 2020), a continental arc setting (An et al. 2013; Tang et al. 2013; Wang et al. 2007b; Yu et al. 2016; Zhong et al. 2017; Zhu et al. 2009), a post-collisional setting (Chen et al. 2020; Feng and Zhu 2019; Ge et al. 2015; Long et al. 2012; Sun et al. 2008; Xiao et al. 2010) or a back-arc extensional setting (Cao et al. 2017; Qian et al. 2006; Su et al. 2018; Wang et al. 2018a, b, 2019; Yan et al. 2015). Due to these controversial interpretations, their tectonic setting, and especially the implication that they have for the formation of the Kazakhstan Orocline, still warrant further elaboration.

In this contribution, we present new zircon U–Pb, whole-rock major and trace element, and Sr–Nd isotopic data of the Carboniferous volcanic rocks from the Wusun Mountain Range, in the southern part of the Balkhash–Yili arc (Su et al. 2018). Our data, together with published results, allow us to uncover the nature of the magma source, geodynamic process as well as the formation of the Kazakhstan Orocline in the Late Paleozoic accretionary orogenesis.

**Geological background**

The Kazakhstan tectonic collage mainly includes the Chin-giz Arc, Kokchetav-North Tianshan Block, Balkash-Yili Block, Devonian Volcanic Belt (DVB) and Stepnyak-North Tianshan Block (SNT) (Fig. 1b; Bazhenov et al. 2012; Windley et al. 2007; Xiao et al. 2015). It welded the Tarim Craton in the south by the intervening South Tianshan Belt (Fig. 1b; Windley et al. 2007; Xiao et al. 2015). The western Chinese Tianshan is the southernmost part of the Kazakhstan collage and can be further divided into four tectonic units, being (1) the North Tianshan Belt, (2) the Yili Block, (3) the Central Tianshan Block and (4) the South Tianshan Belt (Fig. 2). These tectonic units are separated by several suture zones and ductile shear zones. 

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Fig. 1  

(a) Location of the Central Asian Orogenic Belt (modified after Şengör and Natal' in 1996; Şengör et al. 1993);  
(b) geological map of the Kazakhstan collage system in the western CAOB (modified after Windley et al. 2007; Xiao et al. 2015);  
(c) the Kazakhstan Orocline before and after bending (modified after Bazhenov et al. 2012).
The North Tianshan Belt is a Late Paleozoic accretionary complex related to the subduction of the Junggar oceanic plate. It mainly contains Devonian-Carboniferous volcanic rocks, turbidites and ophiolitic mélanges (Gao et al. 1998; Li et al. 2014). The final terrane amalgamation is estimated to have occurred in the Late Carboniferous (~316 Ma) as constrained by ‘stitching granites’ crosscutting the mélangé zone (Han et al. 2010). The South Tianshan Belt is also considered to be an accretionary complex, which resulted from the subduction of the South Tianshan oceanic plate (Gao et al. 1998, 2009a; Xiao et al. 2013). Ophiolitic mélanges, numerous granitic intrusions and an ultrahigh pressure metamorphic belt, crop out along the northern margin of the South Tianshan (Gao and Klemd 2003; Gao et al. 2011; Han et al. 2011; Long et al. 2008, 2011). The ophiolitic mélangé belts discontinuously occur in the Heiyingshan, Kumishi, Kulehu, Baleigong and Guluogou areas (Gao et al. 2006; Han et al. 2011; Jiang et al. 2014; Wang et al. 2011; Yang et al. 2018). The granitoid plutons in the South Tianshan intruded the northern margin of the Tarim Craton and are predominantly composed of syenites, two-mica peraluminous leucogranites and A-type rapakivi granites (Gao et al. 2009a; Gou and Zhang 2016; Gou et al. 2012, 2015; Long et al. 2008, 2011). The HP/UHP metamorphic belt is dominated by foliated metapelites, eclogites, blueschists and marbles (Gao and Klemd 2003; Tan et al. 2019; Zhang et al. 2007, 2013).

The Yili Block is a wedge-shaped domain situated in the easternmost part of the Balkhash-Yili Block, while the adjacent Central Tianshan Block is an arc terrane along the southern margin of the Yili Block (Fig. 2). These two tectonic units merged to form the Yili-Central Tianshan Block as a result of the closure of the ‘Terskey Ocean’ in the Early Paleozoic (Gao et al. 2009b; Han et al. 2011; Wilhem et al. 2012). The basement of the Yili-Central Tianshan Block is composed of Precambrian amphibolitic and granitic gneisses (Chen et al. 1999; Gao et al. 2015; Hu et al. 2000; Huang et al. 2015b; Wang et al. 2014a, b, 2017, 2020). The sedimentary covers are composed of Cambrian and Ordovician chert, and carbonates that crop out in the Sayram Lake and Guozigou area (Che et al. 1994; Coleman 1989; Gao et al. 1998; Liu et al. 2014a; Wang et al. 2008; XBGMR 1993). Silurian flysch and intercalated calc-alkaline volcanic rocks are distributed along the Borohoro Mountain Range (Wang et al. 1994). Devonian rocks are sporadically exposed in the North Tianshan and composed of conglomerates, sandstones, siltstones, rhyolite and andesite (XBGMR 1993). The Carboniferous volcanic rocks are widespread both at the northern and southern margins of the Yili-Central
Tianshan Block, such as in the Borohoro Mountain Range, Keguqin Mountain Range, Tulasu Basin, Awulale Range, Wusun Mountain Range, and the Haerk and Nalati Mountain Range (Fig. 2). These volcanic strata mainly consist of conglomerate, sandstone, tuffaceous sandstones and siltstones (An et al. 2013; Su et al. 2018; Tang et al. 2013; Wang et al. 2007b; XBGMR 1993; Zhu et al. 2009). The Permian sequences are mainly composed of conglomerate, sandstone and small amounts of bimodal volcanic rocks (XBGMR 1993). Early Carboniferous to Permian plutonic rocks also well developed in the Yili-Central Tianshan Block (Bao et al. 2018; Gao et al. 2009a; Han et al. 2010; Long et al. 2011; Wang et al. 2009; Xu et al. 2013; Yin et al. 2016; Yu et al. 2018). The Jurassic strata are made up of fluvio-lacustrine deposits, such as conglomerate, sandstone and mudstone (XBGMR 1993).

The Wusun Mountain Range, located in the southern Yili-Central Tianshan block, crops out along piedmont faults in the northern and southern edges of the block, and are separated by the Yili and Zhaosu basins from the North Tianshan Belt and the Haerk-Nalati Mountain Range, respectively (Fig. 3a, Zhang et al. 1999). The Carboniferous volcanic and sedimentary sequences in the Wusun Mountain range are represented by the Early Carboniferous Dahalajunshan Formation (C1d), the Akeshake Formation (C1a) and the Late Carboniferous Yishijilike Formation (C2y). Angular unconformities delineate their contact zones (Figs. 3 and 4e, j; XBGMR 1993; Li et al. 2020). The Dahalajunshan Formation includes a set of intermediate-felsic lavas, sandstones and conglomerates, as well as minor limestones (Fig. 3). It contains complex disharmonic folds, angular folds, intense corrugation textures and ductile faults (Li et al. 2017b). The Akeshake Formation is mainly made up of clastic rocks from lower shallow marine environments, fossiliferous (corals and brachiopods) carbonates, mudstones, tuffaceous sandstones and siltstones (Figs. 3b, c and 4o). The Yishijilike Formation (C2y) comprises bimodal volcanic rocks such as basalt, basaltic trachy-andesite, dacite and rhyolite, the felsic rocks are in conformable contact with the basaltic rocks (Figs. 3 and 4k). Its tectonic deformation is very weak, without intense folding (Li et al. 2017b). The Yishijilike Formation is unconformably covered by the Permian Wulang conglomerates and Jurassic lacustrine sediments (Fig. 3; XBGMR 1993). The granitic intrusions exhibit a wide range of emplacement ages from the Early Carboniferous to the Permian (Bao et al. 2018; Yu et al. 2018).

Sample description and analytical methods

Sample description

Our samples were collected from the Dahalajunshan and Yishijilike Formations in the Wusun Mountain Range, and sampling locations are shown in Fig. 3.

Samples from the Dahalajunshan Formation contain basalt, dacite-porphyry and dacite (C13ZS01-12). The basalt is dark grey in color, exhibiting a porphyritic texture with 45% of pyroxene phenocrysts. The groundmass is characterized by an intergranular texture and mainly includes fine-grained plagioclase, pyroxene, amphibole and magnetite. Carbonatization took place in the plagioclase (Fig. 4a, b). The grey dacite-porphyry also displays porphyritic texture with phenocrysts (50–60 vol%) of plagioclase (90 vol%) and biotite (10 vol%). The cryptocrystalline groundmass occasionally contains magnetite (Fig. 4c). The phenocrysts (10 vol%) of the dacite are mainly composed of plagioclase and hornblende, while the groundmass is made up of quartz, plagioclase, biotite, magnetite and volcanic glass (Fig. 4d).

The samples from the Yishijilike Formation are bimodal volcanic rocks (C15WS01-68 and C14ZS01-10), which include basalt, basaltic trachy-andesite, dacite and rhyolite. The greyish-green basaltic trachy-andesite displays a porphyritic texture, the phenocryst contains plagioclase (20 vol%) and alkali felspar (10 vol%) that shows carbonatization, and the pilotaxitic groundmass is composed of plagioclase, quartz and volcanic glass (Fig. 4f, g). The dark red rhyolite also has a porphyritic texture comprising alkali feldspar (50 vol%) and plagioclase (5 vol%) phenocrysts, and the groundmass displays flow textures and is made up of quartz, plagioclase and volcanic glass (Fig. 4h, i). The dark grey basalt exhibits a porphyritic texture with plagioclase (30 vol%), olivine (5 vol%) and pyroxene (5 vol%) phenocrysts, the cryptocrystalline groundmass contains olivine and pyroxene (Fig. 4k, l). The greyish-green dacite displays a porphyritic texture, and the phenocryst (70 vol%) comprises plagioclase (60 vol%) and aggregations of quartz and plagioclase. Magnetite (10 vol%) can be recognized in the cryptocrystalline groundmass (Fig. 4k, m). The dacite-porphyry crops out as dikes that intruded the bimodal volcanic rocks, and also exhibits a porphyritic texture with 20 vol% plagioclase as well as 10 vol% quartz phenocrysts, and its cryptocrystalline groundmass contains magnetite (15%) (Fig. 4k, n).
Fig. 3  

a Geological map of the Wusun Mountain Range (modified after Gao et al. 2009a); 
b geological section and sampling location AA’ in Fig. 3a (modified after Wang et al. 2007a; Cao et al. 2017); 
c stratigraphic column of the Wusun Mountain Range (modified from XBGMR 1993). The black star indicates the sample locality from Su et al. (2018)
Analytical methods
Analytical methods are presented in the Supplementary Materials. Zircon U–Pb dating, whole-rock major and trace element and Sr–Nd isotopic compositions of the volcanic rocks are available in Tables A1–3, respectively.

