Geochronology, geochemistry and tectonic implications of early Carboniferous plutons in the southwestern Alxa Block

Zeng-Zhen Wang1,2, Xuan-Hua Chen1,2, Zhao-Gang Shao1,2, Bing Li1,2, Hong-Xu Chen1,2, Wei-Cui Ding1,2, Yao-Yao Zhang1,2 and Yong-Chao Wang1,2

1Chinese Academy of Geological Sciences, Beijing 100037, China and 2SinoProbe Center, Chinese Academy of Geological Sciences and China Geological Survey, Beijing 100037, China

Abstract

The southeastern Central Asian Orogenic Belt (CAOB) records the assembly process between several micro-continental blocks and the North China Craton (NCC), with the consumption of the Paleo-Asian Ocean (PAO), but whether the S-wards subduction of the PAO beneath the northern NCC was ongoing during Carboniferous–Permian time is still being debated. A key issue to resolve this controversy is whether the Carboniferous magmatism in the northern NCC was continental arc magmatism. The Alxa Block is the western segment of the northern NCC and contiguous to the southeastern CAOB, and their Carboniferous–Permian magmatism could have occurred in similar tectonic settings. In this contribution, new zircon U-Pb ages, elemental geochemistry and Sr-Nd isotopic analyses are presented for three early Carboniferous granitic plutons in the southwestern Alxa Block. Two newly identified aluminous A-type granites, an alkali-feldspar granite (331.6 ± 1.6 Ma) and a monzogranite (331.8 ± 1.7 Ma), exhibit juvenile and radiogenic Sr-Nd isotopic features, respectively. Although a granodiorite (326.2 ± 6.6 Ma) is characterized by high Sr/Y ratios (97.4–139.9), which is generally treated as an adakitic feature, this sample has highly radiogenic Sr-Nd isotopes and displays significantly higher K2O/Na2O ratios than typical adakites. These three granites were probably derived from the partial melting of Precambrian continental crustal sources heated by upwelling asthenosphere in lithospheric extensional setting. Regionally, both the Alxa Block and the southeastern CAOB are characterized by the formation of early Carboniferous extension-related magmatic rocks but lack coeval sedimentary deposits, suggesting a uniform lithospheric extensional setting rather than a simple continental arc.

1. Introduction

The Phanerozoic Central Asian Orogenic Belt (CAOB), one of the largest long-lived accretionary orogens worldwide, is situated to the north of the Tarim–North China cratons (Fig. 1a) and formed by complex subduction, accretion and collision processes related to the consumption of the Paleo-Asian Ocean (PAO), with significant crustal growth (Han et al. 1997, 2011; Jahn et al. 2000; Wu et al. 2003; Windley et al. 2007; Xiao et al. 2018). The southeastern CAOB records the Palaeozoic amalgamation between the North China Craton (NCC) in the south and Mongolia, Hunshandake and Songliao blocks within the CAOB in the north (Xu et al. 2013; Zhao et al. 2018; Zhou et al. 2018). The Permian–Early Triassic Solonker suture (Solonker–Xar Moron–Changchun suture) contains the youngest ophiolites within the southeastern CAOB and is usually regarded as the terminal closure site of the PAO (Eizenhöfer & Zhao, 2018; Wilde & Zhou, 2015; Xiao et al. 2003). However, when and how the PAO finally closed in the southeastern CAOB is still controversial, and different opinions can be grouped into three models.

In the first set of models, the subduction of the PAO was continuous from the early Palaeozoic Era to Late Permian–Early Triassic time and led to the successive accretion of micro-continental blocks and magmatic arcs to the northern NCC, with the northern margin of the NCC as a continental arc during Carboniferous–Permian time and the Solonker suture as the final closure site of the PAO (e.g. Xiao et al. 2003, 2009b, 2018; Zhang et al. 2014, 2016d). The second set of models propose the Late Devonian–early Carboniferous closure of the PAO, with the southeastern CAOB in a post-collisional setting since then (e.g. Xu et al. 2013; Tong et al. 2015; Zhang et al. 2015b). The third set of models infer that the large-scale PAO closed before the Late Devonian Epoch, but a new orogenic cycle began with intra-continental rifting within the southeastern CAOB during early Carboniferous time and resulted in the formation of a Red-Sea-like limited ocean basin, with the Solonker suture marking its closure during the Early Triassic Epoch (e.g. Zhang et al. 2015a; Luo et al. 2016; Pang et al. 2016; Zhao et al. 2017; Xu et al. 2018). In the third model, the lithospheric extension may be triggered by slab
break-off (Kozlovsky et al. 2015; Zhang et al. 2012a) and enhanced by slab avalanche-driven wet mantle upwelling rising from the hydrous mantle transition zone (Wang et al. 2015a, 2016a).

To test the likelihood of one of these geodynamic models, a key question is whether the Carboniferous–Permian tectonomagmatic activity of the southeastern CAOB was dominated by
Ordovician plutons are mostly Palaeozoic in age, spanning Middle intruding into Precambrian metamorphic basement rocks crop to the north, and from the North Qilian Orogen to the SW by the Longshoushan Fault (Fig. 1a). Although this block connects the NCC to the east and the Tarim Craton (e.g. Zhao et al. 2005, 2012; Wan et al. 2006; Wang et al. 2016b, 2019a) or the western extension of the Khondalite Belt (e.g. Geng et al. 2010; Zhang et al. 2013a; Zhang & Gong, 2018). However, a close affinity of the Alxa Block to the Tarim or South China cratons had also been proposed (e.g. Tung et al. 2007; Yuan & Yang, 2015; Song et al. 2017), and the amalgamation of this block with the NCC might have taken place during early–middle Palaeozoic time (Dan et al. 2016; Zhang et al. 2016c), although no ophiolitic mélanges have been recognized between them until now. Nevertheless, in any of the proposed models, the Alxa Block has been considered as part of the northern NCC, having been amalgamated at least since the Carboniferous Period.

Three ophiolitic mélanges have been reported in Alxa area (Fig. 1b). Two of them crop out in the NE, including the c. 302 Ma Enger Us and the c. 275 Ma Quagan Qulu ophiolitic mélanges, with their basaltic rocks exhibiting normal mid-ocean-ridge basalt (N-MORB) and boninite-like geochemical features (Zheng et al. 2014), respectively. The Tepai ophiolitic mélangé in the SW is also characterized by boninite-like basaltic rocks, but its formation age is either c. 278 Ma (Zheng et al. 2018) or c. 437–448 Ma (Pan, 2019).

The southwestern Alxa Block between the Longshoushan Fault and the Badain Jaran Desert involves the NW–SE-trending Beidashan and Longshoushan–Heluishan mountains (Fig. 1c). The widespread Precambrian basement rocks in this area include the Neoarchean Beidashan complex (Gong et al. 2012; Zhang et al. 2013a) and Palaeoproterozoic Longshoushan Group (Tung et al. 2007; Gong et al. 2011). They consist of amphibolite- to greenschist-facies metamorphosed igneous and sedimentary rocks and are overlain unconformably by Neoproterozoic greenschist-facies marine clastic and carbonate rocks (Zhang et al. 2016a). In contrast, the upper Carboniferous–middle Permian sedimentary rocks are widely

2. Geological background

The Alxa Block is separated from the CAOB by the Enger Us Fault to the north, and from the North Qilian Orogen to the SW by the Longshoushan Fault (Fig. 1b). It is traditionally considered as the western part of the northern NCC (Fig. 1a), either the western part of the Yinchuan Block (e.g. Zhao et al. 2005, 2012; Wan et al. 2006; Wang et al. 2016b, 2019a) or the western extension of the Khondalite Belt (e.g. Geng et al. 2010; Zhang et al. 2013a; Zhang & Gong, 2018). However, a close affinity of the Alxa Block to the Tarim or South China cratons had also been proposed (e.g. Tung et al. 2007; Yuan & Yang, 2015; Song et al. 2017), and the amalgamation of this block with the NCC might have taken place during early–middle Palaeozoic time (Dan et al. 2016; Zhang et al. 2016c), although no ophiolitic mélanges have been recognized between them until now. Nevertheless, in any of the proposed models, the Alxa Block has been considered as part of the northern NCC, having been amalgamated at least since the Carboniferous Period.

Three ophiolitic mélanges have been reported in Alxa area (Fig. 1b). Two of them crop out in the NE, including the c. 302 Ma Enger Us and the c. 275 Ma Quagan Qulu ophiolitic mélanges, with their basaltic rocks exhibiting normal mid-ocean-ridge basalt (N-MORB) and boninite-like geochemical features (Zheng et al. 2014), respectively. The Tepai ophiolitic mélange in the SW is also characterized by boninite-like basaltic rocks, but its formation age is either c. 278 Ma (Zheng et al. 2018) or c. 437–448 Ma (Pan, 2019).

