**Recognition of a Devonian-early Mississippian plutonic belt in the
Eastern Beishan area, Northwest China, and its tectonic
implications**

Wen Zhang^{1,2,3}, Victoria Pease³, Qingpeng Meng², Rongguo Zheng¹, Tairan Wu^{2,*}

¹ Institute of Geology, Chinese Academy of Geological Sciences, Beijing 100037, China

² Laboratory of Orogenic Belts and Crustal Evolution, Ministry of Education, School of Earth
and Space Sciences, Peking University, Beijing 100871, China

³ Department of Geological Sciences, Stockholm University, SE-106 91, Stockholm, Sweden

* Corresponding author: T. Wu, trwupku@163.com

Abstract

The Beishan area, located in the southernmost part of the Central Asia Orogenic Belt (CAOB), is crucial for understanding the tectonic evolution associated with the closure of Paleo-Asian Ocean. One intermediate and two granitic plutons from the Eastern Beishan area between Mingshui - Shibanjing – Xiaohuangshan (MSX) and Niujuanzi- Xichangjing (NX) ophiolitic belts, including Tongchangkou gabbroic diorite, Northern Tongchangkou and Sandaomingshui plutons, are dated at 426 ± 3 Ma, 408 ± 2 Ma and 365 ± 2 Ma by SIMS U-Pb zircon analyses. The Middle Silurian Tongchangkou gabbroic diorites with medium-K calc-alkaline metaluminous characteristics represent volcanic arc rocks. The Early Devonian Northern Tongchangkou pluton, a highly evolved calc-alkaline mylonitic monzogranite with low $\epsilon_{\text{Nd}}(t)$ (-3.5 and -2.4) and relatively low initial $^{87}\text{Sr}/^{86}\text{Sr}$ (0.707095 and 0.707249), was mainly derived from Mesoproterozoic mafic to intermediate igneous protolith and shows both volcanic arc and post-collisional characteristics. The Late Devonian Sandaomingshui pluton, a calc-alkaline granite with slightly positive $\epsilon_{\text{Nd}}(t)$ (0.6 and 0.9) and low $(^{87}\text{Sr}/^{86}\text{Sr})_i$ (0.705543 and 0.705851), is likely from a more depleted source and represents a volcanic arc granite. Combined with previous studies of Late Paleozoic granites, we find out the widely distributed Permian granites in CAOBB is absent between MSX and NX ophiolitic belts. Given the regional geology, we conclude that the back-arc basin represented by the NX ophiolitic belt closed during Early Devonian and afterward, flat subduction of the oceanic basin represented by the MSH ophiolitic belt occurred. It also indicates that the oceanic crust was still being produced in the Paleo-Asian Ocean during the early Carboniferous.

Keywords: CAOBB, Beishan, Late Paleozoic, Granite, SIMS, Geochemistry

32 **1 Introduction**

33 The Beishan area in northwestern China links the Tarim-Sino-Korean Craton and Kazakhstan
34 Block and plays an important role in unraveling the evolution of the Central Asia Orogenic
35 Belt (CAOB) (Figure 1a) (Li et al., 2017; Wilhem et al., 2012; Xiao et al., 2010; Zuo and He,
36 1990). The geological and tectonic history of the Beishan area is complicated and its
37 Paleozoic tectonic evolution remains highly controversial (Liu and Wang, 1995; Song et al.,
38 2013b; Xiao et al., 2010; Yue et al., 2001; Zuo and He, 1990; Zuo et al., 2003). There are
39 four important ophiolitic belts/sutures in the Beishan area and these include, from north to
40 south, the Late Paleozoic Hongshishan, the Paleozoic Mingshui - Shibanjing -
41 Xiaohuangshan, and Early Paleozoic Hongliuhe- Niujuanzi- Xichangjing ophiolitic belts, as
42 well as the Late Paleozoic Liuyuan - Yin'aoxia fault (Ao et al., 2012, 2016; BGGP, 1969b, c;
43 Dai and Tan, 2008; Guo et al., 2006; Ren et al., 2001; Song et al., 2008, 2015; Su et al., 2013;
44 Tian et al., 2014; Wang et al., 2007; Yang et al., 2010; Yu et al., 2006; Zhang and Guo, 2008;
45 Zheng et al., 2014; Zuo and He, 1990; Zuo et al., 1991) (Figure 1b, c). Among these,
46 Mingshui - Shibanjing - Xiaohuangshan (MSX) and Hongliuhe- Niujuanzi- Xichangjing
47 (HNX) ophiolitic belts are better studied as they represent part of the Paleo-Asian Ocean
48 (Wilhem et al., 2012; Xiao et al., 2010; Zuo and He, 1990). However, which of these
49 represents the final closure of the Paleo-Asian Ocean in the Beishan region is a longstanding
50 matter of debate (Ren et al., 2001; Tian et al., 2014.; Wang et al., 2007; Yang et al., 2010;
51 Zuo and He, 1990; Zuo et al., 1991). Granitoids, especially Late Paleozoic granitoids, are
52 extensive in the Beishan area. Their age and geochemistry can constrain the timing and
53 genesis of granitoid magmatism in the region, both of which are critical for understanding the
54 tectonic evolution of the region. Although granitic plutons are widely distributed between
55 MSX and HNX ophiolitic belts, only a few U-Pb geochronological and geochemical studies
56 of these rocks have been reported (BGGP, 1967, 1969c, 1977c; Song et al., 2013a; Zhang et

al., 2012a; Zheng et al., 2013a). In this study, the geochronology and geochemistry of one intermediate pluton and two granitic plutons from a magmatic belt between the MSX and HNX ophiolitic belts (Figure 1c) are investigated to determine their ages and petrogenesis. These data are then integrated with previous studies of Late Paleozoic granites in the region (Zhang et al., 2012a; Zheng et al., 2013a) in order to constrain the tectonic evolution of the Eastern Beishan area and the closure of the Paleo-Asian Ocean. We document for the first time a Devonian-early Mississippian Late Paleozoic granitic belt in the Eastern Beishan area which allows us to develop a new late Paleozoic tectonic scenario for the evolution of the Beishan area in the CAOB.