Results
Zircon U–Pb dating results
The dacite-porphyry sample (C13ZS01) collected from the Dahalajunshan Formation was dated with the zircon U–Pb method. The zircon crystals are dark in color and semitransparent, they exhibit a roughly euhedral prismatic shape with 120–200 μm in length and aspect ratios of 1–3 (Fig. 5a), and their transparent oscillatory zoning together with relatively high Th/U ratios (0.57–1.06) suggest a magmatic origin. Twelve analyses spots yielded consistent concordant zircon ages, and a weighted mean 206Pb/238U age of 350.3 ± 3.1 Ma (MSWD = 3.5; Fig. 5a) is interpreted as the crystallization age.

A total of five samples were taken from the Yishijilike Formation. From the rhyolite sample C15WS01, twelve zircon grains were analyzed. These zircons are pale in color and dominantly euhedral in shape, with lengths of 60–180 μm and aspect ratios of 1–3. Most of them display well-developed oscillatory zoning on the CL images (Fig. 5b), indicating an igneous origin. The latter is further corroborated by their high Th/U ratios (0.46–1.29). This data are plotted on the concordia diagram showing a consistent distribution with a weighted average 206Pb/238U age of 337.7 ± 2.8 Ma (MSWD = 0.31; Fig. 5b), which is interpreted as the crystallization age. Nine zircon grains from another rhyolite sample (C15WS20) also display typical features of magmatic zircon. They yield a weighted mean 206Pb/238U age of 337.0 ± 3.3 Ma (MSWD = 3.5; Fig. 5a) and a flat HREE pattern ((Gd/Yb)N = 1.42–1.71). They also show slightly negative Eu anomalies (Eu/Eu* = 0.72–1.04) (Fig. 7a). In addition, the ~ 350 Ma samples are also enriched in large ion lithophile elements (LILE; e.g., Rb, Th, U and K) with respect to the high field strength elements (HFSE; e.g., Nb, Ta and Ti) as can be deduced from the trace element spider diagram normalized to the primitive mantle (Fig. 7b).

In contrast, the later-stage volcanic rocks (~ 337–322 Ma) display a dissimilar bimodal geochemical distribution. The ~ 337 Ma volcanic rocks comprise basalt, basaltic trachy-andesite and rhyolite. Among them, the basaltic volcanic rocks have lower SiO2 values (47.22–53.68 wt%), low Fe2O3 (8.92–14.09 wt%), low MgO (0.53–5.59 wt%), MgO contents (5.27–7.34 wt%), except for one sample (C15WS17) with an extremely low total alkali value of 2.08 (Fig. 6a). These rocks have a wide range of SiO2 content (43.90–70.50 wt%), with moderate LREE enrichment ((La/Yb)N = 2.79–5.09) with weak Eu anomalies (Eu/Eu* = 1.52–1.90) with weak Eu anomalies (Eu/Eu* = 0.86–1.05) (Fig. 7a). The felsic volcanics have higher SiO2 (68.85–71.44 wt%), total alkali contents (5.27–7.34 wt%) and a flat HREE pattern ((Gd/Yb)N = 1.42–1.71). They also show slightly negative Eu anomalies (Eu/Eu* = 0.72–1.04) (Fig. 7a). In addition, the ~ 350 Ma samples are also enriched in large ion lithophile elements (LILE; e.g., Rb, Th, U and K) with respect to the high field strength elements (HFSE; e.g., Nb, Ta and Ti) as can be deduced from the trace element spider diagram normalized to the primitive mantle (Fig. 7b).

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The ~322 Ma basaltic rocks have low SiO$_2$ (47.91–54.64 wt%), high Fe$_2$O$_3$ (8.83–12.82 wt%) and MgO (0.66–5.25 wt%), while the felsic series are characterized by higher SiO$_2$ (60.50–71.52 wt%), lower Fe$_2$O$_3$ (2.17–8.85 wt%) and lower MgO (0.28–1.76 wt%). However, the ~322 Ma bimodal volcanic rocks show two types of alkali content. One group exhibits strong alkaline features with Na$_2$O + K$_2$O values ranging from 5.09 to 10.59 wt%, whereas the other group has lower total alkali contents of 4.06–7.07 wt%. Consequently, the alkaline volcanic rocks plot in the fields of trachy-basalt, basaltic trachy-andesite and the trachyte series, while the sub-alkaline volcanics plot in the basalt, basaltic andesite and dacite fields in the TAS diagram, and show a typical calc-alkaline affinity in the AFM diagram (Fig. 6). Total REE contents of these basic rocks range from 85 to 192 ppm with slight enrichment of LREE ((La/Yb)$_N$ = 3.15–6.09), flat HREE ((Gd/Yb)$_N$ = 1.30–1.77), as well as slightly negative Eu anomalies (Eu/Eu* = 0.71–1.00) (Fig. 7c). In the primitive mantle-normalized trace element diagram, it also exhibits enrichment in LILEs (e.g., Rb, Ba, Th, U and K) and depletion in HFSEs (e.g., Nb, Ta and Ti; Fig. 7h).

**Whole-rock Sr–Nd isotopic compositions**

The whole-rock Sr–Nd isotopic compositions are shown in Fig. 8 and Table A3. Almost all the samples plot into the mantle evolution range (Fig. 8a). The ~350 Ma volcanic rocks have the lowest εNd(t) values (+0.5 to +1.6) and medium ($^{87}$Sr/$^{86}$Sr)$_i$ ratios (0.7037–0.7048) (Fig. 8). The ~337 Ma bimodal volcanic rocks have higher εNd(t) values (+2.9 to +3.9) and lower ($^{87}$Sr/$^{86}$Sr)$_i$ ratios. ($^{87}$Sr/$^{86}$Sr)$_i$ values of the basaltic rocks are 0.7042–0.7047 and those of the felsic rocks range from 0.7015 to 0.7034 (Fig. 8a), except for sample C14ZS03 that has an extremely high ($^{87}$Sr/$^{86}$Sr)$_i$ (0.7147) and low εNd(t) value (+0.8). Furthermore, the ~322 Ma bimodal volcanics have higher εNd(t) values (+2.3 to +4.3) than the ~337 Ma series (Fig. 8). The ($^{87}$Sr/$^{86}$Sr)$_i$ values of the ~322 Ma basaltic rocks range from 0.7047 to 0.7068 that are higher than those of the felsic volcanic rocks (0.7046–0.7049). The dacite-porphyry (~313 Ma) has similar Sr–Nd isotope characteristics compared to the ~322 Ma felsic volcanic rocks. It shows εNd(t) values from +3.5 to +3.7 and ($^{87}$Sr/$^{86}$Sr)$_i$ ratios from 0.7047 to 0.7050 (Fig. 8).

**Discussion**

**Magmatic episodes of the Carboniferous volcanic rocks in the Wusun Mountain Range**

According to previous geological mapping, the Dahalajunshan Formation was defined to represent groups of widespread Early Carboniferous volcanic rocks in the western Chinese Tianshan (XBGMR 1993). Although increasing zircon U–Pb isotopic data suggested an unreasonable wide age range for the Dahalajunshan volcanics from 407 to 301 Ma (see Su et al. 2018 for a detailed overview and discussion), our new zircon U–Pb age of the Dahalajunshan volcanic rocks in the Wusun Mountain Range yield ages of ca. 350 Ma, which is consistent with the reported ~355–350 Ma ages by Su et al. (2018) for this volcanic sequence. The newly obtained ages of the Yishijilike Formation volcanic rocks document three eruptive episodes, respectively, at ca.
Fig. 5 Zircon CL images and concordia plots of the zircon U–Pb data of the Carboniferous volcanic rocks. The yellow circles represent sampled domains for zircon U–Pb dating (via SIMS or LA-ICP-MS)
337, 322 and 313 Ma in the southern Yili-Central Tianshan Block. Our results argue against the original definition of the “Late Carboniferous” Yishijilike Formation (XBGMR 1993), but constrain their eruption in late Early Carboniferous to Late Carboniferous timed.

Petrogenesis and magma sources

Our new zircon U–Pb dating results record four volcanic episodes in the Wusun Mountain Range (Fig. 5). The ~ 350 Ma magmatism is characterized by continuous calc-alkaline mafic to more differentiated felsic rocks with low εNd(t) values from +0.5 to +1.6. However, the later ~ 337 and ~ 322 Ma groups are dominated by bimodal volcanic rocks showing distinctive alkaline features and the ~ 313 Ma magmatism is calc-alkaline dacite-porphyry. Isotopically, all of them have relatively higher εNd(t) values (+2.3 to +4.3).

Petrogenesis of the ~ 350 Ma volcanic rocks

The sequential formation of basic to acid rock series is usually controlled by fractional crystallization. The basalt (C13ZS12) contains 5.59 wt% MgO, with a Mg# value of 42, 33 ppm Ni and 129 ppm Cr, which are much lower than typical mantle-derived primary melts (Cr = 300–500 ppm; Frey et al. 1978) and higher than andesitic and dacitic rocks (Fig. S1e; MgO, 0.53–2.70 wt%; Mg#, 26–46; Cr, 9–88 ppm; Ni, 4–15 ppm), indicating that they may have experienced crystal fractionation. The latter is also reflected in the Harker diagram (Fig. S1), from basaltic to felsic rocks, where the contents of TiO₂, Fe₂O₃T and CaO decrease with increasing SiO₂, indicative of fractional crystallization of plagioclase and ferromagnesian minerals.

