Petrogenesis of Early Carboniferous Alkaline Basalt from the Wusun Mountain: Implications for Tectonic Evolution of the Western Yining Block, NW China

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Abstract: Late Paleozoic volcanic rocks are well exposed in the Yining Block, NW China, and are predominately composed of andesites, rhyolites and volcaniclastics as well as minor basalts. Study of the petrology, whole-rock geochemistry and zircon U-Pb dating for the Early Carboniferous alkaline basalts from Wusun Mountain, western Yining Block, constrains their petrogenesis and tectonic evolution. The alkaline basalts consist mainly of plagioclases, mostly albite and labradorite, as well as clinopyroxenes and olivines; zircon U-Pb dating indicates their formation at ca. 350 Ma. Geochemically, the basaltic samples have low SiO_2 contents, and high TiO_2, Al_2O_3 and alkaline contents, coupled with high Na_2O/K_2O ratios, displaying an alkaline basalt affinity. They show remarkable LILE enrichment and HFSE depletion. Meantime, these samples have relatively high TFe_2O_3, MgO, and $Mg^{\#}$ values as well as Ni and Cr, relatively high Sm/Yb and U/Th, suggesting origination from a mantle source metasomatized by slab fluids. They formed in a transitional tectonic setting from arc to intraplate, showing a typical affinity of back-arc basin basalts. The alkaline basalts were likely generated in a nascent back-arc extension setting resulting from slab rollback of the southern Tianshan oceanic lithosphere. A bi-directional subduction model seems more reasonable for the evolution of the southern Tianshan Ocean. These new data will provide a new tectonic model for Late Paleozoic tectonic evolution of the western Yining Block.

Key words: petrology, geochemistry, isotopic dating, alkaline basalt, slab rollback, Yining Block, CAOB

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1 Introduction

The Central Asian Orogenic Belt (CAOB) represents the largest Phanerozoic accretionary tectonic orogen in the world (Jahn et al., 2004; Windley et al., 2007; Shen et al., 2008), and is mainly composed of a series of microcontinents, island arcs, seamounts, and ophiolitic mélanges (Xiao et al., 2014; Yang et al., 2015; Wang et al., 2020). The formation of the CAOB was closely associated with the gradual contraction and final closure of the Paleo-Asian Ocean (PAO) (Wilhem et al., 2012; Li et al., 2013; Li S et al., 2016), and its closure displayed diachronous characteristics in different areas (Li et al., 2013; Wang et al., 2017). Magmatic activities in the CAOB spanned the entire Paleozoic and Mesozoic, and their generation was related to subduction of the PAO and post-orogenic processes, including lithospheric thickening, delamination and asthenospheric upwelling (Sun et al., 2008; Li et al., 2013).

Large volumes of Late Paleozoic volcanic rocks and associated granitoids crop out in the Yining Block, a southwestern part of the CAOB (Fig. 1a; Li et al., 2008; Tang et al., 2014); the rocks are pivotal to decipher the tectonic evolutionary histories of the CAOB during this period. Although many works including on petrology and geochemistry have been done on this Late Paleozoic igneous regime (e.g., Long et al., 2011; An et al., 2013; Li N B et al., 2015), the tectonic setting and deep geodynamic mechanism remain poorly constrained. Some researchers have suggested that the magmatic rocks are associated with a Late Paleozoic extensional setting, encompassing an intracontinental rift as a result of a mantle plume (Xia et al., 2004), post-collisional extension or back-arc basin (Qian et al., 2006; Han et al., 2010) and local extension settings (ridge subduction; Yin et al., 2017b), whereas others tend to support a subduction-related setting as a major viewpoint, such as island arc or continental arc (Wang B et al., 2007; Windley et al., 2007; Zhu et al., 2009; Tang et al., 2013; An et al., 2017; Li Y J et al., 2017; Wang et al., 2018). Additionally, the subduction polarity of the southern Tianshan Ocean, as a branch of the PAO, is still controversial, including northward subduction (Gao and Klemd, 2003; Li J L et al., 2016; Li et al., 2018a), southward subduction (Wang et al., 2011, 2012), and bi-directional subduction models (Huang H et al., 2013; Wang et al., 2016).