2 Geological Setting

The Eastern Beishan area is the eastern part of the Beishan Mountain and its tectonic evolution is highly debated (He et al., 1994, 2005; Li et al., 2017; Liu and Wang, 1995; Xiao et al., 2010; Yang et al., 2010; Zuo and He, 1990; Zuo et al., 1991, 2003). Most ophiolitic belts or sutures in the Eastern Beishan area are poorly understood. Some researchers regard the MSX ophiolitic belt to be the main Early Paleozoic suture that separated the Tarim Craton and Kazakhstan Block (He et al., 1994; Zuo and He, 1990; Zuo et al., 1991, 2003). Early Carboniferous ophiolites were recently discovered along this belt (Zheng et al., 2013b). Other workers regard the main Early Paleozoic suture to be represented by an extensive but discontinuous ophiolitic belt that links the Hongliuhe, Niujuanzi and Xichangjing ophiolites (He et al., 2005; Ren et al., 2001; Tian et al., 2014; Wang et al., 2007; Yang et al., 2010). The Hongshishan ophiolitic belt in northern Beishan is argued to be a Late Paleozoic suture that separated the Tarim Craton and Kazakhstan Block (Gong et al., 2002, 2003; Huang and Jin, 2006), or alternatively the Kazakhstan Block and Siberian Craton (Liu and Wang, 1995). Others have argued that it represents the Paleo-Tianshan-Junggar Ocean (Su et al., 2012).

Xiao et al. (2010) suggested that the Permian Liuyuan mélange zone probably links to the Yin'aoxia fault and appears to be identical to the southern Tien Shan suture zone; thus they concluded that it extended eastwards and connected with the Engger Us ophiolite. However, the Liuyuan mélange zone is also regarded as a suture resulting from the collision between the Tarim Craton and Kazakhstan Block (Liu and Wang, 1995), whereas Zuo and He (1990) regard both the Late Paleozoic Hongshishan ophiolitic belt and Liuyuan - Yin'aoxia fault to represent intracontinental rifts.

The area between the MSX and HNX ophiolitic belts is regarded as a Silurian arc (Xiao et al., 2010; Zuo and He, 1990; Zuo et al., 1991), referred to as the Gongpoquan-Dongqiyishan arc in this study. Zuo and He (1990) thought the basement of the western Gongpoquan-Dongqiyishan arc belt was separated from continental crust to the south when the back-arc basin opened, while the eastern Gongpoquan-Dongqiyishan arc was built on oceanic crust. However, some regard the entire Gongpoquan-Dongqiyishan arc to represent an oceanic arc (Xiao et al., 2010). Early Carboniferous adakite-like granites have also been documented in Dongqiyishan (Zhang et al., 2012a), indicating the southward subducted oceanic crust (represented by the Xiaohuangshan ophiolitic belt) was still being produced in the Paleozoic Asian Ocean during that time. Ordovician, Silurian, Carboniferous and Permian strata also occur in the region and the widely distributed Silurian Gongpoquan Group represents extrusive volcanics, limestone, and marble of oceanic association. No Devonian strata have been reported in this belt (BGGP, 1968b, 1969b, e, 1977b).

3 Sample descriptions

3.1 Tongchangkou pluton

The Tongchangkou pluton lies near the HNX ophiolitic belt (Figure 1, 2). It represents a plutonic sheet more than 30 km long and 1~2 km wide intruded into the Middle to Upper

Silurian Gongpoquan Group and is in contact with Permian Hongyanjing strata along a NW-striking fault contact. The Gongpoquan Group consists of andesite, rhyolite, minor volcanoclastic rocks interbedded with limestone and marble (BGGP, 1968b). The Hongyanjing strata is mainly composed of clastic rocks and carbonaceous pelite interbedded with minor bioclastic limestone and siliceous marl, representing an interactive marine and terrestrial deposit (BGGP, 1968b).

No distinct lithofacies are recognized in the Tongchangkou pluton. The pluton consists of diorite and xenoliths of plagioclase-bearing amphibole schist. Later granites cut the pluton. The modal mineralogy of the pluton includes plagioclase (45-65%, most altered to sericite or saussurite), amphibole (20-40%, past altered to chlorite), biotite (10-25%, most altered to chlorite), with minor alkali feldspar and quartz. Apatite, zircon, titanite, hematite and magnetite are the main accessory minerals.

3.2 Northern Tongchangkou pluton

The Northern Tongchangkou pluton (Figure 1, 2) lies north of the Tongchangkou pluton, represents a nearly NW-striking sheet extending more than 30 km long and 1~6 km wide. It intrudes the Lebaquan Group and the Middle-Upper Silurian Gongpoquan Group. The Lebaquan Group represents a series of regional metamorphic rocks including plagiogneiss, quartzite, mica quartz schist and diopside marble. Their protolith was quartz sandstone, muddy sandstone, sandy shale, mud and limestone. New LA-ICP-MS zircon U–Pb dating of a garnet–mica–quartz schist indicates that six ages of the youngest detrital zircon population yield a weighted mean age of 424 ± 7 Ma (MSWD= 0.79), which constrains the maximum depositional age of the protoliths (Song et al., 2014).

No distinct lithofacies are recognized in this pluton which mainly consists of mylonitic monzogranite. The modal mineralogy includes plagioclase (35-50%, most weakly altered to

sericite), alkali feldspar (15-30%) (mostly perthite and K-feldspar, few microcline), quartz (30-40%), mafic minerals (5-15%; mainly biotite, partly altered to chlorite, epidote, or zoisite) and with minor muscovite. Zircon, monazite, apatite, titanite, hematite and magnetite are the main accessory minerals.

3.3 Sandaomingshui pluton

The Sandaomingshui pluton represents a batholiths covering about 400 km² in the Gongpoquan-Dongqiyishan arc zone (Figures 1, 3). It was reported to be emplaced into the Middle to Upper Silurian Gongpoquan Group and Lower Carboniferous Hongliuyuan Formation (original Liuyuan Formation) (BGGP, 1969b). Hongliuyuan Formation is composed of sandy shale and intermediate to acid volcanic rocks with rare oceanic fauna (BGGP, 1969b; Yang et al., 1997). Xenoliths of the country rock are numerous and well preserved. Strong migmatization along the contact zone occurs.