The ~ 350 Ma volcanic rocks have weakly positive εNd(t) values (+0.5 to +1.6) and low initial ⁸⁷Sr/⁸⁶Sr values, suggesting partial melting of a moderately depleted mantle (Rudnick and Gao 2003). Although mantle-derived magmas potentially assimilate crustal materials during their ascent or storage in a magma chamber, the lack of crustal xenoliths and restricted εNd(t) values exclude the significant influence of crustal assimilation. In addition, trace elements of the ~ 350 Ma rocks show enrichment in LILEs and LREEs, but depletion of HFSEs (e.g., Nb, Ta, and Ti). This suggests that the magma source was most likely modified by slab-derived fluids (Pearce et al. 2005). The typical subduction-related affinity is also confirmed by the enrichment of Th compared to Nb, and as a result the basaltic rocks plot in the volcanic arc field in the Th/Yb vs. Nb/Yb and Th–Hf–Ta diagrams (Fig. 9a, b). Therefore, the ~ 350 Ma volcanic rocks were probably derived from melts sourced from a depleted mantle with metasomatism of subduction-related fluids, without clear evidence for crustal assimilation.

Petrogenesis of the ~ 337 and ~ 322 Ma bimodal volcanic rocks

Petrogenesis of the basaltic rocks

All the 337 and 322 Ma basaltic rocks have low silica, high Mg, positive εNd(t) values (+2.3 to +4.3) and low initial ⁸⁷Sr/⁸⁶Sr ratios (0.7042–0.7069), indicating that they originated from a depleted mantle source (Rudnick and Gao 2003). As shown, the homogeneous Sr–Nd isotopic compositions and the lack of crystal xenoliths exclude an influence of crustal contamination.

Generally, the lithospheric mantle is cold and conductive, it has low εNd(t) values and high initial ⁸⁷Sr/⁸⁶Sr values because of its long isolation from the convective mantle
and interaction with magmas (McDonough and McCulloch 1987). In contrast, the asthenospheric mantle is hot and convective, and isotopically depleted (high $\varepsilon_{Nd}(t)$ values and low initial $^{87}\text{Sr}/^{86}\text{Sr}$ rates). The magma derived from the asthenospheric mantle consequently has a depleted or primitive mantle affinity in both chemical and isotopic compositions. The basaltic rocks of the Yishijilike Formation have high $\varepsilon_{Nd}(t)$ values (+2.3 to +4.3) and low $^{87}\text{Sr}/^{86}\text{Sr}$, ratios (0.7042–0.7068; Fig. 8), displaying typical asthenospheric properties (Saunders et al. 1992). The HFSE (Th, Zr, Nb, Y, etc.) and REE can be used to reveal the original features of the magmatic sources (Pearce 2014). Typical correlations are shown in Fig. S2. In general, the Mid Ocean Ridge Basalts (MORB), typically sourced from the depleted shallow asthenospheric mantle have high Zr/Nb (9–32) and Sm/Nd values (0.28–0.36), low Ta/Yb values (0.04–0.20) and La/Yb values (0.82–2.66; Sun and McDonough 1989). Conversely, basaltic rocks sourced from the lithospheric mantle have lower Zr/Nb (4) and Sm/Nd values (0.18), and high Ta/Yb (1.54) and La/Yb values (10; McDonough 1990). In our study, the Zr/Nb, Sm/Nd, Ta/Yb and La/Yb ratios of the Yishijilike Formation basaltic rock range from 17–31, 0.23–0.28, 0.08–0.20 and 3.88–8.44, respectively. These ratios are similar to MORB characteristics. In the Nb/Yb vs. Zr/Yb diagram, all the basaltic rocks plot within the MORB-OIB array, also indicative of an asthenospheric mantle source (Fig. 9c).

The trace element compositions of our basic rock samples indicate that the asthenospheric mantle source must have experienced mantle metasomatism. The enrichments of LILEs and LREEs, and remarkable negative Nb, Ta, Ti anomalies are in agreement with subduction-related mantle metasomatic features (Pearce and Peate 1995). These features are well demonstrated by the Th/Yb versus Nb/Yb and Th-Hf-Ta diagrams, in which the calc-alkaline basaltic rocks plot in the continental arc field and display arc-type basalt features (Fig. 9a, b). The depleted mantle-derived primary magma probably experienced significant crustal fractionation when forming the ~337 and ~322 Ma basaltic rocks because their Cr (< 80 ppm) and Ni contents (8–17 ppm) are much lower than typical primary mantle-derived magmas (e.g., Cr = 300–500 ppm, Ni = 300–400 ppm; Frey et al. 1978). Furthermore, the negative correlations between TiO$_2$, Fe$_2$O$_3^{T}$, MgO and SiO$_2$ are compatible with fractionation of ferromagnesian minerals (Fig. S1a, c, e), and the moderately negative Eu and Sr anomalies imply the fractionation of plagioclase.

Yb, Gd and Dy generally share similar partition coefficients in spinel, while garnet has a higher partition coefficient for Yb compared to Gd and Dy (Green 2006; Johnson 1994). Therefore, partial melting in the spinel stability field only leads to slight fractionation of Dy/Yb and Gd/Yb, whereas partial melting of garnet-facies mantle may cause notable fractionation of Dy/Yb and Gd/Yb. The ~337 and ~322 Ma basaltic rocks show flat HREE patterns (Fig. 7c, e, g), and their low Dy/Yb and Gd/Yb ratios also plot on the melting curve for spinel peridotite (Fig. 9d), suggesting that the variable degrees (<10%) of partial melting occurred at a relatively shallow depth, mostly within the spinel stability field.

Summarizing, we suggest that the ~337 and ~322 Ma basaltic rocks from the Wusun Mountain Range probably were derived from low degrees (<10%) of partial melting of a depleted spinel-facies asthenospheric mantle, metasomatized by slab-derived fluids, which was also accompanied by crystal fractionation of ferromagnesian minerals and plagioclase, and without crustal contamination.

**Petrogenesis of felsic rocks** The formation of felsic rocks in the bimodal suites is a long-standing, enigmatic petrogenetic issue (Bonnefoi et al. 1995). The felsic rocks of the Wusun Mountain Range show affinity to A-type granites because of their high silica and alkali contents, low MgO, CaO, TiO$_2$ values and high concentrations of Ga, Zr, Nb, Ce and Y (Fig. 9e; Whalen et al. 1987). Additionally, they can be associated with A$_2$-type granites (Eby 1992) based on their relatively high Y/Nb ratios (2.98–4.53) (Fig. 9f).

Several petrogenetic schemes have been proposed for the origin of A-type felsic rocks, including the following: (1) melting of felsic crust (Clemens et al. 1986; Creaser et al. 1991; King et al. 1997; Patiño Douce 1997; Patiño Douce and Beard 1995); (2) fractional crystallization of coeval basaltic magmas with or without crustal contamination (Aydin et al. 2014; Peccerillo et al. 2003; Pin and Paquette 1997; Turner et al. 1992); and (3) magma mixing of mantle-derived mafic and crustal-derived magmas (Foland and Allen 1991; Frost and Frost 1997; Frost et al. 1999; Mingram et al. 2000).

The crust in the western Chinese Tianshan contains fragments of ancient Precambrian crystalline basement as well as juvenile crustal material. The Precambrian crystalline basement in the western Chinese Tianshan exhibits low and negative $\varepsilon_{Nd}(t)$ values (−1.9 to −9.1) (Chen et al. 1999; Hu et al. 2000; Wang et al. 2014a), while the A-type felsic rocks in the Wusun Mountain Range have relatively high $\varepsilon_{Nd}(t)$ values (+3.2 to +4.2). The $\varepsilon_{Nd}(t)$ values of the felsic magmas should be negative or near-zero when...
they would have been generated by the partial melting of the ancient crustal material. Hence the partial melting of Precambrian crystalline basement can be ruled out. Moreover, the $\varepsilon_{Hf}(t)$ values of the Late Devonian to Late Carboniferous felsic rocks in the southern Yili Block range from $-8.19$ to $+8.16$ with variable ancient $T_{DM}^{C}$ values (0.84–1.81 Ga) (Huang et al. 2020), indicating that the partial melting of juvenile crust alone is also not possible to explain the observed signatures. Magma mixing between crustal and mantle sources for the generation of the A-type magmas, where the mantle serves both as a heating source and an important contributor, could be a feasible explanation (Foland and Allen 1991; Frost et al. 1999). However, the $\varepsilon_{Nd}(t)$ values of the Devonian to Early Carboniferous volcanic rocks in the Yili-Central Tianshan Block range from $-5.2$ to $+6.2$ with an average value of $+2.1$ (Table A3), and the crustal components have negative $\varepsilon_{Nd}(t)$ values. Magma mixing of crustal-derived felsic magma and mantle-derived basic magma, therefore, could not have produced the A-type magma with such high $\varepsilon_{Nd}(t)$ values ($+2.3$ to $+4.3$). Hence, magma mixing can also be excluded as sole answer. Given all the above, fractional crystallization seems to be the most reasonable cause to explain the petrogenesis of these felsic rocks. The lack of mafic microgranular enclaves in the felsic rocks, and homogeneous Sr–Nd isotopic compositions with the coeval mafic rocks indicate that they share the same magma source with insignificant crustal contamination (Figs. 4h and 8). This conclusion is also corroborated by the significant negative correlations between $SiO_2$ and $TiO_2$, $Al_2O_3$, $Fe_2O_3^T$, $CaO$ and $MgO$ in the Harker diagrams (Fig. S1) that make a case for crystal fractionation of plagioclase and ferromagnesian minerals. In addition, although the argument against the fractional crystallization model is the absence of intermediate rock compositions (Pin and Paquette 1997), some studies have indicated that magma replenishment coupled with high eruption rates, minimized crustal ponding and limited residence time in the magma chamber can fractionate the magma with higher $SiO_2$ contents (Bonnefoi et al. 1995; Brophy 1991; Geist et al. 1995; Thompson 1972). This process is probably the formation process of the bimodal volcanic rocks.