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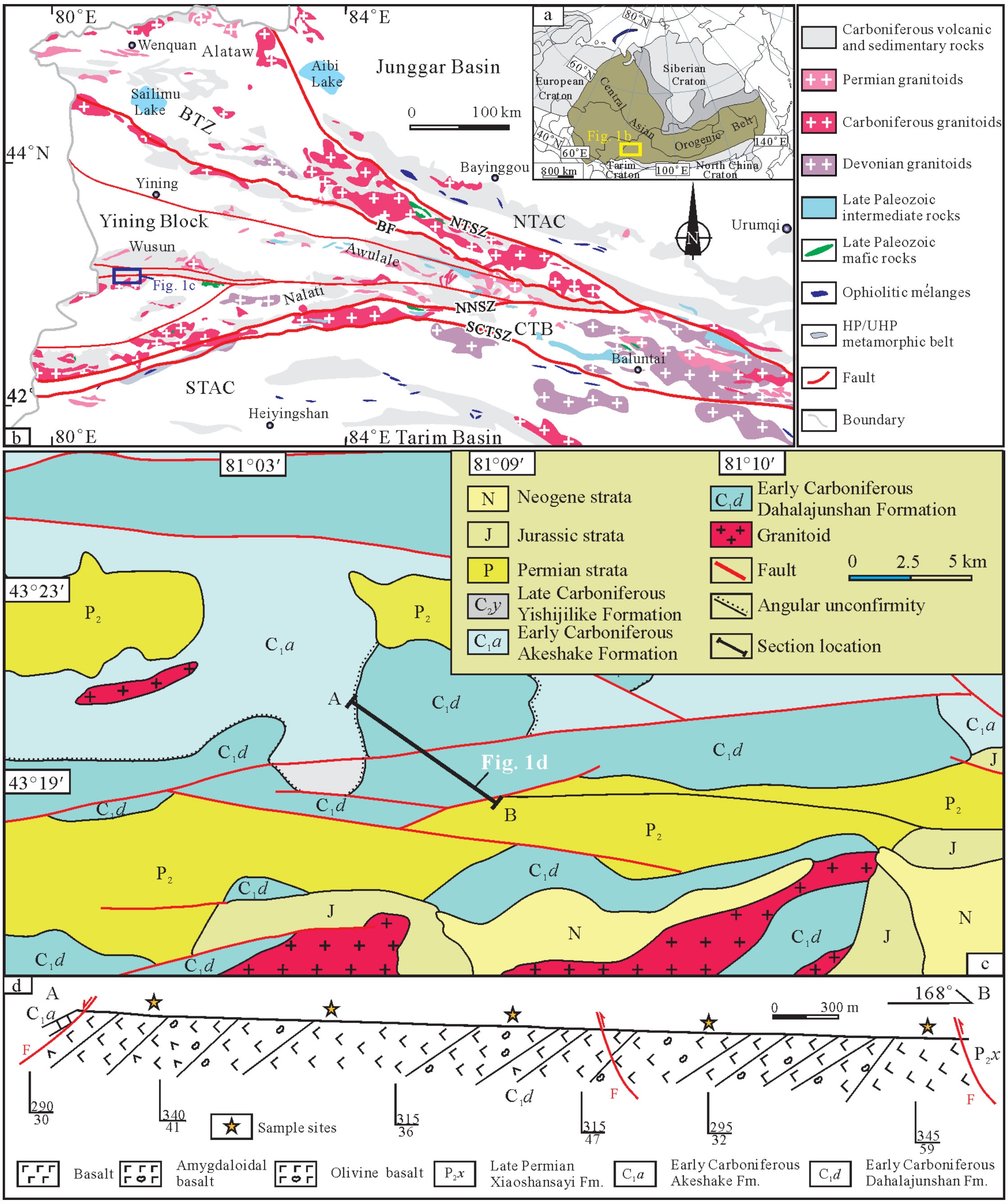

Fig. 1. Geology and location of study area.
(a) Overview map showing the CAOB and adjacent plates; (b) simplified geological map of Chinese western Tianshan; (c) local geological map of the Wusun Mountain; (d) geological section for the C_1d. NTAC–North Tianshan Accretionary Complex; BTZ–Borohara Tectonic Zone; CTB–Central Tianshan Block; STAC–South Tianshan Accretionary Complex; NTSZ–North Tianshan Suture Zone; BF–Borohara Fault; NNSZ–North Nalati Suture Zone; SCTSZ–Southern Central Tianshan Suture Zone.

Widespread occurrence of the Carboniferous magmatic rocks in the Wushun Mountain of the western Yining Block offers an excellent opportunity to examine the tectonic evolutionary histories of the block. In this contribution, building on previously published data on Wusun Mountain and its adjacent regions, we present petrology, whole-rock geochemistry and zircon U–Pb data for the alkaline basalts from the Wusun Mountain, in order to shed light on the petrogenesis and tectonic evolution of this block.

2 Geological Setting

The Chinese western Tianshan is located in the southern part of the CAOB (Fig. 1a). Tectonically, it can be roughly divided, from north to south, into four terranes separated by a sequence of suture zones or large-scale faults, i.e., the North Tianshan Accretionary complex (NTAC), the

Borohara Tectonic zone–Yining Block (BY), the Central Tianshan arc terrane (CTAT), and the South Tianshan Accretionary complex (STAC) (Fig. 1b; Li Y J et al., 2017, 2018a).

The NTAC, sandwiched between the Junggar terrane to the north and the BY to the south, was closely associated with the evolution of the northern Tianshan Ocean. Several typical ophiolitic mélanges have been recognized, such as the Bayingou ophiolites, which predominantly comprise pillow basalts, layered gabbros, serpentinized ultramafic rocks and radiolarian-bearing siliceous rocks (Xu et al., 2006a; Yang et al., 2018). Zircon U-Pb dating of plagiogranite and gabbro from the mélanges yielded ages of 325 Ma and 344 Ma, respectively (Xu et al., 2006a, b). Han et al. (2010) reported ca. 316 Ma for a Sikeshu stitching pluton that intruded into the Bayinggou ophiolites, with timing of emplacement likely representing a pivotal upper-age for the collision between the BY and Junggar terranes. Combined with the discoveries of numerous magmatic rocks with zircon U-Pb ages of 466 to 447 Ma (Hu et al., 2008; Wang et al., 2012) in the northern BY, it is suggested that the initial southward subduction of the northern Tianshan Ocean began in the Middle Ordovician (Huang Z Y et al., 2013), and terminated in the latest Early Carboniferous (An et al., 2013). Contrastingly, the STAC was related to the northward subduction of the southern Tianshan Ocean and Late Paleozoic collision between the Tarim Craton and the BY–CTAT (Li et al., 2018a), an event which is characterized by a high-ultrahigh pressure (HP-UHP) metamorphic belt and associated ophiolitic mélanges (Gao and Klemd, 2003; Zhang et al., 2013; Zhang et al., 2020). The metamorphic belt is dominated by metapelites, eclogites, blueschists and marbles (Gao and Klemd, 2003), with the peak metamorphism time (325–310 Ma) probably representing an important orogenic event (Su et al., 2010). Its formation can be explained using a sediment-type subduction channel model via exhumation back to the surface (Li J L et al., 2016). In the Chinese South Tianshan, ophiolitic mélanges as remnants of the southern Tianshan oceanic crust occur mainly in Heiyingshan, Kumishi, Kulehu, Baleigong and Guluogou areas (Jiang et al., 2014; Yang et al., 2018). In the CTAT, numerous Late Devonian to Carboniferous arc-like volcanic rocks and Permian to Mesozoic sedimentary rocks are well exposed (Yin et al., 2017a) and, additionally, this terrane is characterized by well-defined outcropping of a Precambrian crystallization basement with ages ranging between 1458 Ma and 730 Ma (Ma et al., 2012).