No distinct lithofacies are distinguished in the Sandaomingshui pluton. The pluton mainly consists of biotite granodiorite. The modal mineralogy includes plagioclase (40-50%, most altered to sericite and/or saussurite), alkali feldspar (15-25%) (mostly perthite and K-feldspar, few microcline), quartz (25-35%), mafic minerals (10-15%; mainly biotite, part altered to chlorite, epidote, or zoisite) and minor muscovite. Euhedral-subhedral zircon, anhedral titanite, subhedral-anhedral apatite, hematite and magnetite are the main accessory minerals.

4 Analytical results

See “Supplementary Document 1” for a description of the analytical methods. Samples representing the batholith's principal compositional phase(s) were selected for major and trace element analyses from each pluton. A representative sample of each pluton was selected for geochronology after geochemical analyses. The results 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 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 zircon U-Pb geochronology are presented in “Supplementary document 4. Table S3”. Analyzed crystals include both whole zircon crystals and grain fragments.

4.1 Tongchangkou pluton

Major and trace elements

Low SiO₂ concentrations (50.75-55.62 wt%) define Tongchangkou samples as gabbroic diorites. They have high Al₂O₃ (17.55-18.93 wt%), CaO (6.73-8.39 wt%), Fe₂O₃T (8.68-10.08 wt%), MgO (3.12-6.40 wt%) and TiO₂ (0.86-2.02 wt%). All three samples have higher Na₂O (3.31-4.19 wt%) but lower K₂O (0.56-1.12 wt%) with A/NCK of 0.84 to 0.93 (Figure 4a). They represent a medium-K calc-alkaline series (Figure 4b). The gabbro diorites also show calc-alkaline affinity in FeO- Na₂O+ K₂O-MgO space (Figure 4c, d).

Chondrite-normalized REE patterns (Figure 5a) of the Tongchangkou gabbroic diorites show enrichment of LREE [(La/Yb)_N=5.4-11.2] and slightly negative to positive Eu anomalies (δEu =0.95-1.31). The total REE contents of the Tongchangkou gabbroic diorites lie between enriched MORB (E-MORB; Sun and McDonough 1989) and ocean island basalt (OIB, Sun and McDonough 1989). The distribution patterns are similar to that of OIB. N-MORB-normalized trace element patterns (Figure 5b) show the samples are enriched in LREE, U, K, Sr and Nd, and depleted in Nb, and P. One sample (BS07-111) is distinct with higher Rb, Th and U contents, and depleted in Zr and Ti.

Geochronology

Zircon grains from the Tongchangkou gabbroic diorite (BS07-111) are euhedral, clear to pink and transparent. Aspect ratios = 1:1 to 3:1. Some have inclusions. Most crystals have broad

zoning (Figure 6). No inherited cores are seen in CL nor were older ages obtained during analyses. Integrating crystal shapes, textures and high Th/U ratios (between 0.38 and 1.01) indicate all grains to be magmatic (Belousova et al., 2002; Corfu et al., 2003). Fourteen analyses combine to yield a concordia age of 426 ± 3 Ma, MSWD=1.02 (Figure 7a), which is interpreted as the crystallization age for this sample (BS07-111).

4.2 Northern Tongchangkou pluton

Major and trace elements

SiO₂ contents of the Northern Tongchangkou mylonitic monzogranite range from 73.79-77.09 wt%, Al₂O₃ from 12.07 to 15.03 wt%, MgO from 0.21 to 0.42 wt% with low Mg (Mg#=0.32-0.44), TiO₂ (0.07-0.17 wt%) and CaO (1.05-2.38 wt%). They are peraluminous (A/NCK=1.02-1.09) (Figure 4a), magnesian to ferroan (Fe-no.=0.77-0.85) and medium-K and high-K calc-alkaline (Figure 4b). The total alkali content is 7.42 wt% on average, and Na₂O/K₂O ratios range from 0.32 to 2.58.

Chondrite-normalized REE patterns (Figure 5c) show enrichment in LREE [(La/Yb)_N=6.5-29.6] and negative to slightly positive Eu anomalies (δ Eu=0.26-1.33). N-MORB-normalized trace element patterns (Figure 5d) are enriched in Rb, U, K and Sr, and depleted in Nb, Ta, Ti and P.

Geochronology

Zircon grains from the Northern Tongchangkou pluton (BS07-123 and AB10-80) are euhedral, clear, pink to orange and transparent to opaque. They have lengths of ~70-150 μ m and aspect ratios of 1:1 to 5:1. Some crystals have inclusions and cracks. In CL, most crystals show oscillatory zones and some are partly black (Figure 6). Seven analyses were partly off the crystals (n4156-02, 04, 05, 09, 10, 12 and 13) and three analyses were on cracks (n4156-07, 08, and 14). The remaining four analyses (n4156-01, 03, 06 and 11) have high Th/U

(0.31-0.65) and oscillatory zoning and are interpreted represent magmatic zircon (Belousova et al., 2002; Corfu et al., 2003). They yield a concordia age of 408 ± 3 Ma, MSWD=1.6 (Figure 7b) which is interpreted to be the crystallization age for this sample (AB10-80).

Nd and Sr isotopes

The Northern Tongchangkou granite has high initial $^{87}\text{Sr}/^{86}\text{Sr}$ values of 0.707095 and 0.707249 and negative $\epsilon\text{Nd}(t)$ values of -3.5 and -2.4 (Figure 8). They yield depleted mantle model ages (T_{DM2}) of 1257-1358 Ma.

4.3 Sandaomingshui pluton

Major and trace elements

The Sandaomingshui biotite granodiorite has SiO_2 of 72.09-76.13 wt%, Al_2O_3 from 13.44 to 15.06 wt%, CaO from 1.14 to 2.61 wt%, TiO_2 from 0.05 to 0.19 wt%, MgO (0.33-0.98 wt%), and low Mg# (0.34-0.54). All samples are peraluminous ($\text{A/NCK}=1.01-1.08$; Shand, 1943) (Figure 4a) and magnesian ($\text{Fe-no.}=0.68-0.83$; Frost et al., 2001). The total alkali content is 7.36 wt% (average) and most samples contain more Na_2O than K_2O ($\text{Na}_2\text{O}/\text{K}_2\text{O}=1.42$ on average). They are medium-K to high-K calc-alkaline rocks (Figure 4b).