The southwestern Alxa Block between the Longshoushan Fault and the Badain Jaran Desert involves the NW–SE-trending Beidashan and Longshoushan–Heluishan mountains (Fig. 1c). The widespread Precambrian basement rocks in this area include the Neoarchean Beidashan complex (Gong et al. 2012; Zhang et al. 2013a) and Palaeoproterozoic Longshoushan Group (Tung et al. 2007; Gong et al. 2011). They consist of amphibolite- to greenschist-facies metamorphosed igneous and sedimentary rocks and are overlain unconformably by Neoproterozoic greenschist-facies meta-sedimentary rocks (Zhang & Gong, 2018). Recently, syenite of age c. 1.87 Ga and granitic gneiss of age c. 1.2 Ga were recognized in the Heluishan area (Song et al. 2017; Wang et al. 2019b).

Lower Palaeozoic sedimentary rocks in the southwestern Alxa area crop out only to the south of the Longshoushan Fault (Fig. 1c). They are known as the Dahuangshan Formation and are composed of unmetamorphosed or greenschist-facies marine clastic and carbonate rocks (Zhang et al. 2016a). In contrast, the upper Carboniferous–middle Permian sedimentary rocks are widely
distributed (Fig. 1c). The upper Carboniferous succession consists of interbedded volcanic and clastic rocks in the lower part and shallow-marine bioclastic limestones and sandstones in the upper part, and is conformably overlain by lower–middle Permian strata, which include, from bottom to top, conglomerates, pebbly coarse sandstone, sandstone and siltstone, with volcanic interlayers. Mesozoic terrigenous clastic rocks are extensively distributed in this area (Fig. 1c).

Phanerozoic plutons are voluminous and widely exposed in the southwestern Alxa Block (Fig. 1c), with two magmatic periods of Middle Ordovician–Early Devonian and early Carboniferous–late Permian. Plutons of the earlier period are generally felsic granitoids (Qin, 2012; Wei et al. 2013; Tang, 2015; Liu et al. 2016b; Zhou et al. 2016; Zhang et al. 2018d; Wang et al. 2020), with only a few dolerite dykes (c. 424 Ma) in eastern Longshoushan (Duan et al. 2015). In contrast, plutons of the later period are widely distributed and include peridotite, gabbro, diorite, tonalite, granodiorite, monzogranite and granite (Chen et al. 2013; Jiao et al. 2017; Liu et al. 2017; Xue et al. 2017; Gong et al. 2018a, b; Huo, 2019; Song et al. 2019). In addition, several Triassic plutons crop out in the western Beidashan (Fig. 1c; Gu, 2012).

3. Samples and petrography

In this study, three granitic plutons were investigated and sampled in the southwestern Alxa Block; all are massive and salmon-pink to off-white in colour (Fig. 3). A medium- to coarse-grained alkali-feldspar granite in western Beidashan (17WAL-07; Fig. 1c) is composed of quartz (c. 30%), plagioclase (c. 20%), alkali-feldspar (c. 40%), biotite (c. 10%) and minor hornblende (Fig. 3b). The other two plutons are located in Longshoushan to the north of Shandan County (Fig. 1c). One is medium-grained granodiorite (17WAL-35) composed of quartz (c. 20%), plagioclase (c. 40%), alkali-feldspar (c. 20%) and biotite (c. 20%; Fig. 3d). The other sample is coarse-grained monzogranite (17WAL-39), with similar mineral assemblage of quartz (c. 25%), plagioclase (c. 25%), alkali-feldspar (c. 30%) and biotite (20%; Fig. 3f). Accessory minerals of zircon, apatite and titanite are present in all three plutons.

4. Analytical methods

4.a. Whole-rock major- and trace-element analyses

Fresh granitoid samples were first crushed and then ground to 200 mesh in a tungsten carbide cup and ball mill, and then analysed geochemically at the National Research Center of Geoanalysis, China Geological Survey. Whole-rock major-element oxides were measured using a Malvern Panalytical Axios PW4400 x-ray fluorescence spectrometer (XRF), and the analytical uncertainties are generally between 1% and 5%. The concentrations of trace and rare earth elements were determined by a PerkinElmer NexION 300Q inductively coupled plasma mass spectrometer (ICP-MS), with analytical precision generally better than 5%.
4. Zircon U–Pb dating

Zircon grains were firstly separated by conventional heavy liquid and magnetic techniques, and then hand-picked under a binocular microscope. The selected zircon crystals were mounted in epoxy resin and polished to half thickness. Potential analytical spots were determined based on morphological features and internal structures of zircons on optical and cathodoluminescence (CL) images. Zircon U–Pb analyses on mineral separates from the three samples were conducted in Tianjin Institute of Geology and Mineral Resources, China Geological Survey, China. A Thermo Fisher Scientific multi-collector inductively coupled plasma mass spectrometer (MC-ICP-MS; Neptune) was coupled to a New Wave 193 nm ArF excimer laser ablation system. Detailed procedures are reported (MC-ICP-MS; Neptune) and measurements of zircon standard GJ-1 were carried out using the method of Andersen (2002). Concordia diagrams and ages were obtained using ISOPLOT 4.15 (Ludwig, 2012). Uncertainties of individual measurements were at the 1σ level, but the weighted mean ages and concordia diagrams were given at the 2σ level (95% confidence level).

4.c. Sr-Nd isotopic analyses

The whole-rock Sr and Nd isotopic compositions were determined using a Finnigan MAT-262 mass spectrometer and a Nu Plasma high-resolution MC-ICP-MS, respectively, at the Institute of Geology, Chinese Academy of Geological Sciences, China. The measured 87Sr/86Sr ratio of the SrCO3 standard SRM 987 was 0.710243 ± 0.000012 (2σ), in good agreement with the recommended value of 0.706926 ± 0.000018; Coombs et al. (2004). Two standards of JMC Nd2O3 (reference value = 0.511137 ± 0.000008; Jahn et al. 1980) and GSB 04-3258-2015 (certified value = 0.512438; Tang et al. 2017) were employed during Nd isotopic analyses, with measured 143Nd/144Nd ratios of 0.511123 ± 0.000010 and 0.512441 ± 0.000012 at the 2σ level, respectively. Detailed analytical procedures for both Sr and Nd isotopic compositions are described by Tang et al. (2021). All measured ratios were corrected for mass fractionation by normalizing to 88Sr/86Sr = 0.119465 and 146Nd/144Nd = 0.7219, respectively.

5. Results

Whole-rock major- and trace-element concentrations, LA-ICP-MS zircon U–Pb data and Sr–Nd isotopic compositions are given in online Supplementary Tables S1–S3 (available at http://journals.cambridge.org/geo), respectively.

5.a. Whole-rock major and trace elements

All three plutons have high SiO2 (68.49–77.01 wt%) and K2O + Na2O (8.07–8.25 wt%; Fig. 4a) and low MgO (0.17–0.82 wt%) and MnO (0.03–0.06 wt%), show peraluminous features (A/CNK = 1.04–1.13), and belong to the high-K calc-alkaline series (Fig. 4b). Alkali-feldspar granite 17WAL-07 and monzogranite 17WAL-39 display lower CaO (0.59–0.61 wt%), higher K2O (K2O/Na2O = 1.35–1.55), higher total rare earth element (REE) concentrations (257.58–275.96 ppm) and distinct negative Eu anomalies (δEu = 0.17–0.37; Fig. 5a), with enrichments in large-ion-lithophile elements (LILEs; e.g. Cs, Rb, Th and Pb) and depletions in Nb, Ta, Ba and Sr (Fig. 5b). In comparison, granodiorite 17WAL-35 displays relatively higher CaO (1.52–2.51 wt%) and lower total REE concentrations (114.30–206.16 ppm), with significantly enriched light rare earth elements (LREEs; (La/Yb)N = 35.75–56.24) and positive Eu anomalies (δEu = 1.12–1.14; Fig. 5c). Moreover, it is characterized by enriched LILEs (Cs, Rb, Ba, Th, Pb and Sr) and depleted high-field-strength elements (HFSes; Y, Yb and Lu), with negative Nb–Ta and positive Zr–Hf anomalies, respectively (Fig. 5d).

5.b. Zircon U–Pb ages

Zircon grains from the studied samples are transparent, euhedral and short columnar or prismatic in shape. They exhibit well
preserved concentric magmatic oscillatory zoning, with a few inherited zircon cores appearing occasionally in samples 17WAL-35 and 39 (Fig. 6). For alkali-feldspar granite 17WAL-07, all 24 spots are concordant and cluster together (Fig. 7a). Their Th/U ratios are 0.33–0.51 and they yield a concordia age of 331.6 ± 1.5 Ma; MSWD = 1.01; 2σ, decay-constant errors included), which is consistent with the weighted mean 206Pb/238U age (331.7 ± 1.5 Ma; MSWD = 1.40; 2σ, decay-constant errors included), which yields a concordia age of 331.6 ± 1.5 Ma (MSWD = 0.88; n = 17; 2σ), with Th/U ratios of 0.43–1.03.