The BY also has a Precambrian basement with metamorphic rocks mainly containing high-grade orthogneisses, paragneisses and amphibolites, coupled with micaschists and marbles (Wang et al., 2014; Long and Huang, 2017). These basement rocks were overlain by Paleozoic volcanic-sedimentary strata. Carboniferous volcanic rocks are widely distributed in this block, comprising basalts, basaltic andesites, andesites and rhyolites, as well as pyroclastic rocks (Zhu et al., 2009; Li Y J et al., 2017). Geochemically, the BY Early Carboniferous volcanic rocks are characterized by calc-alkaline series, having high LREE contents and displaying obvious LILE (e.g. Sr, Rb, Ba, Th) enrichment, relative to HFSE (e.g., Nb, Ta, Ti). Therefore, these volcanics have been interpreted as products of arc-related tectonic settings (Tang et al., 2010; An et al., 2013; Li Y J et al., 2017), which mostly resulted from either northward subduction of the southern Tianshan oceanic lithosphere (Li Y J et al., 2017) or southward subduction of the northern Tianshan beneath the Yining–central Tianshan terrane (Wang Q et al., 2007). In contrast, the Late Carboniferous volcanic rocks show distinct differences in rock assemblages, geochemistry and tectonic settings. They are dominated by alkaline rocks and tholeiitic basalts (Li et al., 2018b). A remarkable feature of the Late Carboniferous volcanism is the occurrence of typical bimodal volcanic suites at the Wusun Mountain, Yining Block, with zircon U-Pb ages of ca. 313 Ma (Ning et al., 2019). In addition, in the Awulale Mountain area, Late Carboniferous (ultra-) potassic trachyandesites and trachybasalts are well developed with petrogenesis mostly related to a post-collisional extension setting that was triggered by the detachment of an orogenic root zone (Sun et al., 2008).

Late Paleozoic intrusive magmatism occurred pervasively along the northern and southern margins of the BY (Fig. 1b). The Late Devonian to Early Carboniferous plutons in this block are mainly felsic-intermediate suites mostly belonging to I-type granitoids (Xu X Y et al., 2013), with sparse mafic components (Wang et al., 2019b). Likewise, these rocks exhibit subduction-related geochemical features (Long et al., 2011), consistent with the arc-like interpretation of the concurrent volcanic rocks (Zhu et al., 2009). However, the focus of the post-collisional A-type granitoids is predominately in the latest Late Carboniferous to Early Permian, which were probably related to slab breakoff or lithospheric delamination after the closure of the PAO (Tang et al., 2010; Li N B et al., 2015).

3 Geology of the Wusun Mountain and Samples

The basaltic samples in this study were collected from the Lower Carboniferous Dahalajunshan Formation (Fm.) exposed in the Wusun Mountain (Fig. 1b–d). This mountain extends for ca. 200 km from the national border of China to the eastern Tekesidaban area (Xinjiang), where the major sedimentary successions include from bottom to top: the Lower Carboniferous Dahalajunshan (C_1d), and Akeshake (C_1a), and the Upper Carboniferous Yishijilike Formations (C_2y). The C_1d is characterized by calc-alkaline arc-related intermediate-basic volcanic rocks, with some basalts exhibiting pillow structure (Cao et al., 2017). The C_1a shows neritic, marine-continental transitional affinities, and massive carbonates, sandstones and siltstones, as well as a well-developed rich assemblage of shallow-water fossils (Bai et al., 2015). Relative to the C_1d, the C_2y is dominated by a typical bimodal volcanic suite related to continental lift (Li et al., 2018b; Ning et al., 2019). In addition, Permian to Jurassic strata overlie the Carboniferous outcrop and Late Devonian to Permian granitoids are also exposed in this area, which occur as small plutons or dikes intruding the Late Paleozoic volcanic-sedimentary sequences (Bao et al., 2018). These

Carboniferous volcanic rocks in Wusun Mountain have reliable geochronological data based on highly precise LA-ICP-MS zircon U-Pb dating results (Zhang et al., 2009; Ru et al., 2012; Bai et al., 2015; Cao et al., 2017).

4 Methods

Analyses of whole-rock samples were carried out via X-ray fluorescence (XRF) and inductively coupled-plasma mass spectrometry (ICP-MS) at Chang'an University. All analytical samples were washed repeatedly using 3–5 wt% dilute hydrochloric acid in order to eliminate external materials. The detailed processes are similar to those described by Yang et al. (2015).

U–Pb dating and trace element analyses of zircon were conducted with LA-ICP-MS at the Key Laboratory for the study of focused Magmatism and Giant Ore Deposits, MLR, Xi'an Center of Geological Survey, China Geological Survey (CGS). Zircon 91500 for U-Pb dating was used as external standard, while NIST610 with Si as internal standardization was calibrated against reference materials. Relative values for NIST610 are provided in the GeoReM database (http://georem.mpch-mainz.gwdg.de/). The Glitter 4.4 and Isoplot/Excel 3 were invoked to calculate the ratios of U-Th-Pb elements and weighted mean ages, respectively (Ludwig, 2003). Further detailed analytical procedures and instrumentation conditions can be found in Li Y G et al. (2015).

