

## Original Article

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# Geochemistry, zircon U–Pb geochronology and Hf isotope of the early Permian gabbro and high-Mg diorites from the Zhusileng–Hangwula Belt in the northern Alxa area: Petrogenesis and tectonic implications

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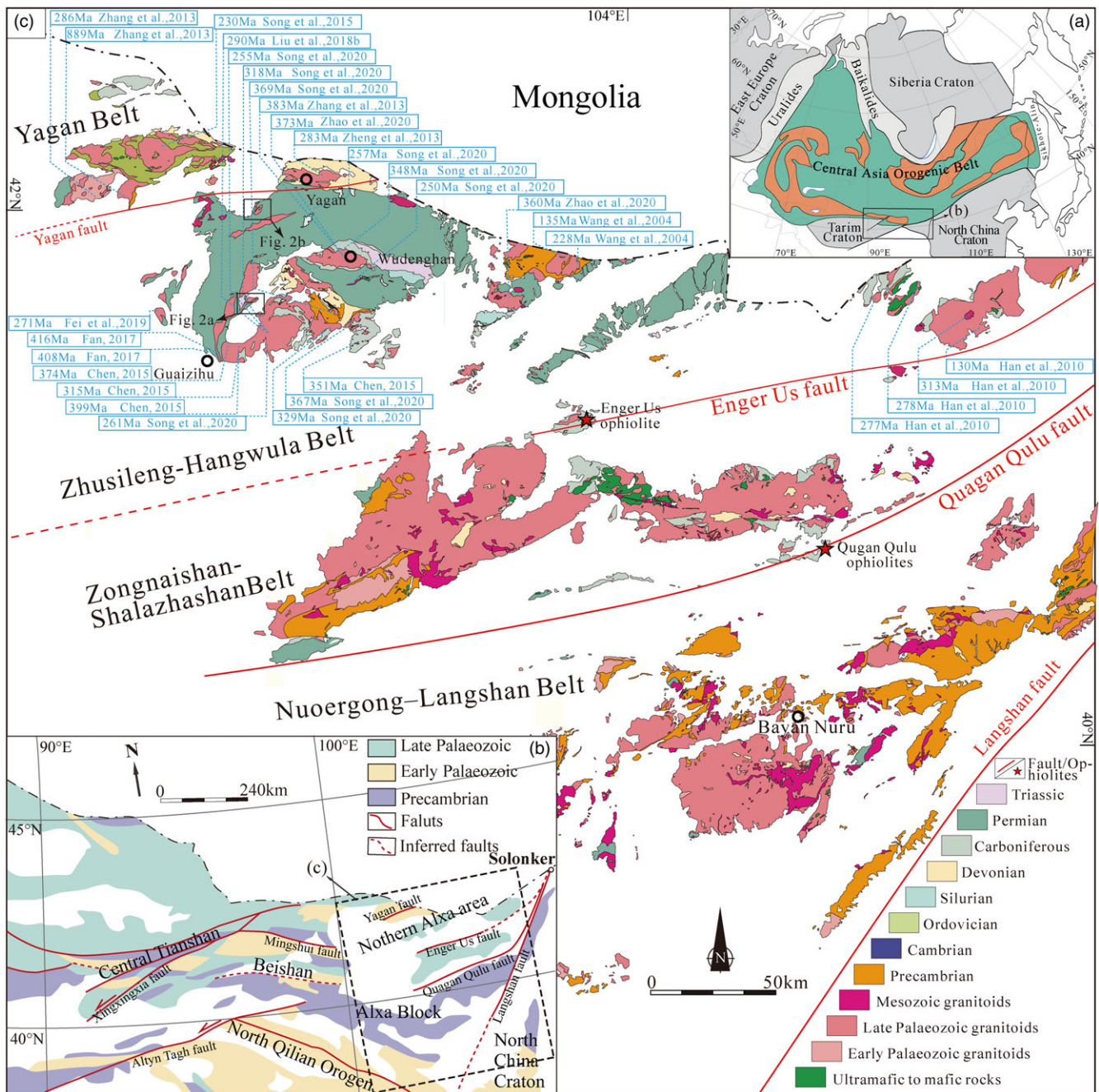
**Abstract**

As the southernmost part of the central segment of the Central Asian Orogenic Belt, the northern Alxa area is characterized by abundant Permian magmatism and records key information on the geological evolution of the Palaeo-Asian Ocean. This study reports new zircon U–Pb and Lu–Hf isotopic and whole-rock geochemical data of the early Permian (285–286 Ma) Huisentala gabbro and Huodonghaer diorites from the Zhusileng–Hangwula Belt in the northern Alxa area. The gabbro is characterized by high Al, Ca, Mg<sup>#</sup> and light rare-earth elements, and low K, P and high field strength elements (e.g., Ti, Nb and Ta). Furthermore, the gabbro shows heterogeneous zircon  $\epsilon_{\text{Hf}}(t)$  value (–2.5 to +2.6). The Huodonghaer diorites show high MgO (3.46–6.32 wt%), Mg<sup>#</sup> (49–58), Sr (408–617 ppm) and Ba (223–419 ppm), and low FeO<sup>T</sup>/MgO (1.27–1.83) and TiO<sub>2</sub> (0.48–0.90 wt%), with geochemical features similar to the high-Mg andesite/diorite. They show radiogenic zircon  $\epsilon_{\text{Hf}}(t)$  values of +1.2 to +4.9 and high Th/Nb ratios. These features suggest that the Huisentala gabbro and the Huodonghaer diorites were derived from the partial melting of mantle peridotite that was metasomatized by subduction-related fluids and by subducted sediment-derived melts, respectively.

**1. Introduction**

The Central Asian Orogenic Belt (CAOB), one of the largest accretionary orogens in the world, is bounded by the Eastern European Craton to the east, the Tarim Craton and North China Craton to the south and the Siberia Craton to the north (Fig. 1a, Şengör *et al.* 1993; Windley *et al.* 2007; Wilhem *et al.* 2012; Xiao *et al.* 2013). The complicated accretionary processes and considerable continental crustal growth of the CAOB from ca. 1000 to 250 Ma were associated with the consumption of the Palaeo-Asian Ocean (PAO) (Hong *et al.* 2004; Jahn *et al.* 2004; Xu *et al.* 2013; Eizenhöfer *et al.* 2014; Xiao *et al.* 2018). The northern Alxa area plays a significant role to constrain the tectonic and crustal evolution of the southern CAOB (Fig. 1a). The northern Alxa area is characterized by the widespread development of late Palaeozoic plutons (Zhang *et al.* 2016, 2017; Liu *et al.* 2018a, b; Fei *et al.* 2019; Li *et al.* 2020; Shi *et al.* 2020; Song *et al.* 2020; Zhao *et al.* 2020). However, its tectonic setting during the late Palaeozoic is still debated. Previous researchers argued that the central PAO closed before the early Permian (Fei *et al.* 2019; Li *et al.* 2020), and the northern Alxa area underwent post-collisional extension during the late Palaeozoic, while other scholars suggested that ocean subduction was still active during the late Palaeozoic, and the central PAO closed in the early Triassic (Song *et al.* 2020; Xie *et al.* 2021).