5.c. Whole-rock Sr–Nd isotopes

The 87Sr/86Sr and 147Sm/144Nd ratios of three granitic samples were calculated using the measured whole-rock Rb, Sr, Sm and Nd concentrations. The alkali-feldspar granite (17WAL-07; t = 332 Ma) has the lowest initial 87Sr/86Sr (0.700128) and highest initial 143Nd/144Nd (0.512219) ratios among the three plutons, with positive ϵNd(t) value (0.16) and Mesoproterozoic Nd model age (TDM = 1207 Ma; Fig. 8). The initial 87Sr/86Sr ratio of the granodiorite (17WAL-35; t = 326 Ma) is low (0.705102), and its initial 143Nd/144Nd ratio and ϵNd(t) value are 0.511358 and −16.80, respectively (Fig. 8). As its ƒSm/Nd (−0.59) significantly deviates from that of the average crust (−0.40; DePaolo et al. 1991), both TDM (1847 Ma) and TDM2 (2446 Ma) were calculated. For the monzogranite (17WAL-39; t = 332 Ma), its initial 87Sr/86Sr and 143Nd/144Nd ratios are 0.717670 and 0.511706, respectively, with negative ϵNd(t) value (−9.85) and Palaeoproterozoic TDM2 (1889 Ma; Fig. 8).
6. Discussion

The well preserved concentric magmatic oscillatory zoning (Fig. 6) and high Th/U ratios (0.33–1.03) of dated zircon grains indicate their magmatic origin (Corfu et al. 2003); the concordia and weighted mean 206Pb/238U ages are therefore interpreted as crystallization ages (Fig. 7). Because several spots from the older age cluster of granodiorite (17WAL-35) are located within the inherited zircon cores (e.g. spot 24 in Fig. 6b), the younger age cluster is employed. The three granitic plutons in the southwestern Alxa Block were therefore formed during late early Carboniferous time (c. 332–326 Ma).

6. a. Petrogenesis of the studied late early Carboniferous granitic plutons

The alkali-feldspar granite (17WAL-07) and monzogranite (17WAL-39) have similar geochemical features, such as high K2O + Na2O (8.10–8.25 wt%), FeOtotal (1.49–1.51 wt%) and FeOt/MgO (4.38–8.87), low CaO (0.59–0.61 wt%), MgO (0.17–0.43 wt%) and P2O5 (< 0.06 wt%), high total REE concentrations (257.58–275.96 ppm) with V-type REE patterns (Fig. 5a), and strongly depleted Ba and Sr (Fig. 5b). These characteristics indicate A-type granite nature, which can be clearly identified on the discrimination diagrams (e.g. Fig. 9b, King et al. 1997). A-type granites may originate from the fractionation of mantle-derived basaltic magmas (Eby, 1990, 1992; Bonin, 2007), the mixing of mantle- and crust-derived magmas (Yang et al. 2006), or the partial melting of crust at high temperatures (Whalen et al. 1987; King et al. 1997). If the plutons had their origin by magma mixing, then they would have intermediate compositions with the presence of profuse mafic microgranular enclaves (MMEs; Yang et al. 2006, 2007; Zhang et al. 2016b), although the MMEs may also be co-genetic with their host granitoids (Zhang & Zhao, 2017). The two A-type granites in the southwestern Alxa Block are rhyolitic in composition (Fig. 4a), but no MMEs were observed (Fig. 3a, e) and their coeval mafic intrusions crop out far away in the northeastern Alxa Block (Wang et al. 2015b; Liu et al. 2016a). They are also characterized by high SiO2 (73.89–77.01 wt%) and K2O/Na2O (1.35–1.55) and are peraluminous (A/CNK = 1.04–1.13), similar to aluminous A-type granites with continental crustal sources (King et al. 1997). Moreover, the alkali-feldspar granite has low positive εNd(t) value (0.16) and Mesoproterozoic Nd model age (1207 Ma; Fig. 8b), which is close to the protolith crystallization age of a granitic gneiss in the Helishan (c. 1200 Ma; Song et al. 2017). Its unusually low initial 87Sr/86Sr value (0.700128; Fig. 8a) may be caused by the strong depletion of Sr (Fig. 5b), as the initial 87Sr/86Sr value was calculated based on the measured whole-rock Sr concentration. The monzogranite has radiogenic Sr–Nd isotopes (Fig. 8a) and a Paleoproterozoic Nd model age (1889 Ma; Fig. 8b). The Paleoproterozoic basement rocks are commonly observed in Longshoushan (Tung et al. 2007; Gong et al. 2011), in addition to a c. 1872 Ma syenite in Helishan (Wang et al. 2019b). The two aluminous A-type granites were therefore most probably the high-temperature partial melts of Palaeo- and Mesoproterozoic crustal materials.

The granodiorite (17WAL-35) is also high-K calc-alkaline (Fig. 4b) and weakly peraluminous (A/CNK = 1.07–1.08) and has depleted HREEs and HFSEs (Fig. 5c, d). It is chemically characterized by high Sr (522.0–918.0 ppm) and low Y (5.36–6.56 ppm) and Yb (0.62–0.75 ppm) concentrations, with high Sr/Y ratios (97.4–139.9). Although high Sr/Y ratio (> 40) usually occurs in adakitic rocks, the high K2O contents (3.59–4.12 wt%) and...
Fig. 7. (a–c) Concordia diagrams showing LA-ICP-MS zircon U–Pb data of the studied late early Carboniferous plutons in the southwestern Alxa Block (all the diagrams and calculations are at the 2σ level).
K$_2$O/Na$_2$O ratios (0.8–1.03) of this granodiorite are more ‘continental’ than typical adakites (Defant & Drummond, 1990; Martin et al. 2005; Moyen, 2009). The coexistence of negative Nb–Ta and positive Zr–Hf anomalies (Fig. 5d) and highly radiogenic Sr–Nd isotopes (Fig. 8a) also suggest a continental crustal source (Rudnick & Gao, 2003). The enrichments of Eu, Ba and Sr are attributed to the large proportion of plagioclase (c. 40%), whereas the low Y concentration may suggest the presence of garnet in the residue, so that the high Sr/Y ratios indicate a deeper crustal level of magma source (Ducea et al. 2015). In addition, c. 2.5 Ga basement rocks and magmatic activity are commonly observed in the southwestern Alxa Block (Zhang et al. 2013a; Zhang & Gong, 2018; Wang et al. 2019b), which is coeval with the two-stage Nd model age of this granodiorite (c. 2446 Ma; Fig. 8b). This granodiorite of high Sr/Y ratio may therefore have its origin in the partial melting of upper Neoarchean lower crust.

6.b. Tectonic setting of the early Carboniferous magmatism in the Alxa Block

Two different tectonic processes accounting for the early Carboniferous magmatism within the Alxa Block were proposed previously: continental arc magmatism induced by the S-wards subduction of the PAO (Liu et al. 2016a; Xue et al. 2017; Gong et al. 2018a), or the collision and amalgamation between the Alxa Block and the NCC (Zhang et al. 2013b; Dan et al. 2016). Noticeably, whether a Palaeozoic suture between the Alxa Block and the NCC existed or not is still in debate, especially with no associated ophiolitic mélanges observed (e.g. Dan et al. 2016; Zhang & Gong, 2018; Wang et al. 2019b), and the early Carboniferous magmatic rocks are widely distributed, rather than along a linear trend in the eastern margin of the Alxa Block (Fig. 1b), so they are less likely attributed to such an amalgamation process. Furthermore, the argument of continental arc magmatism is mainly based on their arc-like geochemical signatures, such as calc–alkaline characteristics (Fig. 4b), negative Nb–Ta anomalies and high Sr/Y ratios (e.g. Liu et al. 2016a; Xue et al. 2017). However, these signatures can also be inherited from magma sources (Wang et al. 2016a), and most granites of high Sr/Y ratio in this area exhibit high K$_2$O/Na$_2$O ratios (0.92–3.70), positive Zr–Hf anomalies and radiogenic Nd–Hf isotopes, indicating derivation by the partial melting of lower continental crust (Fig. 8a; Dan et al. 2016; Xue et al. 2017); this can occur not only in continental arc belts but also in lithospheric extensional environments.