Compositions of major elements in plagioclase were measured using a JEOL JXA-8200 electron microscope from Chang'an University, under the conditions of accelerating potential of 15 kV and sample current of 12 nA. The processes are similar to those described by Pouchou and Pichoir (1984).

5 Results

The Wusun Mountain basaltic samples are characterized mainly by porphyritic textures with phenocrysts of plagioclases (10–25 vol%), clinopyroxenes (1–2 vol%), and olivines (1–2 vol%), as well as amygdaloidal structures (Fig. 2). The matrix is composed of glasses, fine-grained plagioclases, olivines, clinopyroxenes and oxides. In the photomicrographs (Fig. 2c, d), plagioclase crystals are ubiquitous with largest crystal up to 1.5 mm long. Most of crystals are euhedral and oblong-prismatic in form. Note that nearly no aqueous minerals, such as hornblende, can be recognized.

5.1 Zircon features and geochronology

Zircons from the Wusun Mountain basaltic samples are prismatic, transparent to translucent. They are 87–200 μm long and 84–52 μm wide, with length/width ratios of 2:1–4:1. In the CL images (Fig. 3), most grains display relatively clear oscillatory zoning, and meantime have remarkable inherited cores. All the analyzed zircon grains, regardless of being in the core or margin, display high Th/U values (0.1–0.8) (Supplementary Table 1). These features are consistent with an magmatic origin (Hoskin and Schaltegger, 2003). Twenty-six grains are concordant with a wide range varying from 350 to 1096 Ma (Fig. 3), with two major weighted mean $^{206}Pb/^{238}U$ ages between

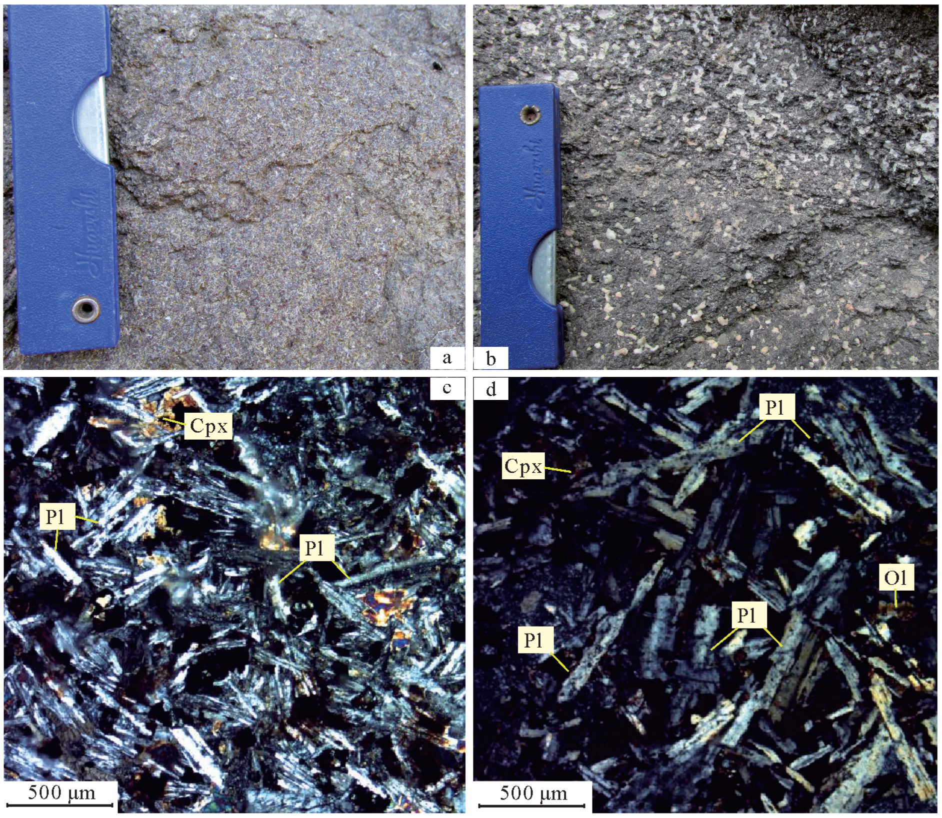

Fig. 2. Field photographs (a–b) and photomicrographs (c–d) of the Wusun Mountain alkaline basalt.
Pl–Plagioclase; Cpx–Clinopgroxene; Ol–Olioine.

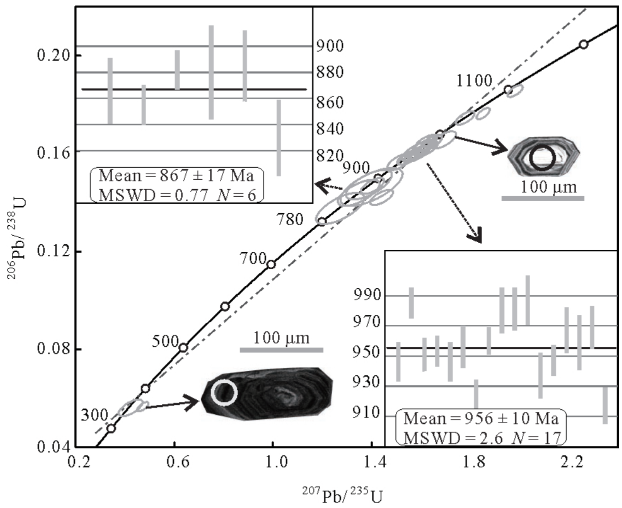

Fig. 3. Zircon U-Pb ages for the Wusun Mountain alkaline basalt.