Chondrite-normalized REE patterns (Figure 5e) show enrichment of LREE [$(\text{La}/\text{Yb})_{\text{N}}=2.3-9.5$] and strongly negative Eu anomalies ($\delta\text{Eu}=0.41-0.92$). N-MORB-normalized trace element patterns (Figure 5f) are enriched in Rb, U and K, and depleted in Nb, Ta, Ti and P.

Geochronology

Zircon grains from the Sandaomingshui pluton (AB10-100) are euhedral, clear to pink and transparent to opaque. The aspect ratios are between 1:1 and 3:1. Some have inclusions. Most grains show oscillatory zoning or broad zones throughout the crystal (Figure 6). Two analyses on cracks (n4153-14 and 15) and two analyses on inclusions (n4153-12 and 16)

were excluded. High Th/U ratios (between 0.41 and 1.39) together with crystal shapes, and textures imply the zircon grains are magmatic (Belousova et al., 2002; Corfu et al., 2003). The analyses represent both rims and cores. Although an inherited core was found (n4153-06/07), it yielded an age similar to the rims. Twelve analyses combine to yield a concordia age of 365 ± 2 Ma, MSWD=1.7 (Figure 7c), which is interpreted as the crystallization age for this sample (AB10-100).

Nd and Sr isotopes

The Sandaomingshui granodiorites have low initial $^{87}\text{Sr}/^{86}\text{Sr}$ values of 0.705543 and 0.705851 and slightly positive $\epsilon\text{Nd}(t)$ values of 0.6 and 0.9 (Figure 8). They samples yield depleted mantle model ages (T_{DM2}) of 948-968 Ma.

5 Discussion

5.1 Magma genesis

5.1.1 The Tongchangkou pluton

The Tongchangkou pluton was considered to be Late Paleozoic in age (BGGP, 1968b). Our new SIMS zircon U-Pb age for the gabbroic diorite (BS07-111) is 426 ± 3 Ma. The diorite is the dominant compositional phase of the pluton and as no inherited zircons were recognized, we interpret the age of this sample to represent the age of the entire Tongchangkou pluton. Inherited zircon grains found in the Early Devonian Gongpoquan granite (BS07-136, 403 ± 3 Ma, $n=11$) were dated at 426 ± 4 Ma (weighted average, $n=7$) by LA-ICP-MS (Zheng et al., 2013a), indicating Middle Silurian igneous rocks were assimilated when Gongpoquan granite formed.

The Tongchangkou gabbroic diorite shows arc-related characteristics (Figure 9a). The Th/Ta and La/Yb ratios of basalts are particularly sensitive to mantle source composition and

mixing processes, but relatively unaffected by different degrees of fractional crystallization or partial melting. The samples seem to define an assimilation and fractional crystallization (AFC) trend (Figure 9b), suggesting a mixed mantle source that included depleted mantle (DM) and enriched mantle (EM). Given its arc signature, enriched [LREE/HREE]_N (Fig. 5a) and mixed mantle source, the Tongchangkou pluton probably formed by partial melting of, or by fractional crystallization of, melts derived from the mantle-wedge (Chappell and White, 1992).

This hypothesis can be further assessed by recognition of metasomatic agents that may be added from the subducted slab to the mantle wedge. Hanyu et al. (2006) argued that the addition of slab fluids should dramatically enrich Ba concentrations while elements less mobile in a fluid would be unaffected. The Tongchangkou samples show striking enrichment in Th/Yb at a constant Ba/La, which is consistent with the contribution of sediment melt to the mantle wedge rather than the addition due to slab-derived fluids (Hanyu et al., 2006) (Figure 9c).

In this case, the sediment component may also be refined using the Th–Nb proxy. High Th/Yb ratios relative to the mantle array support crustal (including eroded sediments) input and hence can be used to recognize oceanic, non-subduction related setting (Pearce, 2008). The Tongchangkou samples define a large spread in Th/Yb over a narrow Nb/Yb (Figure 9d) indicating that crustal input is likely to have occurred via assimilation or deep recycling. Therefore, the Tongchangkou pluton seems to represent normal calc-alkaline subduction-related magma derived from an enriched mantle contaminated by melts of subducted sediment.

5.1.2 Northern Tongchangkou pluton

Four analyses of zircon from the Northern Tongchangkou granite (AB10-80) yield an age of 408 ± 3 Ma which is interpreted to represent the crystallization age of the sample. As no significant compositional diversity occurs in the pluton, this age is likely to represent the age of the entire pluton. In addition, the Gongpoquan granite only 5 km north of the Northern Tongchangkou pluton has a similar age (Zheng et al., 2013a).

The Northern Tongchangkou mylonitic monzogranite is calc-alkaline and peraluminous ($1.0 < A/NCK < 1.1$) with $A/NK > 1.0$. P_2O_5 decreases with increasing SiO_2 , whereas Pb increases, consistent with I-type granitoids (Chappell and White 1992). The Northern Tongchangkou samples are transitional between the fractionated and unfractionated I-type granites of Whalen et al. (1987). They also have very high SiO_2 (> 72 wt.%), low MgO (< 0.5 wt.%), negative to slightly positive Eu anomalies, and negative Nb, Ti and P anomalies consistent with a highly evolved magma (Wu et al., 2003b). The negative anomalies of Nb and Ta are common in continental crust and inherited from chemical differentiation of arc-derived magmas (Castro et al., 2010, 2013). The Northern Tongchangkou monzogranite Nd model ages (Figure 8a) indicate Proterozoic components were involved in its genesis. The combined Sr and Nd isotope characteristics (Figure 8b) suggests that both depleted mantle (or juvenile) and upper continental crustal or sedimentary components likely contribute this Proterozoic component in the genesis of the Northern Tongchangkou monzogranite.

