**Age and petrogenesis of Mingshui-Shuangjingzi granites from
the northern Beishan area, northwest China, and their
implications for tectonic evolution**

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ABSTRACT

The Mingshui and Shuangjingzi granitic plutons are exposed in the northern Beishan area, in the southern Central Asia Orogenic Belt. U–Pb zircon dating indicates that Mingshui secondary intrusive lithofacies and Shuangjingzi quartz monzodiorite formed at 328 ± 2 Ma and 272 ± 2 Ma, respectively. The former is composed of grey white monzogranites and potassic altered flesh red monzogranites. Geochemistry indicates they are calc-alkaline I-type granites. Shuangjingzi granites are mainly composed of unfractionated calc-alkaline I-type quartz monzodiorite, granodiorite and monzogranite. The Mingshui grey white monzogranites with negative initial ϵ_{Nd} (-2.0 to -1.7) and moderate initial $^{87}\text{Sr}/^{86}\text{Sr}$ values (0.706740 to 0.710092) were probably derived from mixing of the depleted mantle (juvenile) component and the Palaeoproterozoic-Archean crust (or sedimentary) component and represent volcanic arc granites. The Shuangjingzi quartz monzodiorites are most likely derived from mafic to intermediate igneous protolith and represent post-collisional granites. This work, combined with the regional geology, suggests the Palaeo-Asian Ocean closed between 328Ma and 272Ma in the northern Beishan area.

KEYWORDS: Central Asia Orogenic Belt; Beishan; Palaeozoic; granite; post-collisional; geochemistry; geochronology

1 INTRODUCTION

The Central Asia Orogenic Belt (CAOB) is one of the largest accretionary orogens on the Earth and the most important area of Phanerozoic continental growth around the world (Şengör et al., 1993; Jahn et al., 2000a; Khain et al., 2003; Kovalenko et al., 2004; Kröner et al., 2007; Windley et al., 2007; Xiao et al., 2009 and references therein) (Figure 1a). During the evolution of the Paleo-Asian Ocean and its continental margins, the CAOB was largely formed by subduction and accretion of juvenile material from Late Mesoproterozoic to Mesozoic (Şengör et al., 1993; Allen et al., 1995; Windley et al., 2007; Xiao et al., 2007, 2010a; Xiao and Santosh, 2014). The Late Paleozoic CAOB is characterized by tectonic transition and crustal growth with intrusions of voluminous juvenile granitoid intrusions (Şengör et al., 1993; Han et al., 1997; Jahn et al., 2000a, 2000b, 2000c; Chen and Jahn, 2002, 2004; Xiao et al., 2004b, 2010a; Windley et al., 2007; Wilhem et al., 2012).

Figure 1 is about here

The Beishan area, located in the central part of the southern CAOB, is the key tectonic position connecting the South Tianshan suture to the west with the Solonker suture to the east (Xiao et al., 2010b). The Tarim Plate and the Kazakhstan Plate were also supposed to be conjunct there. However, it has been a longstanding matter of debate that which ophiolitic belts represent the final closure of the Paleo-Asian Ocean in the Beishan area (Zuo and He, 1990; Zuo et al., 1991; Ren et al., 2001; Wang et al., 2007; Yang et al., 2010; Tian et al., 2014): Late Paleozoic Hongshishan ophiolitic belt, Paleozoic Mingshui - Shibanjing - Xiaohuangshan ophiolitic belt, Early Paleozoic Hongliuhe- Niujuanzi- Xichangjing ophiolitic belt, or Late Paleozoic Liuyuan - Yin'aoxia Fault (BGGP, 1969a, 1969b; Zuo and He, 1990; Zuo et al., 1991; Ren et al.,

2001; Guo et al., 2006; Yu et al., 2006; Wang et al., 2007; Dai and Tan, 2008; Song et al., 2008, 2015; Zhang and Guo, 2008; Yang et al., 2010; Ao et al., 2012, 2016; Su et al., 2013; Zheng et al., 2013a; Tian et al., 2014) (Figure 1b)? The granitoids, especially its age and genesis are critical for understanding the regional tectonic evolution. Most granitoids are well studied in the south of the Mingshui - Shibanjing - Xiaohuangshan ophiolitic belt (Ao et al., 2016; Feng et al., 2012; Li et al., 2013; Song et al., 2013a; Zhang et al., 2010, 2011, 2012a, b, 2015; Zheng et al., 2013a). However, the plutonic rocks near the Hongshishan ophiolitic belt are mostly dated by Ar-Ar method more than ten years ago (Jiang and Nie, 2006a, b; Nie et al., 2002). Due to the remote environment, tough working conditions and the location near to the boundary of China and Mongolia, few U-Pb geochronological and geochemical studies of the extensively exposed granitoids in the north of the Mingshui - Shibanjing - Xiaohuangshan ophiolitic belt have been reported in this decade, which also hindered the study progress of the tectonic evolution of the southern CAOB. In this study, we present new petrographic, geochronological and geochemical data for Mingshui and Shuangjingzi plutons near the north margin of the Mingshui - Shibanjing - Xiaohuangshan ophiolitic belt and to the south of the Hongshishan ophiolitic belt. Combined with geological background, we attempt to understand their relationship to the two adjacent ophiolitic belts and the closure of Paleo-Asian Ocean. It could further constrain the Late Paleozoic tectonic evolution of the Beishan area within the CAOB.