867 ± 17 Ma and 956 ± 10 Ma. The youngest two ages (350 Ma, 353 Ma) represent the eruption age of the volcanic rocks. However, the inherited zircons in these samples give many Late Mesoproterozoic–Early Neoproterozoic ages, which is more likely related to underplating of the basaltic magmas resulting in re-melting of the Precambrian basement in the Yining Block; such reworking of old crustal materials frequently occurred in the Paleozoic (Zhu et al., 2005; Huang et al., 2016).

5.2 Major and trace elements

The Wusun Mountain alkaline basaltic samples have low SiO_2 (46.74–49.21 wt%) contents, and high TiO_2 (1.62–1.96 wt%), Al_2O_3 (16.61–17.50 wt%) and alkaline ($K_2O + Na_2O$ = 4.25–5.03 wt%) contents, with Na_2O/K_2O ratios ranging from 7.1 to 12.5 (Supplementary Table 2). $Mg^{\#}$ values of these samples vary from 45 to 62. On a total alkali vs. silica diagram (Fig. 4a), these samples plot in the basalt field and belong to the alkaline series, consistent with the Rittmann index (δ = 3.8–5.2) (Yang et al., 2015).

All the samples are characterized by relatively low REE contents (77.84–106.3 ppm) and $(La/Yb)_N$ ratios (2.0–2.7). Meantime, they show relatively flat chondrite-normalized HREE patterns with slightly enriched LREE and weakly negative to positive Eu anomalies (δEu = 0.96–1.01) (Fig. 4b). On the trace element spider diagram (Fig. 4c), the basaltic samples present remarkable arc-related LILE enrichment (e.g., Sr, K, Rb, and Ba) and HFSE depletion (e.g., Nb, Ta and P). These features are similar to those of Permian alkaline basalts that were generated in a back-arc basin from the Yushu area, Tibet (Zhang et al., 2016).

6 Discussion

6.1 Timing of magmatism

The Wusun Mountain alkaline basalts from C_1d were previously regarded being formed during the Hercynian (XBGMR, 1993). Numerous dating results from C_1d in the Wusun Mountain have been attained over the past decade: Zhang et al. (2009) provided two LA-ICP-MS zircon U-Pb ages (344 ± 6 Ma, 353 ± 4 Ma), demonstrating its formation in the Early Carboniferous; later, Ru et al. (2012) and Li G Y et al. (2015, 2017) widely reported a series of LA-ICP-MS zircon U-Pb ages for the Early Carboniferous volcanic rocks of C_1d, mainly ranging from 344 to 360 Ma. Furthermore, our field investigations show that C_1d was covered in an angular unconformity by C_1a (Fig. 1c). Furthermore, shallow-marine fossils such as *Lycospora denticulate–Laevigatosporites minor–Auroraspora*, *Palaeosmilia regia* and *Gigantoproductus* sp. have been recognized in C_1a (Ru et al., 2012; Bai et al., 2015), which predominately occurred in the late stage of the Early Carboniferous (Li et al., 2008). Hence, our zircon U-Pb dating results, together with the published data, further indicate that the studied C_1d alkaline basalts were formed in the early stage of the Early Carboniferous (ca. 350 Ma).

6.2 Petrogenesis

The Wusun Mountain basaltic samples have relatively high TFe_2O_3 (11.95–13.69 wt%), MgO (5.12–9.97 wt%), and $Mg^{\#}$ (45–62) values as well as Ni (126–244 ppm) and Cr (48.8–230 ppm), suggesting an origin from a mantle source where the minerals of olivine and spinel occur. Furthermore, the samples have high Sm/Yb (1.7–2.0) ratios. In the melt modeling diagram (Fig. 5a), all the samples plot between garnet + spinel lherzolite (50:50) and garnet–lherzolite curves, high above the spinel–lherzolite melting curve. These features, combined with positive Sr anomalies and low LREE contents and high Sr/

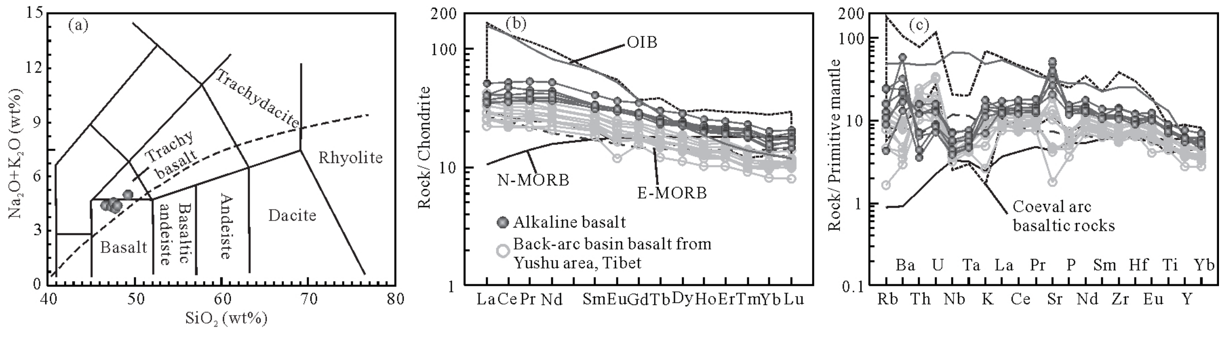

Fig. 4. (a) Total alkalis vs. Silica diagram (TAS, from Le Maitre, 2002); (b) chondrite–normalized rare earth element patterns; (c) primitive mantle–normalized trace multi-element patterns.

Chondrite and primitive mantle values are from Sun and McDonough (1989); back-arc basin basalts are from Zhang et al. (2017); coeval arc basaltic rocks in Chinese western Tianshan are from Li (2017a), Zhu et al. (2009) and Tang et al. (2014).