**Petrogenesis of the ~313 Ma dacite-porphyry**

The ~313 Ma dacite-porphyry, along with contemporaneous rhyolites reported by Cao et al. (2017) in the eastern Wusun Mountain Range, reflects another magmatic event in the Late Carboniferous. Although the dacite-porphyry may not represent an additional bimodal volcanic suite given that it lacks basaltic components, it does exhibit similar geochemical and isotopic features to the ~337 and ~322 Ma felsic rocks (Figs. 6, 7, 8e, f and S1). Therefore, they may share an analogous mode of petrogenesis, implying that the dacite-porphyry might have been derived from partial melting of asthenospheric mantle with insignificant crustal contamination.

**Tectonic implications**

Two sub-parallel magmatic belts occur in the southern Yili-Central Tianshan Block, i.e., the Wusun Mountain Magmatic Belt and the Haerk-Nalati Magmatic Belt (Fig. 2; Su et al. 2018) separated by the Zhaosu basin. Both belts are mainly composed of Carboniferous magmatic rocks (Fig. 2; Gao et al. 2009a; Gou et al. 2012; Huang et al. 2015a, 2020; Long et al. 2011; Ma et al. 2014; Xu et al. 2013; Yu et al. 2016; Zhu et al. 2009, 2010; Yin et al. 2016; Zhang et al. 1999). Some studies suggest that these two Carboniferous magmatic belts constitute magmatic arcs and were
controlled by the subduction of the South Tianshan oceanic plate (Zhu et al. 2009, 2010; Yu et al. 2016; Xu et al. 2013 and references there in). However, in our study we argue that the Wusun Mountain Magmatic Belt is a back-arc edifice based on the specific structural characteristics and rock associations. The Carboniferous volcanic rocks in the Wusun Mountain Belt are grouped in the Dahalajunshan Formation and Yishijilike Formation. The Dahalajunshan Formation displays complicated disharmonic and angular folds, intense corrugation textures and ductile faults. However, the tectonic

![Fig. 9](image.png)

Fig. 9 Our geochemical results plotted in a Nb/Yb-Th/Yb diagram (Pearce and Peate 1995); b Th-Hf-Ta diagram (Wood 1980); c Nb/Yb-Zr/Yb diagram (Pearce and Peate 1995); d Dy/Yb-Gd/Yb diagram (after Tang et al. 2014); e (K$_2$O + Na$_2$O)/CaO versus (Zr + Nb + Ce + Y) diagram (after Whalen et al. 1987); FG represents fractionated felsic granite; OGT represents unFractionated M-, I-, and S-type granite; f diagram discriminating anorogenic and post-collisional granite (after Eby 1992). Symbols used are identical to those in Figs. 6 and 8. Data sources are listed in Table A4.
deformation of the Yishijilike Formation is very weak and lacking folding. These contrasting structural characteristics suggests that the tectonic stress changed from a compression to an extension in the Wusun Mountain Magmatic Belt, and this transition illustrates the back-arc extension in the Wusun Mountain area (Li et al. 2017b). Concerning the rock associations, the Dahalajunshan Formation comprises calc-alkaline mafic to felsic volcanic rock series, while the Yishijilike Formation consists of bimodal volcanic rocks. The Dahalajunshan Formation volcanic rocks probably formed in an initial back-arc extension setting (Su et al. 2018). Next, we will discuss the formation mechanism and tectonic setting of the bimodal volcanic rocks of the Yishijilike Formation.

Bimodal volcanic rocks are generally related to extensional regimes and can be formed in various geodynamic settings (Wang et al. 2000), such as continental rifts (Pin and Marini 1993; Wilson 1989), oceanic islands (Geist et al. 1995), incipient back-arc spreading (Hochstaedter et al. 1990a, b), post-orogenic extensional settings (Coulon et al. 1986), intra-oceanic arcs (Brouxel et al. 1987) and mature islands/active continental margins (Frey et al. 1984; Pin and Paquette 1997). Considering that the Wusun Mountain magmatic belt was built inside the Yili-Central Tianshan Block with widespread continental crustal basement (Hu et al. 2000), the bimodal volcanic rocks are unlikely to have formed in oceanic islands or intra-oceanic arc settings. Furthermore, both the basaltic and felsic rocks of the bimodal volcanics have the same Sr–Nd isotopic compositions, hence excluding the possibility of formation during continental-breakup where the basaltic and felsic rocks come from different magma sources and thus contain distinct Sr–Nd isotopic compositions (Griffiths and Campbell 1990; Wilson 1989). Finally, the absence of intermediate rocks does not support a mature arc setting (Frey et al. 1984; Pin and Paquette 1997). As a result, the Yishijilike bimodal volcanics were most likely formed in a back-arc extension or post-orogenic extensional setting.

Here the key issue to determine the geological setting of the Yishijilike bimodal volcanic rocks lies in the timing of the final collision between the Tarim Craton and the Yili-Central Tianshan Block. It has been proposed that the South Tianshan Belt between these two blocks was formed by the northward subduction and accretion of the South Tianshan oceanic plate. The Akeyazi HP/UHP metamorphic belt with relevant ophiolitic remnants delineate the suture zone (Gao and Klemd 2003; Gao et al. 1998; Han et al. 2011; Long et al. 2011; Qian et al. 2009; Xiao et al. 2013). Recently, a series of studies documented that the closure of the South Tianshan Ocean as well as the final collision between the Yili-Central Tianshan Block and the Tarim Craton happened in the end of Carboniferous. A first argument for this is that the aforementioned HP/UHP metamorphic rocks yielded peak metamorphic ages of ~327–313 Ma (Klemd et al. 2011; Li et al. 2011; Liu et al. 2014b; Su et al. 2010; Yang et al. 2013), which was followed by their rapid exhumation and post-orogenic magmatic events. It is hence thought that this timing constrains the final amalgamation (Gao et al. 2011; Klemd et al. 2005; Wang et al. 2007c). Second, the youngest age group of the ophiolitic remnants along the South Tianshan mélangé belt were constrained at ~320 Ma (Han and Zhao 2018 and references therein), implying that the subduction process of the South Tianshan Ocean should have lasted at least until the Late Carboniferous. Third, the Late Carboniferous (327–310 Ma) detrital zircon from the South Tianshan Belt are likely to record subduction-related magmatic events instead of post-orogenic magmatism (Han et al. 2015, 2016; Ren et al. 2011). Therefore, it is reasonable to interpret the formation of the Yishijilike bimodal volcanic rocks to be the result of back-arc extension rather than a post-orogenic extension setting.

Not only back-arc basin basalts (BABB), but also bimodal volcanic rocks can be formed in a back-arc extensional region (Clift et al. 1995; Gribble et al. 1998; Hawkins et al. 1990; Shinjo et al. 1999; Shinjo and Kato 2000; Stern et al. 1990, 2003). The BABB is commonly generated by the decompressional melting of MORB-like mantle with addition of subduction components (Gribble et al. 1998; Hawkins et al. 1990; Stern et al. 1990). Thus, the BABB, especially those that form in the initial back-arc extension stage, generally display strong arc-like features with high concentrations of LILEs and low concentrations of HFSEs (Hawkins and Melchor 1985; Stern et al. 1990, 2003). At the later stage of back-arc extension, both sub-alkaline BABB which serves as a magma-type intermediate between MORB and island-arc basalts (IAB), and alkaline BABB may appear (Fryer et al. 1981; Gill 1976; Ishizuka et al. 2009). The volcanic rocks of the Wusun Mountain Range are enriched in LILEs, depleted in HFSEs (especially Nb, Ta, Ti), and have high Th/Yb and Nb/Yb ratios. Hence, they exhibit strong arc-like features and point to a subduction-related setting (Figs. 7 and 9a, b). In addition, their REE contents show values that typically lie between OIB and N-MORB, and are similar to a BABB signature (Fig. 7a, c, e, g; Fryer et al. 1981; Gill 1976). On the other hand, their lithology changes from calc-alkaline arc-type series to alkaline bimodal volcanics. The characteristics of felsic rocks of the bimodal volcanic rocks are comparable to A-type granites, indicative of an extensional setting (Fig. 9e, f; Eby 1992). The mafic rocks have relatively high Zr contents and Zr/Y ratios, which are identical to the mafic rocks typical of a within-plate setting (Fig. 10a). Moreover, their low Ti and V/Ti ratios, medium Y and La/Nb ratios are highly comparable to those of BABB (Fig. 10b, c, d). As a result, all the evidence, including the lithologic characteristics, major and trace element features of the Yishijilike volcanic rocks in the Wusun Mountain Range suggest their formation in a back-arc extensional setting.
Finally, crustal thinning and asthenospheric upwelling frequently take place under an extensional tectonic setting. The change of calculated Moho depth can provide crucial evidence for the evaluation of crustal thinning. Based on the consensus that arc magmatism is generated by decompressional melting of the mantle wedge, Mantle and Collins (2008) suggested that the trace element chemistry of arc basalts and Moho depth show good correlation with maximal Ce/Y ratios. Specifically, for rocks having 44–53 wt% SiO₂, > 4 wt.% MgO and < 4 wt.% LOI, the empirical correlation equation is Ce/Y = 0.3029e0.0554Dm, where Dm gives Moho depth. For the Wusun Mountain Range the Early Carboniferous basaltic rocks (> 350 Ma) indicate Moho depths between 26 and 41 km (with an average of 32 km), while the Moho depths during the formation of the younger volcanics from our study area (after 337 Ma) are 19–29 km (with an average of 24 km) (Fig. 11). In addition, the crustal thickness can also be tracked by the Sr/Y ratios of the intermediate rocks (Chapman et al. 2015; Chiaradia 2015; Profeta et al. 2015). Only limited samples with their SiO₂ values ranging from 55 to 68 wt%, MgO contents between 1% and 4%, and Rb/Sr ratios in the range of 0.05–0.2, can be used to calculate the crustal thickness, using the following equation: dm = 1.11*Sr/Y + 8.05 (where dm represents the crustal thickness or depth to Moho; Chapman et al. 2015; Profeta...
et al. 2015). Here we collected published data of intermediate rocks from the arc edifice (Southern Yili-Central Tianshan Block) to make a comparison with the back-arc region (data sources can be found in Table A4). The crustal thickness of the arc (average 43 km) is found to be thicker than the back-arc, while the former shows insignificant changes throughout the entire Carboniferous (Fig. 11). Therefore, this demonstrates that the Wusun Mountain area experienced a significant crustal thinning process. This crustal thinning causes asthenospheric upwelling and hence decompressional melting, with magma from more depleted sources. The $\varepsilon_{Nd}(t)$ values of the ~350, ~337, ~322 and ~313 Ma volcanic rocks show a rising trend with younging ages, representing an increase of the depleted mantle constituents and a decrease of the enriched crustal materials in the source (Fig. 8), which is consistent with the crustal thinning process. In contrast, the $\varepsilon_{Nd}(t)$ values of the Haerk-Nalati arc do not alter significantly, suggesting that their magma sources experienced little or no changes, which is in line with an invariant crustal thickness (Figs. 8 and 11).