2 GEOLOGICAL SETTING

The Mingshui - Shibanjing - Xiaohuangshan ophiolitic belt (also called Xingxingxia-Shibanjing ophiolitic mélange, Xiao et al., 2014) is a continuous EW-trending belt that characterized by tectonic slices of ophiolitic rocks including meta-

ultramafic rocks, mylonitic gabbros, meta-basalts and clastic rocks in a matrix of turbidites (Zuo and He, 1990; He et al., 2002; Nie et al., 2002). Blocks of gneisses, schists, migmatites and marbles also occur (Liu and Wang, 1995). This ophiolitic belt was previously regarded as the main early Paleozoic suture in the Beishan area that separated the Tarim Plate and the Kazakhstan Plate because of the totally different strata on both sides of the belt (Zuo and He, 1990; Zuo et al., 1991, 2003; He et al., 1994). But recently, early Carboniferous ophiolites are discovered along this belt (Zheng et al., 2013a). Basalt and gabbro from the Xiaohuangshan ophiolite are dated at 336 ± 4 Ma (weighted average, $n=14$) and 345 ± 14 Ma (weighted average, $n=4$), respectively. Amphibolite facies metamorphism which has been occurred in most ophiolitic rocks in this belt could have been younger than Silurian (Zuo and He, 1990; Zuo et al., 1991, 2003; Xiao et al., 2014).

The Hongshishan ophiolitic belt (also called the Hongshishan-Baiheshan-Pengboshan ophiolitic belt) is located adjacent to the border area between China and Mongolia. It shows EW-trending arc structure and is composed of a series of NW-NE thrusts and NE-NW strike-slip faults (Huang and Jin, 2006a). Marine sedimentary rocks, limestones and cherts, ultramafic and mafic ophiolitic rocks including pillow basalts, and mylonites in high-strain zones occurred (Zuo and He, 1990; Zuo et al., 1991). In places these rocks are tectonically juxtaposed (Xiao et al., 2010b). The largest outcrop is at Hongshishan, which contains EW-trending tectonic blocks of serpentized ultramafic rocks, gabbroic cumulate rocks, gabbros with minor diabase dikes, pillowed and non-pillowed basalts, cherts, and cherty mudstones (Zuo and He, 1990; Zuo et al., 1991). Recent study shows gabbros from the Hongshishan ophiolite were dated at the age of 347 ± 3 Ma (LA-ICP-MS zircon U-Pb, weighted mean age, Wang et al., 2014).

Geochemical data show that some basalts and gabbros have mid-ocean ridge signatures (Wei et al., 2004; Huang and Jin, 2006a; Wang et al., 2014). According to some researchers, the Hongshishan ophiolitic belt might have been the main Late Paleozoic suture which separated the Tarim Plate and the Kazakhstan Plate (Gong et al., 2002, 2003; Huang and Jin, 2006) or the Kazakhstan Plate and the Siberian Plate (Liu and Wang, 1995), or that represented the Palaeo-Tianshan–Junggar Ocean (Su et al., 2011).

The Gongpoquan-Dongqiyishan arc, located between the Mingshui - Shibanjing - Xiaohuangshan and Niujuanzi- Xichangjing ophiolitic belts is regarded as a Silurian arc (Zuo and He, 1990; Zuo et al., 1991; Xiao et al., 2010b). Ordovician, Silurian, Carboniferous and Permian strata were outcropped but no Devonian strata. Silurian Gongpoquan Group is most distributed and represents a series of oceanic volcanic formation (BGGP, 1968a, 1969a, 1969b, 1977a). The basement of the Gongpoquan-Dongqiyishan arc is regarded as oceanic crust (Xiao et al., 2010b) or oceanic crust in the east and continent crust in the west (Zuo and He, 1990). Early Carboniferous Dongqiyishan adakite-like granites ($356\pm3\text{Ma}$) are discovered (Zhang et al., 2012a). It was consistent with the southward flat subduction of oceanic crust represented by the Mingshui - Shibanjing - Xiaohuangshan ophiolitic belt.