Y ratios (15.9–41.0), suggest that garnet, rather than plagioclase, is retained as residual minerals in the magma source (Green, 2006). The diagram further reveals that the samples have likely undergone relatively low degrees (5–11%) of partial melting of a mantle source composed of garnet + spinel lherzolite. Moreover, high Nb/Ta (14.6–16.5) and Zr/Hf (39.0–43.1) ratios of the samples are close to those of typical OIB (Nb/Ta = 17.8, Zr/Hf = 35.9; Sun and McDonough, 1989), and are distinctly different from the basaltic rocks associated with a depleted mantle source in the Chinese western Tianshan (Fig. 4, 7; Zhu et al., 2005; Tang et al., 2014; Cao et al., 2017; Li Y J et al., 2017). Accordingly, the results imply that the magma source for the Wusun Mountain alkaline basalts is related to the relatively rich mantle.

Generally, melting magmas from subduction zones have relative enrichment in LILE (such as Sr, Rb, Ba and Pb) and depletion in HFSE (such as Nb, Ta and Ti; Pearce and Peate, 1995). Similarly, crustal contamination can also have similar influences on magmas originating from a mantle source (Rudnick and Gao, 2003). The Wusun Mountain dating samples contain numerous inherited zircon cores, revealing that more or less crustal materials were added to the magmas that were derived from a mantle source. However, these studied samples have a restricted range of both Nb/La (0.3–0.5) and Zr/Nb (30.3–42.4) values, and show no significant correlations between $Mg^{\#}$ and Nb/La and Zr/Nb. Accordingly, based on these features, it is suggested that crustal contamination cannot account for the enrichment of LILE and depletion of Nb-Ta (Fig. 4c) during magma ascent. In contrast, the LILE enrichment and HFSE depletion are more likely related to subduction-related fluids or slab melts. Experimental studies have shown that some mobile elements are preferentially linked to the fluid phase, whereas HFSE prefers the solid phase (Hawkesworth et al., 1997). Thus, the ratios of some mobile elements with HFSE, such as Rb/Nb and Th/Nb, are valuable in evaluating fluid activity during partial melting (Zhang et al., 2017). The low Th/Nb (0.1–0.3), but highly variable U/Th (0.2–0.5) and Ba/La (9.5–44.3) values, further suggest that a hydrous-fluid component derived from subducted slab-induced partial melting of the mantle source (Fig. 5b), and generated the Wusun Mountain Early Carboniferous alkaline basalts.

Note that these alkaline basalts in this study have characteristically high Al_2O_3 (16.61–17.50 wt%, average 17.13 wt%) and Sr (555–1113 ppm, average 871 ppm; Fig. 4c) components. Some researchers have proposed that H_2O or high pressure exerts a strong influence on mineral phase stability and crystallization sequence during magmatic evolution, and the effects of both suppress crystallization of plagioclase (Bartels et al., 1991; Ariskin, 1999; Kelley et al., 2010; Grove et al., 2012). At the same time, under high-pressure conditions, olivine and clinopyroxene can crystallize very early in the fractionation sequence, driving Al values in the residual melt to higher values while keeping Si values low (Eason and Sinton, 2006). When late-appearing plagioclase crystallizes, it is rich in Al (Grove et al., 2012). Consequently, it is inferred that H_2O and high pressure could have played an important role in generating the studied alkaline basalts. However, few hydrous minerals from the Wusun Mountain alkaline basalts are seen in the photomicrographs (Fig. 2c, d). Furthermore, based on the results of the electron probe (Supplementary Table 3), plagioclases from the Wusun Mountain basaltic samples mostly belong to albites and labradorites (Fig. 6). Thus, this further supports high-pressure rather than water content suppressing the crystallization of plagioclase in the alkaline basalts and synchronously some elements (such as Ca, Mg and V) are partitioned preferentially into olivine and clinopyroxene in the early fractionation sequence (McKenzie and O'Nions, 1995), resulting in relative enrichment of albites and labradorites, coupled with Al and Sr abundances during late-stage crystallization.

We consider that the Wusun Mountain alkaline basalts originated from a relatively enriched mantle source composed of garnet + spinel lherzolite, with an input of subduction-related hydrous fluids and, moreover, high pressure exerted a strong influence on the magma generation.

6.3 Tectonic setting

Late Paleozoic tectonic settings for the Chinese western Tianshan are still debated, mainly including continental rifting associated with a mantle plume (Xia et al., 2004), post-collision (Han et al., 2010), back-arc extension (Qian et al., 2006; Li et al., 2010) and arc-related settings (e.g., Zhu et al., 2009; Tang et al., 2013; Li G Y et al., 2015;

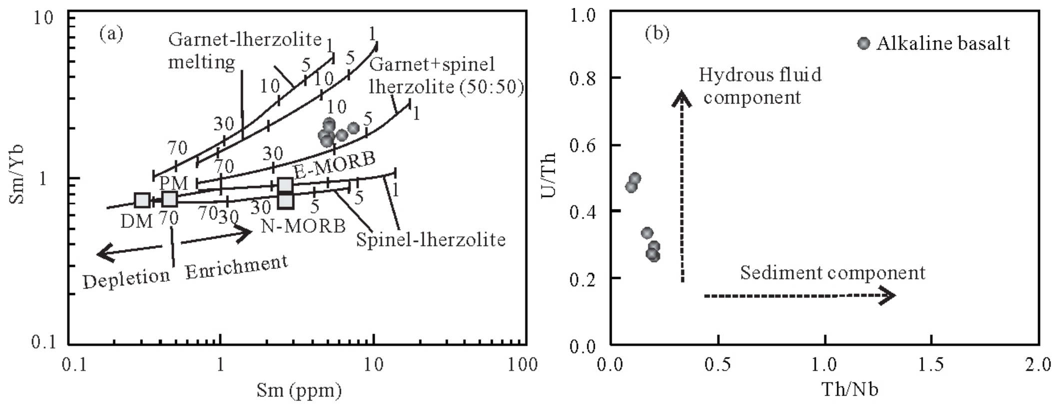

Fig. 5. (a) Sm/Yb vs. Sm diagram (from Zhao and Zhou, 2007); (b) U/Th vs. Th/Nb diagram (from Yang et al., 2015).