It is noteworthy that the early Carboniferous plutons within the Alxa Block are mostly basic or acidic in silica content (Fig. 4), resembling bimodal associations. The felsic plutons plot not only in volcanic arc but also in within-plate and post-collision granite fields (Fig. 9a), with most of them exhibiting radiogenic Sr–Nd isotopes (Fig. 8a). They are characterized by the coexistence of A-type granites, peraluminous granites and calc-alkaline 1-type granitoids (Dan et al. 2016; Liu et al. 2016a; Xue et al. 2017; Zheng et al. 2019), which mostly occur in extensional settings (Maniar & Piccoli, 1989). A-type granites usually indicate high-temperature anatectic conditions related to asthenospheric upwelling in a lithospheric extensional setting (Whalen et al. 1987; Ebty, 1992). The mafic plutons plot mostly in the MORB and within-plate basalt fields, similar to the rift-related Basin-and-Range basalts (Fig. 10), and display juvenile or weakly radiogenic Sr–Nd isotopes (Fig. 8a). It is noteworthy that several of the mafic plutons in the northeastern Alxa Block have hornblende as the dominant mafic mineral and resemble appinitic intrusions in geochemistry (Wang et al. 2015b). Generally, mafic appinitic melts were most likely produced by the partial melting of subduction-modified sub-continental lithospheric mantle (Fig. 10c) and the melting may be triggered by asthenospheric upwelling following slab break-off or delamination after a subduction event (Murphy, 2013). The generation of both the mafic and felsic early Carboniferous plutons within the Alxa Block therefore most likely resulted from the asthenospheric upwelling at that time. Although an upwelling asthenosphere may also occur in a continental arc setting, continental arc magmatism is typically characterized by linear tracks within a specific tectonic unit and dominated by andesitic rocks, with continued major elemental compositions from basalts to rhyolites but without compositional gaps (Ducea et al. 2015). Evidently, this is not the case for the early Carboniferous plutons within the Alxa Block (Figs 1b, 4a).

---

**Fig. 8.** Sr–Nd isotopic features of early Carboniferous plutons in the Alxa Block. Symbols and data sources as for Figure 4.
meaning that their formation in a continental arc is less likely, but rather more likely in a lithospheric extensional setting.

Furthermore, A-type granites are a good indicator of lithospheric extension, but the specific extensional setting could be varied (Sain et al. 2017), including not only rift-related (intraplate) extension (Whalen et al. 1987; Eby, 1992) but also back-arc extension (Karsli et al. 2012; Bickford et al. 2015). The two early Carboniferous aluminous A-type granites in the southwestern Alxa Block are A2 type (Fig. 9d) and therefore represent magmas derived from continental crust that has been through an orogenic cycle of arc magmatism and collision (Eby, 1992). The geochemical similarities between early Carboniferous mafic plutons in the Alxa Block and Basin-and-Range basalts (Fig. 10), which were generated in back-arc extensional setting to the Sierra Nevada arc (Cousens et al. 2019), also suggest a subduction-related tectonic setting. In back-arc extensional setting, the asthenospheric upwelling could be induced by the foundering of arc root during the roll-back process of subducting slab (DeCelles et al. 2009; DeCelles & Graham, 2015). Another possibility is the intra-continental extensional setting, because the sub-continental lithospheric mantle and lower continental crust of the Alxa Block had been modified by subduction during Middle Ordovician–Early Devonian time (Liu et al. 2016; Zhou et al. 2016), and the subduction-related geochemical signatures of later magmas may be inherited from the subduction-modified magma sources (Wang et al. 2016a). Moreover, the extension-related rock associations of calc-alkaline I-type granites, aluminous A2-type granites and peralkaline granites were present in the southwestern Alxa Block from late Silurian–Early Devonian time, following earlier arc magmatism and implying post-collisional setting (Wang et al. 2020). In addition, the cyclical magmatic flare-ups and lulls within each Palaeozoic magmatic stage of the Alxa Block (Fig. 2a) are quite

---

**Fig. 9.** (a) Tectonic discrimination diagrams of Rb versus (Y + Nb) for the early Carboniferous felsic plutons in the Alxa Block (Pearce, 1996). (b) Plot of (K2O + Na2O)/CaO versus Zr + Nb + Ce + Y and (c) plot of Ce versus 10 000×Ga/Al for A-type granites (Whalen et al. 1987). (d) Nb–Y–Ce diagram for distinguishing between A1 and A2 granites (Eby, 1992). Symbols and data sources as for Figure 4.
similar to those of Cordilleran arcs in terms of time span and frequency (DeCelles et al. 2009), but the magmatic hiatus between the two magmatic stages is relatively too long for one single subduction event. The two magmatic stages of the Alxa Block may therefore represent two orogenic cycles and the early Carboniferous extension, as the initiation of the second orogenic cycle, may suggest intra-continental extensional setting. Although more geological evidence is urgently needed to discriminate between the two kinds of extensional settings, a simple continental arc model is less likely for the early Carboniferous magmatism within the Alxa Block.

Additionally, continental arc magmatism is usually accompanied by syn-arc sedimentation in fore-arc or back-arc basins (Ducea et al. 2015), but lower Carboniferous strata are absent from the Alxa Block based on available geological reports. Although a few outcrops in the northern Alxa Block were previously identified as lower Carboniferous deposits, they were recently reassigned as lower–middle Permian strata (Zhang et al. 2018c). By contrast, the upper Carboniferous–middle Permian strata are widely distributed. The sedimentary facies show a distinct change from terrestrial alluvial fan and delta in the lower stratigraphic sections to platform, littoral and shallow-marine in the upper stratigraphic sections, with abundant fossils (e.g. plants, fusulinids, brachiopods, corals) and volcanic interlayers (Bu et al. 2012; Han et al. 2012; Yin et al. 2016; Song et al. 2018). Such a transgression sequence is consistent with the further development of the lithospheric extension.

6.c. Tectonic implications for the development of southeastern CAOB

Even if the Alxa Block was separated from the NCC during the Precambrian Eon, sedimentologic, magmatic and structural evidences (Li et al. 2012a; Dan et al. 2016; Zhang et al. 2013b, 2016c) all suggest that their amalgamation occurred before early Carboniferous time. Palaeomagnetic studies also suggest that the Precambrian micro-continental blocks within the southeastern CAOB (e.g. Mongolia, Songliao and Hunshandake blocks) may
have already accreted to the northern NCC by early Carboniferous time (Pruner, 1992; Li et al. 2012b; Zhao et al. 2013; Zhang et al. 2018a). Furthermore, the Palaeozoic magmatic episodes of the Alxa Block and the southeastern CAOB (including the northern margin of the NCC) are very similar (Fig. 2), indicating comparable tectonic processes. Consequently, the whole region had been experiencing a uniform tectonic regime since early Carboniferous time and, if there was on-going S-wards subduction of the large-scale PAO at that time, the arc-trench system was most likely located to the north of these micro-continental blocks.

Regionally, the early Carboniferous is the initial period of the second magmatic stage (Fig. 2), and magmatic rocks during this period are characterized by the mafic–ultramafic complexes in northern Inner Mongolia (Jian et al. 2012; Zhang et al. 2015c; Li et al. 2018), the appinitic intrusions in the northern NCC (Zhou et al. 2009; Zhang et al. 2012a; Wang et al. 2015b), the calc-alkaline I-type and peraluminous granites with crustal origins throughout the southeastern CAOB (Bao et al. 2007; Zhang et al. 2007, 2011; Liu et al. 2009, 2016a; Blight et al. 2010; Dan et al. 2012; Xue et al. 2017), and the A-type granites newly identified in the southwestern Alxa Block (this study). Such rock associations are commonly associated with asthenospheric upwelling in lithospheric extensional setting. Although some of the basaltic rocks from the mafic–ultramafic complexes exhibit subduction-related geochemical features (Jian et al. 2012; Zhang et al. 2015c; Li et al. 2018), these features can also be imparted by crustal contamination (Xia, 2014) or inherited from magma sources that have been modified by earlier subduction fluids or melts (Wang et al. 2016a). Further, the coeval intrusions are widely distributed (Xu et al. 2014) rather than along one or two specific ribbons as would be expected for a mafic arc, supporting their formation in an extensional tectonic setting. Moreover, if this lithospheric extension occurred in back-arc, then the remnants of the large-scale PAO may be represented by the early Carboniferous Erenhot–Hegenshan ophiolitic mélanges to the north of the micro-continental blocks (Zhang et al. 2015c; Li et al. 2018). Otherwise, the early Carboniferous extension of the southeastern CAOB was probably developed in an intra-continental environment and may represent the initiation of the second orogenic cycle (Xu et al. 2018).

