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Petrogenesis of early Silurian intrusions in the Sanchakou area of Eastern Tianshan, Northwest China, and tectonic implications: geochronological, geochemical, and Hf isotopic evidence

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ABSTRACT

Palaeozoic intrusions in Eastern Tianshan are important for understanding the evolution of the Central Asian Orogenic Belt (CAOB). The Sanchakou intrusions situated in Eastern Tianshan (southern CAOB), are mainly quartz diorite and granodiorite. A comprehensive study of zircon U–Pb ages, zircon trace elements, whole-rock geochemistry, and Lu–Hf isotopes were carried out for the Sanchakou intrusive rocks. LA-ICP-MS zircon U–Pb dating yielded crystallization ages of 439.7 ± 2.5 Ma (MSWD = 0.63, n = 21) for the quartz diorite, and 430.9 ± 2.5 Ma (MSWD = 0.21, n = 21) and 425.5 ± 2.7 Ma (MSWD = 0.04; n = 20) for the granodiorites. These data, in combination with other Silurian ages reported for the intrusive suites from Eastern Tianshan, indicate an early Palaeozoic magmatic event in the orogen. In situ zircon Hf isotope data for the Sanchakou quartz diorite shows εHf(t) values of +11.2 to +19.6, and the two granodioritic samples exhibit similar εHf(t) values from +13.0 to +19.5. The Sanchakou plutons show metaluminous to weakly peraluminous, arc-type geochemical and low-K tholeiite affinities, and display trace element patterns characterized by enrichment in K, Ba, Sr, and Sm, and depletion in Nb, Ta, P, and Ti. The geochemical and isotopic signatures indicate that the Sanchakou dioritic and granodioritic magmas were sourced from a subducted oceanic slab, and subsequently underwent some interaction with peridotite in the mantle wedge. Combined with the regional geological history, we suggest the Sanchakou intrusions formed due to the northward subduction of the Palaeo-Tianshan Ocean beneath the Dananhu–Tousuquan arc during early Silurian time.

1. Introduction

The Central Asian Orogenic Belt (CAOB), one of the largest Phanerozoic accretionary orogens in the world (Goldfarb et al. 2001, 2014; Windley et al. 2007; Safonova 2009; Xiao et al. 2013; Deng et al. 2014a; Deng and Wang 2015; Wang et al. 2015c, 2015d), formed by multiple accretionary and collisional events that occurred from early Neoproterozoic to Permian time and were driven by the successive closure of the Palaeo-Asian Ocean (Şengör et al. 1993; Jahn 2004; Xiao et al. 2010; Deng et al. 2014b, 2015; Shen et al. 2014; Zhang et al. 2016b). The Eastern Tianshan orogenic belt in Northwest China lies along the southern margin of the CAOB (Figure 1A and B) and contains widespread Palaeozoic intermediate-felsic intrusions (Mao et al. 2005; Charvet et al. 2007; Zhou et al. 2010; Pirajno 2013; Wang et al. 2014, 2016; Xiao et al. 2015). These intrusions are of considerable geological interest, not only because they are spatially and genetically associated with numerous metal deposits, especially porphyry systems, such as the Tuwu–Yandong Cu deposits (Shen et al. 2014; Wang et al. 2015a, 2015b), Chihu Cu deposit (Zhang et al. 2016a), Sanchakou Cu deposit (Qin et al. 2009), and Yuhai Cu deposit (Zang 2014), but also because they offer an opportunity to unravel the mechanism of magma formation and geodynamic evolution of the Eastern Tianshan orogenic belt.

In the past decades, numerous studies have examined late Palaeozoic magmatic rocks in the Eastern Tianshan orogenic belt (Mao et al. 2008; Pirajno et al. 2011; Shen et al. 2012a; Wang et al. 2015c), exemplified by Tuwu, Yandong, Chihu, and Linglong felsic intrusions, and Huangshan and Xiangshan mafic intrusions, which were interpreted to have formed in subduction arc and post-collisional settings, respectively (Qin et al. 2009, 2011; Su et al. 2012; Shen et al. 2014; Wang et al. 2015a, 2015b; Zhang et al. 2016a). However, less attention has been paid to the early Palaeozoic igneous rocks in this orogenic
belt. There is no consensus for the regional geological history, magmatic activities, and associated mineralization (Rui et al. 2002; Gu et al. 2006; Han et al. 2006; Li et al. 2006; Chen et al. 2011; Pirajno 2013; Zang 2014), largely related to a lack of geochronological and geochemical data on early Palaeozoic igneous rocks. The Sanchakou area, located within eastern part of the Eastern Tianshan, is an ideal area to investigate the geodynamic processes of early Palaeozoic magmatic activity, because of its linkage to the Dananhu–Tousuquan arc and the Kanggur–Huangshan ductile shear zone (Figure 1C). To date, little research has been undertaken on the Sanchakou area, which precludes a comprehensive understanding of the petrogenesis and its relationship to Cu mineralization. Here, we present new LA-ICP-MS zircon U–Pb dating, whole-rock geochemical data, and zircon trace element and Hf isotopic compositions of the Sanchakou quartz diorite and granodiorite in an attempt to better constrain the timing of magmatic activities, the petrogenesis of these intrusions, and the geodynamic setting of early Silurian magmatism in Eastern Tianshan orogenic belt and elsewhere in CAOB.