The Mingshui-Hanshan tectonic zone, located between the Mingshui - Shibanjing - Xiaohuangshan and Hongshishan ophiolitic belts, is considered as a Mesoproterozoic microcontinent (Zuo and He, 1990). It extends a set of highly metamorphosed rocks (also called the Beishan complex), especially in the Hanshan–Weiboshan area. The metamorphic rocks mainly consist of amphibole schist, biotite-plagioclase gneiss, quartz schist, and migmatite, which are similar to the composition of the Xingxingxia Group in the Middle Tianshan block (Zuo and He, 1990). Diagonal

bedding in middle Ordovician turbidites on the northern flank of the Yuanbaoshan area indicates that there was a palaeocontinent on its southern side (Zuo et al., 1991). A single-grain zircon U-Pb upper intercept age of 2656 ± 146 Ma for a granitic gneiss from the south of the Hongshishan area was reported and argued for the existence of Archean crystalline basement in the Beishan (Sun et al., 2005). Carboniferous felsic volcanic rocks are widely distributed in the Mingshui-Hanshan tectonic zone. Carbonates and clastic sedimentary rocks including terrestrial clastic rocks that are intercalated with cherts, limestones and volcanic rocks also occur (Zuo and He, 1990; Xiao et al., 2010b). Previous studies show that the volcanic rocks have a calc-alkaline signature, indicating a subduction-related environment (Zuo and He, 1990; Liu and Wang, 1995; Wei et al., 2004; Huang and Jin, 2006a). Different opinion thinks that the Mingshui-Hanshan tectonic zone is an intraoceanic arc (called the Heiyingshan arc) that may have been generated by the north-dipping subduction in the middle Devonian and attached to the Gongpoquan-Dongqiyishan arc in the middle- late Carboniferous (Xiao et al., 2010b).

3 SAMPLE DESCRIPTIONS

3.1 Mingshui pluton

The Mingshui pluton lies near the Mingshui - Shibanjing - Xiaohuangshan ophiolitic belt (Figures 1 and 2). It is emplaced into the Lebaquan Group and Lower Carboniferous Baishan Formation. The Lebaquan Group includes a series of regional metamorphic rocks as plagiogneiss, quartzite, mica quartz schist and diopside marble. The original rocks are quartz sandstone, muddy sandstone, sandy shale, mud and limestone. It was thought to be formed in the early Silurian (BGGP, 1969a) or Mesoproterozoic (Feng and Zuo, 1993) or the same strata with Lower Silurian

Gongpoquan Formation (Yang et al., 1997). Recent studies demonstrate that the Lebaquan Complex recorded polyphase deformational events during the middle Paleozoic to the Permian and represents a subduction-accretionary complex formed in a forearc setting (Song et al., 2013; Guo et al., 2014). In the Mingshui area, metamorphic conglomerate and marble are most seen in the Baishan Formation (BGGP, 1969a). The Baishan Formation (original Baishan Group) consists of thick volcanic rocks, phyllite, sandstone and limestone. Its lower part is mainly acid-intermediate volcanic rocks and upper part is phyllite with iron-riched quartzite or sandstone, which represents submarine to neritic regressive sedimentary environment (BGGP, 1969a, 1969c; Yang et al., 1997).

Figure 2 is about here

The Mingshui pluton represents a batholith covering more than 500km² with clear lithofacies. Central lithofacies (7.5km in width) consist of porphyritic-like or large-porphyritic plagiogranites. Marginal lithofacies (1.1km in width) is comprised of gneissic fine granodiorites. Secondary intrusive lithofacies that strike east-west (5km in width) and emplaced into the central lithofacies, is derived from the same magma and composed of porphyritic-like intermediate-fine monzogranites (BGGP, 1969a) (Figure 4a). All three lithofacies are potassic altered, especially the central lithofacies. In this study, the secondary intrusive lithofacies which have the least potassic altered rocks were collected to analyze. Two different color monzogranites found in the secondary intrusive lithofacies: grey white and flesh red. But no obvious boundaries were observed between them. The modal mineralogy of these two types of color samples are similar, including plagioclase (25-35%, part weakly altered to sericite), alkali feldspar (20-30%, mostly perthite and K-feldspar, few microcline), quartz (35-45%), mafic

minerals (8-15%, mainly biotite, part altered to chlorite, epidote, or zoisite) and a few muscovite. Euhedral-subhedral zircon, euhedral-anhedral monazite, euhedral-anhedral apatite, hematite and magnetite are their main accessory minerals. The flesh red samples are potassic altered and have more alkali feldspars than grey white samples.

3.2 Shuangjingzi pluton

Shuangjingzi pluton (Figures 1 and 3) represents is a 400 km² batholith emplaced into the Lebaquan Group and Lower Carboniferous Lvtiaoshan Formation and Baishan Formation. The Lvtiaoshan Formation represents a series of littoral to submarine transgressive graywackes, shales and siliceous rocks covered by the Baishan Formation conformably (BGGP, 1969a, 1969c; Yang et al., 1997).