In addition to the intrusions, the early Carboniferous sedimentary rocks are mostly absent from the southeastern CAOB, indicating regional uplift related to asthenospheric upwelling during the initial stage of the lithospheric extension. The Carboniferous metamorphic rocks are high-temperature–low-pressure and show a clockwise P–T path, involving pre-peak heating with slight decompression, peak and post-peak cooling stages, also suggesting an extension process (Zhang et al. 2018b).

Subsequently, the late Carboniferous–Permian magmatism in the southeastern CAOB became intense (Fig. 2) with the formation of the widespread bimodal volcanic rocks, continental basaltic intrusions, calc-alkaline I-type granites, peraluminous S-type granites, A-type granites and several peralkaline magmatic belts (e.g. Jahn et al. 2009; Zhang et al. 2012b, 2015b, 2016d, 2017b; Pang et al. 2016, 2017; Zhao et al. 2016a; Ji et al. 2018; Wang et al. 2021b), implying further development of the early Carboniferous extension. This is also consistent with the occurrence of many late Carboniferous–Permian mafic dykes (Fig. 3a) with MORB or within-plate basalt geochemical signatures in this region (Lin et al. 2014). Accordingly, the late Carboniferous–Permian Solonker, Enger Us and Quagan Qulu ophiolitic mélanges (Jian et al. 2010; Zheng et al. 2014), which contain MORB-type intrusions, continental basalts and terrigenous sediments (Luo et al. 2016; Shi et al. 2016), may represent the newly opened limited ocean basins and mark the strongest extension (Xu et al. 2014, 2018). The late Carboniferous–Permian sedimentary sequences are also widely exposed throughout the southeastern CAOB. They vary from plant fossil-bearing terrigenous clastic rocks to shallow-marine clastic and carbonate sediments.
depositions, with basal conglomerates, and are transgression sequences related to regional extension (Zhao et al. 2016b; Ji et al. 2020; Wang et al. 2021a).

To summarize, we propose a lithospheric extensional process rather than a simple continental arc for the tectono-magmatic development of the southeastern CAOB during early Carboniferous time (Fig. 11). The early Carboniferous extension-related magmatism and the absence of coeval sedimentary successions may reflect the onset of asthenospheric upwelling and regional uplift, and therefore mark the initiation of the lithospheric extension. Nevertheless, the asthenospheric upwelling could be induced by either slab roll-back or slab break-off of the subducted PAO; more geological, geochemical, geophysical and palaeontological evidence is therefore needed to further constrain the specific tectonic setting of this extension, either back-arc or intra-continental.

7. Conclusions

The early Carboniferous (c. 332–326 Ma) granodiorite with high Sr/Y ratio, A-type monzogranite and A-type alkali-feldspar granite in the southwestern Alxa Block were most likely formed by partial melting of Neoarchean, Palaeoproterozoic and Mesoproterozoic crustal sources heated by upwelling asthenosphere in an lithospheric extensional setting. According to regional geological correlations, a uniform lithospheric extensional setting, either back-arc or intra-arc but not a simple continental arc, is suggested for both the Alxa Block and the southeastern CAOB during early Carboniferous time, with the development of extension-related magmatism and the absence of coeval sedimentary rocks.

Supplementary material. To view supplementary material for this article, please visit https://doi.org/10.1017/S0016756821000984

Acknowledgements. We are grateful to Yurong Cui (Tianjin Institute of Geology and Mineral Resources) and Suohuan Tang (Institute of Geology, Chinese Academy of Geological Sciences) for their help with zircon U–Pb dating and isotopic analyses, respectively. Special thanks are extended to Professor Peter Clift and anonymous reviewers for their constructive comments. This work was financially supported by China Geological Survey (grant number DD20190011), Chinese Academy of Geological Sciences (grant number IKY202011) and National Key Research and Development Program of China (grant number 2018YFC0603701).

Declaration of interest. The authors declare that they have no known conflicts of interests or personal relationships that could have appeared to influence the work reported in this paper.

References

Andersen T (2002) Correction of common lead in U–Pb analyses that do not report 204Pb. Chemical Geology 192, 59–79.
Bao Q, Zhang C, Wu Z, Wang H, Li W, Sang J and Liu Y (2007) SHRIMP U–Pb zircon geochronology of a Carboniferous quartzite diorite in Baiyingao area, Inner Mongolia and its implications. Journal of Jilin University (Earth Science Edition) 37, 15–23 (in Chinese with English abstract).
Bickford ME, Schmus WR, Karlstrom KE, Mueller PA and Kamenev GD (2015) Mesoproterozoic-trans-Laurentian magmatism: a synthesis of continent-wide age distributions, new SIMS U–Pb ages, zircon saturation temperatures, and HF and Nd isotopic compositions. Precambrian Research 265, 286–312.
Blight JHS, Crowley QG, Petterson MG and Cunningham D (2010) Granites of the Southern Mongolia Carboniferous Arc: new geochronological and geochemical constraints. Lithos 116, 35–52.
Bonin B (2007) A-type granites and related rocks: evolution of a concept, problems and prospects. Lithos 97, 1–29.
Bu J, Niu Z, Wu J and Duan X (2012) Sedimentary characteristics and age of Amushan formation in Ejin Banner and its adjacent areas, western Inner Mongolia. Geological Bulletin of China 31, 1669–83 (in Chinese with English abstract).
Chen W, Zhou W, Chen K, Liu M, Wang T, Fang M, He H and Zhang B (2013) Subduction-related Early Permian granodiorite in Jinchangshan of Alashan, Inner Mongolia: Evidences from zircon U–Pb geochronology and geochemistry. Journal of Mineralogy and Petrology 33, 53–60 (in Chinese with English abstract).
Chen Y, Zhao R, Wang G, Rong X and Li T (2020) Geochronology, geochemical characteristics and significances of quartz monzonite in Niujiaosuo, Longhoushan, Gansu. Journal of East China University of Technology (Natural Science) 43, 21–29 (in Chinese with English abstract).
Coombs ML, Clague DA, Moore GF and Couzens BL (2004) Growth and collapse of Waianae Volcano, Hawaii, as revealed by exploration of its submarine flanks. Geochemistry, Geophysics, Geosystems 5, Q05006, doi: 10.1029/2004GC000717.
Corfu F, Hanchar JM, Hoskin PWO and Kinney P (2003) Atlas of zircon textures. Reviews in Mineralogy and Geochemistry 53, 469–500.
Couzens BL, Henry CD, Stevens C, Varve S, John DV and Wetmore S (2019) Igneous rocks in the Fish Creek Mountains and environs, Battle Mountain area, north-central Nevada: a microcosm of Cenozoic igneous activity in the northern Great Basin, Basin and Range Province, USA. Earth-Science Reviews 192, 403–44.
Cui Y, Zhou H, Geng J, Li H and Li H (2012) In-situ LA-ICP-MS U–Pb isotopic dating of monazite. Acta Geologica Sinica 33, 865–76 (in Chinese with English abstract).
Dan W, Li XH, Guo J, Liu Y and Wang XC (2012) Paleoproterozoic evolution of the eastern Alxa Block, westernmost North China: evidence from in situ zircon U–Pb dating and HF–O isotopes. Gondwana Research 21, 838–64.
Dan W, Li XH, Wang Q, Tang GJ and Liu Y (2014) An Early Permian (ca. 280 Ma) silicic igneous province in the Alxa Block, NW China: a magmatic flare-up triggered by a mantle-plume? Lithos 204, 144–58.
Dan W, Li XH, Wang Q, Wang XC, Wyman DA and Liu Y (2016) Phanerozoic amalgamation of the Alxa Block and North China Craton: evidence from Paleozoic granitoids, U–Pb geochronology and Sr–Nd–Pb–HF–O isootope geochemistry. Gondwana Research 32, 105–21.
DeCelles PG, Duca MN, Kapp P and Zandt G (2009) Cyclicity in Cordilleran Orogenic systems. Nature Geoscience 2, 251–7.
DeCelles PG and Graham SA (2015) Cyclical processes in the North American Cordilleran Orogenic system. Geology 43, 499–502.
Defant MJ and Drummond MS (1990) Derivation of some modern arc magmas by melting of young subducted lithosphere. Nature 347, 662–5.
Depaolo DJ, Linn AM and Schubert G (1991) The continental crustal age distribution: methods of determining mantle separation ages from Sm-Nd isotopic data and application to the Southwestern United States. Journal of Geophysical Research 96, 2071–88.
Duan J, Li C, Qian Z and Jiao J (2015) Geochronological and geochemical constraints on the petrogenesis and tectonic significance of Paleozoic dolerite dykes in the southern margin of Alxa Block, North China Craton. Journal of Asian Earth Sciences 111, 244–53.
Duca MN, Saleby JB and Bergantz G (2015) The architecture, chemistry, and evolution of continental magmatic arcs. Annual Review of Earth and Planetary Sciences 43, 101–1033.
Eby GN (1990) The A-type granitoids: a review of their occurrence and chemical characteristics and speculations on their petrogenesis. Lithos 26, 115–34.
Eby GN (1992) Chemical subdivision of A-type granitoids: petrogenesis and tectonic implications. Geology 20, 641–4.
Eisenhöfer PR and Zhao G (2018) Solonker Suture in East Asia and its bearing on the final closure of the eastern segment of the Palaeo-Asian Ocean. Earth-Science Reviews 186, 153–72.
Geng Y, Wang X, Wu C and Zhou X (2010) Late-Palaeoproterozoic tectonothermal events of the metamorphic basin in Alxa area: evidence from geochronology. Acta Petrologica Sinica 26, 1159–70 (in Chinese with English abstract).
Gong J, Zhang J, Wang Z, Yu S and Wang D (2018a) Late Ordovician–Carboniferous tectonic evolutionary history of the Alxa Block: constrained by the multistage magmatic-metamorphic-deformation events in Beidaihe area. Acta Petrologica et Mineralogica 37, 771–98 (in Chinese with English abstract).