In summary, we conclude that a back-arc extensional tectonic setting was responsible for the generation of the volcanic rocks of the Wusun Mountain Range (Yishijilike Formation).

**Geodynamic implication: back-arc extension in the Yili-Central Tianshan Block**

The subduction of oceanic lithosphere at convergent plate boundaries generally shows a one-sided subduction pattern, while the subducted slab sinks, the overriding plate moves horizontally (Gerya et al. 2008). Based on the kinematic framework and the resulting geological characteristics at convergent plate boundaries, resulting accretionary orogens can be subdivided into retreating and advancing types (Cawood and Buchan 2007; Cawood et al. 2009). For the retreating types, the upper plate moves away from the downgoing plate, and long-term extension (e.g. back-arc basin) will develop. Reversely, when the overriding plate moves towards the downgoing plate, advancing-type orogens are formed and result in foreland fold-and-thrust belts as well as in crustal thickening (Cawood and Buchan 2007; Cawood et al. 2009). Regarding the retreating-type orogens, the oceanic plate will be older, colder and denser when it moves away from a spreading plate. As the oceanic plate is denser than the surrounding mantle, it will subduct under the upper crust and will also have a tendency to roll back because of the negative buoyancy (Schellart and Lister 2004). The rollback of an oceanic plate will give rise to the extension of the overriding continental plate, cause crustal thinning and produce back-arc magmatism. This latter will result in mantle decompressional melting and upwelling as well as potentially some crustal melting under a high geothermal gradient.

Meanwhile, the subduction of the oceanic plate will also generate arc magmatism by partial melting of the metasomatized mantle wedge (Gerya et al. 2008; Hall et al. 2003; Ishizuka et al. 2011). The progressive magmatic activity will make the back-arc lithosphere hotter, weaker and easier to extend along the continental marginal plate boundaries such as in the case of the circum-Pacific orogens (Collins 2002; Hyndman and Currie 2011; Hyndman et al. 2005).

Late Paleozoic magmatic activity in the western Chinese Tianshan is thought to be controlled by the subduction processes of both the Junggar and South Tianshan oceanic plates (Gao et al. 1998, 2009a; Han et al. 2011, 2015; Xiao et al. 2013). In this context, the Carboniferous magmatism has been extensively studied with various hypotheses. It was considered to develop in an intracontinental rift setting (Xia et al. 2012; Xia and Li 2020), a continental arc setting (An et al. 2013; Tang et al. 2013; Wang et al. 2007b; Yu et al. 2016; Zhong et al. 2017; Zhu et al. 2009), a post-collisional setting (Chen et al. 2020; Feng and Zhu 2019; Ge et al. 2015; Long et al. 2012; Sun et al. 2008) or a back-arc extensional setting (Cao et al. 2017; Qian et al. 2006; Su et al. 2018; Wang et al. 2018a, b,2019; Yan et al. 2015) on the basis of geochemical features of different studied targets. These complex Carboniferous magmatic rocks were subdivided into four main belts, from north to south, as the Keguqinshan-Tulasu, Awulale, Wusun Mountain and Haerk-Nalati domains, according to their geographical distribution characteristics (e.g. Su et al. 2018). The formation mechanism of each magmatic belt should be carefully treated with the comprehensive consideration of its spatial–temporal distribution and associated tectonic events. With regard to the magmatic belt of the Wusun Mountain Range, there are two main hypotheses as regard to its petrogenesis. One hypothesis states that it is the southward subduction of the Junggar oceanic plate and the coeval back-arc extension in the Yili-Central Tianshan Block that led to its formation (Cao et al. 2017). This hypothesis is based on the top-to-the north ductile shearing deformation observed in the Kekesu-Akeyazi-Atbashy HP–UHP metamorphic complex (Charvet et al. 2011; Wang et al. 2010). However, other authors insisted that the building of the Wusun Mountain Belt was the result of the northward subduction of the South Tianshan oceanic plate (Bao et al. 2018; Su et al. 2018; Zhu et al. 2009), which is supported by the evidence that: (1) a LP/HT metamorphic belt (Li and Zhang 2004) and a HP/UHP metamorphic belt constitute a paired metamorphic belt at the northern margin of the South Tianshan Belt (Gao and Klemd 2003; Hegner et al. 2010; Klemd et al. 2011; Tan et al. 2019; Zhang et al. 2007); (2) Late Devonian to Late Carboniferous arc calc-alkaline rocks are widely distributed in the Haerk-Nalati range (Gao et al. 2009a; Long et al. 2011; Xu et al. 2013; Zhu et al. 2009; Yin et al. 2016); and (3) the northern part of the Tarim Craton was regarded as a Paleozoic passive
continental margin (Windley et al. 1990; Xiao et al. 2013). On the other hand, the Wusun Mountain Belt is situated to the north of the Haerk-Nalati igneous belt at distances of up to 100 km, and the latter has similar emplacement ages of calc-alkaline arc magmatism (Fig. 2; Gao et al. 2009a; Long et al. 2011; Zhu et al. 2009 and references therein), it would be unrealistic if these two near-parallel magmatic belts were two distinct arc edifices formed under a same subduction scenario. Given all that, we argue that the Carboniferous arc-back-arc system in the southern part of the Yili-Central Tianshan Block was probably controlled by northward subduction of the South Tianshan oceanic plate (e.g., Bao et al. 2018; Su et al. 2018).

The extension in the Wusun Mountain back-arc region was probably due to the trench retreat of the subducting South Tianshan oceanic plate during the Late Devonian to Late Carboniferous. Trench retreat commonly causes crustal thinning in a retreating-type accretionary orogen (Cawood et al. 2009). Therefore, changes in crustal thickness provide crucial evidence to refine the subduction-accretion process. In the case of Wusun Mountain volcanic rocks, the decreasing Ce/Y ratios evidence a crustal thinning process in the Yili-Central Tianshan Block (Fig. 11). Further, slab rollback or trench retreat is always accompanied by the underplating of juvenile mantle-derived materials, with increased $\varepsilon_{Hf}(t)$ values (Kemp et al. 2009). Although $\varepsilon_{Hf}(t)$ data from the Wusun Mountain magmatic belt is scarce, the $\varepsilon_{Hf}(t)$ values of the Southern Yili Block display an increase from the Late Devonian to Late Carboniferous (Huang et al. 2020). In addition, the $\varepsilon_{Hf}(t)$ values have a linear relationship with the $\varepsilon_{Nd}(t)$ values of magmatic rocks in the western Chinese Tianshan ($\varepsilon_{Hf} = 1.36\varepsilon_{Nd} + 2.95$; Huang et al. 2020). Based on the positive linear relationship, the $\varepsilon_{Hf}(t)$ values of volcanics in the Wusun Mountain should also gradually increase due to the $\varepsilon_{Nd}(t)$ values increase with younger ages (Fig. 8). Therefore, the decreasing Ce/Y ratios and increasing $\varepsilon_{Nd}(t)$ values might indicate that the South Tianshan oceanic plate rolled back and the trench retreated during the Late Devonian to Late Carboniferous.

A tentative model is proposed here to illustrate the tectonic processes concerning the evolution of Carboniferous arc-back-arc system along the southern margin of the Yili-Central Tianshan Block (Fig. 13). In the Latest Devonian to Early Carboniferous, the northward subduction of South Tianshan oceanic plate under the Yili-Central Tianshan Block produced the Haerk-Nalati magmatic arc (Fig. 13b; Gao et al. 2009a; Long et al. 2011; Xu et al. 2013; Zhu et al. 2009 and references therein). During this period, the South Tianshan oceanic plate whose density was denser than the underlying mantle, had a tendency to roll back due to the negative buoyancy. This ultimately resulted in the back-arc extension in the north of Haerk-Nalati range. The early-stage back-arc extension (362–350 Ma) caused partial melting of continental crust and triggered granitic intrusion as well as decompressional melting of the depleted mantle, which had been metasomatized by subduction-related fluids to generate the arc-like Dahalajunshan volcanic rocks in the Wusun Mountain Range (Figs. 13b and 3c; Bao et al. 2018; Su et al. 2018). This process is comparable to the modern analog of the northern Mariana Trough, where the early back-arc basin basalts display strong arc-like characteristics (Stern et al. 1990). The continuous extension led to the opening of a limited back-arc basin, in which the Akeshake Formation limestones were deposited and covered the Dahalajunshan Formation strata (Figs. 13b, 3c and 4e, o). The extension lasted until the Late Carboniferous (later than ~ 337 Ma) with the occurrence of increased decompressional melting of asthenospheric mantle, resulting in the formation of the Yishijilike bimodal volcanics (Figs. 13b and 3c). This scenario resembles the formation process of the present-day Okinawa Trough (Shinjo et al. 1999; Shinjo and Kato 2000). The massive magmatism affected the geothermal gradient and thus the strength regime of the back-arc region in the southern Yili-Central Tianshan Block, by making it thinner, hotter and weaker. Consequently, as a product of back-arc extension, the Wusun magmatic belt developed its thin lithosphere (Figs. 11 and 13b). This process is similar to most of the mobile belts located in current or recent back-arc regions on the Earth (Hyndman and Currie 2011; Hyndman et al. 2005).

