Timing, petrogenesis, and tectonic setting of late Paleozoic granites from the northern part of northern Alxa region, northwest China and implications for their tectonic evolution

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Abstract

The Wudenghan, Huhetaoergai and Zhuxiaobuguhe plutons, northern Alxa region, southern Central Asia Orogenic Belt (CAOB) are dated at 383 ± 3 Ma, 356 ± 3 Ma and 286 ± 2 Ma respectively (U-Pb zircon). The Late Devonian Wudenghan monzogranite, a highly-fractionated I-type granite with higher $\varepsilon_{\text{Nd}}(t)$ (-0.2 to -0.1) and lower $(^{87}\text{Sr}/^{86}\text{Sr})_t$ (0.704719 to 0.706113), is from Mesoproterozoic mafic-intermediate igneous protolith with minor addition of mantle-derived magmas and shows post-collisional characteristics. The Huhetaoergai granodiorite with medium-K calc-alkaline peraluminous characteristics represents a volcanic arc granite and is generated from partial melting of a lower continental crust. The Early Permian Zhuxiaobuguhe pluton, an unfractionated calc-alkaline granodiorite with low $\varepsilon_{\text{Nd}}(t)$ (-2.0 to -1.1) and low $(^{87}\text{Sr}/^{86}\text{Sr})_t$ (0.708370 to 0.708462), was likely derived from partial melting of the basal oceanic crust of a paleo-volcanic arc and represents a post-collisional granite. Our revised tectonic evolution of the region includes the closure of an ocean between passive margin and volcanic arc during the Late Silurian to Middle Devonian resulting in the formation of the Late Devonian Wudenghan monzogranite during regional foundering, southward subduction of the ocean in the north led to the formation of the Huhetaoergai volcanic-arc granite during Early Carboniferous, and emplacement of the Zhuxiaobuguhe pluton in the Late Devonian to Early Permian during post-tectonic extension.

Keywords: Granite, Alxa, CAO, Paleozoic

1. Introduction

The northern Alxa region is located in the west of Inner Mongolia, China, and links the central part of the southern Central Asia Orogenic Belt (CAOB) (Figure 1a, b). This is also

where the North China Plate, the Tarim Plate, and/or the Kazakhstan Plate meet (Figure 1b) (Wang et al., 1994; Wu et al., 1998). Its evolution is related to the evolution of the Paleozoic Asian Ocean and its continental margins (Kröner et al., 2012, 2014; Şengör et al., 1993; Windley et al., 2007; Wilhem et al., 2012; Xiao et al., 2009a, 2009b, 2013). The geological evolution of the area is so complicated that the relationship between the three plates and the Paleozoic evolution remains highly controversial (Wang et al., 1994; Wu et al., 1998; Zheng et al., 2014). Three important ophiolitic belts or sutures are reported in the northern Alxa region (Figure 1c). From north to south, they include the Yagan Fault, the Engger Us Ophiolitic Belt, and the Qagan Qulu Ophiolitic Belt (Wang et al., 1994; Wu and He, 1992; Wu et al., 1998). The Engger Us Ophiolitic Belt is regarded as the suture between the North China Plate and the Tarim Plate (Wang et al., 1994; Wu and He, 1992; Wu et al., 1998) or the major suture between north margin of Alxa block (NMAB) and the CAO (Zheng et al., 2014). The NMAB is usually considered as the western part of the North China Plate (Zhao et al., 2005), but recent years, many papers suggest the Alxa Block is not a part of the North China Craton (e.g., Dan et al., 2014; Zhang et al., 2011). The timing of obduction of the Engger Us Ophiolitic Belt and the Qagan Qulu Ophiolitic Belt has not been confirmed (Wang et al., 1994; Wu and He, 1993; Zheng et al., 2014) and, consequently, the timing of ocean closure represented by them remains controversial.

Most of the igneous rocks in the northern Alxa region are granites ranging in age from the Precambrian to the Mesozoic (Geng et al., 2002; Shi et al., 2014; Wang et al., 1994; Zhang et al., 2013; Zheng et al., 2013a; Yang et al., 2014). Due to the barren environment and tough working conditions, few of granites in the north of the Engger Us Ophiolitic Belt are well-studied, which constrains the tectonic interpretation of the northern Alxa region (Wang et al., 1994; Zheng et al., 2013). We present new geochronological and geochemical data from three Late Paleozoic granitic plutons from west of the Huhetaoergai, the Zhuxiaobuguhe and

Wudenghan areas. These data constrain their age relationship and petrogenesis, and also contribute to the understanding of the adjacent ophiolitic belts and their relationship to the Late Paleozoic tectonic evolution of the northern Alxa region.