Calc-alkaline, I-type granitoids are usually generated by I) partial melting of mafic to intermediate igneous sources, II) by advanced assimilation and fractional crystallization of mantle-derived basaltic parental magmas, or III) by mixing of mantle-derived magmas with crustal-derived material (e.g. De Paolo, 1981; Li et al., 2007; Sisson et al., 2005; Hildreth and Moorbath, 1988). The high initial Sr isotopic ratios (0.707095 and 0.707249) and negative $\epsilon_{Nd}(t)$ values (-3.5 and -2.4) of the Northern Tongchangkou pluton indicate the involvement of an old (Mesoproterozoic) mafic to intermediate igneous protolith. If the Northern

Tongchangkou pluton was generated by mixing between intracrustal mafic igneous rock-derived magmas and mantle-derived magmas, the relatively narrow range of isotopic data and its chemical composition suggests that it can occur only if mixing occurs in a single batch. Thus, the Northern Tongchangkou granites are most likely derived from Mesoproterozoic mafic to intermediate igneous protolith.

The Gongpoquan leucogranites and S-type monzogranite also formed in Early Devonian time (Zheng et al., 2013a). It also has LREE enrichment $[(La/Yb)_N=2.74-22.78]$, negative to slightly positive Eu anomalies ($\delta Eu=0.83-1.08$), enrichments in Cs, Rb, Ba, Th, U, and K, and depletions in Nb, Ta, P and Ti. Inherited xenocrysts were identified during U-Pb SIMS zircon analysis, which consistent with crustal assimilation or magma hybridization. Although the Northern Tongchangkou monzogranite has a similar age and Nd model age as the Gongpoquan granites, they cannot have been derived from the same sources due to their distinct geochemical characteristics.

5.1.3 Sandaomingshui pluton

The zircon U-Pb SIMS age of Sandaomingshui biotite granodiorite (AB10-100) is 365 ± 2 Ma. As no significant compositional diversity occurs in the pluton and no inheritance was recognized during zircon analysis, this age is interpreted to probably represent the age of the entire Sandaomingshui pluton.

To date, few Late Devonian granites have been reported from the Eastern Beishan area. A similar age pluton is the Early Carboniferous Dongqiyishan adakite-like granite at 356 ± 3 Ma (Zhang et al., 2012a). It is located ca. 80 km east of the Sandaomingshui pluton and is interpreted to be formed by melting of subducted oceanic crust with significant assimilation of lower continental crust. The Dongqiyishan adakite-like granite has stronger enrichment of LREE $[(La/Yb)_N=7.9-34.2]$ and positive to weakly negative Eu anomalies ($\delta Eu=0.81-2.32$).

In comparison, the Sandaomingshui granodiorite has distinct chondrite-normalized REE patterns, high SiO₂ (>72%), low Al₂O₃ (<15%), Sr (>400 ppm) and Sr/Y <40. The Sandaomingshui granodiorite and Dongqiyishan granite are derived by different process.

The Sandaomingshui granodiorite, similar to the Northern Tongchangkou monzogranite, represents a calc-alkaline I-type granite. However, unlike the suggested genesis proposed by Whalen et al. (1987), these plutons are not as highly evolved. Negative Nb, Ti and P anomalies indicate the fraction of Ti-bearing phases and apatite (Wu et al., 2003b). Weakly negative Eu, slightly positive Sr, and no Ba anomalies support the minor separation of feldspar and plagioclase during crystal fractionation. The initial $\epsilon\text{Nd}(t)$ values of the Sandaomingshui granodiorite are slightly positive (0.6 to 0.9), implying an important role for a depleted mantle source with a crustal component (or juvenile) (Figure 8a). The Nd model age ($T_{\text{DM2}} \sim 950\text{Ma}$) is relatively young compared with that of the Northern Tongchangkou monzogranite, indicating a lower proportion of the crustal component. Low initial $^{87}\text{Sr}/^{86}\text{Sr}$ values (0.70543-0.70585) and positive initial ϵNd indicate that the Sandaomingshui granodiorite implies a depleted mantle (or juvenile) dominated component (Figure 8b). Therefore, the Northern Tongchangkou monzogranite likely represents a mantle-derived basaltic parental magma with advanced assimilation and fractional crystallization.

5.2 Devonian - early Mississippian Middle Plutonic Belt of Beishan

From geochronological analyses of Late Paleozoic granites in this study and previous investigations (BGGP, 1967, 1969c, 1977c; Feng et al., 2012; Li et al., 2013; Song et al., 2013a; Wang et al., 2009a; Zhang et al., 2010, 2011, 2012a, b, 2015; Zheng et al., 2013a) (Figure 1), three distinct plutonic belts can be recognized in the Beishan region. The plutonic belt north of the MSX ophiolitic belt is composed of late Mississippian-Early Permian granitoids (Zhang, 2013). The southern plutonic belt lies south of the HNX ophiolitic belt and represents Pennsylvanian-Permian granitoids (Zhang et al., 2015). The middle plutonic belt is

located between the MSX and HNX ophiolitic belts and comprises much older granites of Devonian-early Mississippian age. Permian granites have not previously been recognized in the middle plutonic belt (Figure 1c).

The general enrichment of LREE/HREE and negative Nb-Ta-Ti anomalies of the Tongchangkou gabbroic diorite indicates arc-related characteristics (Figure 5) and from its trace elements (Figure 10a, b) it represents volcanic arc rocks (Defant and Drummond, 1990; Martin, 1986). The Northern Tongchangkou and Sandaomingshui granitoids also represent volcanic arc rocks, but a few are transitional from volcanic arc to post-collisional rocks (Martin, 1986; Harris et al., 1986; Pearce, 1996; Pearce et al., 1984) (Figure 10a, c).