Implications for the formation of the Kazakhstan Orocline

The formation of the SW CAOB stands in close relationship with the bending of the Kazakhstan Orocline. The latter is mainly made up of a Devonian Volcanic Belt (DVB) and the Balkhash-Yili arc (Bazhenov et al. 2012; Li et al. 2018; Windley et al. 2007; Xiao and Santosh 2014; Xiao et al. 2015; Yakubchuk 2017). The bending of the Kazakhstan Orocline is documented by paleomagnetic data (Abrajevitch et al. 2007, 2008; Levashova et al. 2012; Li et al. 2018; Van der Voo et al. 2006; Yi et al. 2015). The north branch of the orocline has rotated clockwise ~ 112–126° during the Late Devonian to Early Carboniferous and ~ 15–28° between the Late Carboniferous and Late Permian (Abrajevitch et al. 2008; Levashova et al. 2012; Li et al. 2018; Yi et al. 2015). The south branch is characterized by a ~ 39–40° anticlockwise rotation during the Late Carboniferous to Late Permian, while Late Devonian to Early Carboniferous data are lacking (Li et al. 2018; Wang et al. 2007a; Yi et al. 2015). Two kinds of bending were suggested to interpret the origin of the Kazakhstan Orocline. One scenario is the buckling of a quasi-linear orogenic belt due to the convergence and collision of the Tarim and Siberia continents (Abrajevitch et al. 2008; Van der Voo 2004; Xiao et al. 2010). The other model
argues that asymmetric trench retreat, related to the roll back of the subducting Junggar oceanic plate played an important role (Li et al. 2017a, 2018; Xiao et al. 2018).

The particularity of the south branch of the Kazakhstan Orocline is that its formation was controlled by simultaneous subduction of two oceanic plates (South Tianshan and Junggar oceanic plates) during the Late Paleozoic (Gao et al. 2009a; Han et al. 2010, 2011, 2015; Xiao et al. 2013). Previous models stressed that the south branch was pinned or fixed by the subduction of the Junggar oceanic plate before the Late Carboniferous (Li et al. 2017a, 2018; Yi et al. 2015). However, even though the northward subduction of the South Tianshan oceanic plate during the Late Devonian to Early Carboniferous is coeval with the first-stage bending of the Kazakhstan Orocline (Gao et al. 2009a, b; Han et al. 2015; Huang et al. 2020; Li et al. 2017a, 2018 and references therein), its role in the formation of the Kazakhstan Orocline has not received adequate attention (Abrajevitch et al. 2008). Based on the special spatial and temporal distribution characteristics and potential genetic relationships, both the subduction of these two oceanic plates should be taken into consideration to decipher the bending of Kazakhstan Orocline (Huang et al. 2020).

In a subduction scenario, different slab widths control the diverse curvature of subduction zones and their tendency to retreat backwards with time (Schellart et al. 2007). Narrow slabs (≤ 1500 km) retreat fast and develop a concave geometry towards the mantle wedge side (Fig. 12b), while wider slabs (≥ 4000 km) develop a convex geometry with slow trench retreat (Fig. 12a; Schellart et al. 2007). In addition, the transition from subduction to collision can also cause block rotations and back-arc extension in the upper plate, accompanied with crustal thinning, asthenospheric upwelling and decompressional melting (Fig. 12c; Gutiérrez-Alonso et al. 2012; Wallace et al. 2005). As for the SW CAOB, the South Tianshan Belt is about 1300 km in length and the quasi-linear DVB and BY are almost three times longer than the subduction zone of the South Tianshan Ocean (Fig. 1b, c). Based on the research of Schellart et al. (2007), the long trench of the Junggar Ocean seems to have retreated towards the opposite direction of the subduction and displays a convex geometry (Fig. 12a, d). Therefore, the rotation should be clockwise in the northern and anticlockwise in the southern sections of the Junggar Ocean trench (Fig. 12d). In contrast, the short trench of the South Tianshan Ocean was concave, and its rotation would have been clockwise in the west, and anticlockwise in the east of the South Tianshan Ocean trench (Fig. 12b, d; Abrajevitch et al. 2007, 2008; Levashova et al. 2012; Van der Voo et al. 2006; Wang et al. 2007a; Yi et al. 2015). The retreating-type subduction of the South Tianshan oceanic plate in the southern BY is deemed responsible for the back-arc extension in the Wusun Mountain area (Fig. 13a).

During the Late Devonian to Carboniferous progressing subduction of the South Tianshan oceanic plate resulted in plate roll-back, with its narrow trench displaying a concave geometry (Schellart et al. 2007). However, the consequent collision of the Tarim Craton and Yili-Central Tianshan Block eventually made the trench develop in a linear belt rather than a concave one (Figs. 1b, 12d and 13b). Meanwhile, the trench of the Junggar Ocean developed a convex geometry because of its long and asymmetric trench retreat (Li et al. 2017a, 2018; Schellart et al. 2007; Xiao et al. 2018). In contrast, the wide Junggar Ocean supplied broad space for retreat of its trench, which thus displayed convex geometry (Figs. 12d and 13b; Li et al. 2018; Xiao et al. 2018). The double subduction zones pinned and fixed the south end of the Kazakhstan Orocline, and the trench retreat of the Junggar Ocean dragged the north end to curve (Abrajevitch et al. 2008; Li et al. 2017a, 2018). The curvature process is for example similar to the formation of the curved New Hebrides arc in the Cenozoic (Li et al. 2018; Schellart et al. 2002, 2006). The subduction of the New Hebrides slab produced the New Hebrides arc followed by fast slab rollback, causing convex curvature of the New Hebrides arc and the back-arc extension of the North Fiji Basin (Schellart et al. 2002, 2006, 2007). In analogy with the SW CAOB, during the Late Devonian to Late Carboniferous, the subduction of the South Tianshan oceanic plate and slab roll back produced the Nalati-Haerk arc and the Wusun Mountain back-arc domain in the southern Yili-Central Tianshan Block. The Wusun Mountain and Nalati-Haerk magmatic belts thus constitute an arc-back-arc system in the SW CAOB (Fig. 13b). The fixing at the southern section and curvature of the northern one developed a first-stage curved geometry of the Kazakhstan Orocline (Fig. 13b; Abrajevitch et al. 2008; Li et al. 2017a, 2018). The further bending of the Kazakhstan Orocline in the Permian was associated with the convergence of the Siberian and Tarim cratons, during which strike-slip faults/shear zones cut through the oroclinal structure and the complete consumption of the Junggar oceanic plate in the core of the Kazakhstan Orocline (Li et al. 2017a, 2018; Xiao et al. 2010, 2015, 2018; Yi et al. 2015).

Conclusions

(1) Our zircon U–Pb dating results of the volcanic rocks of the Wusun Mountain Belt reveal four significant Carboniferous eruptive episodes in the southern Yili-Central Tianshan Block at ~350, ~337, ~322 and ~313 Ma.

(2) Our petrological and geochemical data suggest that the Dahalajunshan Formation (~350 Ma) contains basic to acid rock associations that exhibit calc-alkaline features, while the Yishijilike Formation (~337, ~322.
Fig. 12 (a) and (b) progressive evolution of subduction zone dynamics with simulations for different width of the trench: a $W=6000$ km; b $W=600$ km (modified from Schellart et al. 2007). c Schematic diagram for collision-induced rotation. CPBM: convergent plate boundary microblock (modified from Wallace et al. 2005). d Rollback-related tectonic model for the Kazakhstan Orocline (modified after Bazhenov et al. 2012; Li et al. 2017a, 2018) (1) ~ NW–SE quasi-linear subduction zone in the Early Devonian; (2) schematic illustration of the bending of the Kazakhstan collage system. See text for detailed discussion.
and ~313 Ma) comprises bimodal volcanics that contain both calc-alkaline and alkaline rocks.

3. The ~350 Ma Dahalajunshan volcanic rocks were derived from a depleted mantle source associated with subduction-related fluids. The ~337, ~322 and ~313 Ma Yishijilike bimodal volcanic rocks originated from low degrees (< 10%) of partial melting of a more depleted spinel-facies asthenospheric mantle source, also with involvement of subduction-related fluids. The felsic series of the bimodal volcanics were formed by fractional crystallization of the coeval basaltic magmas.

4. Available geochemical and geochronological data indicate that the formation of the Carboniferous volcanic rocks of the Wusun Mountain Range was associated with the evolution of an arc-back-arc system resulting...
from the northward subduction of the South Tianshan oceanic plate during the Late Devonian to Late Carboniferous. The retreating-type South Tianshan Orogen played a vital role in the bending of the Kazakhstan Orocline, it pinned and fixed the south end of the Kazakhstan Orocline and accommodated the oroclinal bending.

Supplementary Information

The online version contains supplementary material available at https://doi.org/10.1007/s00531-021-02111-y.

Acknowledgements

This work is financially supported by grants of the NSFC (41872082, 41622205) and the fundamental research funds for the Central Universities (2652018116 and 2652018135). The support provided by the China Scholarship Council (CSC, 201908320260) is appreciated for financing the research stay of the first author in Belgium. Dr. Minjia Sun and Ms. Xiaomei Ma are thanked for their kind assistance during the field work. We appreciate Prof. Xiaoping Xia for generous help during laboratory analysis. We would like to thank the editor for handling the manuscript, and two anonymous reviewers for their constructive and inspiring comments.

Author contributions

KC designed this project and wrote the manuscript, MS, ZH and JDG helped with the writing of the final version of the manuscript. XW and ZB participated in field work and data interpretation. All authors approved the manuscript and agreed to its submission to the International Journal of Earth Sciences.

Funding

This work is financially supported by grants of the NSFC (41872082, 41622205) and the fundamental research funds for the Central Universities (2652018116 and 2652018135).

Data availability

All data used in this manuscript are found in Appendix Tables 1–4, and all data archiving is underway. We plan to use the EarthChem Library to store our data, and now we temporarily upload a copy of our data as Supporting Information for review purposes.

Declarations

Conflict of interest

No conflict of interest exists in the manuscript submission, and the manuscript is approved by all authors for publication. I declare on behalf of my co-authors that the work described is original and has not been published previously or under consideration for publication elsewhere, in whole or in part.