Figure 3 is about here

Lithofacies are not well developed. The pluton mainly consists of quartz monzodiorite (Figure 4a). The modal mineralogy includes plagioclase (50-55%, most alteration to sericite and saussurite), alkali feldspar (10-20%, mainly perthite and microcline), quartz (5-15%), amphibole (10-25%) and chlorite (10-15%). Zircon, titanite, apatite, hematite, magnetite and ilmenite are the main accessory minerals. There is also minor secondary carbonate mineralization. In addition, granodiorite and monzogranite are also found in the pluton. Granodiorite (BS07-180) is composed of plagioclase (~50%, a few parts alternate to sericite and saussurite), alkali feldspar (~10%, mainly perthite and few microcline), quartz (~25%, vermicular quartz occurs), amphibole (~5%) and chlorite (~8%). Monzogranite (BS08-172) is medium-grained and composed of alkali feldspar (~38%, mainly perthite and microcline), quartz (~27%), plagioclase (~27%, most alteration to sericite and saussurite), biotite (~5%, most alter to chlorite) and very few muscovite. Both granodiorite and monzogranite have similar

main accessory minerals with quartz monzodiorite. No obvious boundaries or contacts among these three types of rocks.

Figure 4 is about here

4 ANALYTICAL RESULTS

See “Supplementary Document 1” for a description of the analytical methods. Results of major and trace element analyses are given in “Supplementary document 2. Table S1” and the values of Sun and McDonough (1989) were used for chondrite and MORB element normalization. The isotopic results of Mingshui samples are summarized in “Supplementary document 3. Table S2”. Nd model ages were calculated with $f_{\text{Sm/Nd}}$ of -0.2 to -0.6. Analytical results of SIMS and LA-ICP-MS zircon U-Pb geochronology are presented in “Supplementary document 4. Table S3” and “Supplementary document 5. Table S4”, respectively. Analyzed crystals include both whole zircon crystals and grain fragments.

4.1 Mingshui pluton

4.1.1 Major and trace elements

The Mingshui grey white monzogranites have high SiO_2 contents (>75 wt%), Al_2O_3 ~13 wt%, MgO from 0.18 to 0.38 wt% with low Mg# (0.24-0.35) [$\text{Mg\#} = \text{Mg}^{2+}/(\text{Mg}^{2+} + \text{Fe}^{2+})$ (Irving and Green, 1976)], TiO_2 (0.11-0.19 wt%) and CaO (0.89-1.94 wt%). All samples are peraluminous ($\text{A/NCK} = 1.07\text{-}1.21$) (Shand, 1943; Zen, 1988) (Figure 4b) and ferroan ($\text{Fe-no.: FeOT}/(\text{FeOT} + \text{MgO}) = 0.82\text{-}0.89$) (Frost et al., 2001). The total alkali content ($\text{Na}_2\text{O} + \text{K}_2\text{O}$) is between 5.93 and 7.26 wt%, and samples contain more K_2O than Na_2O ($\text{Na}_2\text{O}/\text{K}_2\text{O} < 1$). Geochemically, the Mingshui grey white monzogranite represents a medium-K to high-K calc-alkaline series (Figures 4c and d).

Compare to the Mingshui grey white monzogranites, the Mingshui flesh red monzogranites have similar SiO_2 contents (>75 wt%) and Al_2O_3 (~ 13 wt%), but lower MgO (0.09-0.18 wt%), Mg# (0.17-0.26), TiO_2 (0.05-0.08 wt%) and CaO (1.01-1.29 wt%), and higher Na_2O (3.04-3.34 wt%) and K_2O (4.43-4.91 wt%). They are also peraluminous ($\text{A/NCK}=1.00-1.03$) (Shand, 1943; Zen, 1988) (Figure 4b) and ferroan ($\text{Fe-no.}=0.89-0.93$) (Frost et al., 2001). The total alkali content is between 7.66 and 8.05 wt% with $\text{Na}_2\text{O}/\text{K}_2\text{O}<1$. Geochemically, the Mingshui flesh red monzogranites represent high-K calc-alkaline series (Figures 4c and d).

Trace elements analyses show two types of Mingshui monzogranites are slightly different (Table 1). The grey white monzogranites have high Sr (>200 ppm) and Ba (490-2195 ppm) contents and show enrichment of LREE [$(\text{La}/\text{Yb})_{\text{N}}=16.7-32.7$] and weakly negative to positive Eu anomalies ($\delta\text{Eu}=0.77-1.84$) (Figure 5a). The flesh red monzogranites have lower Sr (<200 ppm) and Ba (183-369 ppm) contents and less enrichment of LREE (<10) and more negative Eu anomalies (0.53-0.59). N-MORB-normalized trace element patterns (Figure 5b) of grey white and flesh red monzogranites are similar. Both show enrichments of Rb, K, and U and depletions in Nb, Ti and P. But flesh red monzogranites have depleted Ba and most grey white monzogranites have enriched Ba (Figure 5b).

Figure 5 is about here

Combining thin-sections, major and trace element analyses, and previous studies (BGGP, 1969a), the flesh red monzogranites are more likely represent potassic altered Mingshui grey white monzogranites. Therefore, the Mingshui grey white monzogranites were chosen for Sr-Nd isotopic analyses and zircon dating.