2. Geological backgrounds

2.1 Geological units

Six geological units are delimited in the northern Alxa region (Figure 1). From north to south, they are the Huhetaoergai tectonic zone, the Zhusileng tectonic zone, the Guaizihu tectonic zone, the Zongnaishan-Shalazhashan tectonic zone, the Wuliji tectonic zone, and the Yabulai-Bayinnuoergong tectonic zone (Figure 1b) (Wu et al., 1998; Wang et al., 1994; Zhang et al., 2013). The latter three units are interpreted to belong to north margin of the Alxa block, whereas the former three belong to the CAOBS (Wang et al., 1994, 1994b; Zhang et al., 2013; Zheng et al., 2014) (Figure 1). Together the latter three zones comprise a complete trench-arc-basin system of Late Paleozoic age, with the Wuliji granite in the Zongnaishan-Shalazhashan tectonic zone representing the mature arc of this system, similar to today's Japanese island arc (Feng et al., 2013; Wang et al., 1994, 1994b; Zhang et al., 2013). The Qagan Qulu Ophiolitic Belt is considered to be the suture formed by the closure of the back-arc basin in the Late Paleozoic (Wu and He, 1992, 1993; Wu et al., 1998; Zheng et al., 2014). The zones of the CAOBS are less studied. The Huhetaoergai tectonic zone is argued to be a paleo-volcanic arc developed on oceanic crust preserved when the ocean closed during the Late Silurian-Devonian (Wang et al., 1994) or Permian (Wu et al., 1998). The passive continental margin represented by the Zhusileng tectonic zone and Guaizihu tectonic zone became an active continental margin in the end of the Early Paleozoic and was in the extension during the Carboniferous-Permian (Wang et al., 1994; Wu et al., 1998). The Yagan Fault is considered to be an important boundary separating strata of different affinities. Rocks

in the fault zone are highly fragmented and some ultramafic rocks are present (Wang et al., 1994; Wu et al., 1998) (Figure 1c), but no other ophiolitic components are recognized so far.

2.2 Paleozoic strata in the Huhetaoergai tectonic zone and Zhusileng tectonic zone

In the Huhetaoergai tectonic zone, Middle Ordovician strata are the only Early Paleozoic strata exposed. They are divided into lower, middle and upper parts: neritic intermediate volcanic rocks, clastic rocks and intermediate-acidic volcanic rocks, respectively (BGGP, 1980). Due to faults, the Middle Ordovician strata are not exposed in the Zhusileng tectonic zone (Figure 1). However, it preserves a continuous sedimentary record from Cambrian to Middle Silurian (Wang et al., 1994). Thick carbonates, silicalites and flysch reflect a passive continental margin environment (Wang et al., 1994; Wu et al., 1998).

Lower Devonian to Lower Carboniferous-lower part of Upper Carboniferous strata are dominated by littoral- neritic volcanic and clastic rocks in the Huhetaoergai tectonic zone. Devonian strata are well developed in the Zhusileng tectonic zone. Its western part mainly consists with neritic clastic rocks and biohermal limestone and its eastern part is composed of unstable neritic volcanic and clastic rocks. In the Wudenghan area, an Early Carboniferous anticline folds grey-green graywacke and feldspathic graywacke with grey-green andesitic basalts (BGGP, 1981a). Lower Carboniferous strata including neritic volcanic and clastic rocks also occur in the Zhusileng tectonic zone. Permian strata are widely distributed in both Huhetaoergai tectonic zone and Zhusileng tectonic zone (Figure 1c) (BGGP, 1980, 1981a; BGNHAR, 1982a). Lower Permian strata in the Huhetaoergai tectonic zone comprise clastic rocks in the lower part and volcanic rocks with graywacke in the upper part, indicating an unstable neritic environment (BGGP, 1980, 1981a). It coincides with the abundant Lower Permian Shuangbaotang Formation in the Zhusileng tectonic zone (BGGP, 1981a; BGNHAR, 1982a). The lower part of Shuangbaotang Formation (previously the Maihanhada Formation)

represents a normal neritic-coastal sedimentary environment and consists of clastic rocks and carbonates (BGMRIMAR, 1991; Li et al., 1996). Its upper part (previously the Aqide Formation) comprises neritic clastic rocks and eruptive intermediate-acidic volcanic rocks in an oceanic basin (BGMRIMAR, 1991; Li et al., 1996). In addition, the Upper Permian Haersuhai Formation is exposed in both the Huhetaoergai tectonic zone and the Zhusileng tectonic zone (BGGP, 1980, 1981a; BGNHAR, 1982a) and represents a flysch that formed in sequentially coastal, neritic and marine-terrestrial environments. The lower part of Haersuhai Formation comprises coarse clastic rocks, carbonates and intermediate-acidic volcanic rocks and its upper part is composed of thick fine clastic rocks and pelitic rocks with a few limestones.

3. Sample descriptions

Wudenghan pluton. The Wudenghan pluton in the Zhusileng tectonic zone covers about 120 km² and was emplaced in the core of a Late Carboniferous anticline (Figure 1c). Plutonic lithofacies are not well developed and consist mainly of biotite granodiorite and biotite monzogranite. As the whole pluton is highly weathered, especially the granodiorite, only the biotite monzogranite was studied. The monzogranite is medium-grained (3-5 mm). The modal mineralogy includes plagioclase (25-35 %, mostly altered to sericite and partly altered to epidote), perthitic feldspar (25-40 %, partly altered to clay minerals), quartz (30-40 %), mafic minerals (8-15 %, mainly biotite, altered to chlorite) and minor muscovite. Zircon, monazite, apatite, hematite and magnetite are the main accessory minerals.

Huhetaoergai pluton. The Huhetaoergai pluton is in the Huhetaoergai tectonic zone and represents a batholith covering about 80 km². In the southeast, it intrudes Mesoproterozoic sandstone (Figure 1c). Banded structure and weakly developed gneissic fabric are present. The banded structure comprises 2 to 3 cm wide light and dark parallel laminations. Generally,

coarse quartz, plagioclase and feldspar comprise the light bands and fine biotite and plagioclase form the dark bands. Most minerals are aligned parallel to the bands. Elongate marble xenoliths parallel to the gneissic schistosity or laminations are also present (BGGP, 1980).