References

Abrajevitch A, Van der Voo R, Levashova N, Bazhenov M (2007) Paleomagnetism of the mid-Devonian Kurgasholak Formation, Southern Kazakhstan: constraints on the Devonian paleogeography and oroclinal bending of the Kazakhstan volcanic arc. Tectonophysics 441:67–84. https://doi.org/10.1016/j.tecto.2007.06.008

Abrajevitch A, Van der Voo R, Bazhenov ML, Levashova NM, McCausland PJ (2019) The role of the Kazakhstan orocline in the late Paleozoic amalgamation of Eurasia. Tectonophysics 455:61–76. https://doi.org/10.1016/j.tecto.2008.05.006

Allen MB, Windley BF, Zhang C (1992) Palaeozoic collisional tectonics and magmatism of the Chinese Tien Shan, central Asia. Tectonophysics 220:89–115. https://doi.org/10.1016/0040-1951(93)90225-9

An F, Zhu YF, Wei SN, Lai SC (2013) An Early Devonian to Early Carboniferous volcanic arc in North Tianshan, NW China: geo-chronological and geochemical evidence from volcanic rocks. J Asian Earth Sci 78:100–113. https://doi.org/10.1016/j.jseaes.2013.07.037

Aydin F, Schmitt AK, Siebel W, Sonmez M, Ersoy Y, Lermi A, Dirik K, Duncan R (2014) Quaternary bimodal volcanism in the Nijfe Volcanic Complex (Cappadocia, central Anatolia, Turkey): age, petrogenesis and geochemical implications. Contrib Miner Petrol 168:1078. https://doi.org/10.1007/s00410-014-1078-3

Bao ZH, Cai KD, Sun M, Xiao WJ, Wan B, Wang YN, Wang XS, Xia XP (2018) Continental crust melting induced by subduction initiation of the South Tianshan Ocean: insight from the latest Devonian granitic magmatism in the southern Yili Block, NW China. J Asian Earth Sci 153:100–117. https://doi.org/10.1016/j.jseaes.2017.04.026

Bazhenov ML, Levashova NM, Degtaryev KE, Van der Voo R, Abrajevitch AV, McCausland PJ (2012) Unraveling the early–middle Paleozoic paleogeography of Kazakhstan on the basis of Ordovician and Devonian palaeomagnetic results. Gondwana Res 22:974–991. https://doi.org/10.1016/j.gr.2012.02.023

Bonnefoi CC, Provost A, Albarède F (1995) The “Daly gap” as a magmatic catastrophe. Nature 378:270–272. https://doi.org/10.1038/378270a0

Brophy JG (1991) Composition gaps, critical crystallinity, and fractional crystallization in orogenic (calc-alkaline) magmatic systems. Contrib Miner Petr 109:173–182. https://doi.org/10.1007/BF00306477

Brouxel M, Lapierre H, Michard A, Albarède F (1987) The deep layers of the Central Apennines: evidence for the shape of the lithosphere beneath the Apennines. Earth Planet Sci Lett 85:386–400. https://doi.org/10.1016/0012-821X(87)90135-X

Cao YC, Wang B, Jahn B-M, Cluzel D, Shu LS, Zhong LL (2017) Late Paleozoic arc magmatism in the southern Yili Block (NW China): insights to the geodynamic evolution of the Balkhash–Yili continental margin, Central Asian Orogenic Belt. Lithos 278–281:111–125. https://doi.org/10.1016/j.lithos.2017.01.023

Cawood PA, Buchan C (2007) Linking accretionary orogenesis with supercontinent assembly. Earth-Sci Rev 82:217–256. https://doi.org/10.1016/j.earscirev.2007.03.003

Cawood PA, Kroner A, Collins WJ, Kusky TM, Mooney WD, Windley BF (2009) Accretionary orogens through Earth history. Geol Soc Lond 318:1–36. https://doi.org/10.1144/SP318.1

Cawood P, Leitch E, Merle RE, Nemchin A (2011) Orogenesis without out-collision: stabilizing the Terra Australis accretionary orogen, eastern Australia. Geol Soc Am Bull 123:2240–2255. https://doi.org/10.1130/B30415.1

Chapman JB, Ducea MN, DeCelles GP, Profeta L (2015) Tracking changes in crustal thickness during orogenic evolution with Sr/Y: an example from the North American Cordillera. Geology 43:919–922. https://doi.org/10.1130/G36996.1

Charvet J, Shu LS, Laurent-Charvet S (2007) Paleozoic structural and geodynamic evolution of eastern Tianshan (NW China): welding of the Tarim and Junggar plates. Episodes 30:162–186. https://hal-insa.archives-ouvertes.fr/insu-00179631