4.1.2 Nd and Sr isotopes

The Mingshui grey white monzogranites have initial $^{87}\text{Sr}/^{86}\text{Sr}$ values of 0.706740 to 0.710092 and negative $\epsilon\text{Nd}(t)$ values of -2.0 to -1.7. $T_{\text{DM2}} = 1125\text{-}1149$ Ma.

4.1.3 Geochronology

Zircon grains from the Mingshui grey white monzogranite (AB09-115) are euhedral, clear, pink to orange and transparent or brown and turbid to opaque. Aspect ratios (AR) range from 2:1 to 5:1. Some have inclusions and inherited cores. In cathodoluminescence (CL), most crystals show oscillatory zoning with homogeneous unzoned cores (Figure 6). Most analyses located on oscillatory zoning and one analysis (number n4157-09) on the core. No older ages were obtained during analyses. Two analyses off the crystals (numbers n4157-06 and 08) and two analyses on cracks (numbers n4157-03 and 15) were excluded. Th/U ratios of the other eight analyses are between 0.26 and 0.55. Integrating crystal shapes, textures and Th/U contents of the zircons, the majority of grains are presumed to be magmatic (Belousova et al., 2002; Corfu et al., 2003). Eleven analyses combine to yield a concordia age of 328 ± 2 Ma, MSWD=1.6 (Figure 7a), which is interpreted as the crystallization age for this sample (AB09-115).

Figure 6 is about here

Figure 7 is about here

4.2 Shuangjingzi pluton

4.2.1 Major and trace elements

The SiO_2 contents of the Shuangjingzi quartz monzodiorites range from 56.13 to 63.13 wt%, Al_2O_3 from 15.39 to 18.00 wt%, MgO from 2.13 to 3.56 wt% with

low Mg# (0.50-0.54), TiO₂ (0.86-1.18 wt%) and CaO (4.12-5.90 wt%). All of the quartz monzodiorites are metaluminous (A/NCK=0.83-0.92) (Figure 4b) and magnesian (Fe^{no.}=0.67-0.71). The total alkali content (Na₂O+K₂O) is 6.82 wt% on average, and all samples contain more Na₂O than K₂O (Na₂O/K₂O>1). They have high-K calc-alkaline characteristics (Figures 4c and d). The Shuangjingzi granodiorite (BS07-180) has higher SiO₂ and much lower CaO, MgO, Fe₂O₃ and TiO₂ (Table 1). Compared to granodiorite, the Shuangjingzi monzogranite (BS07-172) has higher SiO₂ and even lower CaO, MgO, Fe₂O₃ and TiO₂ (Table 1). All three types of granites belong to high-K calc-alkaline metaluminous series.

Chondrite-normalized REE patterns (Figure 5a) of Shuangjingzi granites show enrichment of LREE [(La/Yb)_N=4.2-4.5] and negative Eu anomalies (δEu=0.45–0.97). N-MORB-normalized trace element patterns (Figure 5b) show the samples are enriched in LREE, Rb, U, K, Sr and Nd, and depleted in Ba, Nb, Ti and P. The monzogranite (BS07-172) has stronger Eu anomalies (δEu=0.45) (Figure 5b), Th enrichment and P and Ti depletion. The granodiorite (BS07-180) has relatively lower REE and other trace element contents (Figure 5b).

4.2.2 Geochronology

Zircon grains from the Shuangjingzi quartz monzodiorite (BS07-177) are euhedral, clear to pink and transparent. AR=1:1 to 5:1. Some have inclusions, but no inherited cores are seen in CL nor are older ages obtained during analyses. Most crystals have broad oscillatory zones (Figure 6). Integrating crystal shapes, textures and high Th/U ratios (between 0.52 and 1.72), all grains are presumed to be magmatic (Corfu et al., 2003). Eighteen analyses combine to yield a concordia age of 272±2 Ma,

MSWD=0.49 (Figure 7b), which is interpreted as the crystallization age for this sample (BS07-177).

5 DISCUSSION

5.1 Genesis

5.1.1 Mingshui granites

One sample (AB09-115) from secondary intrusive lithofacies of the Mingshui pluton is 328 ± 2 Ma determined by SIMS zircon U-Pb dating. It is much older than the lower limit age (232 ± 4 Ma, Ar-Ar, feldspar) reported by Jiang and Nie (2006a). However, this Early Carboniferous age hardly represents the age of the entire pluton. It gives a lower limit. The Mingshui pluton could form a little bit earlier than 328 ± 2 Ma.