The northern Alxa area, as the southernmost part of the central segment of the CAOB, is located at a crucial junction between the Solonker Suture and the Central Tianshan Arc and the Beishan Orogenic Belt (Fig. 1b). In this study, we present new geochronological, geochemical and zircon Hf isotopic data for the early Permian gabbro and diorites from the Zhusileng–Hangwula Belt in the northern Alxa area. These results, combined with published data, are used to discuss the petrogenesis of the igneous rocks and tectonic setting and to reconstruct the geological evolutionary history of the central part of the southern CAOB during the late Palaeozoic.



**Figure 1.** (Colour online) (a) The Location of the northern Alxa area in the simplified tectonic sketch map of the Central Asian Orogenic Belt (CAOB) (Modified after Eizenhöfer *et al.* 2014). (b) Tectonic outline of the southern CAOB in north China (after Chen *et al.* 2019). (c) Geological map of the northern Alxa area and adjacent tectonic units (modified after Liu *et al.* 2018a).

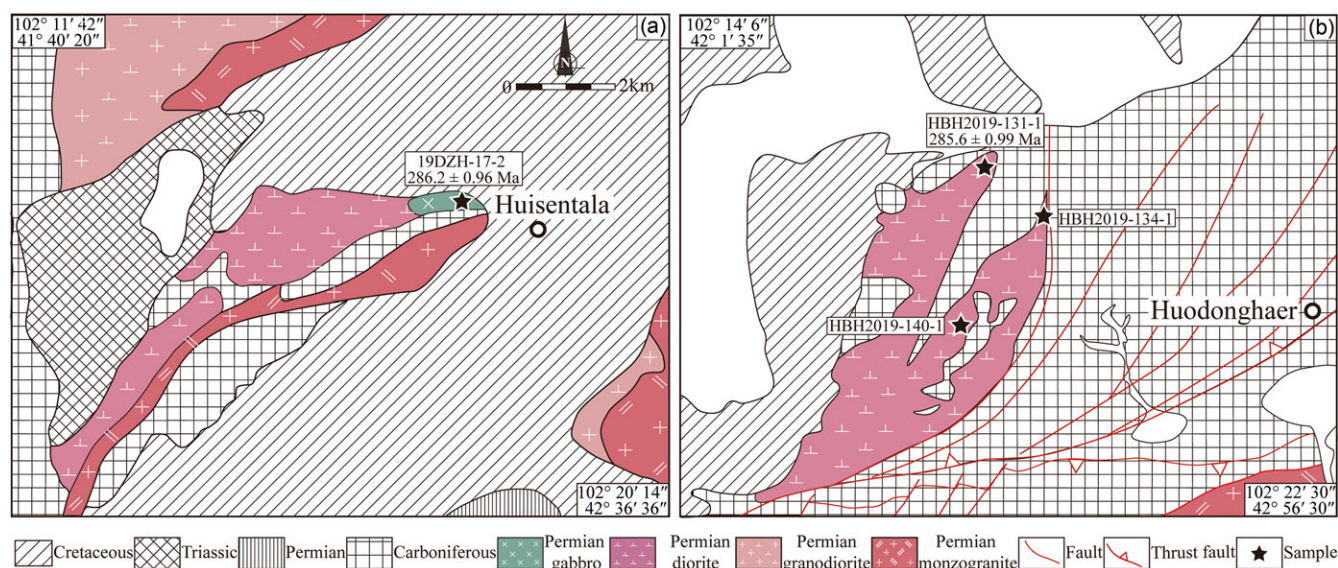
## 2. Geological setting and samples

The northern Alxa area, the southernmost segment of the CAOB, is divided into two parts by the Yagan fault: from north to south, the Yagan Belt and the Zhusileng–Hangwula Belt (Fig. 1a). Two important faults, the Enger Us fault and the Quagan Qulu fault, are characterized by ophiolitic mélanges (Fig. 1b; BGMIRM, 1991; Wu & He, 1993; Wu *et al.* 1998).

The Quagan Qulu fault separates the Zongnaishan–Shalazhashan Belt and the Nuorgong–Langshan Belt (Fig. 1b). The Nuorgong–Langshan Belt is mainly composed of Precambrian basement rocks

and late Palaeozoic magmatic rocks (321–265 Ma). As shown in recent studies (Geng & Zhou, 2012; Wang *et al.* 2016, 2021; Zheng *et al.* 2018; Zheng *et al.* 2019), the Precambrian rocks comprise Palaeoproterozoic gneisses and amphibolites, with small amounts of Neoproterozoic granites (970–880 Ma), and the Phanerozoic rocks are mainly composed of granites, diorites and minor gabbro (321–265 Ma). By comparison, 301–247 Ma magmatic rocks and late Palaeozoic sediments, with some Mesozoic granites, dominate in the Zongnaishan–Shalazhashan Belt (Shi *et al.* 2014; Zheng *et al.* 2014; Song *et al.* 2017). A few Precambrian metamorphic rocks with ages of





**Figure 2.** (Colour online) Geological maps showing sampling locations and ages. (a) Huisentala area (modified after the 1: 200,000 geological maps from BGMIR, 1991). (b) Huodonghaer area (after the 1: 200,000 geological maps from BGMIR, 1991).

1.5–1.4 Ga have also been reported (Qing, 2010; Song, 2014; Shi *et al.* 2016; Wang *et al.* 2019), indicating that the tectonic affinity of the Zongnaishan–Shalazhashan Belt, which was treated as a part of the Alxa Block, was uncertain given the occurrence of Mesoproterozoic rocks in the Zongnaishan area.

The Yagan Belt mainly contains Palaeozoic volcano-sedimentary strata (Wu & He, 1993) and plutons (397–220 Ma; Zheng *et al.* 2013; Liu *et al.* 2018a), with some Neoproterozoic granite (Zhang *et al.* 2016). Based on litho-tectonic comparisons, the Yagan and Zhusileng–Hangwula Belts have been generally considered the eastern extension of the Beishan Orogenic Belt (Wu *et al.* 1998).