The pluton is heterogeneous with variable composition and irregular lithofacies. However, it is predominantly fresh red biotite granite and grey biotite granodiorite. The biotite granite is the Neoproterozoic in age and emplaced by the biotite granodiorite (Zhang, 2013). In this study, we mainly focus on the biotite granodiorite. It has a porphyritic-like texture. Most phenocrysts (8-24 mm) are euhedral-subhedral plagioclase (25-35 %). The matrix (<4 mm) includes plagioclase (35-45 %, partly altered to sericite and epidote), quartz (20-35 %, some recrystallization has occurred), biotite (15-20 %, partly altered to chlorite) and perthitic feldspar (10-15 %). Zircon, titanite, apatite, hematite and magnetite are the main accessory minerals.

Zhuxiaobuguhe pluton. The Zhuxiaobuguhe pluton is to the west of the Huhetaoergai pluton in the Huhetaoergai tectonic zone (Figure 1c) and is larger than the Huhetaoergai pluton. Its northern part intrudes Middle Ordovician dacite and rhyolite. No clear evidence for recrystallization or thermal metamorphism is found in the wallrock, but the pluton has a well-developed foliation. Plutonic lithofacies are not well developed. Marble xenoliths have similar structures to those in the Huhetaoergai pluton (BGGP, 1980).

The Zhuxiaobuguhe pluton consists mainly of porphyritic hornblende-biotite granodiorite. The phenocrysts (mostly 4-10 mm, some can reach 20 mm) include euhedral-subhedral plagioclase (10-30 %). The matrix (0.1-3 mm) includes plagioclase (40-50 %, mostly altered to sericite and epidote), quartz (15-25 %, with pronounced abundant recrystallization), hornblende (5-15 %, some altered to uraltite and actinolite), biotite (10 %, mostly altered to

chlorite) and perthitic feldspar (<5 %). Large subhedral titanite (about 1 mm) is abundant. Zircon, apatite, hematite and magnetite also occur as accessory minerals.

4. Analytical results

See “Supplementary Document 1” and Zhang et al. (2015) for a description of the analytical methods. For each pluton, samples representing the batholith's principal compositional phases were selected for major and trace element analyses. The results are given in “Supplementary Document, Table 1”. After geochemical analyses, a representative sample of each pluton was selected for geochronology. One sample (AB10-48) was dated by LA-ICP-MS and two samples (W08-170 and AB10-30) by SIMS. Analytical results are shown in “Supplementary Documents, Tables 2 and 3”, respectively. Integrating crystal shapes, textures, and high Th/U ratios of the zircons, the majority of grains are presumed to be magmatic (Belousova et al., 2002; Corfu et al., 2003). A few analyses showing apparently old (AB10-48-31, n4158-02 and 04) or discordant (n4159-08) ages, analyses on cracks (n4159-05 and 15) or inclusions (n4159-14), or partly off the crystal (n4158-13, n4159-02, 03, 04 and 10), are excluded from the age calculations. The isotopic results are summarized in “Supplementary Document, Table 4”. Determination of 'initial' data is based on the geochronology. Nd model ages have been calculated with $f_{\text{Sm/Nd}}$ of -0.2 to -0.6.

4.1 Wudenghan pluton

Major and trace elements

Wudenghan biotite monzogranite has high SiO₂ contents (>75 wt%) and low Al₂O₃ (12.27-13.09 wt%), CaO (0.44-0.67 wt%) and MgO (0.09-0.21 wt%) with low Mg# [0.14-0.27; $\text{Mg}^{2+}/(\text{Mg}^{2+}+\text{Fe}^{2+})$, Irving and Green, 1976]. All samples are metaluminous (A/NCK <1.1) (Figure 2a) and ferroan [$\text{Fe}\# = \text{FeO}^{\text{T}}/(\text{FeO}^{\text{T}}+\text{MgO})=0.88-0.94$] (after Frost et al., 2001). The

total alkali content ($\text{Na}_2\text{O}+\text{K}_2\text{O}$) is 8.23 wt% on average, and all samples contain more K_2O than Na_2O ($\text{Na}_2\text{O}/\text{K}_2\text{O}=0.71\text{-}0.78$). Using the classification of Irvine and Baragar (1971), the Wudenghan monzogranite represents a high-K calc-alkaline series (Figure 2b). Chondrite-normalized REE patterns (Figure 3a) (Sun and McDonough, 1989) show enrichment of LREE [$(\text{La}/\text{Yb})_{\text{N}}=4.5\text{-}6.3$] and strongly negative Eu anomalies ($\delta\text{Eu}=0.27\text{-}0.31$). N-MORB-normalized trace element patterns (Figure 3b) (Sun and McDonough, 1989) are enriched in LREE, Rb, U and K, and depleted in Ba, Nb, Ti and Zr.

Geochronology

Zircon grains from this granite (AB10-30) are euhedral, clear to pink and transparent with AR= 1:1 to 3:1. Some grains have inclusions. In CL images, most show oscillatory zoning or broad zones (Figure 5a). One core was found (n4159-03). Th/U ratios=0.38-0.59. Seven analyses were concordant and combined to yield a concordia age of 383 ± 3 Ma (MSWD=2.3) (Figure 6a), which is interpreted as the crystallization age for sample AB10-30.