Granitic rocks have commonly been divided into I-, S-, M and A-types according to their protolith nature (Pitcher, 1982, 1997; Chappell and White, 1974, 2001). The Mingshui monzogranites have very high contents of SiO_2 (>75 wt%) and low abundances of MgO (≤ 0.38 wt%). In the discrimination diagrams for A-type granite of Whalen et al. (1987), the Mingshui grey white monzogranites are plotted in the field of unfractionated I-, S- and M- type granites and flesh red monzogranites straddle the fields of fractionated and unfractionated I-, S- and M- type granites ($10000 \cdot \text{Ga}/\text{Al} < 2.6$, $\text{Zr} + \text{Nb} + \text{Ce} + \text{Y} < 350$ ppm, Whalen et al., 1987). M-type granite is rare. Large volumes of Mingshui granite make it unlikely been M-type granite. I- and S- types of granites are highly studied in the Lachlan Fold Belt (Chappell and White, 1974, 1992, 2001). The Mingshui grey white monzogranites have most $\text{A}/\text{NCK} < 1.1$, most CIPW normative corundum $< 1\%$, $\text{P}_2\text{O}_5 < 0.05$ wt% and negative correlation between SiO_2 and P_2O_5 . These features are considered as important criteria for distinction of I- from S-type

granitoids (Chappell and White, 1992, 2001). So, the Mingshui grey white monzogranites are unlikely to be S-type granite. Instead, they should represent I-type granites. Separation of feldspar and plagioclase of the Mingshui grey white monzogranites appear minor, as suggested by weakly negative to positive Eu and Ba anomalies and no negative Sr anomalies. On the other hand, the Mingshui flesh red monzogranites have lower A/NCK (1.00-1.04), CIPW normative corundum <1% (0.02-0.51%, 0.27% on average), and stronger separation of feldspar and/or plagioclase, as shown by negative Eu and Ba anomalies. In the classification diagram of Sylvester (1989), the Mingshui grey white monzogranites plot in field of highly fractionated calc-alkaline granite. As potassic alteration of the Mingshui flesh red monzogranites have changed their original characteristics, we mainly focused on the gneiss of Mingshui grey white monzogranites.

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. DePaolo, 1981; Hildreth and Moor bath, 1988; Sisson et al., 2005; Li et al., 2007). In addition, $\epsilon\text{Nd}(t)$ is near 0 (-2.0 to -1.1) and T_{DM2} is calculated at ca. 1.1Ga, reflecting Mesoproterozoic-age components, suggesting that both mantle and crustal components play important parts in the genesis. The AFC of newly mantle-derived components model is not favored, because the Mingshui pluton are predominately felsic. According to Jiang and Nie (2006b), two monzogranites (NSJ01-25 and NSJ01-13) from southwest of the Mingshui pluton have $\epsilon\text{Nd}(t)=-8.64$ and -13.87 (calculated by using age 218Ma, biotite, Ar-Ar, from Jiang et al., 2003) (Figure 2). If using 328Ma obtained in this study to recalculate the initial ϵNd ,

we get $\epsilon\text{Nd}(t)=-6.9$ and -12.7 and $\text{TDM}_2=1556\text{-}2038\text{Ma}$. It suggests that the Mingshui pluton is likely generated by mixing of the depleted mantle (juvenile) component and the Palaeoproterozoic-Archean crust (or sedimentary) component, which was required in view of predominant Mesoproterozoic- Paleoproterozoic Nd model ages. Partial melting of mafic protolith may provide an alternative interpretation for the origin of the Mingshui pluton. However, in the Zr versus La and La versus La/V diagrams (Figure 8a, b), the Mingshui grey white monzogranites define a straightly positive correlation line and a curved line, respectively, implying that their compositional variations are mainly controlled by the magma mixing instead of partial melting process (Schiano et al., 2010). Thus, Mingshui I-type granites derived from magma mixing.

Figure 8 is about here

5.1.2 Shuangjingzi pluton

LA-ICP-MS zircon U-Pb dating of a sample (BS07-177) from quartz monzodiorite is $272\pm 2\text{Ma}$. As quartz monzodiorite is the dominant component of the pluton and no inheritance is found in the zircon analysis, the age of this sample (BS07-177) represents the age of the pluton. Therefore, the Shuangjingzi pluton is emplaced in $272\pm 2\text{Ma}$. Due to its remoteness and previous technique, few U-Pb ages were reported in the area.

Shuangjingzi granites are calc-alkaline. In generation discrimination diagrams of Whalen et al. (1987), they plotted in the field of unfractionated M-, I- and S-type granites. This is also confirmed by trace elements analyses. Weakly negative to positive Eu and Sr anomalies show minor separation of feldspar and plagioclase. Slightly negative Nb-Ti and P anomalies indicate few fractionation of Ti-bearing phases (ilmenite, titanite, etc.) and apatite (Wu et al., 2003). Large volumes of

Shuangjingzi granites and a few mafic xenoliths found in the pluton make it unlikely been M-type granite. The Shuangjingzi granites have high sodium ($>3.2\%$), $A/NCK < 1.1$, CIPW normative corundum $< 1\%$ and decreasing P_2O_5 and increasing Pb with increasing SiO_2 . So the Shuangjingzi granite is not S-type but belong to I-type (Chappell and White, 1992, 2001).