The Zhusileng–Hangwula Belt is characterized by widespread Palaeozoic to Mesozoic volcano-sedimentary formations and magmatic rocks as well as minor Precambrian rocks (BGMIR, 1991; Wu & He, 1993; Yin *et al.* 2015). The Mesoproterozoic–early Neoproterozoic rocks (1400–916 Ma) are sporadically exposed in the region (Wang *et al.* 2002; Zhou *et al.* 2013; Deng *et al.* 2022a; Yu *et al.* 2022). The early Palaeozoic strata only include Cambrian limestone, late Ordovician limestone and early Silurian siliceous rocks. Late Palaeozoic strata are composed of clastic rocks, limestone and minor volcanic rocks, which are unconformably overlain by late Triassic and Cretaceous continental clastic sediments (Chen *et al.* 2019). The Phanerozoic intrusions in the Zhusileng–Hangwula Belt were generated during the middle–late Devonian (399–373 Ma), late Carboniferous–middle Permian (325–263 Ma) and middle–late Triassic (250–216 Ma), including gabbro, diorite, granodiorite, granite and monzogranite (Fig. 1c; Wang *et al.* 2002; Li, 2006; Han *et al.* 2010; Dang *et al.* 2011; Chen, 2015; Zhang *et al.* 2017; Liu *et al.* 2018a; Shi *et al.* 2018; Chen *et al.* 2019; Li *et al.* 2020; Song *et al.* 2020; Deng *et al.* 2022b, 2023, b; Fei *et al.* 2019; Zhao *et al.* 2020).

For this study, samples of gabbro and diorites were examined, and sample locations can be found in Fig. 2. The Huisentala gabbro (19DZH-17-2) is black and grey-coloured, moderate- to coarse-grained and is mainly composed of plagioclase (~60%), hornblende (~20%), biotite (~15%) and minor quartz (~5%) (Fig. 3a). The Huodonghaer diorites, intruded by granodiorite, show dark green colour and moderate to coarse-grained texture (Fig. 3b). They are strongly weathered and mainly consist of plagioclase

(~75%), hornblende (~10%), biotite (~10%) and minor quartz (~5%) (Fig. 3c).

### 3. Analytical methods

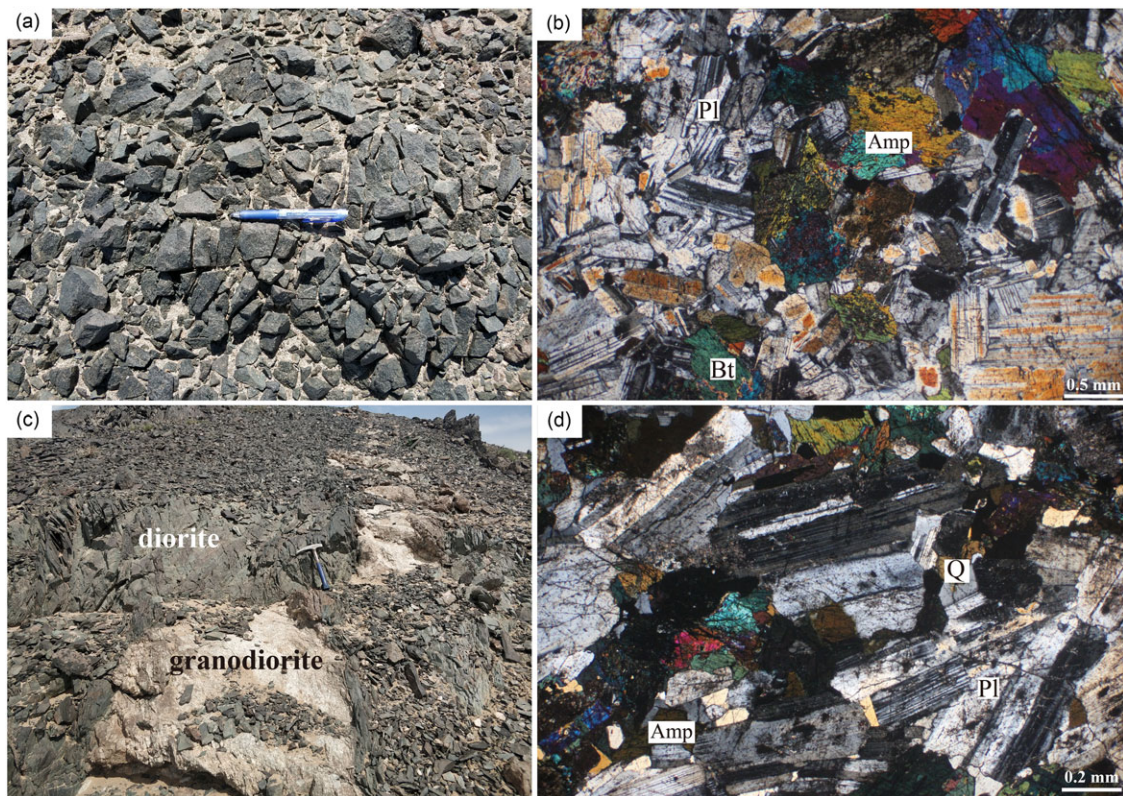
#### 3.a. Zircon U–Pb dating

After crushing, zircon crystals were extracted using heavy liquid and magnetic techniques. Zircons were hand-picked and mounted in epoxy resin and polished to about half of their size to expose the core of the grain. The detailed procedure can be found in Song *et al.* (2002). The cathodoluminescence (CL) images of zircon were obtained using a scanning electron microscope (IT-500, Japan) at Beijing Geoanalysis Co., Ltd (Beijing, China). Analytical spots for U–Pb dating were chosen after combined studies of transmitted and reflected light microscope and CL images. Laser ablation inductively coupled plasma-mass spectrometry (LA-ICP-MS) zircon U–Pb analyses were carried out using an Agilent 7900 ICP-MS equipped with a 193-nm laser ablation system at the Institute of Geology, Chinese Academy of Geological Sciences in Beijing, China. The detailed procedure is the same as described by Hou *et al.* (2007). Zircon 91500 and GJ-1 were used as primary and secondary standards for U–Pb dating, respectively (Jackson *et al.* 2004). ISOPLOT 3.0 was used to plot the concordia diagrams and perform the weighted mean calculations (Ludwig, 2003). Uncertainties are quoted at 2 $\sigma$  level for individual analysis, and the weighted mean ages are given at the 95% confidence level.