Nd and Sr isotopes

The Wudenghan monzogranite has low initial $^{87}\text{Sr}/^{86}\text{Sr}$ of 0.704719 to 0.706113 and slightly negative $\varepsilon_{\text{Nd}}(t)$ of -0.2 to -0.1. They indicate modern to Proterozoic-age components when intrusive age is plotted against $\varepsilon_{\text{Nd}}(t)$ (Figure 4a). Single-stage model ages (T_{DMI}) are 1097-1123 Ma.

4.2 Huhetaoergai pluton

Major and trace elements

The Huhetaoergai biotite granodiorite has relatively lower SiO_2 (64.42-71.37 wt%) and TiO_2 (0.43-0.67 wt%) but much higher Al_2O_3 (14.88-17.95 wt%), CaO (2.87-4.20 wt%) and MgO (1.24-1.78 wt%) with high Mg# (0.49-0.53). $\text{Na}_2\text{O}/\text{K}_2\text{O}$ ratios for the granodiorite are 1.9 on

average with lower total alkali content (5.52-6.34 wt%) than the Huhetaoergai granodiorite. It is metaluminous to peraluminous ($A/NCK=1.07-1.12$) (Shand, 1943; Zen, 1988) (Figure 2a) and magnesian ($Fe\#=0.69-0.71$), and belongs to the medium-K calc-alkaline series (Figure 2b). On Na_2O+K_2O vs. SiO_2 diagram (Figure 2c), the granite plots in the sub-alkaline field. Chondrite-normalized REE patterns (Figure 3c) (Sun and McDonough, 1989) show enrichment of LREE [$(La/Yb)_N=4.2-11.9$] and positive to slightly negative Eu anomalies ($\delta Eu=0.91-1.25$). N-MORB-normalized trace element patterns (Figure 3d) (Sun and McDonough, 1989) show that the samples are enriched in Rb, K, Pb and Sr, and depleted in Nb and P.

Geochronology

Zircon grains from this granite (AB10-48) are euhedral, clear to pink and transparent. Aspect ratios (AR) range from 1:1 to 5:1. Some have inclusions and inherited cores. Most analyses represent idiomorphic grains with oscillatory zoning throughout the crystal (Figure 5b). One core was found and a slightly older age was obtained (AB10-48-31). Twenty-eight analyses combine to yield a concordia age of 356 ± 3 Ma (MSWD=1.3) (Figure 6b), which is interpreted as the crystallization age for sample AB10-48.

4.3 Zhuxiaobuguhe pluton

Major and trace elements

Major elements of the Zhuxiaobuguhe hornblende-biotite granodiorite have similar characteristics to the Huhetaoergai biotite granodiorite. SiO_2 contents range from 62.96 to 69.95 wt%, Al_2O_3 from 15.18 to 17.23 wt%, MgO from 1.29 to 2.31 wt% with high $Mg\#$ (0.49-0.53), TiO_2 (0.47-0.78 wt%) and CaO (2.66-5.46 wt%). All samples are metaluminous and metaluminous ($A/NCK=0.94-1.05$) (Figure 2a) and magnesian ($Fe\#=0.68-0.72$). The

total alkali content is between 5.37 and 6.54 wt%, and all samples contain more Na₂O than K₂O (Na₂O/K₂O=2.11-3.13). Geochemically, the Zhuxiaobuguhe granodiorite represents a medium-K calc-alkaline series (Figures 2b, c). Chondrite-normalized REE patterns (Figure 3e) (Sun and McDonough, 1989) show higher enrichment of LREE [(La/Yb)_N=9.9-22.3] and weakly negative Eu anomalies (δEu=0.77-0.96). N-MORB-normalized trace element patterns (Figure 3f) (Sun and McDonough, 1989) show enrichments of LREE, Rb, K and Nd, and depletions in Ba, Nb, Ti and P.

Geochronology

Zircon grains from this granite (W08-170) are euhedral, clear to pink and transparent. AR=5:1. Some grains have inclusions. Most crystals have broad oscillatory zoning. Neither zircon cores nor old inherited ages were obtained (Figure 5c). Th/U=0.74-1.73. Eleven analyses combine to yield a concordia age of 286±2 Ma (MSWD=0.95) (Figure 6c), which is interpreted as the crystallization age for sample W08-170.

Nd and Sr isotopes

The Zhuxiaobuguhe granodiorite has initial ⁸⁷Sr/⁸⁶Sr of 0.708370 to 0.708462 and negative ε_{Nd}(t) of -2.0 to -1.1 (Table 2). They indicate modern to Proterozoic-age components (Figure 4a). T_{DMI} = 1000-1013 Ma.

5. Discussion

5.1 Genesis of Late Paleozoic granites in the northern part of northern Alxa region

5.1.1 Late Devonian Wudenghan pluton

This pluton was previously considered to be Late Paleozoic in age (BGGP, 1981a). Our new SIMS zircon U-Pb age from biotite monzogranite (AB10-30) is 383 ± 3 Ma. From the

mineralogical and geochemical characteristics, such as the absence of alkaline minerals, high SiO_2 contents (>75 wt%) and K_2O (>4.5 wt%), low $\text{Na}_2\text{O}/\text{K}_2\text{O}$ and Ga/Al ratios, low MgO (<0.3 wt%), etc., the Wudenghan monzogranite is interpreted to represent a highly fractionated high-K calc-alkaline rock (e.g. Sylvester, 1989; Whalen et al., 1987). It is metaluminous, with $\text{A}/\text{CNK}<1.1$ and $\text{A}/\text{NK}>1$, which implies the Wudenghan granite is not S-type, but I-type. The low Fe/Mg , Ga/Al , and contents of Zr, Nb, Ga, Y, Ce, Sr and CaO indicate that it is not an alkaline granite (A-type granite) but a fractionated felsic granite (Whalen et al., 1987). This is also supported by the striking depletions in Ba, Nb, Eu and Ti (Figure 3b). According to Wu et al. (2003b), negative Nb-Ti anomalies are related to fractionation of Ti-bearing phases (ilmenite, titanite, etc.), negative P anomalies result from apatite separation and strongly negative Eu anomalies require extensive fractionation of plagioclase and/or K-feldspar. The fractionation of K-feldspar would produce negative Eu-Ba anomalies. Therefore, the Wudenghan granite can be described as evolved I-type granite, possibly representing fractionated melts from a parental calc-alkaline magma.