5.3 Tectonic evolution

5.3.1 Middle Silurian

The middle Silurian Tongchangkou pluton probably represents a part of the Gongpoquan-Dongqiyishan arc, which formed by the southward subduction of the oceanic crust represented by the MSX ophiolitic belt or the northward subduction of the oceanic basin represented by the HNX ophiolitic belt. Recent geochronological investigations of the HNX ophiolitic belt indicate that the ocean formed in early Cambrian (plagiogranite from Yueyashan-Xichangjing ophiolites, 533 ± 2 Ma, SIMS; gabbro cumulate from the Hongliuhe Ophiolite, 516 ± 7 Ma, SIMS) (Ao et al., 2012; Zhang and Guo, 2008) through Late Devonian (gabbro from Niujuanzi ophiolites, 447 ± 4 Ma, LA-ICP-MS) (Wu et al., 2012) time and still existed in the Early Devonian (gabbro from Niujuanzi ophiolites, 410 ± 4 Ma, LA-ICP-MS) (Tian et al., 2014). Undeformed ~ 405 Ma (biotite, Ar-Ar) granitoids intruded the Hongliuhe Ophiolite, suggesting that the ocean closed prior to 405 Ma (Guo et al., 2006; Zhang and Guo, 2008). According to Zhang et al. (2012a), this ophiolitic belt does not represent a plate tectonic suture as it is emplaced into Upper Ordovician strata; as the Upper Ordovician

sedimentary formations on both sides of the ophiolitic belt are the same, Early Paleozoic deposition was apparently continuous. Consequently, it seems instead to represent a back-arc basin (BGMGRP 1989; Zuo and He, 1990). A new $^{206}\text{Pb}/^{238}\text{U}$ age of $336\pm 4\text{Ma}$ (weighted average, $n=14$) from basalt of the Xiaohuangshan ophiolite indicates subduction was ongoing in the Early Carboniferous (Zheng et al., 2013b). Therefore, it seems that a complete trench-arc-basin system existed in middle Silurian time.

The basement to the Gongpoquan-Dongqiyishan arc has been regarded as continental crust in the west and oceanic crust in the east (Zuo and He, 1990), or as entirely oceanic arc (Xiao et al., 2010). Recently, Song et al. (2015) find out that volcanic rocks from the Gongpoquan Group in the Lebaquan area have lots of Precambrian detrital zircons, which is different from typical oceanic arc, but more like the Japan arc instead. The entirely oceanic model cannot interpret the Precambrian ages. So the Tongchangkou pluton, which in the west, should form in a Japan-type subduction system.

5.3.2 Early Devonian

The fault-controlled Northern Tongchangkou pluton is elongate NW-SE. The pluton is generally fragmented, mylonitic, and enclaves are well developed. In the Cordilheria of southern Brazil, low-angle deformation of granitic rocks was considered to be syn-orogenic, while granitic rocks emplaced during the development of transcurrent shear zones were considered late-orogenic; the later were argued to promote deformation and dynamic metamorphism along mylonitic zones (Nardi and Frantz 1995). Analogously, the Northern Tongchangkou mylonitic monzogranite probably formed in the post-collisional compressive stage. The Northern Tongchangkou mylonitic monzogranite has mainly volcanic arc characteristics (Figure 10c). It's not surprising as it were probably derived from subducted materials within the mantle (Castro et al., 2013; Hacker et al., 2011). In addition, Early Devonian Gongpoquan monzogranite was also regarded as post-collisional granite (Zheng et

al., 2013a). In this case, a back-arc basin to the south (represented by the Niujuanzi-Xichangjing ophiolitic belt) closed before the Early Devonian Northern Tongchangkou and Gongpoquan granites were emplaced into the Gongpoquan-Dongqiyishan arc.

There are not Devonian strata in the region of the Gongpoquan-Dongqiyishan arc (BGGP, 1968b, 1969b, e, 1977b). However, in the Dundunshan area to the west, the Silurian-Lower Devonian Sangejing Formation comprises marine and terrestrial volcanic-molasse deposition and the Upper Devonian Dudushan Formation records terrestrial volcanic deposition (He et al., 2004; Li et al., 2011; Zuo and He, 1990). In the Pingtoushan area also to the west, a thrusting occurred in the late Silurian and middle Devonian (Liu et al., 2002). In addition, the ocean represented by the Hongliuhe Ophiolite closed prior to 405 Ma (Zhang and Guo, 2008). Therefore, orogeny occurred in the Western Beishan area at least before middle Devonian time. Isotopic data from the Northern Tongchangkou and Gongpoquan monzogranites indicate old continental crust (or sediment derived therefrom) plays an important part in their genesis and could have been provided by the basement of the Japan-type Gongpoquan arc or by the continental crust to the south during the closure of the back-arc basin represented by the HNX ophiolitic belt.

5.3.3 Late Devonian

The Sandaomingshui pluton was reported to be emplaced into the middle to upper Silurian Gongpoquan Group and the lower Carboniferous Hongliuyuan Formation. However, our geochronological data give a Late Devonian age for the Sandaomingshui pluton. Since it is impossible for a Late Devonian pluton to intrude Lower Carboniferous strata, the age of the Hongliuyuan Formation is incorrect or the Sandaomingshui pluton does not intrude the Hongliuyan Formation. In either case, the age of the country rock must pre-date c. 365 Ma.

The geochemical and isotopic data document little continental crust involved in the genesis of the Sandaomingshui granite; thus it is more likely to represent an oceanic arc rather than a continental arc setting. The pluton is in the middle of the Gongpoquan-Dongqiyishan arc. The Sandaomingshui pluton preserve geochemical oceanic arc signatures, consequently we interpret the Sandongmingshui pluton was built on an oceanic crust. Therefore, the Sandaomingshui pluton was most likely formed by the southward subduction of oceanic crust represented by the MSH ophiolitic belt.

5.3.4 Early Carboniferous

The Early Carboniferous Dongqiyishan adakite-like granite (356 ± 2 Ma) (Zhang et al., 2012a) and Shibanjing strongly foliated granite (349 ± 5 Ma) occur in the eastern Gongpoquan-Dongqiyishan arc (Song et al., 2013a). The Shibanjing granite has a typical volcanic arc signature and is interpreted to have formed in a subduction-accretion setting. Through the study of Dongqiyishan adakite-like granite, Zhang et al (2012a) concluded that it was consistent with the southward subduction of oceanic crust (represented by the MSX ophiolitic belt) and indicated that oceanic crust was still being produced in the Paleo-Asian Ocean during the Early Carboniferous. A back-arc basin, represented by the Xichangjing ophiolitic belt, closed before Carboniferous time, allowing lower crustal material to be assimilated and giving the Dongqiyishan adakite-like granites their crustal signature. An oceanic ridge progressively approaching the continental margin allows subduction of a younger, hotter slab, increasing the geotherm and promotes melting of the lower continental crust. Subsequent flattening of the slab since Ordovician time results in a tightly coupled subducting slab and lower crust which facilitated the formation of Dongqiyishan adakite-like granites (Zhang et al., 2012a).