#### 3.b. Zircon Lu–Hf isotopic analyses

Zircon Hf isotope analyses were conducted using a multiple collector inductively coupled plasma-mass spectrometer (MC-ICP-MS, Neptune Plus, Thermo Fisher Scientific, Germany) equipped with a femtosecond ( $\lambda = 343$  nm) laser-ablation system (J-200, Applied Spectra, USA) at the National Research Center for Geoanalysis in Beijing. To evaluate the quality of the data, Temora and Plesovice zircon were used as the standards and exhibited  $^{176}\text{Hf}/^{177}\text{Hf}$  ratios of  $0.282692 \pm 0.000018$  (2 $\sigma$ ,  $n = 15$ ) and  $0.282480 \pm 0.000021$  (2 $\sigma$ ,  $n = 49$ ), respectively. The analytical details and interference correction





**Figure 3.** (Colour online) Representative outcrops and microphotographs of investigated gabbro and diorites from the Zhusileng–Hangwula Belt. (a) and (b) Gabbro (sample 19DZH-017-2). (c) and (d) Diorite (sample HBH2019-131-1). Amp, Amphibole; Bt, Biotite; Pl, Plagioclase; Qtz, quartz.

method of  $^{176}\text{Yb}$  on  $^{176}\text{Hf}$  can be found in Zhou *et al.* (2018) and Wu *et al.* (2006), respectively. The  $^{176}\text{Lu}$  decay constant of  $1.865 \times 10^{-11} \text{ yr}^{-1}$  (Scherer *et al.* 2007) was used to calculate the initial  $^{176}\text{Hf}/^{177}\text{Hf}$  ratios. The chondritic values of 0.0336 and 0.282785 for  $^{176}\text{Lu}/^{177}\text{Hf}$  and  $^{176}\text{Hf}/^{177}\text{Hf}$ , respectively, reported by Bouvier *et al.* (2008), were used for the calculation of the  $\epsilon_{\text{Hf}}$  values. The depleted mantle Hf model ages ( $T_{\text{DM}}$ ) were calculated using the measured  $^{176}\text{Lu}/^{177}\text{Hf}$  ratios based on the assumption that the depleted mantle reservoir has a linear isotopic growth from  $^{176}\text{Hf}/^{177}\text{Hf} = 0.279718$  at 4.55 Ga to  $^{176}\text{Hf}/^{177}\text{Hf} = 0.283250$  at present, with  $^{176}\text{Lu}/^{177}\text{Hf}$  ratio of 0.0384 (Griffin *et al.* 2000). Two-stage model ages ( $T_{\text{DM2}}$ ) were also calculated, assuming that the parental magma was produced from an average continental crust ( $^{176}\text{Lu}/^{177}\text{Hf} = 0.015$ ; Griffin *et al.* 2002).

### 3.c. Major and trace element analyses

The samples were crushed and ground to 200 mesh. Whole-rock major and trace element analyses were obtained at ALS Chemex Co., Ltd (Guangzhou, China) using X-ray fluorescence spectrometer (XRF), ICP-MS and inductively coupled plasma-atomic emission spectrometry (ICP-AES). Details of the analytical procedure can be found in Zhou *et al.* (2002) and Liu *et al.* (2008). One pulp sample was fused with lithium metaborate–lithium tetraborate flux, including an oxidizing agent (lithium nitrate), and then poured into a platinum mold. The resultant disc was then analysed by XRF spectrometry. The XRF analysis was determined in conjunction with a loss-on-ignition at 1000 °C. The resulting data from both analyses were combined to produce a ‘total’. One prepared sample was added to lithium metaborate/lithium tetraborate flux, mixed well and fused in a furnace at 1025 °C. The resulting melt was then dissolved and cooled in an acid

mixture containing nitric, hydrochloric and hydrofluoric acids. This solution was then analysed by ICP-MS. Another prepared sample was digested with perchloric, nitric and hydrofluoric acids. The residue was leached with dilute hydrochloric acid and diluted to volume. The solution was then analysed using ICP-MS for ultratrace level elements. The same solution was also analysed using ICP-AES for trace level elements. Results were corrected for spectral inter-element interferences. The analytical accuracy and precision for the trace elements and major elements were found to be better than 5% and 10%, respectively.

## 4. Results

The U–Pb zircon isotopic data are listed in Supplementary Table 1, the Lu–Hf isotopic analyses in Supplementary Table 2 and major and trace element data are presented in Supplementary Table 3.