Gong J, Zhang J, Wang Z, Yu S, Wang D and Zhang H (2018b) Zircon U–Pb dating, HF isotopic and geochemical characteristics of two suites of gabbros in the Beidaihe region, western Alxa Block: its implications for evolution of the Central Asian Orogenic Belt. Acta Geologica Sinica 92, 1369–88 (in Chinese with English abstract).

Gong J, Zhang J and Yu S (2011) The origin of Longhuoshan Group and associated rocks in the southern part of the Alxa Block: constraint from LA-ICP-MS U–Pb zircon dating. Acta Petrologica et Mineralogica 30, 795–818 (in Chinese with English abstract).

Gong J, Zhang J, Yu S, Li H and Hou K (2012) Ca. 2.5 Ga TTG rocks in the western Alxa Block and their implications. Chinese Science Bulletin 57, 4064–76 (in Chinese with English abstract).

Gu G (2012) The preliminary studies on the origin and tectonic setting of Early Mesozoic granites in the southwest margin of Alxa. M.Sc. thesis, Lanzhou University, China. Published thesis (in Chinese with English abstract).

Han BF, He GQ, Wang XC and Guo ZJ (2011) Late Carboniferous collision between the Tarim and Kazakhstan–Yili terranes in the western segment of the South Tianshan Orogen, Central Asia, and implications for the Northern Xinjiang, western China. Earth-Science Reviews 109, 74–93.

Han BF, Wang SG, Jahn BM, Hong DW, Kagami H and Sun YL (1997) Depleted-mantle source for the Ulungur River A-type granites from Xinjiang, China: geochemistry and Nd-Sr isotopic evidence, and implications for Phanerozoic crustal growth. Chemical Geology 138, 135–59.

Han W, Liu X, Li J and Shi J (2012) Sedimentary environment of the Early Carboniferous plutons in SW Alxa Block granitoid magmatism in the Mongolian Central Asian Orogenic Belt. Lithos 261–262, 25–45.

Han W, Liu D, Kröner A, Windley BF, Shi Y, Zhang W, Zhang F, Miao L, Zhang L and Yang W (2015) The preliminary studies on the origin and tectonic setting of Early Carboniferous plutons in SW Alxa Mongolia: tectonic position, geochemistry and correlation with igneous activity of the Central Asian Orogenic Belt. Journal of Asian Earth Sciences 113, 524–41.

Li J, Zhang J and Qu J (2012a) Amalgamation of the North China Craton with Alxa Block in the late of Early Paleozoic: evidence from sedimentary region, the Niushou Mountain, Ningxia Hui Autonomous Region, NW China. Geological Review 58, 208–14 (in Chinese with English abstract).

Li P, Zhang S, Gao R, Li H, Zhao Q, Li Q and Guan Y (2012b) New Upper Carboniferous–Lower Permian palaeomagnetic results from the central Inner Mongolia and their geological implications. Journal of Jilin University (Earth Science Edition) 42, 423–40 (in Chinese with English abstract).

Li Y, Wang G, Santosh M, Wang J, Dong P and Li H (2018) Supra-subduction zone ophiolites from Inner Mongolia, North China: Implications for the tectonic history of the southeastern Central Asian Orogenic Belt. Gondwana Research 59, 126–43.

Lin L, Xiao WJ, Wan B, Windley BF, Ao S, Han C, Feng J, Zhang J and Zhang Z (2014) Geochronologic and geochemical evidences for persistence of south-dipping subduction to Late Permian time, Langshan area, Inner Mongolia: implications for formation of accretionary orogeneses in the southern Altaiids. American Journal of Science 314, 679–703.

Liu J, Chi X, Zhang X, Ma Z, Zhao Z, Wang T, Hu Z and Zhao X (2009) Geochronological study of Carboniferous plutons and their significance. Acta Geologica Sinica 83, 365–76 (in Chinese with English abstract).

Liu M, Zhang D, Xiong G, Zhao H, Di Y, Wang Z and Zhou Z (2016a) Zircon U–Pb age and Pb isotopic and geochemical of Carboniferous intrusions from the Langshan area, Inner Mongolia: petrogenesis and tectonic implications. Journal of Asian Earth Sciences 120, 139–58.

Liu Q, Zhao G, Han Y, Eizenhöfer PR, Zhu Y, Hou W, Zhang X and Wang B (2017) Geochronology and geochemistry of Permian to Early Triassic granitoids in the Alxa Terrane: constraints on the final closure of the Paleo-Asian Ocean. Lithosphere 9, 1646.641.

Liu Q, Zhao G, Sun M, Han Y, Eizenhöfer PR, Hou W, Zhang X, Zhu Y, Wang B, Liu D and Xu B (2016b) Early Paleozoic subduction processes of the Paleo-Asian Ocean: insights from geochronology and geochemistry of Paleozoic plutons in the Alxa Terrane. Lithos 262, 546–60.

Liu W, Pan J, Liu X, Wang K, Wang G and Xue P (2019) Petrogenesis and tectonic implication of Qingshanbao pluton in Longzhou Mountains, Gansu: constraints from elemental geochemistry, zircon U–Pb age and Sr-Nd isotopes. Journal of Mineralogy and Petrology 39, 26–40 (in Chinese with English abstract).

Ludwig KR (2012) User’s Manual for Isoplot 3.75: A Geochronological Toolkit for Microsoft Excel. Berkeley: Berkeley Geochronology Center, Special Publication no. 5, 75 pp.

Luo ZW, Xu B, Shi GZ, Zhao P, Faure M and Chen Y (2016) Solonker ophiolite in Inner Mongolia, China: a late Permian continental margin-type ophiolite. Lithos 261, 72–91.

Maniar PD and Piccoli PM (1989) Tectonic discrimination of granitoids. Geological Society of America Bulletin 101, 635–43.

Martin H, Smithies RH, Rapp R, Moyen JF and Champion D (2005) An overview of adakite, tonalite–trondhjemite–granodiorite (TTG), and sanukitoid: relationships and some implications for crustal evolution. Lithos 79, 1–24.

Moyen JF (2009) High Sr/Y and La/Yb ratios: the meaning of the ‘adakitic signature’. Lithos 112, 356–74.
Murphy JB (2013) Appinite suites: a record of the role of water in the genesis, transport, emplacement and crystallization of magma. Earth-Science Reviews 119, 35–59.

Pan X (2019) Petrogenesis of Tebas basic-ultrabasic pluton in the Beidashan area in the southern margin of the Alxa block and its tectonic significance. M.Sc. thesis, Chang’an University, Published thesis (in Chinese with English abstract).

Pang CJ, Wang XC, Xu B, Luo ZW and Liu YZ (2017) Hydrous parental magmas of Early to Middle Permian gabbroic intrusions in western Inner Mongolia, North China: new constraints on deep-Earth fluid cycling in the Central Asian Orogenic Belt. Journal of Asian Earth Sciences 144, 184–204.

Pang CJ, Wang XC, Xu B, Zhao JX, Feng YX, Wang YY, Luo ZW and Liao W (2016) Late Carboniferous N-MORB-type basalts in central Inner Mongolia, China: products of hydrous melting in an intraplate setting? Lithos 261, 55–71.

Pearce JA (1996) Source and settings of granitic rocks. Episodes 19, 120–5.

Pearce JA and Norry MJ (1979) Petrogenetic implications of Ti, Zr, Y, and Nb variations in volcanic rocks. Contributions to Mineralogy and Petrology 69, 33–47.

Pruner P (1992) Palaeomagnetism and palaeoecography of Mongolia from the Carboniferous to the Cretaceous—final report. Physics of the Earth and Planetary Interiors 70, 169–77.