2. Geological setting

The Eastern Tianshan orogenic belt is an approximately 300 km wide collage bounded by the Junggar Basin to the north and the Tarim Basin to the south (Figure 1B; Chen et al. 2012b), and can be divided into the Bogeda–Hae like belt, the Jueluotage belt, and the Central Tianshan Terrane from north to south (Figure 1C; Pirajno et al. 2011; Chen et al. 2012b; Xiao et al. 2013), with a series of approximately E–W-trending regional-scale faults defining the boundaries, including the Dacaotan, Kanggur, Yamansu, and Aqikuduke faults, and some small-scale faults (Figure 1C; Mao et al. 2005, 2008; Chen et al. 2012a; Huang et al. 2013).

The Jueluotage belt may be subdivided into the Dananhu–Tousuquan arc belt, the Kanggur–Huangshan ductile shear zone, and the Aqishan–Yamansu arc belt, which are separated by the Kanggur and Yamansu faults (Figure 1C). The Dananhu–Tousuquan arc belt is mainly composed of Devonian volcanic and clastic sedimentary rocks of the Dananhu Formation; Carboniferous turbidites of the Gandun Formation; Carboniferous basaltic to andesitic volcanic and sedimentary rocks of the Qi’eshan Group; Permian calc-alkaline volcanic, pyroclastic, and clastic rocks; Jurassic sandstone; and Cenozoic cover (Zhou et al. 2008, 2010; Shen et al. 2014; Xiao et al. 2015). Intrusions were widely emplaced in the arc during the Devonian to Carboniferous, associated with several important porphyry Cu deposits of different sizes, including the Tuwu, Yandong, Linglong, Chihu, and
Fuxing deposits (Figure 1C). The middle Kanggur–Huangshan ductile shear zone is mainly composed of Devonian–Carboniferous volcanioclastic rocks, basalt, tuff, limestone, sandstone, and ophiolitic slice (Mao et al. 2008; Zhang et al. 2008; Xiao et al. 2010). Permain mafic and ultramafic intrusions (e.g. Xiangshan, Huangshandong, Huangshan, and Hulu) are common within the eastern Kanggur–Huangshan ductile shear zone (Han et al. 2006; Qin et al. 2011; Zhang et al. 2015a). The Aqishan–Yamansu arc belt is composed of early Carboniferous basalt, andesite, dacite, and tuff of the Yamansu Formation and late Carboniferous rhyolite of the Tugutubulake Formation (Chen et al. 2012a; Xiao et al. 2013; Hou et al. 2014). Numerous arc-related late Palaeozoic granitoids intrude this belt (Wang et al. 2005; Wu et al. 2006a; Zhou et al. 2010; Zhang et al. 2015a), including the Weiquan granodiorite (297 ± 3 Ma), Bailingshan granodiorite (317.7 ± 3.7 Ma), Hongyuntan granodiorite (328.5 ± 9.3 Ma), and Xifengshan granite (349 ± 3.4 Ma).

The Sanchakou pluton is situated in the eastern Dananhu–Tousuquan arc belt, approximately 120 km southeast of Hami City, Xinjiang (Figure 1C). The main lithostratigraphic units in the Sanchakou area include: the lower Carboniferous Gandun Formation, consisting of turbidites, argillaceous slate and siltstone intercalated with lithic sandstone; lower Carboniferous Wutongwozi Formation spilite–keratophyric series; and the overlying Miocene Taoshuyuan Formation and Quaternary sediments (Qin et al. 2009; Wang et al. 2015f). The major structures in the Sanchakou pluton are NE-trending ductile shear faults that are related to the Kanggur–Huangshan ductile shear zone, whereas NW- and NE-trending structures are also present within the area (Figure 2; Li et al. 2004; Lang et al. 1992). These well-developed faults control the distribution of major strata and intrusive rocks at Sanchakou. The intrusions generally occur as stocks or dikes with an outcrop area of approximately 65 km² (Figure 2; Li et al. 2004; Qin et al. 2009), and are mainly composed of diorite and granodiorite (Figure 3A and B), with minor gabbro, tonalite, muscovite granite, and alkali-feldspar granitic rocks. The quartz diorite and granodiorite host most of the Cu mineralization (Figure 4A–C). The ore minerals at Sanchakou are dominated by chalcopyrite and bornite (Figure 4D), accompanied by minor pyrite, molybdenite, and chalcolite. Chalcopyrite generally is disseminated (Figure 4A) or cloudy (Figure 4B and C) structure in the ore-hosting intrusive rocks. The main gangue minerals consist of quartz, biotite, K-feldspar, sericite, with minor chlorite, epidote, and calcite.