Shuangjingzi granites have much lower SiO_2 than Mingshui grey white monzogranites. They are predominately intermediate rocks and have a wide range of chemical compositions. Most have $Na_2O/K_2O > 1$. Experimental studies suggest that Na-rich melts with intermediate to silicic compositions may be produced by about 20–40% dehydration melting of basaltic amphibolites at 1050–1100°C (Rushmer, 1991; Rapp, 1995; Rapp and Watson, 1995). In a molar $Al_2O_3/(MgO+FeOT)$ versus molar $CaO/(MgO+FeOT)$ diagram (Figure 8c, Altherr et al., 2000), most Shuangjingzi granites (I-type) plot in the field of partial melts from basalt-derived sources. Therefore, the Shuangjingzi pluton can be interpreted to be from partial melting of basaltic sources.

5.2 Tectonic implications

Figure 9 is about here

Early Carboniferous

The geochemical and isotopic data document both mantle and continental crust were involved in the genesis of the Mingshui pluton. The Mingshui grey white samples have mainly volcanic arc characteristics (Figure 9; Harris et al., 1986; Pearce et al., 1984; Pearce, 1996).

Volcanism is well developed during Early Carboniferous in the Mingshui-Hanshan tectonic zone. “Lower Carboniferous” Baishan Formation consists of intermediate rocks and interbedded by abundant continental detrital sediments and

turbidite and silicalite. It was regarded as representing a continental slope environment (BGGP, 1969a; Zuo and He, 1990) or a continental arc environment (Huang and Jin, 2006b). Recent study shows a Baishan Formation tuff sample from the Hongshishan area was dated at the age of $315 \pm 3\text{Ma}$ (LA-ICP-MS, zircon U-Pb), which belong to the Late Carboniferous (Lu et al., 2013).

Moreover, the ocean represented by the Hongshishan ophiolitic belt was open in the Early Carboniferous ($347 \pm 3\text{Ma}$) (Wang et al., 2014). According to Huang and Jin (2006a), the ocean represented by the Hongshishan ophiolitic belt may subduct southwards and generated the extensive volcanic sedimentary rocks of the Baishan Formation, forming the Mingshui-Hanshan arc-accretionary complex to the south during Late Carboniferous to earliest Early Permian. However, Zuo and He (1990) thought the northern Beishan area (north of the Mingshui-Shibanjing-Xiaohuangshan ophiolitic belt) represents an intracontinental rift environment during Carboniferous. Extension facilitated upwelling and decompression melting of the mantle asthenosphere can produce mafic magmas and then provided enough heat inducing crustal anatexis to form the granitic magmatism (e.g. Mingshui monzogranites). Through the study of the Hongshishan ophiolite and combining with previous studies, Wang et al. (2014) proposed that the Hongshishan ophiolite represented an embryonic ocean (e.g. Rea Sea) crust which is formed in a transition tectonic setting from continental rift to ocean during Early Carboniferous. Moreover, alkaline to peralkaline granites are more likely produced related to the embryonic ocean rather than medium-K to high-K calc-alkaline Mingshui monzogranites. Whereas, the ocean represented by Mingshui-Xiaohuangshan ophiolitic belt still existed during the early Carboniferous in the Xiaohuangshan area ($336 \pm 4\text{Ma}$) (Zhang et al., 2013) and in the Jijitaizi area ($321 \pm 4\text{Ma}$) (Li et al., 2012).

Thus, it is more likely that the Mingshui pluton formed in a continental arc setting, which is the product of northward subduction of the ocean represented by the Mingshui-Xiaohuangshan ophiolitic belt instead of the product formed related to the embryonic ocean represented by the Hongshishan ophiolitic belt. However, further studies on the subduction direction need to be paid more attention.

Early Permian

Geochemistry shows Early Permian Shuangjingzi granite has both volcanic arc and post-collisional characteristics (Figure 9; Harris et al., 1986; Pearce, 1996; Pearce et al., 1984). Trace elements analyses also show arc-related characteristics, such as enriched LREE coupled with negative Nb-Ta-Ti anomalies. However, it is well-known that this arc-like geochemical signature could be inherited from a source derived from subducted materials within the mantle (Castro et al., 2010, 2013; Hacker et al., 2011). The Shuangjingzi pluton locates in the core of one anticlinorium in the Mingshui-Hanshan tectonic zone. The direction of primary flow structure consists with EW extending of the pluton and regional strata striking (BGGP, 1969c; Zuo and He, 1990). However, no deformation or metamorphism occurs in the Shuangjingzi pluton. In addition, no contemporaneous volcanism was found as no Permian strata exposed in the Mingshui-Hanshan tectonic zone. So the Shuangjingzi pluton was unlikely formed in the volcanic arc environment. Instead, it indicates the post-collisional stage. Besides, widely distributed Permian granites in the Beishan area (Zhang et al., 2012b, 2015; Zhang, 2013) also indicate Permian Beishan was under extension (Zuo and He, 1990; Zhao et al., 2006; Song et al., 2016). In the CAOB, Permian is well-known as a post-collisional transitional period (Han et al., 1997; Jahn et al., 2004; Xiao et al., 2004a). Early Permian granitoids of the CAOB typically have post-collisional signatures (Han et

al., 1997, 1999; Heinhorst et al., 2000; Wang et al., 2009; Yu et al., 2009; Glorie et al., 2011; Zhang et al., 2015).