Calc-alkaline, I-type granitoids are usually generated by partial melting of mafic to intermediate igneous sources, or by advanced assimilation fractional crystallization of mantle-derived basaltic parental magmas, or by mixing of mantle-derived magmas with crustal-derived materials (e.g. De Paolo, 1981; Li et al., 2007; Sisson et al., 2005; Hildreth and Moorbath, 1988). The low initial Sr isotopic ratios (0.704719 to 0.706113) and slightly negative $\varepsilon_{\text{Nd}}(t)$ values (-0.2 to -0.1) of the Wudenghan pluton indicates probably the crust-mantle interactions. Through the study of the Zaya highly fractionated I-type granitoids, Zhu et al. (2009) pointed out mantle wedge basaltic melts and the induced crustal melts can mix to form hybrid melts parental to the highly fractionated I-type granitoids. However, plutons formed via mixing between two end-magmas with distinctive chemical and isotopic compositions should significantly varied chemical and isotopic compositions. The relatively

narrow range of isotopic data and the chemical compositions suggests that the Wudenghan pluton cannot be generated by mixing between intracrustal mafic igneous rock-derived magmas and mantle-derived magmas. Based on the criteria employed by Watson and Harrison (1983), zircon saturation temperature (T_{Zr}) calculated for the Wudenghan pluton yields values of 766–779 °C (average 772°C), which is considered as the maximum initial magma temperatures at the source (Miller et al., 2003). It is more similar to the granites involving mantle-derived material in their generation [e.g. the Fogang granite in South China (728–840°C) (Li et al., 2007) and the Zaya granite in Tibet (789–821°C) (Zhu et al., 2009)], rather than the crust-derived granites [e.g. the Miocene leucogranite in North Himalaya (667–769°C) (Zhang et al., 2004)]. In addition, the Wudenghan pluton is defined as cold granites ($T_{Zr} < 800^{\circ}\text{C}$), which appear to form at temperatures too low for dehydration melting involving biotite or hornblende and probably require fluid influx (Miller et al., 2003). According to Miller et al (2003), fluids could ascend into the zone of melting as a consequence of dehydrations of underthrust sedimentary rocks or of hydrous mafic silicates in ultramafic-mafic rocks. The intermediate-mafic rocks reported in the Devonian strata in this area likely could release adequate fluids during cooling in the continental crust. Thus, the Wudenghan pluton, having Sm-Nd T_{DM1} ages = ca. 1110 Ma, was derived from Mesoproterozoic mafic-intermediate igneous protolith with minor addition of mantle-derived magmas. The new mantle input likely played a more important role as heat source for the formation of the granites (Li et al., 2007).

5.1.2 Early Carboniferous Huhetaoergai pluton

The pluton was previously regarded as being Early Paleozoic (BGGP, 1980) or late Neoproterozoic (689 Ma, TIMS zircon U-Pb, Wang et al., 1994) in age. Our new LA-ICP-

MS zircon U-Pb age (AB10-48) is 356 ± 3 Ma. It represents the age of the Huhetaoergai biotite granodiorite pluton.

High $\text{Na}_2\text{O}/\text{K}_2\text{O}$ ratio and high Mg# indicate the Huhetaoergai granodiorite is an unfractionated calc-alkaline rock (Whalen et al., 1987). Smaller geochemical anomalies (Figure 3) also suggest that fractionation was not extensive. Separation of feldspar in the Huhetaoergai granodiorite appears minor, as suggested by positive to slightly negative Eu anomalies. Positive Rb and Pb anomalies indicate the addition of continental crustal component. The slightly high Mg# (0.51 on average) may reflect a significant input from mantle-derived magma (Kelemen, 1995). But no mafic enclaves occur in the Huhetaoergai pluton. So a crust and mantle mixing model is not favored for the origin of the magma. T_{Zr} calculated for the Huhetaoergai pluton with inherited zircons is $737\text{--}779$ °C (average 754 °C). As no Early Carboniferous mafic rocks were reported in the Huhetaoergai area until now, the origin of the water-rich fluid in the source is problematic. One reasonable explanation is the contribution of subduction-related fluid. Thus, the magma of the Huhetaoergai pluton could be interpreted to be derived from a lower continental crust which has been influenced by inputs of a subduction-related fluid.

5.1.3 Early Permian Zhuxiaobuguhe pluton

Zhuxiaobuguhe and Huhetaoergai plutons were previously regarded as a single pluton separated by Upper Jurassic and Quaternary strata (BGGP, 1980; Wang et al., 1994). SIMS zircon U-Pb dating (W08-170) gives an age of 286 ± 2 Ma. As no significant compositional diversity occurs in the Zhuxiaobuguhe pluton, the age of this sample represents the age of the entire Zhuxiaobuguhe pluton. Therefore, the Zhuxiaobuguhe pluton was emplaced at 286 ± 2 Ma and is not contiguous with the Huhetaoergai pluton.