3. Samples and petrology

Eleven least altered samples of quartz diorite and granodiorite were collected from outcrops or from the open pit mine for LA-ICP-MS zircon U–Pb dating, whole-rock major and trace element compositions, and in situ Hf isotopic and whole-rock geochemical analyses; sampling locations are shown in Figure 2. Quartz diorite shows light grey colour and displays medium-grained texture (Figure 3A). It exhibits massive structure, consisting of plagioclase (~50 vol. %), hornblende (~20 vol. %), biotite (~15 vol. %), quartz (~10 vol. %), and K-feldspar (~5 vol. %) (Figure 5), with accessory magnetite, apatite, and zircon. Plagioclase is characterized by a hypidiomorphic, tabular texture with polysynthetic twinning (Figure 3C). Hornblende is dominated by a xenomorphic tabular texture, and biotite shows hypidiomorphic–xenomorphic flaky or fragmental texture. Granodiorite is light grey to grey-white and shows medium-coarse grain texture and massive structure (Figure 3B). The rock is primarily composed of plagioclase

![Figure 2. Simplified geological map of the Sanchakou intrusions (modified from Sun et al. 2009).](image-url)
(~40 vol. %), quartz (~25 vol. %), K-feldspar (~15 vol. %), hornblende (~10 vol. %), and biotite (~5 vol. %) (Figure 5), with accessory magnetite, apatite, and zircon. Plagioclase generally appears as hypidiomorphic–xenomorphic board (Figure 3D). Hornblende is characterized by hypidiomorphic, tabular texture, and quartz is characterized by xenomorphic granular texture with weak silicification.

4. Analytical methods

Zircons were separated from dioritic and granodioritic samples using conventional heavy liquids, magnetic separation techniques, and handpicking under a binocular microscope at the Langfang Regional Geological Survey in Hebei Province, China. The zircons were then mounted in epoxy before polishing with a diamond
compound to reveal the internal structures. To characterize the internal structures of the zircons and select potential sites for U–Pb dating, cathodoluminescence (CL) images were collected using a CL spectrometer (Garton Mono CL3+) attached to a Quanta 200 F ESEM with a scanning time of 2 min under operating conditions of 15 kV and 120 nA. The instruments are housed at Peking University, Beijing, China. Based on the CL images, we selected zircons that were transparent, unfractured, and inclusion-free for isotopic analyses.

LA-ICP-MS zircon U–Pb dating and trace element analyses were synchronously conducted on an Agilent 7500a ICP-MS, equipped with a 193 nm laser ablation system, housed at the State Key Laboratory of Geological Process and Mineral Resources of the China University of Geosciences, Beijing. During the analyses, the laser spot was 10 or 23 μm in different samples. The $^{207}$Pb/$^{206}$Pb and $^{206}$Pb/$^{238}$U ratios were calculated using the GLITTER program, and then corrected using zircon TEMORA-1 as an external standard. The detailed analytical procedures are similar to those described by Yuan et al. (2004) and Wu et al. (2006b). Error on individual analysis by LA-ICP-MS is quoted at the 1σ confidence level. The results were processed using ISOPLOT software (Ludwig 2003).

Major and trace element analyses of the dioritic and granodioritic samples were conducted at the test centre of the Beijing Research Institute of Uranium Geology. The samples were chipped and powdered to about 200 mesh for major and trace element analyses. Major elements were determined by a Philips PW 2404 X-ray fluorescence (XRF) spectrometer with a rhodium X-ray source. The testing precision was better than 1%, and the detailed analytical procedures were after Norrish and Hutton (1969). Sample powders for trace element analyses were accurately weighed (25 mg) into Savillex teflon beakers within a high-pressure bomb, and then digested using HF + HNO$_3$ + HClO$_4$ acid to assure complete dissolution of refractory minerals. Trace elements, including rare earth elements, were determined using an Element-I plasma mass spectrometer (Finnigan-MAT Ltd. German), and national geological standard reference samples GSR-3 and GSR-15 were used for analytical quality control. The analytical precision for trace elements was better than 5%, and the analytical procedures were described by Qi et al. (2000).