Therefore, based on geochronology, geochemical characteristics and regional geology, the Early Permian Shuangjingzi granites are interpreted as post-collisional granites. The Palaeo-Asian Ocean closed between 328Ma and 272Ma in the northern Beishan area.

6 CONCLUSIONS

1) Relatively fresh Mingshui grey white monzogranites are unfractionated I-type granites with calc-alkaline characteristics. They are Early Carboniferous in age with negative initial ϵ_{Nd} (-2.0 to -1.7) and moderate initial $^{87}\text{Sr}/^{86}\text{Sr}$ values (0.706740 to 0.710092) and probably derived from mixing of the depleted mantle (juvenile) component and the Palaeoproterozoic-Archean crust (or sedimentary) component. The pluton is formed in a continental arc setting.

2) The early Permian Shuangjingzi pluton is composed of unfractionated calc-alkaline I-type quartz monzodiorite, granodiorite and monzogranite. The magma is derived from partial melting of the basal oceanic crust. They formed in the post-collisional extensional stage.

3) The Palaeo-Asian Ocean probably closed between 328Ma and 272Ma in the northern Beishan area.

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Author contributions

W. Zhang, V. Pease and T. Wu designed the project. W. Zhang, T. Wu and R. Zheng conducted the fieldwork and collected all samples. W. Zhang and Q. Meng finished all the analyses. W. Zhang wrote the initial draft, with all authors contributing to the discussion of the final paper.

APPENDIXES

Supplementary Material 1. Appendix S1

Supplementary Material 2. Table S1

Supplementary Material 3. Table S2

Supplementary Material 4. Table S3

Supplementary Material 5. Table S4

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FIGURE CAPTIONS

Figure 1. (a) Beishan area in the Central Asian Orogenic Belt (after Jahn et al., 2000b); (b) Simplified map of the Beishan area showing the main ophiolite belts and major faults (after Zuo and He, 1990); (c) Simplified geological map of the Eastern Beishan area (after BGGP, 1967, 1968a, b, 1969a, b, c, d, e, f, 1971a, b, 1977a, b, c, 1979). References for age data: 1= this study; 2 = Zheng et al., 2013b; 3 = Song et al., 2014; 4 = Zhang et al., 2012a; 5 = Zhang, 2013; 6 = Li et al., 2013; 7 = Zhang et al., 2011; 8 = Zhang et al., 2010; 9 = Feng et al., 2012; 10 = Zhang et al., 2015.

Figure 2. The Mingshui pluton in the northern Beishan area (after BGGP, 1969a, c).

Figure 3. The Shuangjingzi pluton in the northern Beishan area (after BGGP, 1969a, c).

Figure 4. Geochemical classification diagrams of southern Beishan granites. (a) QAP diagram (after Streckeisen, 1976); (b) $Al_2O_3/(CaO+Na_2O+K_2O)$ versus $Al_2O_3/(Na_2O+K_2O)$ diagram (after Shand, 1943); (c) SiO_2-K_2O diagram (fields from Rickwood, 1989); (d) SiO_2 versus Na_2O+K_2O diagram (after Irvine and Baragar, 1971).

Figure 5. Normalized REE and trace elements patterns for Mingshui (a, b) and Shuangjingzi (c, d) samples. Chondrite and N-MORB normalization values from (Sun and McDonough, 1989).

Figure 6. Cathodoluminescence (CL) images of zircons from the Mingshui and Shuangjingzi samples.

Figure 7. U-Pb Concordia plots for the Mingshui and Shuangjingzi analyses. Plots generated using Isoplot (Ludwig, 2003).

Figure 8. Petrogenetic diagrams for Mingshui and Shuangjingzi analyses. (a) Zr versus La diagram. The inset is a schematic Ch1 versus Ch2 diagram (h1 and h2 being two highly incompatible elements) with curves showing calculated melt compositions produced by fractional crystallization, partial melting and magma mixing processes (after Schiano et al., 2010). (b) La versus La/V diagram. The inset is a schematic CI versus CI/CC diagram (I and C being incompatible and compatible elements, respectively) with curves also showing compositions produced by magma mixing, fractional crystallization and partial melting processes (after Schiano et al., 2010). (c) $(\text{Al}_2\text{O}_3/\text{MgO} + \text{FeOT})$ molar vs. $(\text{CaO}/\text{MgO} + \text{FeOT})$ molar for Shuangjingzi granites (after Altherr et al., 2000).

Figure 9. (a) Trace element tectonic discrimination diagrams for granites (Pearce, 1996); (b) Rb/30–Hf–3Ta diagrams (Harris et al., 1986) (WPG-within plate granites, syn-COLG-syn-collision granites, VAG-volcanic arc granites, ORG-ocean ridge granites, POG-post-collisional granites).