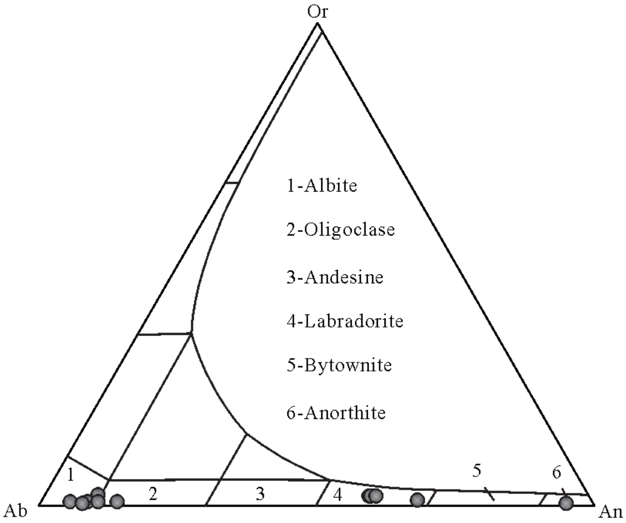

Fig. 6. Diagram of Or-Ab-An for plagioclase from the Wusun Mountain alkaline basalt.
Or–orthoclase; Ab–albite; An–anorthite.

Wang et al., 2019a). Late Devonian to Early Carboniferous volcanic rocks are extensively distributed along the southern margin of the BY, NW China, and these are important for understanding the geodynamical processes of Chinese western Tianshan. These volcanic rocks are mainly composed of calc-alkaline basalts, andesites, rhyolites and volcanic clastic rocks (An et al., 2013; Li Y J et al., 2017), with minor alkaline basalts (Qian et al., 2006). The rock associations are not consistent with those of a mantle plume (Xu Y G et al., 2013), thus excluding the possibility of a mantle plume setting. Geochemically, the volcanic rocks display enrichment of LREE and mobile elements (such as Sr, K, Rb, Ba and Th), and Nb, Ta and Ti depletions (Zhu et al., 2009), which are analogous with subduction zone magmatism where a subducted slab releases fluids or melts into the overlying mantle wedge inducing partial melting to form the arc magmatic rocks. A remarkable feature of Chinese southern Tianshan to the south of the Yining Block is the presence of many ophiolite relics and eclogite-bearing HP-UHP metamorphic rocks (Gao and Klemd, 2003; Han and Zhao, 2018), which have been invoked to confine the time-scale of the South Tianshan Ocean. Fossil data and isotopic dating results reveal that the ages of the ophiolites from Chinese southern Tianshan are confined to the period of the Early Silurian to Early Carboniferous (Long et al., 2006). The peak metamorphism ages of the HP-UHP metamorphic rocks occurred during ca. 325–310 Ma (Gao et al., 2006; Su et al., 2010). Thus, these results show that the subduction of the Chinese southern Tianshan Ocean most likely lasted until the latest Early Carboniferous. This is also supported by a regional tectonic unconformity between the Lower Carboniferous Akeshake Fm. and the Upper Carboniferous Yishijilike Fm. (Li et al., 2018b).

Thus, based on the discussions above, the ca. 350 Ma Wunsun Mountain alkaline basalts could have been formed in a subduction-related setting. In the Nb × 2-Zr/4-Y and Hf/3-Th-Ta ternary discrimination diagrams (Fig. 7a, b), these basalts are dominated by arc-types but also exhibit a mixing trend between volcanic arc and MORB-type magmas. In the Zr/Y-Zr diagram (Fig. 7c), however, the samples plot in the within-plate basaltic field. We further use the Th/Yb-Nb/Yb diagram (Fig. 7d) to discriminate tectonic setting and find the basalts plot in the volcanic arc basaltic field consistent with the Permian back-arc basin basalts from the Yushu area, Tibet (Zhang et al., 2017) (Fig. 4b, c) and that of basalts in the Quaternary Okinawa Trough, Japan (Shinjo et al., 1999). Moreover, compared with the coeval basaltic magmas with typical continental arc affinities in the YB, the studied alkaline basalts show lower Th/Yb and Nb/Yb ratios, and have higher Zr/Y ratios (Fig. 7; Zhu et al., 2009; An et al., 2013; Tang et al., 2013; Li G Y, 2017). Therefore, the Wusun Mountain alkaline basalts are more likely to have formed in a transitional tectonic setting from arc to intraplate, showing a typical feature of back-arc basin basalts (Shinjo et al., 1999). This is also supported by the coeval occurrences of I-type granitoids with ages of 362–360 Ma in the Wusun Mountain area, which were thought to be generated in a back-arc extensional system (Bao et al., 2018). However, as discussed above, the Wusun Mountain alkaline basalts display an affinity of high Al_2O_3 contents, which could have resulted from a relatively high-pressure condition. Consequently, we argue that the Wusun Mountain alkaline basalts were most likely formed in a nascent back-arc basin that was still dominated by a convergent tectonic regime.