5.4 Absence of late Mississippian- Permian magmatism in the Beishan Middle Plutonic Belt

Flat subduction was proposed for the Dongqiyishan area (Zhang et al., 2012a). Gutscher et al. (2000) pointed out that once flat subduction continues for several million years, the asthenospheric wedge disappears and a volcanic gap results, as in modern-day central Chile or Peru. Therefore, the absence of Permian granites can be explained with the flat subduction model. The back-arc basin represented by the HNX ophiolitic belt probably subducted both northward and southward. As in the north of the Niujuanzi ophiolite, there are lots of southward thrusting, which cannot be interpreted satisfactorily by the southward-only subduction model (Song et al., 2014). Furthermore, the Gongpoquan-Dongqiyishan arc is more likely to be a Japan-type arc in the west and an oceanic arc in the middle and east. As post-collisional granites are derived mainly by differentiation of underplated basic magmas (Han et al., 1997), partial melting of over-thickened crust could produce differentiated melts. Combining with previous work on granite genesis (Feng et al., 2012; Zhang et al., 2010, 2011, 2012a, b, 2015; Zheng et al., 2013a) and tectonic evolution (Xiao et al., 2010; Zuo and He, 1990), a new tectonic scenario for the evolution of the Eastern Beishan area is developed below (Figure 11).

- Ordovician

The oceanic basin represented by the MSX ophiolitic belt subducted and the Gongpoquan-Dongqiyishan volcanic arc began to form on a continental crust in the west and on an oceanic arc in the east.

- Ordovician–Early Silurian

A Back-arc basin represented by the Gongpoquan–Xichangjing ophiolitic belt formed in Ordovician–Early Silurian and the oceanic ridge progressively approached the volcanic arc margin. Japan-type arc began to form in the west of the Gongpoquan-Dongqiyishan arc.

• Middle Silurian

Before Silurian time, the oceanic crust represented by the Mingshui-Shibanjing-Xiaohuangshan ophiolitic belt subducted southward and formed the “trench-arc-basin” system that included i) the Gongpoquan-Dongqiyishan was a Japan-type arc in the west and an oceanic crust in the east and an oceanic arc in the east and ii) the back-arc basin represented by the Gongpoquan–Xichangjing ophiolitic belt. Arc volcanism was still active during the Middle Silurian and the Tongchangkou gabbroic diorite was emplaced.

• Late Silurian-Early Devonian

The closure of the back-arc basin followed with the collision of the Gongpoquan-Dongqiyishan arc and the Mazongshan Block to the south during Late Silurian-Early Devonian time. The arc was transformed to juvenile continental crust in whole. The Northern Tongchangkou and Gongpoquan post-collisional granites formed.

• Late Devonian-Early Carboniferous

The oceanic crust continued subducting southward and induced the formation of the younger Sandaomingshui arc-related granodiorites. From the Dongqiyishan adakite-like magmatism, we infer an oceanic ridge progressively approached the continental margin allowing subduction of a younger, hotter slab, increasing the geotherm and promoting melting of the lower continental crust. Subsequent flattening of the subducting slab, together with crustal thickening from closure of the back-arc basin, led to the formation of a tightly coupled subducting slab and lower crust which resulted in the Dongqiyishan adakite-like magmatism. Closure of the back-arc basin potentially provides the continental component seen in the isotopic signature of the Dongqiyishan pluton and required by the AFC modeling. At this time, the oceanic crust also began subducting on its northern margin.

• Late Carboniferous-Middle Permian

The main ocean closed. In the north, post-collisional granites with volcanic arc characteristics were emplaced. In the south, the break-off of the flat subducting slab resulted in the extension and thinning of the crust, opening of a rift, and emplacement of abundant granitic plutons.

5.2.3 Links to Southern Tianshan

The Beishan area could be the westward continuation of southern Tianshan (Xiao et al., 2010). There are two popular models for linking the South Tianshan Ocean in the Beishan area. 1) The MSX ophiolitic suture links to the South Tianshan Suture Zone (Wilhem et al., 2012). By comparing the Beishan regional geology with surrounding regions (Chinese Tianshan, Tarim and Inner Mongolia), these authors pointed out that the Xiaohuangshan Suture Zone was linked to the South Tianshan Suture Zone. However, they believed the two suture zones represented back-arc basins and that the main oceanic basin was represented by the Hongshishan ophiolite belt and the Central Tianshan Suture. 2) The Permian Liuyuan mélangé could be identical to the South Tianshan Suture Zone (Xiao et al., 2010, 2014). It is the major suture zone that separates the Tianshan-Beishan region from the northern active margin of the Tarim Craton. The results from this study favor the first model. A late Silurian-late Devonian (ca. 426–387 Ma) granitoid belt also occurs in the South Tianshan Accretionary Complex (Guo et al., 2013; Jia et al., 2013; Lin et al., 2013; Wang et al., 2009b; Xu et al., 2006; Zhu et al., 2008a) and is interpreted to have formed during the southward subduction of the South Tianshan Ocean. Since the Beishan Middle Plutonic Belt is inferred to have formed by the southward subduction of the oceanic crust represented by the MSX ophiolitic belt, it is reasonable to assume a connection to the South Tianshan Ocean. According to Jiang et al. (2014), the South Central Tianshan Ophiolite Belt may represent fragments of a wide ocean that lasted until the early Carboniferous (ca. 332 Ma), whereas the South Tianshan Ophiolite Belt may have been derived from a forearc rifting setting that

existed during the early Silurian to the early Carboniferous (ca. 439-356 Ma). Similar to the tectonic framework of the South Tianshan Ocean, the MSX ophiolitic belt represents a fragment of the main ocean that existed until early Carboniferous (ca. 336 Ma) time (Zhang et al., 2012a; Zheng et al., 2013b) and the HNX ophiolite belt represented a back-arc basin that existed during early Cambrian to middle Silurian (ca. 533-426 Ma) time.