Similar to the Huhetaoergai granodiorite, the Zhuxiaobuguhe granodiorite is an unfractionated calc-alkaline rock (Whalen et al., 1987). Slightly negative initial ϵ_{Nd} (-2.0 to -1.1) and low initial $^{87}\text{Sr}/^{86}\text{Sr}$ (0.708370-0.708462) indicate of probably the crust-mantle interactions. Similar to the origin of the Huhetaoergai pluton, the Wudenghan pluton is most likely from partial melting of mafic to intermediate igneous sources. The mantle signature is easily explained by the basal oceanic crust of the paleo-volcanic arc in the Huhetaoergai tectonic zone. T_{Zr} of the Zhuxiaobuguhe pluton is 777-805 °C (average 790°C), which is higher than either Late Devonian Wudenghan pluton or Early Carboniferous Huhetaoergai pluton, but still lower than 800 °C. Heavy coeval volcanic eruption occurred in the Huhetaoergai area (Wang et al., 1994), so cooling of the intermediate-mafic rocks could provide fluids needed for the magma melting.

It is notable that the Yagan pluton of similar age (283 ± 2 Ma, SIMS zircon U-Pb) also occurs in the Huhetaoergai tectonic zone (Figure 1) (Zheng et al., 2013). The Yagan monzogranite represents unfractionated metaluminous to peraluminous high-K calc-alkaline granodiorite melt. It has higher SiO_2 (66.96-70.71 wt%) and total alkali contents ($\text{Na}_2\text{O} + \text{K}_2\text{O} = 7.24\text{-}9.19$ wt%), with lower TiO_2 (0.21-0.29 wt%), CaO (2.07-2.43wt%) and $\text{Na}_2\text{O}/\text{K}_2\text{O}$ (1.04-1.34). The chondrite-normalized REE patterns show less enrichment of LREE [$(\text{La}/\text{Yb})_{\text{N}} = 5.0\text{-}11.0$] and more negative Eu anomalies ($\delta\text{Eu} = 0.59\text{-}0.77$). Compared to the Zhuxiaobuguhe granodiorite, the Yagan monzogranite has lower initial $\epsilon_{\text{Nd}}(t)$, similar initial $^{87}\text{Sr}/^{86}\text{Sr}$ (Figure 4b, Table 5) and an older T_{DMI} age (1162-1821 Ma) (Zheng et al., 2013). Consistent with the Zhuxiaobuguhe pluton, T_{Zr} of the Yagan pluton is also lower than 800 °C (743-768 °C, average 754°C) with inherited zircon. Therefore, Early Permian granites in the Huhetaoergai tectonic zone were generated from partial melting of the basal oceanic crust of the paleo-volcanic arc.

6. Tectonic implications

6.1 Wudenghan pluton

All samples from the Wudenghan monzogranite have post-collisional and highly fractionated calc-alkaline characteristics (Pearce, 1996; Whalen et al., 1987). Almost all the highly fractionated granites resemble to each other, no matter whether they form in arc, collision or rift zones. They just converge in either major or trace element geochemistry. It is very difficult to use such rock types to infer tectonic environments. Instead, high-K calc-alkaline series commonly post-date the ending of subduction by as much as 30-50 Ma (Bonin, 1990). The Wudenghan pluton also has arc-related characteristics, such as enriched LREE coupled with negative Nb-Ta-Ti anomalies. This arc-like geochemical signature would be inherited from the source that was probably derived from subducted materials. The Wudenghan pluton intrudes the Zhusileng tectonic zone (Figure 1) which represents the passive continental margin from Cambrian to Middle Silurian (Wang et al., 1994; Wu et al., 1998). Wang et al. (1994) thought the ocean between the Zhusileng tectonic zone and Huhetaoergai tectonic zone closed during Late Silurian-Devonian according to the marine molasse in the Middle Devonian Wotuoshan Formation in the Zhusileng tectonic zone. The lower part of the Wotuoshan Formation is composed of grey conglomerate and pebbly coarse sandstone, the middle part includes varicolored calcic feldspathic quartz sandstone, calcic tuffaceous sandstone and siltstone with thin-layered limestone, and the upper part is grayish brown middle-coarse feldspathic quartz sandstone. But the most debatable question is that the Wotuoshan Formation doesn't define as the classic molasse. It's difficult to conclude the oceanic basin between the Huhetaoergai tectonic zone and Zhusileng tectonic zone closed before Late Devonian based on this "molasse". In this case, either the Late Devonian Wudenghan pluton represents a post-collisional granite or volcanic arc granite is crucial to constrain the tectonic environment of Devonian Zhusileng tectonic zone. Wu et al. (1998)

interpreted that Devonian deposition in the Zhusileng tectonic zone implies stable littoral environment. It seems that the Wudenghan pluton is unlikely to reflect volcanic arc environment. Therefore, the Wudenghan pluton most likely represents a post-collisional granite. Thus, it provides new evidence that the basin between the Zhusileng tectonic zone and Huhetaoergai tectonic zone was closed before Late Devonian.