In situ zircon Hf isotopic analyses were measured using a Neptune MC-ICP-MS, equipped with a Geolas 193 nm laser-ablation system at the Institute of Geology and Geophysics, Chinese Academy of Sciences, in Beijing. Lu–Hf isotope of zircons were acquired on the same spot as U–Pb ages with spot size of 60 μm and a 6 Hz pulse frequency, and the international standard zircon sample GJ-1 was used as a reference. Details on the instrumental conditions and data acquisition were comprehensively described by Wu et al. (2006b). In order to correct the isobaric interferences of $^{176}$Lu and $^{176}$Yb on $^{176}$Hf, $^{176}$Lu/$^{175}$Lu = 0.02658 and $^{176}$Yb/$^{175}$Yb = 0.796218 (Chu et al. 2002) ratios were assumed. Zircon GJ-1 was used as the reference standard and yielded a weighted average $^{176}$Hf/$^{177}$Hf ratio of 0.282006 ± 0.000006 and $^{176}$Lu/$^{177}$Hf ratio 0.00024 (2σ, n = 71). The initial $^{176}$Lu/$^{176}$Hf ratios were calculated by using a decay constant of $1.867 \times 10^{-11}$ year$^{-1}$ for $^{176}$Lu (Söderlund et al. 2004). The chondritic values of the $^{176}$Lu/$^{177}$Hf ratio of 0.0332 and $^{176}$Hf/$^{177}$Hf ratio of 0.282772 (Blichert-Toft and Albarède 1997) were adopted to calculate the $\varepsilon_{Hf(t)}$ values. The $T_{DM}$ (depleted mantle model age) was measured in reference to the depleted mantle at a present-day $^{176}$Lu/$^{177}$Hf ratio of 0.0384 and $^{176}$Hf/$^{177}$Hf ratio of 0.28325 (Griffin et al. 2002). The $T_{DM}$ (crustal model age) was calculated using an average continental crustal $^{176}$Lu/$^{177}$Hf ratio of 0.015 (Griffin et al. 2002).

5. Result

5.1. Zircon U–Pb ages

The analytical results of three samples from the Sanchakou quartz diorites and granodiorites are listed in Supplementary Table 1 (see http://dx.doi.org/10.1080/00206814.2016.1152516 for supplementary tables), and representative zircon CL images are shown in Figure 6.

One sample SCK-3 of the Sanchakou quartz diorites was chosen for LA-ICP-MS zircon U–Pb dating and 25

Figure 5. QAP modal diagram showing the classification of the Sanchakou intrusions (after Le Maitre et al. 2002). Q, quartz; A, alkali-feldspar; P, plagioclase.
zircon rims were dated. The zircon grains are euhedral-subhedral and show prismatic forms (150–230 μm long), with aspect ratios of 1:1 to 2:1, and exhibit well-developed oscillatory zoning in CL images (150–230 μm long), with aspect ratios of 1:1 to 2:1, and exhibit well-devel-

oped oscillatory zoning in CL images (Figure 6A). Except for four discordant spots (05, 06, 22, and 23), the remaining 21 analyses from the quartz diorite sample (SCK-3) give concordant 206Pb/238U ages ranging from 428 to 447 Ma, with a weighted mean age of 439.7 ± 2.5 Ma (MSWD = 0.63; Figure 7A). The low U (37–506 ppm) and Th (10–228 ppm) contents, integrated with the internal structure and morphology of the zircons, suggest that the weighted mean age can be interpreted as the magma emplacement age of the quartz diorite at Sanchakou.

Two samples of Sanchakou granodiorites, SCK-4 and SCK-2, were selected for LA-ICP-MS zircon U–Pb dating. Zircons from both samples are prismatic, euhedral, range in length from 150 to 350 μm, with an aspect ratio of 2:1 to 3:1, and display clear oscillatory zoning in CL images (Figure 6B and C). The U (29–452 ppm) and Th (7–448 ppm) contents, combined with the structural features in CL images, suggest these are typical magmatically crystallized zircon (Hoskin and Schaltegger 2003). Twenty-five zircon grains from sample SCK-4 were analysed. Among these, 21 spot analyses show concordant ages from 426 to 439 Ma with a weighted mean 206Pb/238U age of 430.9 ± 2.5 Ma (MSWD = 0.21; Figure 7B), which is considered to represent the crystallization age of the rock. Twenty-five zircons from the sample SCK-2 were also analysed. Among these, 20 spot analyses are clustered around 206Pb/238U ages in the range of 424–429 Ma, with an error weighted mean age of 425.5 ± 2.7 Ma (MSWD = 0.04; Figure 7C), which also represents the crystallization age of the intrusion. Therefore, we suggest that the magma emplacement of the Sanchakou granodiorites occurred at ca. 431–426 Ma.