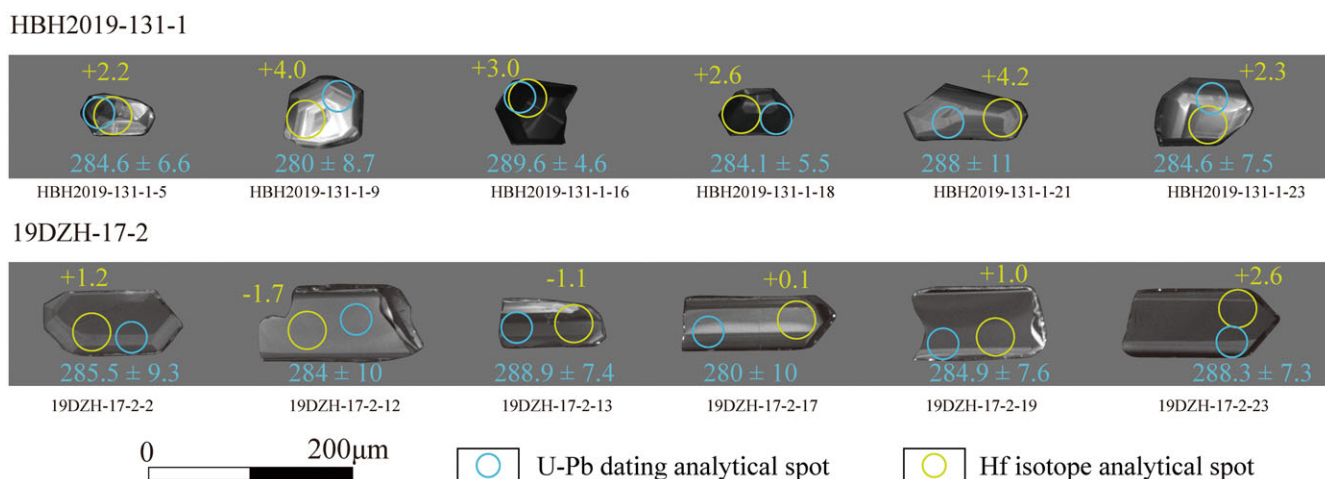
### 4.a. Zircon U–Pb ages

#### 4.a.1. Gabbro

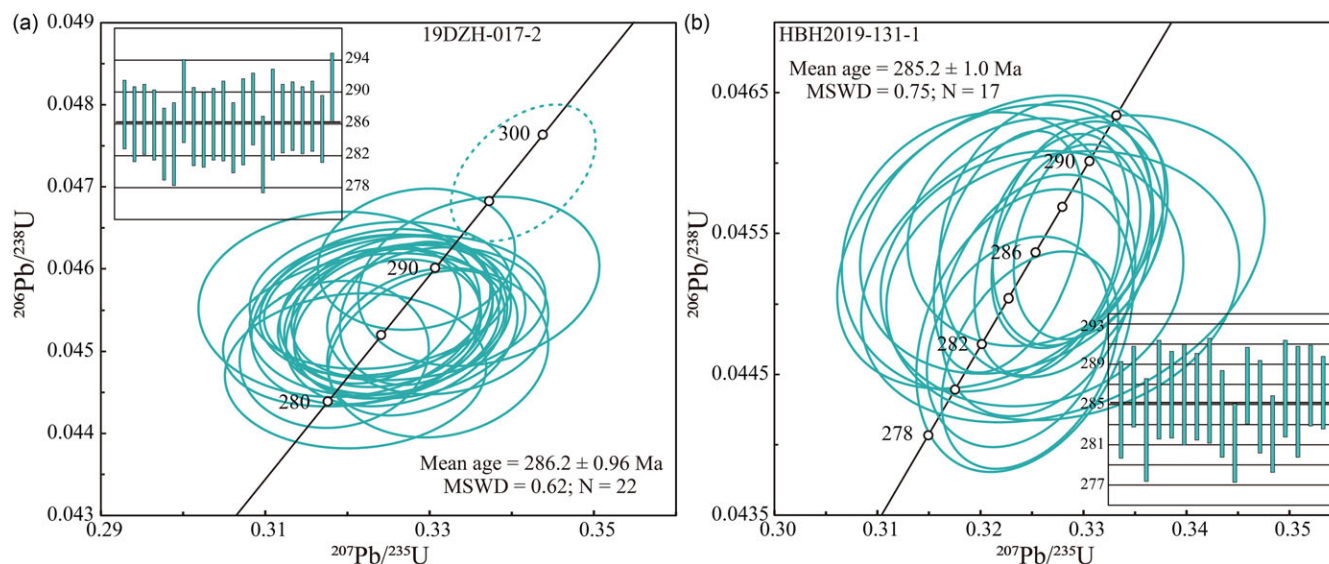
Zircon grains are euhedral and stubby, 50–100 × 100–200 μm in size and exhibit concentric oscillatory zoning (Fig. 4). Except for the older spot 9, 22 concordant spots for sample 19DZH-17-2 yield a weighted mean  $^{206}\text{Pb}/^{238}\text{U}$  age of  $286.2 \pm 0.96$  Ma (MSWD = 0.62, Th/U = 0.52–1.07; Fig. 5a).

#### 4.a.2. Diorite

Zircon from the investigated diorite is all euhedral, prismatic and stubby. They have well-preserved oscillatory zoning and 30–80 × 60–180 μm in size (Fig. 4). Twenty-three spots were analysed for sample HBH2019-131-1, except for 6 older and younger spots,



**Figure 4.** (Colour online) Cathodoluminescence (CL) images of representative zircons from studied gabbro and diorites. The blue line circle represents the spot of LA-ICP-MS analysis for U-Pb dating. The yellow line circle represents the spot of LA-MC-ICP-MS analysis for Lu-Hf isotope compositions. Apparent ages (in blue) and  $\epsilon_{\text{Hf}}(t)$  values (in yellow) are denoted.



**Figure 5.** (Colour online) Concordia diagrams of LA-ICP-MS zircon U-Pb data from investigated gabbro and diorites in the Zhushileng-Hangwula Belt.

17 concordant spots yield a weighted mean  $^{206}\text{Pb}/^{238}\text{U}$  age of  $285.2 \pm 1.0$  Ma (MSWD = 0.75; Fig. 5b), with Th/U ratios of 0.52–1.55.

#### 4.b. Zircon Hf isotopic compositions

Twenty zircon grains from sample 19DZH-17-2 have variable  $\epsilon_{\text{Hf}}(t)$  values between  $-2.5$  and  $+2.6$  (Fig. 6), two-stage model ages ( $T_{\text{DM2}}$ ) of 1.96–1.49 Ma and initial  $^{176}\text{Hf}/^{177}\text{Hf}$  ratios of 0.282908–0.282971. Seventeen zircons from sample HBH2019-131-1 yield positive  $\epsilon_{\text{Hf}}(t)$  values between  $+1.2$  and  $+4.9$  (Fig. 6), two-stage model ages ( $T_{\text{DM2}}$ ) of 1.62–1.29 Ga and initial  $^{176}\text{Hf}/^{177}\text{Hf}$  ratios of 0.282627–0.282733.

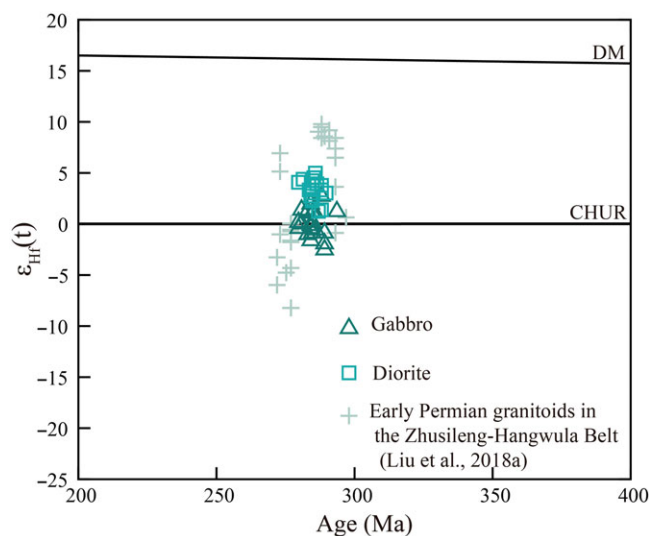
#### 4.c. Whole-rock major and trace elements

The gabbro sample exhibits low contents of  $\text{SiO}_2$  (49.36 wt%) and  $\text{K}_2\text{O}$  (0.52 wt%), and high contents of  $\text{Fe}_2\text{O}_3^{\text{T}}$  (7.98 wt%),

$\text{CaO}$  (12.45 wt%) and  $\text{Mg}^\#$  [ $67.49$ ,  $\text{Mg}^\# = \text{Mg}/(\text{Mg} + \text{Fe}^{2+})$ ], which place the gabbro in the metaluminous field in the A/CNK [(molecular ratio of  $\text{Al}_2\text{O}_3/(\text{CaO} + \text{Na}_2\text{O} + \text{K}_2\text{O})$ ] versus A/NK [(molecular ratio of  $\text{Al}_2\text{O}_3/(\text{Na}_2\text{O} + \text{K}_2\text{O})$ ] diagram (Fig. 7b; Frost *et al.* 2001). The gabbro is transitional between calc-alkaline and tholeiitic (Fig. 7c) and exhibits total rare-earth elements (REEs) concentrations of 61.94 and slightly enriched light rare-earth elements (LREEs) [(La/Yb)<sub>N</sub> = 1.18], with almost no Eu anomalies [ $\delta\text{Eu} = 1.05$ ,  $\delta\text{Eu} = \text{EuN}/(\text{EuN} \times \text{GdN})^{1/2}$ ] (Fig. 8a). The gabbro exhibits enrichments in Rb, U and Sr, and depletions in Nb, Ta and Zr (Fig. 8d).