In addition, Devonian post-collisional granites are widely reported in other areas in the CAOB. In the Altai-Sayan Fold Belt which is the northwestern part of the CAOB between the Siberian Craton and the Kazakhstan Microcontinent, Silurian-Early Devonian (400-425 Ma) granitoids formed during the Andean-type collision and Middle-Late Devonian (360-395 Ma) granitoids were the result of the closure of the Paleo-Asian Ocean, in particular the continental collision between the Altai-Mongolia and Siberia (Glorie et al., 2011). The study of Paleozoic synorogenic plutons in the CAOB, Northwest China, indicates that the time of subduction and accretion mainly occurred in Late Ordovician-Early Devonian (ca. 460-410 Ma) (Wang et al., 2006). In the Late Silurian (ca. 420 Ma), the oceanic basin bounding the terranes of the Southern Mongolia Microcontinent began to converge (Helo et al., 2006; Yarmolyuk et al., 2008). In the middle part of the eastern Beishan area (between the Xiaohuangshan and Niujuanzi-Xichangjing ophiolitic belts), Early Devonian granites show post-collisional characteristics, which is resulted from the closure of the back-arc basin (represented by the Niujuanzi-Xichangjing ophiolitic belt) (Zhang, 2013).

6.2 Huhetaoergai pluton

The Huhetaoergai granodiorite's trace element compositions define it as volcanic arc granite (Pearce, 1996; Pearce et al., 1984). It's consistent with the sedimentary record in the Huhetaoergai tectonic zone (BGGP, 1980) which also reflects a volcanic arc environment during Early Carboniferous. The Lower Carboniferous strata with continuous deposition of

391 acidic volcanic rocks in the lower part and clastic rocks in the upper part represent a littoral-
392 neritic depositional setting. It is only exposed in the extreme north near Mongolia. The lower
393 part of Upper Carboniferous strata, contacted with the Lower Carboniferous strata by fault,
394 also represents a littoral environment. From bottom to top, there are grey-yellowish green
395 fine-grained arkosic graywacke interbedded with intermediate volcanic rocks, intermediate-
396 acidic volcanic rocks and quartz sandstone. Fault contact is shown between the bottom and
397 middle layers. In addition, the upper part of the Upper Carboniferous strata has not been
398 discovered in the Huhetaoergai tectonic zone until now. Therefore, the geochemistry of the
399 Huhetaoergai granodiorite combined with the sedimentary history indicates that the
400 Huhetaoergai area could be in a volcanic arc setting during Early Carboniferous and the
401 oceanic basin was still open at that time. However, the study of the Wudenghan pluton
402 already shows that the basin between the Zhusileng tectonic zone and the Huhetaoergai
403 tectonic zone had been closed before Devonian. Whereas, the ocean between the
404 Huhetaoergai tectonic zone and the Mongolia terrane in the north could be still open during
405 Early Carboniferous.

406 The Huhetaoergai tectonic zone extends to the northeast into Mongolia as the Hashaat
407 Terrane, which is interpreted as fragments of island arcs in the Palaoasian ocean system
408 (Badarch et al., 2002 and references therein). Besides, it occurs between the back-arc basin
409 represented by the Atasbogad Terrane and the cratonal block represented by the Tsagaan Uul
410 Terrane of southern Mongolia. The Jindouaobao gneiss (Wang et al., 2001) testifies that the
411 Zhusileng tectonic zone is the continuation of the Tsagaan Uul Terrane and they may
412 represent a part of South Gobi microcontinent (Badarch et al., 2002). Lamb et al. (2001)
413 points out Devonian strata of southern Mongolia represent components of two arc systems,
414 including a trapped ocean basin that developed into a back-arc basin (e.g. the Atasbogad
415 Terrane, Badarch et al., 2002) and the Carboniferous arc was probably a continuation of the

Devonian arc system and was built in part upon Devonian strata (e.g. the Hashaat Terrane, Badarch et al., 2002). Consist with the study in southern Mongolia, Early Carboniferous Huhetaoergai tectonic zone was in volcanic arc environment. Therefore, the Huhetaoergai pluton represents volcanic arc granite.

6.3 Zhuxiaobuguhe pluton

Early Permian granitoids of the CAOBS typically have post-collisional signatures (Glorie et al., 2011; Han et al., 1997, 1999; Heinhorst et al., 2000; Wang et al., 2009). Trace element compositions of samples from the Zhuxiaobuguhe pluton are consistent with volcanic arc to post-collisional settings (Pearce, 1996; Pearce et al., 1984). Samples from Yagan monzogranite of similar age (283 ± 2 Ma) in the Huhetaoergai tectonic zone are also reported to have both volcanic arc and post-collisional characteristics (Zheng et al., 2013) (Figure 1). Previously, two distinct tectonic environments have been suggested for the Huhetaoergai tectonic zone in the Permian (Wang et al., 1994b; Wu et al., 1998). Wu et al. (1998) argued northward subduction of oceanic crust between the Huhetaoergai tectonic zone and the Zhusileng tectonic zone in the Permian resulted in rifting of the Zhusileng tectonic zone. However, though Wang et al. (1994) agreed that in the Permian the Zhusileng tectonic zone was in a rifting stage, they suggested that this was the result of the southward subduction of oceanic crust represented by the Engger Us Ophiolitic Belt and that the Permian Huhetaoergai -Zhusileng tectonic zones together were involved in rifting. Sedimentary investigations show the Permian strata of the Huhetaoergai tectonic zone and Zhusileng tectonic zone may be correlated. In this case, there should not be an ocean between Huhetaoergai tectonic zone and Zhusileng tectonic zone in the Permian, conflicting with the idea of Wu et al. (1998). Besides, Lamb et al. (2001) points out Permian strata record mainly nonmarine basins and the closing of the ocean basin between southern Mongolia and the

tectonic blocks of China. Consequently we conclude that the Permian Huhetaoergai tectonic zone represents a rifting environment rather than an active margin.