5.2. Zircon geochemistry and Ti-thermometry

Zircon grains from ca. 440 Ma quartz diorites display pronounced light rare earth element (LREE) depletion with LaN/YbN = 0.00003–0.00185, positive Ce anomalies with Ce/Ce* = 3.70–93.31, but negative Eu anomalies with Eu/Eu* = 0.52–0.80 (Figure 8A). They show variable SmN/LaN ratios ranging from 3 to 191, with La contents of 0.03–1.84 and Th/U ratios of 0.22 to 0.45 (Supplementary Tables 2 and 1; see http://dx.doi.org/10.1080/00206814.2016.1152516 for supplementary tables). The Ti contents in zircon grains are similar and vary from 3.78 to 10.99 ppm (average 6.91 ppm). Zircon grains from ca. 431–426 Ma granodiorites have similar chondrite normali-

zed rare earth element (REE) patterns with significant heavy rare earth element (HREE) enrichments (LaN/YbN = 0.00001–0.00209), and show strong positive Ce anomalies (Ce/Ce* = 3.82–318.14) and negative Eu anomalies (Eu/Eu* = 0.44–0.72) (Figure 8B and C), except for one outlier of 1.10. The grains show highly variable SmN/LaN ratios of 10–2906, with La contents of 0.02–1.65 and Th/U ratios of 0.22–1.10 (Supplementary Table 2). They exhibit relatively variable Ti contents ranging from 3.96 to 77.35 ppm (average 9.74 ppm). The calculated results of Ti-in-zircon thermometer can be used to determine the genetic setting of zircons (Fu et al. 2009; Watson et al. 2006). Calculated Ti-in-zircon thermometer temperatures vary from 662°C to 749°C (average 707°C, n = 25) in the quartz diorite, and 680–815°C (average 730°C, n = 25) and 665°C to 959°C (average 720°C, n = 25) in the granodiorites (Supplementary Table 2). Magmatic zircons crystallize from ore-forming fluids at temperatures higher than 600°C (Fu et al. 2009; Wan et al. 2012). Therefore, the high formation temperatures and Th/U ratios of zircons from the Sanchakou area can be taken as evidence for their crystallization from magmas.
5.3. Whole-rock major and trace elements

Whole-rock major-trace elements and rare earth elements in eight representative samples, which include three quartz diorites (SCK-5, SCK-8, and SCK-3) and five granodiorites (SCK-2, SCK-4, SCK-6, SCK-7, and SCK-9) are presented in Supplementary Table 3. These samples plot in the diorite and granodiorite fields, respectively, on the Na$_2$O+K$_2$O vs. SiO$_2$ diagram (Figure 9A; Le Maitre 2002).

Quartz diorite samples are characterized by intermediate SiO$_2$ (61.57–63.50 wt.%), high MgO (1.93–1.98 wt.%), low K$_2$O contents (0.20–0.56 wt.%) (Figure 9A), and A/CNK ratios (Al$_2$O$_3$/(CaO+Na$_2$O+K$_2$O), mole ratio) of 0.93–1.12. They also show low-K tholeiite characteristics with K$_2$O/Na$_2$O ratios ranging from 0.06 to 0.15. The Mg# values [100 × molecular Mg$^{2+}$/(Mg$^{2+}$ + Fe$^{3+}$)] of the quartz diorite samples vary from 36 to 44 (Supplementary Table 3). Granodioritic samples display slightly higher SiO$_2$ (63.81–66.41 wt.%), MgO (1.30–2.03 wt.%), and low K$_2$O contents (0.17–0.50 wt.%). On a K$_2$O vs. SiO$_2$ diagram (Figure 9B; Rollinson 1993), all granodioritic samples plot in the low-K tholeiite field. They have low A/CNK values in the range of 0.99–1.10.
indicating metaluminous to weakly peraluminous series (Maniar and Piccoli 1989). The samples from the dioritic and granodioritic intrusions have similar REE and trace element patterns (Figure 10A and B). In the chondrite-normalized REE diagram (Boynton 1984), the intrusive samples are characterized by high concentrations of LREEs and low contents of HREEs, with a clear LREE/HREE fractionation ((La/Yb)_N = 7.12–48.43), prominent LREE fractionation, and positive Eu anomaly (Eu/Eu* = 0.98–1.61) (Figure 10A). In the N-MORB-normalized trace element spider diagram (Bevins et al. 1984), these rocks are characterized by distinctly negative Nb, Ta, Th, Pb, and Ti anomalies, with positive K, Ba, Sr, U, and Sm anomalies (Figure 10B).