Such formations of an incipient back-arc basin are broadly attributed to rollback of a subducting oceanic slab

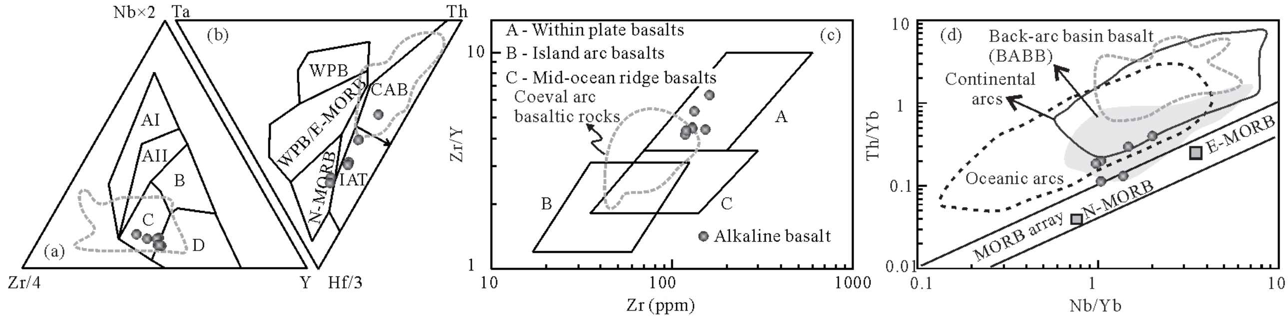

Fig. 7. Tectonic discrimination diagrams.
(a) Nb×2-Zr/4-Y diagram (from Meschede, 1986); (b) Hf/3-Th-Ta diagram (from Wood, 1980); (c) Zr/Y-Zr diagram (from Pearce and Norry, 1979); (d) Th/Yb–Nb/Yb diagram (from Pearce and Peate, 1995). BABB from the Middle Okinawa Trough (after Shinjo et al., 1999) and the Yushu area, Tibet (from Zhang et al., 2017); coeval arc basaltic rocks in the Chinese western Tianshan are from Li (2017a), Zhu et al. (2009) and Tang et al. (2014).

(Heuret and Lallemand, 2005; Nakakuki and Mura, 2013; Zhang et al., 2016), which not only provides a high heat flux, but also causes an extensional stress field under the overriding plate (Windley et al., 2007; Yin et al., 2017a). Thus, data from the Wusun Mountain Early Carboniferous alkaline basalts, combined with other published extension-related data (Qian et al., 2006; Li et al., 2010; Bao et al., 2018) and regional geology, suggest that a slab rollback as the southern Tianshan oceanic crust subducted northward beneath the Yining Block, might have given rise to the formation of these magmatic rocks in a nascent back-arc basin (Fig. 8). Slab rollback-triggered back-arc basins have been widely reported in the CAOB, such as in western Junggar (Ren et al., 2014), eastern Tianshan (Zhang et al., 2019), and South Mongolia (Li S et al., 2016).

Collectively, the Early Carboniferous Wusun Mountain alkaline basalts in the Yining Block likely formed in the setting of a nascent back-arc basin, and might have been triggered by the slab rollback of northward subduction of the South Tianshan oceanic lithosphere. Furthermore, slab rollback may have played an important role in the evolutionary processes of the CAOB.

6.4 Subduction polarity

The subduction polarity of the southern Tianshan Ocean has been hotly debated in recent years, including northward (Zhu et al., 2005; Gao et al., 2006; Li et al., 2018b), southward (Wang et al., 2012) and bi-directional subduction models (Huang H et al., 2013; Zhao et al., 2015; Wang et al., 2016). Previous studies have demonstrated that widespread Late Paleozoic magmatic rocks in the Wusun Mountain, Awulale Mountain and the southern margins of the YB were related to the northward subduction of the southern Tianshan Ocean (Zhu et al., 2009; Li Y J et al., 2017). This is also supported by the HP-UHP metamorphic belt developed in the STAC, which was the result of northward deep subduction of the southern Tianshan Ocean (Gao and Klemd, 2003; Li J L et al., 2016). Similarly, the formation of the Wusun Mountain alkaline basalts of this study is interpreted as a result of the northward subduction of the southern Tianshan Ocean. However, a sequence of Middle to Late Paleozoic magmatic records reveal that the northern Tarim Craton to the south of the YB was an active continental margin, associated with the southward subduction of the southern Tianshan Ocean (Wang et al., 2011; Wang et al., 2016). Consequently, our results, together with the published data, support a bi-directional subduction model for the Paleozoic evolution of the southern Tianshan Ocean.

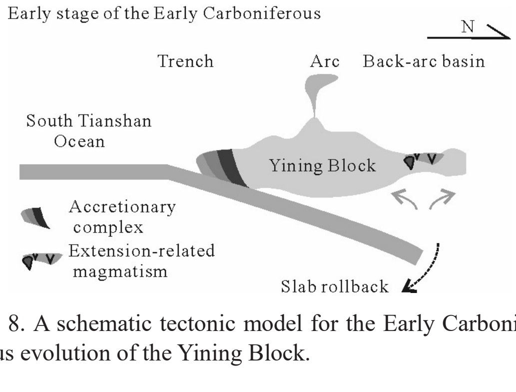

Fig. 8. A schematic tectonic model for the Early Carboniferous evolution of the Yining Block.

7 Conclusions

(1) The Early Carboniferous Wusun Mountain alkaline basalts originated from a relatively enriched mantle source composed of garnet + spinel lherzolite, with an input of subduction-related hydrous fluids. Moreover, high pressure exerted a strong influence on the magma generation.

(2) Taking into account all available data, we propose that the Wusun Mountain alkaline basalts were likely generated in a nascent back-arc extensional basin setting, which might have been triggered by slab rollback of the northward subduction of the South Tianshan oceanic lithosphere.

(3) A bi-directional subduction model is more reasonable for the Paleozoic evolution of the South Tianshan Ocean.

Thus, we argue that the formation of alkaline basalts in the Early Carboniferous was possibly related to the incipient back-arc extensional basin induced by slab rollback of the southern Tianshan oceanic lithosphere that was subducted northward below the Yining Block during Late Paleozoic time.

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