7. Tectonic Model

This study, combined with previous investigations into granite genesis (Zheng et al., 2013) (Table 1) and tectonic evolution (Wang et al., 1994; Wu et al., 1998), allows us to develop a new Late Paleozoic tectonic scenario for the evolution of northern part of the northern Alxa region (Figure 7).

- Neoproterozoic-Middle Silurian: Paleo-Asian Ocean represented probably by the Yagan Fault started to subduct northward from the Middle Ordovician at least and volcanic arc represented by the Huhetaoergai tectonic zone formed on the oceanic basin. The Zhusileng tectonic zone represents a passive continental margin (Wang et al., 1994). Later in the Early Paleozoic, a back-arc basin formed after the Huhetaoergai volcanic arc and began to subduct southward.
- Late Silurian-Devonian: The oceanic basin between the Huhetaoergai tectonic zone and Zhusileng tectonic zone closed before Late Devonian. Founding of the thicken crust happened and resulted in the highly fractionated I-type Wudenghan granite.
- Early Carboniferous: The basin between the Huhetaoergai tectonic zone and the Siberian Plate continued subducting southward. In the beginning of Early Carboniferous, the Western Huhetaolegai granodiorite formed as volcanic arc granite.
- Late Carboniferous: All the ocean closed in the Northern Alxa region.
- Early Permian: The Huhetaoergai-Zhusileng tectonic zones entered into a period of extension allowing the Zhuxiaobuguhe and Yagan plutons to be emplaced.

8. Conclusions

1) The Late Devonian Wudenghan monzogranite is a highly-fractionated calc-alkaline granite with higher initial ϵ_{Nd} (-0.2 to -0.1) and lower initial $^{87}\text{Sr}/^{86}\text{Sr}$ values (0.704719 to 0.706113). It probably was derived from Mesoproterozoic mafic-intermediate igneous protolith with minor addition of mantle-derived magmas and formed in response to the foundering of the thickened crust after the collision between a volcanic arc and the passive margin. The Wudenghan pluton constrained the lower limit of the closure time of the oceanic basin between the Huhetaoergai and Zhusileng tectonic zones.

2) Early Carboniferous Huhetaoergai granodiorite represents a volcanic arc granite. It formed by the partial melting of a lower continental crust which probably has been influenced by inputs of a subduction-related fluid. During Early Carboniferous, the oceanic basin with the Huhetaoergai tectonic zone in the south and the Mongolia terrane in the north still existed.

3) The Early Permian Zhuxiaobuguhe pluton is not part of the Huhetaoergai pluton. It is composed of unfractionated calc-alkaline granodiorite with low initial ϵ_{Nd} (-2.0 to -1.1) and low initial $^{87}\text{Sr}/^{86}\text{Sr}$ values (0.708370 to 0.708462). The magma is derived from partial melting of the basal oceanic crust of the paleo-volcanic arc. The Huhetaoergai tectonic zone entered into the post-collisional extensional stage during Early Permian.

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Figure Captures

Figure 1. (a) The northern Alxa region in China. (b) The northern Alxa region in the Central Asian Orogenic Belt (modified after Jahn et al., 2000b), CAOBB is all white area. (c) Simplified geological map of the northern Alxa region (modified after BGGP, 1979, 1980, 1981a, 1981b; BGIMAR, 1980; BGNHAR, 1976, 1980a, 1980b, 1980c, 1980d, 1982a, 1982b). Six tectonic zones from north to south: HZ- Huhetaoergai tectonic zone, ZZ- Zhusileng tectonic zone, GZ - Guaizihu tectonic zone, ZSZ - Zongnaishan-Shalazhashan tectonic zone, WZ. Wuliji tectonic zone, YBM - Yabulai-Bayinnuoergong tectonic zone.

Figure 2. Major element characteristics of Alxa granites. (a) after Shand (1943); (b) fields from Rickwood (1989); (c) after Irvine and Baragar (1971).

Figure 3. Chondrite-normalized REE patterns (a, c and e) and N-MORB-normalized trace elements patterns (b, d and f) for the Wudenghan monzogranite, Huhetaoergai granodiorite and Zhuxiaobuguhe granodiorite (normalized values after Sun and McDonough, 1989).

Figure 4. Isotopic data. (a) $\epsilon_{Nd}(t)$ versus intrusive age; (b) $\epsilon_{Nd}(t)$ vs $(^{87}Sr/^{86}Sr)_i$ ratios. The lower crust and upper crust fields are from Wu et al. (2003).

Figure 5. Cathodoluminescence (CL) images of zircons from (a) the Wudenghan monzogranite, (b) the Huhetaoergai pluton and (c) the Zhuxiaobuguhe granodiorite.

Figure 6. U-Pb Concordia plot for (a) the Wudenghan monzogranite, (b) the Huhetaoergai granodiorite and (c) the Zhuxiaobuguhe granodiorite. Unfilled symbols excluded from final synthesis.

Figure 7. Figures A-F: Schematic tectonic evolution of the northern Alxa region (based on this work, Zhang et al., 2013 and Zheng et al., 2013) and modified after Wang et al. (1994) and Wu et al. (1998).