5.4. Zircon Hf isotope

In situ Hf isotopic data for zircons from three samples of SCK-3 (quartz diorite), SCK-4, and SCK-2 (granodiorite) are shown in Figure 11, and the zircon Hf isotopic data and calculation results are listed in Supplementary Table 4. Twenty-one zircon grains from sample SCK-3 (439.7 ± 2.5 Ma) were analysed for Hf isotopic compositions, and the results show _176^Hf/^{177}Hf ratios ranging from 0.282821 to 0.283068, _176^{Yb}/^{176}Hf ratios from 0.017831 to 0.065735, and _176^{Lu}/^{176}Hf ratios from 0.000849 to 0.002941. They have f_{Lu/Hf} in the range of...
–0.97 to –0.91, with an average of –0.95. The positive ε\text{Hf}(t) values of zircons and Hf isotopic crustal model ages (T\text{DM}^c) vary from +11.2 to +19.6, and from 173 to 709 Ma, respectively (Supplementary Table 4; Figure 11).

Twenty-one zircons analyses were obtained for granodiorite sample SCK-4 (430.9 ± 2.5 Ma), yielding 176Hf/177Hf ratios from 0.282888 to 0.283036, 176Yb/176Hf ratios from 0.012865 to 0.121129, and 176Lu/176Hf ratios from 0.000691 to 0.005704. They have positive ε\text{Hf}(t) values and Hf isotopic crustal model ages (T\text{DM}^c) ranging from +13.0 to +7.8, and from 279 to 587 Ma, respectively (Supplementary Table 4). Twenty zircons from granodiorite sample SCK-2 (425.5 ± 2.7 Ma) were analysed, yielding 176Hf/177Hf ratios from 0.282984 to 0.283073, 176Yb/176Hf ratios from 0.018874 to 0.065469, and 176Lu/176Hf ratios from 0.001024 to 0.003224. The positive ε\text{Hf}(t) values of zircons and Hf isotopic crustal model ages (T\text{DM}^c) vary from +13.2 to +19.5, and from 167 to 568 Ma, respectively (Supplementary Table 4).

6. Discussion

6.1. Ages of the magmatic events in Eastern Tianshan

The available geochronological data clearly show three main magmatic episodes for the Eastern Tianshan orogenic belt (Wang et al. 2006a, 2015e, 2016; Mao et al. 2008, 2014; Zhang et al. 2008; Zhou et al. 2010; Chen et al. 2014). The youngest magmatism occurred in the Triassic and includes: (1) the ~227 Ma Baishan granite porphyry plutons associated with Mo deposit (Wang et al. 2015e); (2) the 234–232 Ma Dongcebi porphyritic granite and granite porphyry plutons associated with Mo deposit (Zhang et al. 2015b); (3) the ~237 Ma fine-grained granite located in the Weiya area (Zhang et al. 2005); and (4) the ~210 Ma Tianhu monzonitic granite (Li and Chen 2004), which were formed in an intracontinental setting. The second episode of magmatism occurred during the late Palaeozoic (369–286 Ma). Representative examples include: (1) the 288–286 Ma Huangshan and Xiangshan mafic rocks formed in a post-collisional setting (Zhou et al. 2010; Qin et al. 2011); and (2) the 332–369 Ma Tuwu and Yandong ore-forming porphyries that formed in an arc setting associated with the northward subduction of the Palaeo-Tianshan ocean (Rui et al. 2002; Shen et al. 2014; Wang et al. 2015a, 2015b). The earliest magmatic episode occurred during the early Palaeozoic, and is rarely recognized in the Eastern Tianshan orogenic belt. However, recent studies reveal some early Palaeozoic magmatic events in the orogen (Shu et al. 2004; Zhang et al. 2008; Lei et al. 2011; Wang et al. 2015f). Typical examples include the Dananhu monzogranite (383 ± 9 Ma, Song et al. 2002), the Xingxingxia granodiorite (425 ± 4 Ma; He et al. 2012), the Yuhai granodiorite (422.3 ± 4 Ma; Zang 2014), the Weiya granulite (343.7 ± 2.5 Ma; Shu et al. 2004), and Mishigougabro (468 Ma; Shu et al. 1999), which represent a significant early Palaeozoic magmatic hydrothermal event.

In this study, we present new zircon U–Pb data for three representative intrusive samples collected from the Sanchakou area located in the interior of the Dananhu–Tousuquan arc belt (Figure 1C). The zircon U–Pb dating results indicate that the Sanchakou quartz diorite was emplaced at 439.7 ± 2.5 Ma (Figure 7A), whereas the granodiorite formed at 430.9 ± 2.5 to 425.5 ± 2.7 Ma (Figure 7B and C). This result is inconsistent with most previous studies that proposed an early Permian age for the intrusive rocks (278–276 Ma; Lang et al. 1992; Li et al. 2004), but comparable to the zircon U–Pb age (443 ± 2.9 Ma) for the granodiorite recently reported by Wang et al. (2015f). It is increasingly clear that the Sanchakou area experienced multi-stage magmatism, and that the earliest stage of magmatism might have occurred during the early Silurian (443–426 Ma). These geochronological data, as well as the previous ages mentioned above, demonstrate that the early Palaeozoic magmatic activity was also developed in Eastern Tianshan orogenic belt.