6 Conclusions

- 1) The Beishan Middle Plutonic Belt located between the MSX ophiolitic belt and the HNX ophiolitic belt comprises Devonian-early Mississippian granites. No Pennsylvanian-Permian granites are found in the Middle Plutonic Belt.
- 2) Within the Beishan Middle Plutonic Belt, the Middle Silurian Tongchangkou gabbroic diorite formed in a volcanic arc setting. The Early Devonian Northern Tongchangkou mylonitic monzogranite represents a post-collisional granite with low initial ϵNd (-3.5 to -2.4) and low initial $^{87}\text{Sr}/^{86}\text{Sr}$ values (0.707095 to 0.707249). The Late Devonian Sandomingshui granodiorite has volcanic arc characteristics with initial $^{87}\text{Sr}/^{86}\text{Sr}$ values of 0.705543 and 0.705851 and slightly positive $\epsilon\text{Nd}(t)$ values of 0.6 and 0.9.
- 3) The back-arc basin represented by the HNX ophiolitic belt closed during the Late Silurian to Early Devonian. The oceanic basin represented by the MSX ophiolitic belt existed through the early Mississippian.
- 4) The Gongpoquan-Dongqiyishan arc was a Japan-type arc in the west and an oceanic crust in the east.
- 5) Flat subduction beneath the Gongpoquan-Dongqiyishan arc resulted in a Pennsylvanian-Permian magmatic gap.
- 6) The MSX Suture Zone may represent the westward extension of the South Tianshan Suture Zone.

Acknowledgements

We gratefully acknowledge financial support from National Natural Science Foundation of China (grant number 41430210), the National Program on Key Basic Research Project (2016YFC0600310), National Natural Science Foundation of China (grant to T. Wu, no. 41372225), China Scholarship Council (grant to W. Zhang, file no. 2010601124) and the Swedish Research Council (grant to V. Pease). The PetroTectonics Analytical Facility is funded by the Knut and Alice Wallenberg Foundation and Department of Geological Sciences, Stockholm University. This is a Nordsim publication (no. XXX). The Nordsim facility is jointly funded by the Nordic countries.

Supplementary Material 1. Appendix S1

Supplementary Material 2. Table S1

Supplementary Material 3. Table S2

Supplementary Material 4. Table S3

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875 **Figure Captions**

876 Figure 1. (a) Beishan area in the Central Asian Orogenic Belt (after Jahn et al., 2000); (b)
 877 Simplified map of the Beishan area showing the main ophiolite belts and major faults (after
 878 Zuo and He, 1990); (c) Simplified geological map of the Eastern Beishan area (after BGGP,
 879 1967, 1968a, b, 1969a, b, c, d, e, 1971a, b, 1977a, b, c, 1979). References for age data: 1=
 880 this study; 2 = Zheng et al., 2013a; 3 = Song et al., 2013a; 4 = Zhang et al., 2012a; 5 = Zhang
 881 2013; 6 = Li et al., 2013; 7 = Zhang et al., 2011; 8 = Zhang et al., 2010; 8 = Feng et al., 2012;
 882 9 = Zhang et al., 2012b; 10 = Zhang et al., 2015.

883 Figure 2. The Tongchangkou and Northern Tongchangkou plutons, Eastern Beishan area
 884 (after BGGP, 1968b, 1969b).

885 Figure 3. The Sandaomingshui pluton, Eastern Beishan area (after BGGP, 1969b).

886 Figure 4. Major element characteristics of Eastern Beishan granites. (a)
 887 $\text{Al}_2\text{O}_3/(\text{CaO}+\text{Na}_2\text{O}+\text{K}_2\text{O})$ versus $\text{Al}_2\text{O}_3/(\text{Na}_2\text{O}+\text{K}_2\text{O})$ diagram (after Shand, 1943); (b) SiO_2 –
 888 K_2O diagram (fields from Rickwood, 1989); (c) SiO_2 versus $\text{Na}_2\text{O}+\text{K}_2\text{O}$ diagram (after Irvine
 889 and Baragar, 1971); (d) $\text{Na}_2\text{O}+\text{K}_2\text{O} - \text{FeOT} - \text{MgO}$ diagram (after Irvine and Baragar, 1971).

890 Figure 5. Normalized REE and trace element patterns for the Tongchangkou (a,b), Northern
 891 Tongchangkou (c,d) and Sandaomingshui (e,f) samples. Chondrite and N-MORB
 892 normalization values from Sun and McDonough, 1989).

893 Figure 6. Cathodoluminescence (CL) images of zircons from the Tongchangkou, Northern
 894 Tongchangkou and Sandaomingshui samples. All scale bars = 50 μm .

895 Figure 7. U-Pb Concordia plot for the Tongchangkou (a), Northern Tongchangkou (b) and
896 Sandaomingshui (c) analyses. Plots generated using Isoplot (Ludwig, 2003).

897 Figure 8. Isotopic data. (a) $\epsilon\text{Nd}(t)$ versus intrusive age; (b) $\epsilon\text{Nd}(t)$ vs $(^{87}\text{Sr}/^{86}\text{Sr})_t$ ratios (lower
898 crust and upper crust fields from Wu et al., 2003a).

899 Figure 9. (a) Y versus Zr diagrams (after Muller et al., 1992); (b) Th/Ta versus La/Yb
900 diagram (Condie, 2001); (c) Th/Yb vs. Ba/La discrimination diagrams for metasomatic
901 agents added to the mantle wedge (Hanyu et al., 2006); (d) Nb/Yb versus Th/Yb diagram
902 (after Pearce, 2008). PM-primordial mantle, DM-depleted mantle, EM-enriched mantle, OIB-
903 oceanic island basalt, MORB-middle oceanic ridge basalt, AFC-assimilation and fractional
904 crystallization, UC-upper crust, HIMU-high μ (U + Th)/Pb reservoir.

905 Figure 10. (a) La_N/Yb_N versus Yb_N (Martin 1986); (b) Sr/Y versus Y (Defant and Drummond,
906 1990); (c) Trace element tectonic discrimination diagrams for granites (Pearce, 1996) (WPG-
907 within plate granites, syn-COLG-syn-collision granites, VAG-volcanic arc granites, ORG-
908 ocean ridge granites, POG-post-collision granites).

909 Figure 11. Schematic tectonic evolution of the Beishan Middle Plutonic Belt. See text for
910 details. Based on data from this study; BGGP, 1967; Feng et al., 2012; Xiao et al., 2010;
911 Zhang et al., 2010, 2011, 2012a, b, 2015; Zheng et al., 2013a; Zuo and He, 1990.