Qin H (2012) Petrology of Early Paleozoic granites and their relation to tectonic evolution of orogen in the North Qilian Orogenic Belt. Ph.D. thesis, Chinese Academy of Geological Sciences, China. Published thesis (in Chinese with English abstract).

Rudnick RL and Foster S (2003) Composition of the continental crust. In Treatise on Geochemistry, volume 3 (eds HD Holland and KK Turekian), pp. 1–64. Amsterdam: Elsevier Science Ltd.

Sain A, Saha D, Joy S, Jelsma H and Armstrong R (2017) New SHRIMP age and microstructures from a deformed A-type granite, Kanigiri, Southern India: constraining the Hiatus between orogenic closure and postorogenic rifting. The Journal of Geology 125, 241–59.

Saunders AD, Storey M, Kent RW and Norry MJ (1992) Consequences of plume-lithosphere interactions. In Magmatism and the Causes of Continental Break-up (eds BC Storey, T. Alabaster and RJ Pankhurst), pp. 41–60. Geological Society of London, Special Publication no. 68.

Shervais JW (1982) Ti-V plots and the petrogenesis of modern and ophiolitic lavas. Earth and Planetary Science Letters 59, 101–18.

Shi G, Song G, Wang H, Huang C, Zhang L and Tang J (2016) Late Paleozoic tectonics of the Solonker Zone in the Wuliji area, Inner Mongolia, China: insights from stratigraphic sequence, chronology, and sandstone geochemistry. Journal of Asian Earth Sciences 127, 100–18.

Slama J, Košler J, Condon DJ, Crowley Jl, Gerdes A, Hanchar JM, Horwood MSA, Morris GA, Nasdala L, Tubrett MN and Whitehouse MJ (2008) Plesovice zircon–A new natural reference material for U–Pb and Hf isotopic microanalysis. Chemical Geology 249, 1–35.

Song D, Xiao W, Collins A, Glorise S and Han C (2019) Late Carboniferous–Early Permian arc magmatism in the southwestern Alxa Tectonic Belt (NW China): constraints on the Late Palaeozoic subduction history of the Paleo-Asian Ocean. Geological Journal 54, 1046-63.

Song D, Xiao W, Collins AS, Glorise S, Han C and Li Y (2017) New chronological constraints on the tectonic affinity of the Alxa Block, NW China. Precambrian Research 299, 230–43.

Song D, Xiao W, Collins AS, Glorise S, Han C and Li Y (2018) Final subduction processes of the Paleo-Asian Ocean in the Alxa Tectonic Belt (NW China): constraints from field and chronological data of Permian arc-related volcano-sedimentary rocks. Tectonics 37, 1658–87.

Song S, Niu Y, Su L and Xie X (2013) Tectonics of the North Qilian orogen, NW China. Gondwana Research 23, 1378–401.

Sun SS and McDonough W (1989) Chemical and isotopic systematics of oceanic basalts: implications for mantle composition and processes. In Magmatism in the Ocean Basins (eds AD Saunders and MJ Norry), pp. 313–45. Geological Society of London, Special Publication no. 42.

Tang L (2015) Granites’ characteristics and zircon LA-ICP-MS U–Pb dating of Jiling area in Longshoushan, Gansu province. M.Sc. thesis, East China Institute of Technology, China. Published thesis (in Chinese with English abstract).

Tang S, Li J, Liang X, Zhang L, Li G, Pu W, Li C, Yang Y, Chu Z, Zhong J, Hou K and Wang X (2017) Reference material preparation of 40Ar/39Ar and 40Ar/39Ar isotope ratio. Rock and Mineral Analysis 36, 163–70 (in Chinese with English abstract).

Tang S, Li J, Pan CX, Liu H and Yan B (2021) Production and certification of the reference material GBW04139, GBW04140 and GBW04141 as Rb-Sr and Sm-Nd isotope analysis. Rock and Mineral Analysis 40, 284–94 (in Chinese with English abstract).

Tong Y, Jahn BM, Wang T, Hong DW, Smith EL, Sun M, Gao JF, Yang QD and Huang W (2015) Permian alkali granites in the Erenhot–Hegenhan belt, northern Inner Mongolia, China: model of generation, time of emplacement and regional tectonic significance. Journal of Asian Earth Sciences 97, Part B, 320–36.

Tung K, Yang H, Liu D, Zhang J, Tseng C and Wan Y (2007) SHRIMP U–Pb geochronology of the detrital zircons from the Longshouhang Group and its tectonic significance. Chinese Science Bulletin 52, 1414–25.

Wan Y, Song B, Liu D, Wilde SA, Wu J, Shi Y, Yin X and Zhou H (2006) SHRIMP U–Pb zircon geochronology of Palaeoproterozoic metasedimentary rocks in the North China Craton: evidence for a major Late Palaeoproterozoic tectonomagmatic event. Precambrian Research 149, 249–71.

Wang J, Li X, Ning W, Kusky T and Deng H (2019a) Geology of a Neoarchean suture: evidence from the Zunhua ophiolitic melange of the Eastern Hebei Province, North China Craton. Geological Society of America Bulletin 131, 11–2.

Wang XC, Wilde SA, Li QL and Yang YN (2015a) Continental flood basalts derived from the hydrous mantle transition zone. Nature Communications 6, 7700, doi: 10.1038/ncomms8700.

Wang XC, Wilde SA, Xu B and Pang CJ (2016a) Origin of arc-like continental basalts: implications for deep-Earth fluid cycling and tectonic discrimination. Lithos 261, 5–45.

Wang Y, Xu B, Song S, Zhao P, Zhang J and Yan L (2021a) A late Paleozone extension basin constrained by sedimentology and geochronology in eastern Central Asia Orogenic Belt. Gondwana Research 89, 265–86.

Wang ZZ, Chen X, Li B, Zhang Y and Xu S (2019b) The discovery of the Palaeoproterozoic syenite in Helishan, Gansu Province, and its implications for the tectonic attribution of the Alxa Block. Geology in China 46, 1094–104 (in Chinese with English abstract).

Wang ZZ, Chen X, Shao Z, Li B, Ding W, Zhang Y, Wang Y, Zhang Y, Xu S and Qin X (2020) Petrogenesis of the Late Silurian–Early Devonian granites in the Longshouhang–Helishan area, Gansu Province, and its tectonic implications for the Early Paleozoic evolution of the southwestern Alxa Block. Acta Geologica Sinica 94, 2243–61 (in Chinese with English abstract).

Wang ZZ, Han BF, Feng LX and Liu B (2015b) Geochronology, geochemistry and origins of the Paleozoic–Triassic plutons in the Langshan area, western Inner Mongolia, China. Journal of Asian Earth Sciences 97, Part B, 337–51.

Wang ZZ, Han BF, Feng LX, Liu B, Zheng B and Kong LJ (2016b) Tectonic attribution of the Langshan area in western Inner Mongolia and implications for the Neoarchean–Paleoproterozoic evolution of the western North China Craton: evidence from LA-ICP-MS zircon U–Pb dating of the Langshan basement. Lithos 261, 278–95.

Wang ZZ, Han BF, Feng LX, Liu B, Zheng B, Kong LJ and Qi CY (2021b) Early–Middle Permian plutons in the Langshan area, western Inner Mongolia, China, and their tectonic implications. Lithos 382–383, 105934.

Wei Q, Hao I, Lu J, Zhao Y, Zhao X and Shi H (2013) LA-UCP-MS zircon U–Pb dating of Hexipu granite and its geological implications. Bulletin of Mineralogy, Petrology and Geochemistry 32, 729–35 (in Chinese with English abstract).

Whalen J, Currie K and Chappell B (1987) A-type granites: geochemical characteristics, discrimination and petrogenesis. Contributions to Mineralogy and Petrology 95, 49–59.

Whitaker ML, Nokvasil H, Lindsey DH and McCurry M (2008) Can crystallization of olivine tholeite give rise to potassic rhyolites?—an experimental investigation. Bulletin of Volcanology 70, 417–34.

Wilde SA & Zhou JB (2015) The late Paleozone to Mesozoic evolution of the eastern margin of the Central Asian Orogenic Belt in China. Journal of Asian Earth Sciences 113, 909–21.
Early Carboniferous plutons in SW Alxa Block

Xue S, Ling MX, Liu YL, Zhang H and Sun W

Xu B, Zhao P, Bao Q, Zhou Y, Wang Y and Luo Z

Xu B, Charvet J, Chen Y, Zhao P and Shi G

Xiao W, Windley BF, Yong Y, Yan Z, Yuan C, Liu C and Li J

Zhang J, Gong J, Ju S, Li H and Hou K (2013a) Neoarchean–Paleoproterozoic multiple tectonothermal events in the western Alxa block, North China Craton and their geological implication: evidence from zircon U–Pb ages and Hf isotopic composition. Precambrian Research 235, 36–57.