6.2. Petrogenesis and magma source

All Sanchakou intrusive samples are characterized by high Al2O3 (15.98–17.56 wt.%), Sr (652–773 ppm), and Sr/Y ratios (68–120), and low Yb (0.44–1.33 ppm) and Y (5.43–11.1 ppm), and obvious positive Eu anomalies (Eu/Eu* = 0.98–1.61), showing geochemical affinity with adakites (Defant and Drummond 1990). In the (La/Yb)N vs. YbN discrimination diagram, the Sanchakou intrusive rocks also plot well within the adakitic field (Figure 12A). We therefore suggest that the Sanchakou intrusions can be classified as adakitic rocks. There are several mechanisms proposed for the genesis of adakitic magmas, including: (1) partial melting of delaminated lower crust (Guo et al. 2006; Kadioglu and Dilek 2010); (2) partial melting of hydrated mafic rocks in a thickened lower crust (Guan et al. 2012; Hou et al. 2013; Sui et al. 2013); (3) partial melting of subducted oceanic crust with or without contributions from the mantle wedge (Defant and Drummond 1990; Zhu et al. 2009; Sun et al. 2010, 2011); and (4) crustal assimilation and fractional
crystallization (AFC) processes involving parental basaltic magmas (Macpherson et al. 2006; Richards and Kerrich 2007).

Experimental and geochemical studies indicate that subducted slab-derived adakites generally have high MgO, CaO, Cr, and Ni contents and Mg# values (>40), due to interaction with the overlying peridotite in the mantle wedge during magma ascent, whereas lower crust-derived adakites have low compatible trace elements (e.g. Cr and Ni) (Yogodzinski and Kelemen 1998; Rapp et al. 1999; Zhu et al. 2009; Guan et al. 2012). Adakitic intrusions in the Sanchakou area exhibit moderate MgO contents and Mg# values, ranging from 1.30 to 2.03 wt.% and 36–46, respectively, which are consistent with being subducted oceanic slab-derived adakites (Figure 12B), such as the Tuwu–Yandong tonalites (Wang et al. 2015a, 2015b) in Eastern Tianshan. This interpretation is also supported by high Cr concentration (69.6–118 ppm) of the Sanchakou intrusions (Supplementary Table 3). Thus, these geochemical characteristics indicate that these magmas were probably derived from partial melting of a subducted slab, which subsequently hybridized by mantle wedge.

In addition, the adakitic intrusions at Sanchakou are unlikely to reflect AFC processes of parental basaltic magmas (Macpherson et al. 2006; Richards and Kerrich 2007), because they exhibit no obvious systematic variations in geochemical compositions associated with AFC (Castillo et al. 1999; Macpherson et al. 2006). Furthermore, the trace element signatures of the these rocks show positive correlation between Zr/Nb and Zr values, as well as La/Yb and La values, indicating that the partial melting process was dominant in their petrogenesis (Figure 12C and D). The pronounced LREE fractionation and weak HREE depletion patterns (Figure 10A) of the Sanchakou intrusions further demonstrate that they fit with generation from partial melting of subducted oceanic crust (Defant and Drummond 1990; Sun et al. 2010, 2011).

This interpretation is also supported by the positive zircon εHf(t) values (+11.2 to +19.6) recorded in the Sanchakou intrusions. In the εHf(t) vs. U–Pb age diagram (Figure 11), zircons from these samples show a spread of εHf(t) values near the depleted mantle evolution line, comparable to those of the Silurian intrusions in Southern Tianshan (e.g. Baicheng) (Zhao et al. 2015) and Carboniferous intrusions (e.g. Tuwu and Yandong) in the Dananhu–Tousuquan arc belt formed by partial melting of subducted oceanic crust (Zhang et al. 2004, 2008; Shen et al. 2014). The zircon Hf isotopic
compositions of the adakitic tonalites from the Tuwu–Yandong areas show variable εHf(t) values ranging from 6.9 to 17.2 (Wang et al. 2015a, 2015b). In comparison, the relatively inhomogeneous Hf isotopic composition (8.4 units) recorded in the Sanchakou intrusions suggest strong interaction between subducted oceanic crust and mantle wedge peridotite during the formation of adakitic intrusions.