The diorites have low  $\text{SiO}_2$  (51.40–56.54 wt%), high  $\text{Al}_2\text{O}_3$  (15.02–18.42 wt%),  $\text{MgO}$  (3.46–6.42 wt%),  $\text{Mg}^\#$  (49.37–58.33) and  $\text{Fe}_2\text{O}_3^{\text{T}}$  (7.03–10.55 wt%), as well as low  $\text{K}_2\text{O} + \text{Na}_2\text{O}$  (3.87–4.33 wt%). They are metaluminous (A/CNK = 0.66–0.94; Fig. 7b) and belong to the tholeiitic to high calc-alkaline series (Fig. 7c). These diorites have total REE concentrations of





**Figure 6.** (Colour online) Zircon Hf isotopic compositions of the early Permian gabbro and diorites from the Zhusileng-Hangwula Belt. The  $\epsilon_{\text{Hf}}(t)$  values of the early Permian granitoids are from Liu *et al.* (2018a).

47.75–88.75 and enrichments in LREEs [(La/Yb)<sub>N</sub> = 3.44–6.37], with almost no Eu anomalies ( $\delta\text{Eu} = 0.71\text{--}1.02$ ) (Fig. 8a). Furthermore, they show enrichments in Rb, U, Pb and Sr, and depletions in Nb and Ta (Fig. 8b).

## 5. Discussion

The weighted mean  $^{206}\text{Pb}/^{238}\text{U}$  ages of  $286.2 \pm 0.96$  Ma and  $285.2 \pm 1.0$  Ma are interpreted as crystallization ages of gabbro and diorite, respectively.

### 5.a. Petrogenesis

#### 5.a.1. Gabbro

The early Permian gabbro in the Zhusileng-Hangwula Belt yielded variable zircon  $\epsilon_{\text{Hf}}(t)$  values (−2.5 to +2.6) and old  $T_{\text{DM}2}$  ages (1.96–1.49 Ga, average 1.68 Ga). The heterogeneous zircon  $\epsilon_{\text{Hf}}(t)$  values can be attributed either to melts derived from an asthenospheric mantle with crustal contamination or to those from an enriched lithospheric mantle (Wu *et al.* 2007). The gabbro sample exhibits high Al, Ca and Fe, and low Si, K and P, indicating a parental mantle source instead of crustal materials (e.g., Rundick & Gao, 2003). Furthermore, the content of  $\text{Mg}^\#$  (67.49) of this gabbro is close to the primary mantle-derived magma ( $\text{Mg}^\# = 68\text{--}73$ , Hess & Wiebe, 1989), ruling out crustal assimilation by primary mantle-derived magma. Therefore, we suggest that the Huisentala gabbro was likely derived from an enriched lithospheric mantle.

On the chondrite-normalized REE diagram (Fig. 8a), the gabbros are characterized by enrichments in LREEs. As shown in the primitive mantle-normalized trace-element spider diagram (Fig. 8b), the gabbro is characterized by relative enrichment in large ion lithophile elements (LILEs) and U, and depletion in high field strength elements (HFSEs) (e.g., Ti, Nb and Ta), indicative of arc geochemical affinities. Crustal contamination or magma source metasomatization by subduction-related materials may result in the negative Nb–Ta–Ti anomalies (Sun & McDonough, 1989; Chen *et al.* 2011; Tang *et al.* 2014; Xia, 2014). However, crustal contamination can be

ruled out in the generations of the Huisentala gabbro due to its high content of  $\text{Mg}^\#$ . Moreover, the gabbro displays high Ba/Th ratio (43.73) and relatively low Hf/Sm ratio (0.73), indicating the contribution of subduction-related fluids in its generations (La Flèche Camire & Genner, 1998; Pearce & Stern, 2006). Xia *et al.* (2007) suggested that magmatic rocks influenced by subduction fluids/melts usually present low Zr contents (<130 ppm) and Zr/Y ratios (<4). The Huisentala gabbro has low content of Zr (64 ppm) and Zr/Y ratio (3.66). Therefore, we proposed that the Huisentala gabbro was derived from an enriched lithospheric mantle metasomatized by subduction-related fluids.

#### 5.a.2. Diorite

The Huodonghaer diorites have high MgO (3.46–6.32 wt%), Cr (average 73.33 ppm) and Ni (average 23.10 ppm), as well as low  $\text{FeO}^\text{T}/\text{MgO}$  (1.27–1.83) ratios,  $\text{TiO}_2$  (0.48–0.90 wt%) and (La/Yb)<sub>N</sub> (3.44–6.37) ratios, indicating high-Mg andesite compositions (Kelemen *et al.* 2003; Tatsumi, 2006; Zhao *et al.* 2009). The Huodonghaer diorites have a higher  $\text{Mg}^\#$  range (49.37–58.33) than pure crustal melts (Patiño Douce & Beard, 1995; Rundick & Gao, 2003), so they most likely formed from mantle melts that were influenced by crustal materials rather than from a crustal source (Jiang *et al.* 2009; Dong *et al.* 2012).

Partial melting of mantle peridotite that is metasomatized by the slab melts or subducted sediment-related melts has been regarded as the most likely petrogenetic model for high-Mg diorite (Martin *et al.* 2005; Moyaen, 2009; Dong *et al.* 2012). High-Mg diorite derived from the reaction between mantle peridotite and slab melts usually exhibits adakite-like geochemical characteristics, such as high  $\epsilon_{\text{Nd}}(t)$  values, high Sr contents, low Y and Yb contents, high Sr/Y and (La/Yb)<sub>N</sub> ratios (Yin *et al.* 2015). However, the Huodonghaer diorites display positive zircon  $\epsilon_{\text{Hf}}(t)$  values (+1.2 to +4.9), high Y (13.20–19.30) and Yb (1.41–2.07), and low Sr/Y (21.14–45.61) and (La/Yb)<sub>N</sub> ratios (3.44–6.37). In addition, they have consistently low U/Th (0.12–0.33) and high Th/Nb (0.37–0.77) ratios, similar to the marine sediments (Fig. 9a). Furthermore, the Huodonghaer diorites have high and variable Th/Yb ratios, inconsistent with Ba/La ratios, which also support the involvement of a sediment-derived melts rather than of slab-derived fluids (Tatsumi, 2006; Fig. 9b). Because Ba is more soluble in aqueous fluids than La (Hanyu *et al.* 2006), the Ba/Th ratios should be markedly increased if oceanic crust-derived melts are involved in the production of magmas. Therefore, we suggest that the Huodonghaer diorites were derived from the partial melting of mantle peridotite that was metasomatized by the subducted sediment-derived melts.

#### 5.b. Tectonic implications

The Zhusileng-Hangwula Belt, located in the southernmost segment of the CAOB, is a pivotal region for determining the tectonic evolutionary history of the PAO. The Zhusileng-Hangwula Belt experienced multiple magmatic activities from the end of the early Palaeozoic to the late Palaeozoic, including four stages of ca. 399–373, 325–310, 296–263 and 250–216 Ma (Dang *et al.* 2011; Liu *et al.* 2018a, b; Shi *et al.* 2018; Chen *et al.* 2019; Fei *et al.* 2019; Li, 2020; Song *et al.* 2020; Zhao *et al.* 2020). However, as we mentioned in the introduction, the tectonic setting of the northern Alxa Block during the late Carboniferous–Permian is still ambiguous.