Charvet J, Shu LS, Laurent-Charvet S, Wang B, Faure M, Cluzel D, Chen Y, De Jong K (2011) Palaeozoic tectonic evolution of the Tianshan belt, NW China. Sci China Earth Sci 54:166–184. https://doi.org/10.1007/s11430-010-4138-1
Gou LL, Zhang LF, Lü Z, Shen TT (2015) Geochemistry and geochronology of S-type granites and their coeval MP/HT meta-sedimentary rocks in Chinese Southwest Tianshan and their tectonic implications. J Asian Earth Sci 107:151–171. https://doi.org/10.1016/j.jseaes.2015.04.020
Green NL (2006) Influence of slab thermal structure on basalt source regions and melting conditions: REE and HFSE constraints from the Garibaldi volcanic belt, northern Cascadia subduction system. Lithos 87:23–49. https://doi.org/10.1016/j.lithos.2005.05.003
Gribble RF, Stern RJ, Bloomer SH, Stüber D, O’Hearn T, Newman S (1996) MORB mantle and subduction components interact to generate basalts in the southern Mariana Trough back-arc basin. Geochim Cosmochim Acta 60:2153–2166. https://doi.org/10.1016/S0012-821X(96)00078-6
Gribble RF, Stern RJ, Newman S, Bloomer H, O’Hearn T (1998) Chemical and isotopic composition of lavas from the northern Mariana Trough: implications for magmagenesis in Back-arc Basins. J Petrol 39:125–154. https://doi.org/10.1093/petroj/39.1.125
Griffiths RW, Campbell IH (1990) Stirling and structure in mantle starting plumes. Earth Planet Sci Lett 99:66–78. https://doi.org/10.1016/0012-821X(90)90071-5
Gutiérrez-Alonso G, Johnston S, Weil A, Pastor-Galán D, Fernández-Suárez J (2012) Buckling an orogen: the Cantabrian Orocline. GSA Today 22:4–9. https://doi.org/10.1130/GSATG141A.1
Hall CE, Gurnis M, Sdrolias M, Lavier LL, Müller RD (2003) Catastrophic initiation of subduction following forced convergence across fracture zones. Earth Planet Sci Lett 212:15–30. https://doi.org/10.1016/S0012-821X(03)00242-5
Han YG, Zhao GC, Sun M, Eizenhöfer PR, Hou WZ, Zhang XR, Liu Han BF, He GQ, Wang XC, Guo ZJ (2011) Late Carboniferous collision processes during the amalgamation of the Central Asian Orogenic Belt along the South Tianshan suture zone. Lithos 246–247:1–12. https://doi.org/10.1016/j.lithos.2015.12.016
Hawkins JW, Melchior JT (1985) Petrology of Mariana trough and Lau Basin Basalts. J Geophys Res 90:11431–11468. https://doi.org/10.1029/JB090iB13p11431
Hawkins JW, Lonsdale PF, Macdougall JD, Volpe AM (1990) Petrology of the axial ridge of the Mariana Trough backarc spreading center. Earth Planet Sci Lett 100:226–250. https://doi.org/10.1016/0012-821X(90)90187-3
Hegner E, Klemr L, Krner A, Corsini M, Alexeev DV, Iaccheri LM, Zack T, Dulska P, Xia X, Windley BF (2010) Mineral ages and P-T conditions of Late Paleozoic high-pressure eclogite and provenance of mélange sediments from Abtashi in the south Tianshan orogen of Kyrgyzstan. Am J Sci 310:916–950. https://doi.org/10.2475/09.2010.07
Heuret A, Lallemand S (2005) Plate motions, slab dynamics and back-arc deformation. Phys Earth Planet Inter 149:31–51. https://doi.org/10.1016/j.pepi.2004.08.022
Hochstaedter AG, Gill JB, Kusakabe M, Newman S, Pringle M, Taylor B, Fryer P (1990a) Volcanism in the Sumisu Rift, I. Major element, volatile, and stable isotope geochemistry. Earth Planet Sci Lett 100:179–194. https://doi.org/10.1016/0012-821X(90)90184-Y
Hochstaedter AG, Gill JB, Morris JD (1990b) Volcanism in the Sumisu Rift, II. Subduction and non-subduction related components. Earth Planet Sci Lett 100:195–209. https://doi.org/10.1016/0012-821X(90)90185-Z
Hu AQ, Jahn B-M, Zhang G, Chen YB, Zhang QF (2000) Crustal evolution and Phanerozoic crustal growth in northern Xinjiang: Nd isotopic evidence. Part I. Isotopic characterization of basement rocks. Tectonophysics 328:15–51. https://doi.org/10.1016/S0040-1951(00)00176-1
Huang H, Zhang ZC, Santosh M, Zhang DY, Wang T (2015a) Petrogenesis of the Early Permian volcanic rocks in the Chinese South Tianshan: implications for crustal growth in the Central Asian Orogenic Belt. Lithos 228–229:23–42. https://doi.org/10.1016/j.lithos.2015.04.017
Huang ZY, Long XP, Kründer A, Yuan C, Wang YJ, Chen B, Zhang YY (2015b) Neoproterozoic granite gneisses in the Chinese Central Tianshan Block: implications for tectonic affinity and Precambrian crustal evolution. Precambrian Res 269:73–89. https://doi.org/10.1016/j.precamres.2015.08.005
Huang H, Wang T, Tong Y, Qin Q, Ma XX, Yin JY (2020) Rejuvenation of ancient micro-continents during accretionary orogenesis: insights from the Yili Block and adjacent regions of the SW Central Asian Orogenic Belt. Earth Sci Rev 208:103255. https://doi.org/10.1016/j.earscirev.2020.103255
Hyndman RD, Currie CA (2011) Why is the North America Cordillera high? Hot backarc, thermal isostasy, and mountain belts. Geol Soc Am Bull 122:627–640. https://doi.org/10.1130/B26491.1
Ishizuka O, Yuasa M, Tamura Y, Shukuno H, Stern RJ, Naka J, Joshima M, Taylor RN (2010) Migrating shoshonitic magmatism tracks subduction. Am J Sci 310:916–950. https://doi.org/10.1139/e71-055
Ishizuka O, Yuasa M, Taylor RN, Sakamoto I (2009) Two contrasting magmatic types coexist after the cessation of back-arc spreading. Chem Geol 266:274–296. https://doi.org/10.1016/j.chemgeo.2009.06.014
Ishizuka O, Yuasa M, Tamura Y, Shukuno H, Stern RJ, Naka J, Yoshima M, Taylor RN (2010) Migrating shoshonitic magmatism tracks Izu–Bonin–Mariana intra-oceanic arc rift propagation. Earth Planet Sci Lett 294:111–122. https://doi.org/10.1016/j.epsl.2010.03.016
Ishizuka O, Taylor RN, Yuasa M, Ohara Y (2011) Making and breaking an island arc: a new perspective from the Oligocene Kyushu-Oriomo ocean. Tectonics 30:1–23. https://doi.org/10.1029/2010TC002394
Jiang T, Gao I, Klemr R, Qian Q, Zhang X, Xiong XM, Wang XS, Tan Z, Chen BX (2014) Paleozoic ophiolitic mélanges from the South Tianshan Orogen, NW China: geological, geochemical and geochronological implications for the geodynamic setting. Tectonophysics 612–613:106–127. https://doi.org/10.1016/j.tecto.2013.11.038
Pearce JA, Peate DW (1995) Tectonic implications of the composition of volcanic arc magmas. Annu Rev Earth Planet Sci 23:251–285
Pearce JA, Stern RJ (2006) Origin of back-arc basin magmas: trace element and isotope perspectives. Geophys Monogr 166:63–86. https://doi.org/10.1029/166GM06
Pearce JA, Stern RJ, Bloomer SH, Fryer P (2005) Geochemical mapping of the Mariana arc-basin system: implications for the nature and distribution of subduction components. Geochem Geophys Geosyst 6:1–27. https://doi.org/10.1029/2004GC000895
Pecceirillo A, Barberio MR, Ayalew D, Barbieri M, Wu TW (2003) Relationships between mafic and peralkaline silicic magmatism in continental rift settings: a petrological, geochemical and isotopic study of the Gedessa Volcano, Central Ethiopian Rift. J Petrol 44:2003–2032. https://doi.org/10.1093/petrology/egg068
Pin C, Marini F (1993) Early Ordovician continental break-up in Variscan Europe: Nd-Sr isotope and trace element evidence from bimodal igneous associations of the Southern Massif Central, France. Lithos 29:177–196. https://doi.org/10.1016/0024-4937(93)90016-6
Pin C, Paquette J (1997) A mantle-derived bimodal suite in the Hercynian Belt: Nd isotope and trace element evidence for a subduction-related rift origin of the Late Devonian Brevonne metavolcanics, Massif Central (France). Contrib Miner Petr 129:222–238. https://doi.org/10.1007/s004100050334
Profeta L, Ducea MN, Chapman JB, Paterson SR, Gonzales SMH, Kirsch M, Petrescu L, DeCelles PG (2015) Quantifying crustal thickness over time in magmatic arcs. Sci Rep 5:17786. https://doi.org/10.1038/srep17786
Qian Q, Gao J, Xiong XM, Long LL, Huang DZ (2006) Petrogenesis and tectonic settings of carboniferous volcanic rocks from north Zhaosu, western Tianshan Mountains: constraints from petrology and geochemistry. Acta Petrol Sin 22:1307–1323 (in Chinese with English abstract)
Qian Q, Gao J, Klemd R, He GQ, Song B, Liu DY, Xu RH (2009) Early Paleozoic tectonic evolution of the Chinese South Tianshan Orogen: constraints from SHRIMP zircon U-Pb geochronology and geochemistry of basaltic and dioritic rocks from Xiate, NW China. Int J Earth Sci 98:551–569. https://doi.org/10.1007/s00531-007-0268-x
Ren R, Han BF, Ji QJ, Zhang L, Xu Z, Su L (2011) U-Pb age of detrital zircons from the Teker River, Xinjiang, China, and implications for tectonomagmatic evolution of the South Tian Shan Orogen. Gondwana Res 19:460–470. https://doi.org/10.1016/j.gr.2010.07.005
Rudnick RL, Gao S (2003) Composition of the continental crust. Treatise Geochim 3:1–64. https://doi.org/10.1016/b978-0-08-095975-7.00301-6
Saunders A, Storey M, Kent R, Norry M (1992) Consequences of plume-lithosphere interactions. Geol Soc Lond 68:41–60. https://doi.org/10.1144/GSL.SP.1992.068.01.04
Schellart WP, Lister GS (2004) Tectonic models for the formation of arc-shaped convergent zones and backarc basins. In: Sussman AJ, Weil AB (eds) Orogenic curvature: integrating paleomagnetic and structural analyses, vol 383. Geological Society of America Special Paper, Boulder, pp 237–258
Schellart W, Lister G, Jessell MW (2002) Anlogue modeling of arc and backarc deformation in the New Hebrides arc and North Fiji Basin. Geol 30:311–314. https://doi.org/10.1130/0091-7613(2002)030<0311:AMAOABSE2>CO;2
Schellart WP, Lister GS, Toy VG (2006) A Late Cretaceous and Cenozoic reconstruction of the Southwest Pacific region: tectonics controlled by subduction and slab rollback processes. Earth-Sci Rev 76:191–233. https://doi.org/10.1016/j.earsrev.2006.01.002
Schellart WP, Freeman J, Stegman DR, Moresi L, May D (2007) Evolution and diversity of subduction zones controlled by slab width. Nature 446:308–311. https://doi.org/10.1038/nature05615
Şengör AMC, Natali in BA (1996) Turkic-type orogeny and its role in the making of the continental crust. Annu Rev Earth Planet Sci 24:263–337. https://doi.org/10.1146/annurev.earth.24.1.263
Şengör AMC, Natali in BA, Brutman VS (1993) Evolution of the Altai tectonic collage and Palaeeozoic crustal growth in Eurasia. Nature 364:299–307. https://doi.org/10.1038/364299a0
Shervais JW (1982) Ti-V plots and the petrogenesis of modern and ophiolitic lavas. Earth Planet Sci Lett 59:101–118. https://doi.org/10.1016/0012-821X(82)90120-0
Shinjo R, Kato Y (2000) Geochemical constraints on the origin of bimodal magmatism at the Okinawa Trough, an incipient back-arc basin. Lithos 54:117–137. https://doi.org/10.1016/S0024-4937(00)00034-7
Shinjo R, Chung SL, Kato Y, Kimura M (1999) Geochemical and Sr-Nd isotopic characteristics of volcanic rocks from the Okinawa Trough and Ryukyu Arc: implications for the evolution of a young, intracontinental back arc basin. J Geophys Res 104:10591–10608. https://doi.org/10.1029/99JB00040
Stern RJ, Lin PN, Morris JD, Jackson C, Fryer M, Bloomer P, Sherman H, Ito E (1990) Enriched back-arc basin basalts from the northern Mariana Trough: implications for the magmatic evolution of back-arc basins. Earth Planet Sci Lett 100:210–225. https://doi.org/10.1016/0012-821X(90)00186-2
Stern RJ, Fouch MJ, Klemperer SL (2003) An overview of the Izu Bonin-Mariana subduction factory. Geophys Monogr 138:175–222. https://doi.org/10.1029/138gm10
Su W, Gao J, Klemd R, Li JL, Zhang X, Li XH, Chen NS, Zhang L (2010) U-Pb zircon geochronology of Tianshan eclogites in NW China: implication for the collision between the Yili and Tarim blocks of the southwestern Altai. Eur J Miner 22:473–478. https://doi.org/10.1127/0935-1221/2010/0022-2040
Su WB, Cai KD, Sun M, Wan B, Wang XS, Bao ZH, Xiao WJ (2018) Carboniferous volcanic rocks associated with back-arc extension in the western Chinese Tianshan, NW China: insight from temporal-spatial character, petrogenesis and tectonic significance. Lithos 310–311:241–254. https://doi.org/10.1016/j.lithos.2018.04.012
Sun SS, McDonough WF (1989) Chemical and isotopic systematics of oceanic basalts: implications for mantle composition and processes. Geol Soc Lond 42:313–345. https://doi.org/10.1144/GSL.SP.1989.042.01.19
Sun LH, Wang YJ, Fan WM, Zi JW (2008) Post-collisional potassic magmatism in the Southern Awulale Mountain, western Tianshan Orogen: petrogenetic and tectonic implications. Gondwana Res 14:383–394. https://doi.org/10.1016/j.gr.2008.04.002
Tan Z, Agard P, Monié P, Gao J, John T, Bayet L, Jiang T, Wang XS, Hong T, Wan B, Caron B (2019) Architecture and P-T-deformation-time evolution of the Chinese SW-Tianshan HP/UHP complex: implications for subduction dynamics. Earth-Sci Rev. https://doi.org/10.1016/j.earscirev.2019.102894
Tang GJ, Wang Q, Wyman DA, Sun M, Zhao ZH, Jiang QZ (2013) Petrogenesis of gold-mineralized magmatic rocks of the Taerbiace area, northwestern Tianshan (western China): constraints from geochronology, geochemistry and Sr-Nd-Pb-Hf isotopic compositions. J Asian Earth Sci 74:113–128. https://doi.org/10.1016/j.jseaesr.2013.03.022
Tang GJ, Chung SL, Wang Q, Wyman DA, Dan W, Chen HY, Zhao ZH (2014) Petrogenesis of a late carboniferous maic dike–granitoid association in the western Tianshan: response to the geodynamics of oceanic subduction. Lithos 202:85–99. https://doi.org/10.1016/j.lithos.2014.04.010