In summary, the Sanchakou adakitic (quartz diorite and granodiorite) magmas are interpreted to be derived from the partial melting of subducted oceanic crust, and these magmas interacted further with peridotite in the mantle wedge.

6.3. Geodynamic implications

Previous studies infer for the Eastern Tianshan the simultaneous southward and northward subduction of the Palaeo-Tianshan oceanic plate during the Carboniferous formed the Aqishan–Yamansu and the Dananhu–Tousuquan arcs, respectively (Han et al. 2006; Wang et al. 2006b, 2015a; Zhang et al. 2008). In the Dananhu–Tousuquan arc belt, Late Devonian to early Carboniferous volcanic and plutonic rocks, including the Tuwu, Yandong, and Chihu intrusive rocks, display an obvious subduction-related component as evidenced by positive bulk εNd(t) and zircon εHf(t) values (Tang et al. 2010; Su et al. 2012; Wang et al. 2014, 2015a), formed in a subduction-related setting. Since the early Permian, the Eastern Tianshan is considered to have entered the post-collisional stage, based on the presence of the youngest ophiolite of ~310 Ma along with widespread bimodal volcanic rocks of ~290 Ma (Chen et al. 2011; Qin et al. 2011; Su et al. 2012; Xiao et al. 2013).

LA-ICP-MS zircon dating and geochemical data presented in this study provide solid evidence for the existence of subduction-related adakitic rocks in Eastern Tianshan during early Silurian time. This arc magmatism significantly predates the opening of the Palaeo-Tianshan ocean and suggests the northward subduction of oceanic crust prior to ~440 Ma. The geochemical characteristics of the ca. 440 Ma quartz diorite and ca. 431–426 Ma granodiorite in the Sanchakou area of the Eastern Tianshan, such as positive Eu anomalies, significant LREE enrichment, and low HREE abundances, are comparable with those of Tuwu–Yandong arc magmatic rocks (Zhang et al. 2008; Xiao et al. 2015; Wang et al. 2015a, 2015b). Moreover, they are also similar to those of modern arc-type volcanics and arc-related plutons, i.e. negative anomalies of Nb, Ta, Zr, Hf, and Ti and positive Pb anomalies (Figure 10A; Briquè et al. 1984; Pearce et al. 1984; Sun and McDonough 1989; Altherr et al. 2008; Boari et al. 2009). In the Th/Yb vs. Ta/Yb and Th/Yb vs. Nb/Yb discrimination diagrams (Figure 13A and B), all samples fall within the oceanic arc field (Whattam and Hewins 2009), and close to E-MORB area (Pearce and Peate 1995; Sayt and Göncüoğlu 2009), which are characteristics of island arc igneous rocks emplaced during Silurian subduction of an oceanic slab. Therefore, the Sanchakou quartz diorite and granodiorites most likely formed in the Dananhu–Tousuquan island arc.

Taking all of the above into account, we suggest that the initiation of northward subduction of the Palaeo-Tianshan ocean beneath the Dananhu–Tousuquan arc occurred as early as early Silurian time, and that arc magmatism in the Sanchakou area began ca. 440–426 Ma (Figure 14). The interaction between subducted oceanic slab and mantle wedge peridotite could have formed the Sanchakou adakitic magmas.

Figure 13. (A) Th/Yb vs. Ta/Yb diagram (Whattam and Hewins 2009). (b) Th/Yb vs. Nb/Yb diagram (Pearce and Peate 1995; Sayt and Göncüoğlu 2009).
7. Conclusions

(1) LA-ICP-MS zircon U–Pb dating indicates that the Sanchakou quartz diorite was emplaced at ca. 440 Ma, and the granodiorite was emplaced at ca. 431–426 Ma, which represents a prominent early Palaeozoic magmatic event in Eastern Tianshan orogenic belt.

(2) Petrographic and geochemical data suggest that the Sanchakou dioritic and granodioritic plutons is low-K tholeiite; enriched in K, Ba, Sr, U, and Sm; markedly depleted in Nb, Ta, Pb, and Ti; and shows geochemical affinities similar to those of adakites. These characteristics and zircon Hf isotopic data indicate that the Sanchakou intrusions can be attributed to the partial melting of subducted oceanic crust and that these magmas subsequently interacted with mantle wedge.

(3) Our new data combined with regional geological history suggest that the Sanchakou intrusions were generated in an arc setting during the early Silurian. This implies that the initiation of northward subduction of the Palaeo-Tianshan ocean beneath the Dananhu–Tousuquan arc was present as early as ca. 440 Ma in Eastern Tianshan.

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Disclosure statement

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Figure 14. Simplified cartoon showing the tectonic model for the formation of the Silurian intrusions in the Sanchakou area of Eastern Tianshan.


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