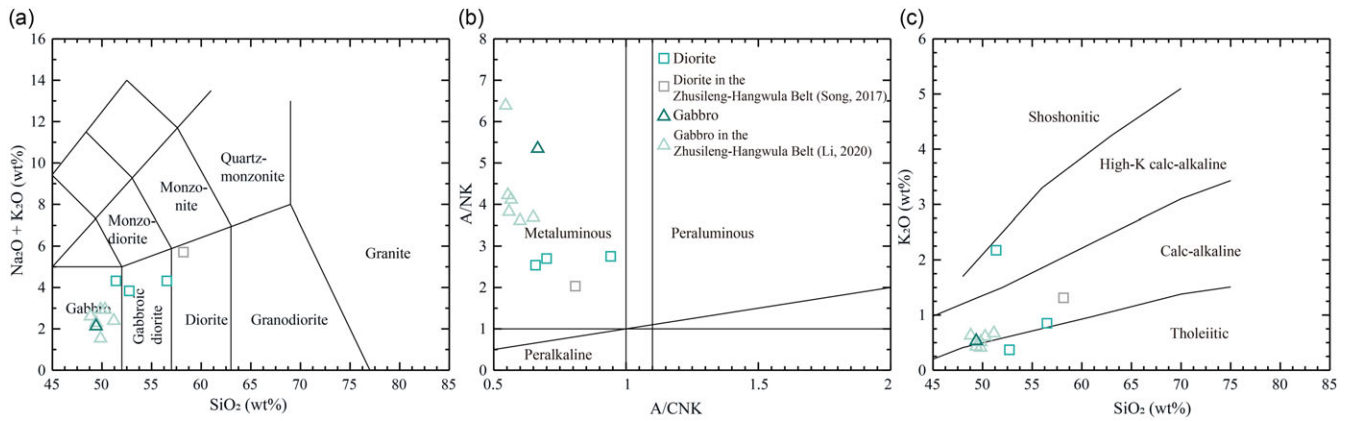


Figure 7. (Colour online) Diagrams showing major element features of the studied gabbro and diorites.

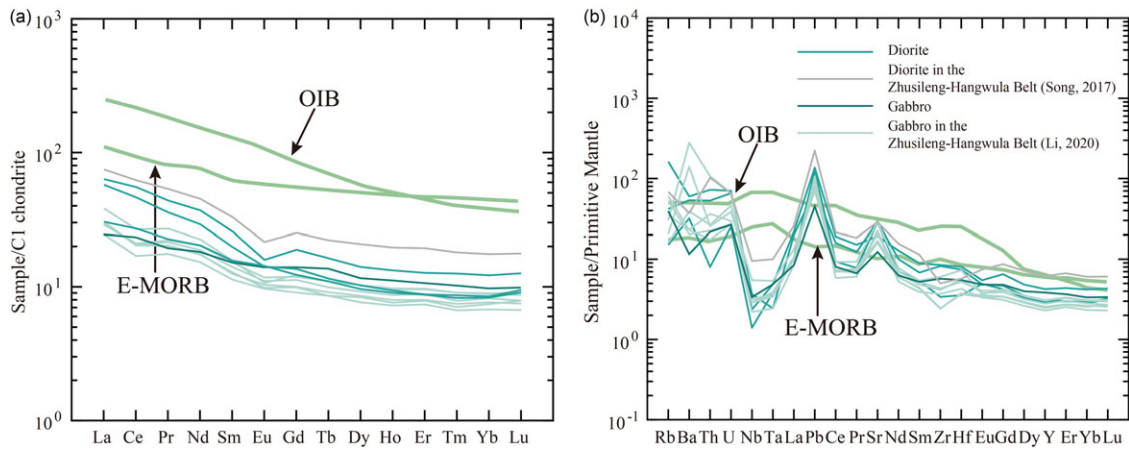


Figure 8. (Colour online) (a) Chondrite-normalized rare earth element patterns and (b) primitive mantle-normalized trace element spider diagrams for the investigated gabbro and diorites from the Zhushileng-Hangwula Belt. Compositions of chondrite and primitive mantle refer to Sun and McDonough (1989).

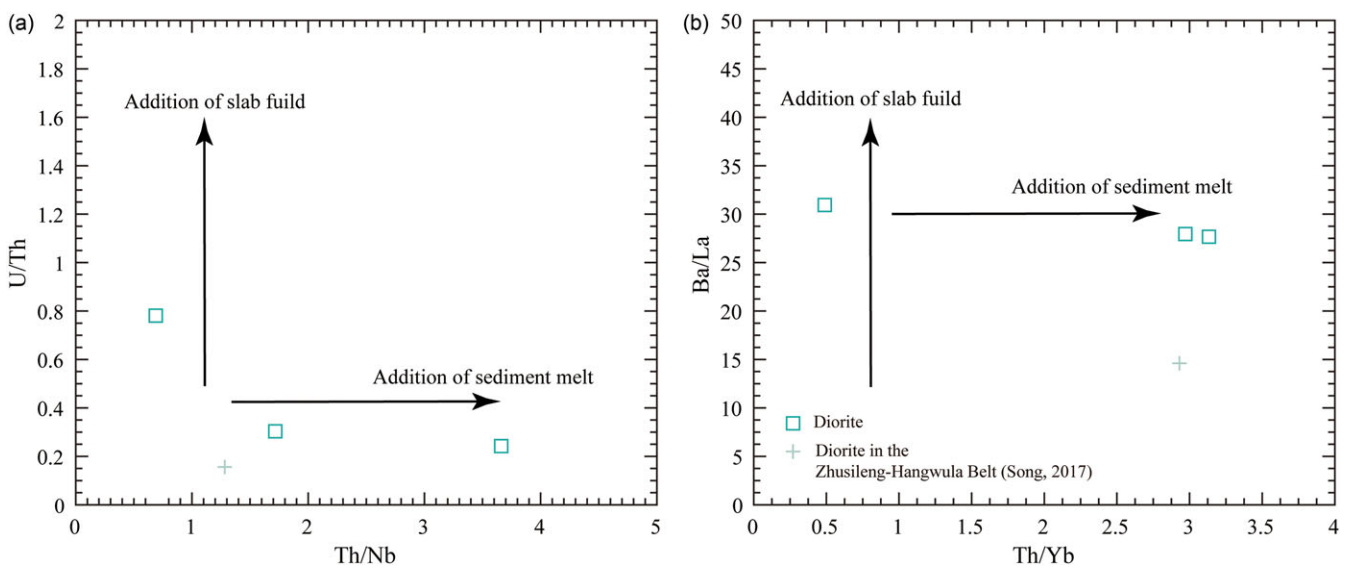
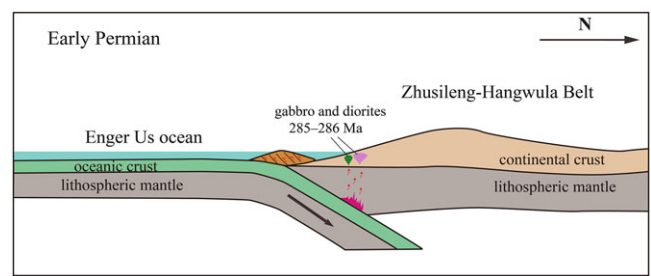


Figure 9. (Colour online) (a) Th/Nb versus U/Th and (b) Th/Yb versus Ba/La discrimination diagrams (modified after Tatsumi, 2006 and Hanyu et al. 2006).