Zhang J, Li J, Xiao W, Wang Y and Qi W (2013b) Kinematics and geochronology of melt thrust geodetic deformation along the eastern Alxa block, NW China: new constraints on the relationship between the North China Plate and the Alxa block. Journal of Structural Geology 57, 38–57.

Zhang J, Wang T, Castro A, Zhang L, Shi X, Tong Y, Zhang Z, Guo L, Yang Q and Jaccarini LM (2016b) Multiple mixing and hybridization from magma source to final emplacement in the Permian Yamatu Pluton, the northern Alxa Block, China. Journal of Petrology 57, 933–80.

Zhang J, Wei C and Chu H (2015a) Blueschist metamorphism and its tectonic implication of Late Paleoaeoc–Early Mesozoic metabasites in the mélangé zones, central Inner Mongolia, China. Journal of Asian Earth Sciences 97, Part B, 352–64.

Zhang J, Wei C and Chu H (2018b) New model for the tectonic evolution of Xing’an-Inner Mongolia Orogenic Belt: evidence from four different phases of metamorphism in Central Inner Mongolia. Acta Petrologica Sinica 34, 2857–527 (in Chinese with English abstract).

Zhang J, Zhang B and Zhao H (2016c) Timing of amalgamation of the Alxa Block and the North China Block: constraints based on detrital zircon U–Pb ages and sedimentologic and structural evidence. Tectonophysics 668–669, 65–81.

Zhang L, Zhang H, Zhang S, Xiong Z, Luo B, Yang H, Pan F, Zhou X, Xu W and Guo L (2017a) Lithospheric delamination in post-collisional setting: evidence from intrusive magmatism from the North Qilianshan ophiolite to the southern margin of the Alxa block, NW China. Lithos 288–289, 20–34.

Zhang Q, Liu Z, Chai S, Xu Z, Zhao Q and Xu X (2011) Geochronology and geochemistry of granodiorites from Wulan area of Urad Zhongqi, Inner Mongolia. Journal of Mineralogy and Petrology 31, 7–14 (in Chinese with English abstract).

Zhang S and Zhao Y (2017) Cogenetic origin of mafic microgranular enclaves in calc-alkaline granitoids: the Permian plutons in the northern North China Block. Geosphere 13, 482–517.

Zhang SH, Zhao Y, Liu JM and Hu ZC (2016d) Different sources involved in generation of continental arc volcanism: the Carboniferous–Permian volcanic rocks in the northern margin of the North China block. Lithos 240–243, 382–401.

Zhang SH, Zhao Y, Song B, Yang ZY, Hu JM and Wu H (2007) Carboniferous granitic plutons from the northern margin of the North China block: implications for a late Palaeozoic active continental margin. Journal of the Geological Society 164, 451–63.

Zhang SH, Zhao Y, Ye H, Liu JM and Hu ZC (2014) Origin and evolution of the Bainaimiao arc belt: implications for crustal growth in the southern Central Asian orogenic belt. GSA Bulletin 126, 1275–300.

Zhang X, Gao Y, Wang Z, Liu H and Ma Y (2012a) Carboniferous amphibole intrusions from the northern North China Craton: geochemistry, petrogenesis and tectonic implications. Journal of the Geological Society 169, 337–51.

Zhang X, Xue F, Yuan L, Ma Y and Wilde SA (2012b) Late Permian apatite–granite complex from northwest Liaoning, North China Craton: petrogenesis and tectonic implications. Lithos 155, 201–17.

Zhang X, Yuan L, Xue F, Yan X and Mao Q (2013b) Early Permian A-type granites from central Inner Mongolia, North China: magmatic tracer of post-collisional tectonics and oceanic crustal recycling. Gondwana Research 28, 311–27.

Zhang Y, Niu Y, Wei J, Shi J and Song B (2018a) Chronology of the Haobiru Formation in the Haobiru area of northern Alxa, Inner Mongolia and its geological implications. Geological Bulletin of China 37, 51–62 (in Chinese with English abstract).

Zhang Z, Chen Y, Li K, Li J, Yang J and Qian X (2017b) Geochronology and geochemistry of Permian bimodal volcanic rocks from central Inner Mongolia, China: implications for the late Paleozoic tectonic evolution of the south-eastern Central Asian Orogenic Belt. Journal of Asian Earth Sciences 135, 370–89.

Zhang Z, Li K, Li, Tang W, Chen Y and Luo Z (2015c) Geochronology and geochemistry of the Eastern Erenhot ophiolitic complex: implications for the tectonic evolution of the Inner Mongolia–Daotingan Orogenic Belt. Journal of Asian Earth Sciences 97, 279–93.

Zhang Z, Wang K, Wang G, Liu X, Liu W and Wu B (2018d) Petrogenesis and tectonic significances of the Paleozoic Jiling syenite in the mountain
Longshou area, Gansu province. *Geological Review* **64**, 1017–29 (in Chinese with English abstract).

Zhao G, Cawood PA, Li S, Wilde SA, Sun M, Zhang J, He Y and Yin C (2012) Amalgamation of the North China Craton: key issues and discussion. *Precambrian Research* **222–223**, 55–76.

Zhao G, Sun M, Wilde SA and Li SZ (2005) Late Archean to Paleoproterozoic evolution of the North China Craton: key issues revisited. *Precambrian Research* **136**, 177–202.

Zhao G, Wang Y, Huang B, Dong Y, Li S, Zhang G and Yu S (2018) Geological reconstructions of the East Asian blocks: from the breakup of Rodinia to the assembly of Pangea. *Earth-Science Reviews* **186**, 262–86.

Zhao P, Chen Y, Xu B, Faure M, Shi G and Choulet F (2013) Did the Paleo-Asian Ocean between North China Block and Mongolia Block exist during the late Paleozoic? First paleomagnetic evidence from central-eastern Inner Mongolia, China. *Journal of Geophysical Research: Solid Earth* **118**, 1873–94.

Zhao P, Jahn BM, Xu B, Liao W and Wang Y (2016a) Geochemistry, geochronology and zircon Hf isotopic study of peralkaline-alkaline intrusions along the northern margin of the North China Craton and its tectonic implication for the southeastern Central Asian Orogenic Belt. *Lithos* **261**, 92–108.

Zhao P, Xu B, Tong Q, Chen Y and Faure M (2016b) Sedimentological and geochronological constraints on the Carboniferous evolution of central Inner Mongolia, southeastern Central Asian Orogenic Belt: Inland sea deposition in a post-orogenic setting. *Gondwana Research* **31**, 253–70.

Zhao P, Xu B and Zhang C (2017) A rift system in southeastern Central Asian Orogenic Belt: constraint from sedimentological, geochronological and geochemical investigations of the Late Carboniferous-Early Permian strata in northern Inner Mongolia (China). *Gondwana Research* **47**, 342–57.

Zhao X, Liu C, Wang J, Zhang S and Guan Y (2020) Geochemistry, geochronology and Hf isotope of granitoids in the northern Alxa region: implications for the Late Paleozoic tectonic evolution of the Central Asian Orogenic Belt. *Geoscience Frontiers* **11**, 1711–25.

Zheng R, Li J, Xiao W and Wang L (2018) A new ophiolitic mélangé containing boninitic blocks in Alxa region: implications for Permian subduction events in southern CAOB. *Geoscience Frontiers* **9**, 1355–67.

Zheng R, Li J, Zhang J, Xiao W and Li Y (2019) Early Carboniferous high Ba-Sr granitoid in southern Langshan of northeastern Alxa: implications for accretionary tectonics along the southern Central Asian Orogenic Belt. *Acta Geologica Sinica (English Edition)* **93**, 820–44.

Zheng R, Wu T, Zhang W, Xu C, Meng Q and Zhang Z (2014) Late Paleozoic subduction system in the northern margin of the Alxa block, Altaiids: geochronological and geochemical evidences from ophiolites. *Gondwana Research* **25**, 842–58.

Zhou JB, Wilde SA, Zhao GC and Han J (2018) Nature and assembly of microcontinental blocks within the Paleo-Asian Ocean. *Earth-Science Reviews* **186**, 76–93.

Zhou XC, Zhang HF, Luo BJ, Pan FB, Zhang SS and Guo L (2016) Origin of high Sr/Y-type granitic magmatism in the southwestern of the Alxa Block, Northwest China. *Lithos* **256–257**, 211–27.

Zhou Z, Zhang H, Liu H, Liu C and Liu W (2009) Zircon U-Pb dating of basic intrusions in Siziwangqi area of middle Inner Mongolia, China. *Acta Petrologica Sinica* **25**, 1519–28 (in Chinese with English abstract).