Fei *et al.* (2019) proposed that the late Carboniferous to early Permian intrusions in the Zhusileng–Hangwula Belt formed in a post-collision setting, which indicates that the PAO had closed before the early Permian (Li *et al.* 2020), and then evolved into an extensional setting to form a rift along the north Alxa Block. However, the Palaeozoic strata in the Zhusileng area formed an NW–SE-trending anticline, which was intruded by late Palaeozoic granite (Zhang *et al.* 2022). The youngest strata involved in this fold are early Permian, and they are unconformably covered by late Permian strata (Liu *et al.* 2019). The formation of this anticline reflected horizontal compression that occurred during the early to late Permian, probably as a result from the closure of the PAO. The report of radiolarians fossil (Xie *et al.* 2014) and late Carboniferous normal mid-ocean ridge basalts exposed in the Enger Us ophiolite (~302 Ma, Zheng *et al.* 2014) imply that the PAO still existed during the late Carboniferous–early Permian. Liu *et al.* (2017) suggested that a switch of the tectonic settings, which was attributed to the final closure of the PAO, occurred at 280–265 Ma, according to the marked shift of zircon  $\epsilon_{\text{Hf}}(t)$  values and whole-rock  $\epsilon_{\text{Nd}}(t)$  values of the granitoids from the northern Alxa Block. Therefore, a post-collisional setting is not consistent with the derivation of the early Permian intrusions from the Zhusileng–Hangwula Belt.

The gabbro exhibits enrichment in LREE and U, and depletion in HFSE (e.g., Ti, Nb and Ta), indicative of arc-like geochemical affinities (Fig. 8), and we suggest that the gabbro was derived from an enriched lithospheric mantle metasomatized by subduction-related fluids. Furthermore, we identified that almost coeval high-Mg diorites occur in the Zhusileng–Hangwula Belt. High-Mg diorites are generally related to the subduction of a young and/or hot oceanic slab (e.g., ridge subduction) (Rogers & Saunders, 1989; Furukawa & Tatsumi, 1999). Sedimentological and palaeocurrents analyses on early Permian strata in the Zhusileng area also supported a subduction setting (Chen *et al.* 2011; Jiang *et al.* 2012; Shi *et al.* 2013; Zhang *et al.* 2022). Moreover, Li (2020) proposed that the gabbros in the Yagan metamorphic core complex have been strongly deformed and formed dykes, most of which are cut by normal faults resulting from the extensional deformation of the crust in this region. That implies that the formation of the gabbro was prior to the extensional event occurring after the closure of the PAO. Furthermore, coeval granitoid displaying volcanic arc affinities have also been verified in the Zhusileng–Hangwula Belt (Li *et al.* 2020; Song *et al.* 2020; Zhao *et al.* 2020; Deng *et al.* 2022b). For instance, the 298–290 Ma granitoids in the Zhusileng–Hangwula Belt were generated by magma mixing and formed in a subduction setting (Liu *et al.* 2018a). Therefore, we propose that the early Permian gabbro and coeval high-Mg diorites in the Zhusileng–Hangwula Belt are formed in an ocean slab subduction environment (Fig. 10).

We believe that the PAO in the middle part of the southern CAOB closed during the middle-late Permian for the following reasons: (1) middle-late Permian A-type and bimodal volcanic rocks found in this unit (Song *et al.* 2018, 2019, 2020; Li, 2019) indicate a post-collisional tectonic setting in the Zhusileng–Hangwula Belt after the early Permian; (2) late Permian sandstones (256–254 Ma) are interpreted to have formed in a post-collision setting, as suggested by geochemical characteristics (Liu *et al.* 2019; Shi *et al.* 2020) and (3) heavy mineral features of the Permian strata in Zhusileng and adjacent areas reveal that the detritus was sourced from both the northern and southern Alxa Block, which support that the PAO closed between the early and late Permian (Chen *et al.* 2019; Zhang *et al.* 2022). Thus, the Zhusileng–Hangwula Belt



**Figure 10.** (Colour online) Schematic cartoon showing the early Permian tectonic model of the Zhusileng–Hangwula Belt.

was an ocean subduction setting during the early Permian, then transitioned from subduction to collision and then to post-collision in the middle-late Permian probably due to the closure of the PAO along the Enger Us suture.

## 6. Conclusions

Based on the geochronological, geochemical and zircon Hf isotopic data for the gabbro and diorites in the Zhusileng–Hangwula Belt and previous studies, the following conclusions can be drawn:

- (1) Zircon LA-ICP MS U–Pb age data show that the monzogranites, Huisentala gabbro and Huodonghaer diorites from the Zhusileng–Hangwula Belt were formed during the early Permian (291–285 Ma).
- (2) The Huisentala gabbro yielded variable zircon  $\epsilon_{\text{Hf}}(t)$  values (–2.5 to +2.6) and old  $T_{\text{DM}2}$  ages (1.96–1.49 Ga, average 1.68 Ga). The gabbro sample exhibits high Al, Ca, Fe, Mg<sup>#</sup> and LREE, and low Si, K, P and HFSE, with slightly negative Eu anomalies, and was likely derived from an enriched lithospheric mantle metasomatized by subduction-related fluids. The Huodonghaer diorites exhibit high-Mg diorite-like geochemical compositions, such as high MgO, Sr and Cr contents, and low FeO/MgO ratios. They show moderate zircon  $\epsilon_{\text{Hf}}(t)$  values (+1.2 to +4.9) and Mesoproterozoic two-stage model ages (1.62–1.29 Ga), indicating that the diorites are derived from partial melting of mantle peridotite that was metasomatized the subducted sediment-derived melts.
- (3) Combined with other geological evidence, we propose that the early Permian gabbro and coeval high-Mg diorites from the Zhusileng–Hangwula Belt formed in an ocean subduction setting and probably are associated with the tectonic evolution of the PAO along the Enger Us suture.

**Supplementary material.** The supplementary material for this article can be found at <https://doi.org/10.1017/S0016756823000444>

**Data availability statement.** The data that support the findings of this study are available in the supplementary material of this article.

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