Petrogenesis of Late Carboniferous granitoids in the Chihu area of Eastern Tianshan, Northwest China, and tectonic implications: geochronological, geochemical, and zircon Hf–O isotopic constraints

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ABSTRACT
This contribution presents new SIMS zircon U–Pb geochronology, major and trace element geochemistry, and zircon Hf–O isotope systematic on an example of Late Carboniferous granodiorite and porphyritic granodiorite intrusions from the Chihu area of Eastern Tianshan, Xinjiang. SIMS zircon U–Pb dating indicates that the Chihu granodiorite and porphyritic granodiorite formed at 320.2 ± 2.4 Ma and 314.5 ± 2.5 Ma, respectively. These rocks are metaluminous to weakly peraluminous with an A/CNK value of 0.92–1.58, as well as low 10000 Ga/Al, Zr + Nb + Y + Ce, and FeO/MgO values, which suggest an I-type normal island arc magmatic suite. The porphyritic granodiorite has a slightly higher Sr/Y ratio (28–37) and lower Y (6.9–11.7 ppm) and Yb (0.98–1.49 ppm) contents, suggesting mild adakite affinities. In situ Hf–O isotopic analyses using LA-ICP-MS-MC and SIMS indicate that the εHf(t) and δ18O values of granodiorite zircons vary from +11.5 to +14.9 and 5.85 ‰, respectively, similar to values for porphyritic granodiorite zircons, which vary from +11.9 to +17.2 and 3.78 to 4.71 ‰, respectively. The geochemical and isotopic data imply that the Chihu granodiorite and porphyritic granodiorite share a common origin, most likely derived from partial melts of the subduction-modified mantle. Based on the regional geological history, geochemistry of the Chihu intrusions, and new isotopic studies, we suggest that the Late Carboniferous magma was generated during the period of the northward subduction of the Palaeo-Tianshan ocean plate beneath the Dananhu–Tousuquan island arc.

1. Introduction

The Central Asian Orogenic Belt (CAOB) is one of the largest Phanerozoic accretionary orogenic belts on Earth (Şengör et al. 1993; Safonova 2009; Xiao et al. 2013; Goldfarb et al. 2014), and consists of microcontinental blocks, island arcs, oceanic crustal remnants, and continental marginal facies rocks (Coleman 1989; Jahn 2004; Windley et al. 2007; Li et al. 2013a; Pirajno 2013; Wang et al. 2015a, 2015b). The Eastern Tianshan orogenic belt in Northwest China is located in the southern margin of the CAOB (Figure 1(A) and (B)) and contains abundant Carboniferous to Permian granitic rocks (Qin et al. 2002, 2011; Zhou et al. 2010; Su et al. 2012; Shen et al. 2014; Wang et al. 2015a, 2015b), and subordinate Devonian and Triassic granitoids (Chen et al. 2014; Han et al. 2014; Zhang et al. 2015a). This region is also one of the important Cu, Au, Fe, Mo, Ag metallogenic belts in China, and the mineralization is closely related to the granitic rocks (Han et al. 2006; Liu et al. 2007; Pirajno et al. 2011; Chen et al. 2012a, 2012b; Huang et al. 2013; Wang et al. 2015c). Consequently, Eastern Tianshan granitoids provide an excellent opportunity to study CAOB tectonic evolution and the associated metallogenesis. However, the petrogenesis and geodynamic setting of the granitoids are still under debate, with suggested settings such as rift (Qin et al. 2002), back-arc basin (Xu et al. 2003), passive continental margin (Li et al. 2003), island arc (Mao et al. 2005; Zhang et al. 2008; Wang et al. 2015a, 2015b), ridge subduction environment (Sun et al. 2010, 2011), or post-collision setting (Gu et al. 2006; Zhou et al. 2008).

Previous studies mostly focused on the Palaeozoic mineralization and magmatism in the eastern and western parts of the Eastern Tianshan orogenic belt, whereas less attention has been paid to Palaeozoic granitoids in the central part of the belt. The regional tectonic evolution of the Eastern Tianshan has not been adequately understood.
constrained until now, largely due to a lack of detailed geochronological and geochemical data. The Chihu area, located in the central Eastern Tianshan orogenic belt, is an ideal area to investigate the geodynamic processes of magmatism because of its linkage to the Dananhu–Tousuquan arc and the Kanggur–Huangshan ductile shear zone (Figure 1(C)). Similar to the nearby late Palaeozoic Tuwu–Yandong intrusions (Zhang et al. 2004; Shen et al. 2014; Wang et al. 2015a, 2015b; Xiao et al. 2015), Chihu calc-alkaline granitoids are important intrusions in the Eastern Tianshan orogenic belt (Wang et al. 2006a; Wu et al. 2006c; Gao et al. 2015). The Tuwu–Yandong Cu deposits, located ~30 km west of the Chihu deposit in the Dananhu–Tousuquan arc belt, have been studied for geochronology (Liu et al. 2003; Chen et al. 2005; Wang et al. 2014), isotopic geochemistry (Zhang et al. 2004; Shen et al. 2012; Gao et al. 2015; Xiao et al. 2015), and tectonic setting (Shen et al. 2014; Gao et al. 2015; Wang et al. 2015a, 2015b) of the intermediate-felsic intrusions. However, none of these studies have focused on the Chihu area to date, which precludes our understanding of the Chihu granitoids. Here, we present secondary ion mass spectrometry (SIMS) zircon U–Pb, whole-rock geochemistry, and Hf–O isotopic data of the Chihu granodiorite and porphyritic granodiorite in an attempt to better constrain the timing of magmatic activities, the petrogenesis of these granitoids, and the geodynamic setting of Carboniferous magmatism in the Eastern Tianshan orogenic belt.

2. Regional geology

The Eastern Tianshan orogenic belt, located between the Junggar Basin and Tarim Basin (Figure 1(B)), is a typical Palaeozoic island arc system characterized by a complicated tectonic history (Qin et al. 2002; Charvet et al. 2007; Huang et al. 2013; Pirajno 2013; Deng and Wang 2015). It can be divided into three major tectonic zones from the north to the south: the Bogeda–Haerlike belt, the Jueluotage belt, and the Central Tianshan Terrane (Figure 1(C); Pirajno et al. 2011; Chen et al. 2012b). The Bogeda–Haerlike belt comprises well-developed Ordovician–Carboniferous volcanic rocks, granites, and mafic–ultramafic intrusions (e.g. Gao et al. 2015). The Jueluotage belt is characterized by Palaeozoic volcanic and sedimentary rocks, intruded by voluminous Carboniferous–Permian felsic and mafic–ultramafic complexes (e.g. Zhou et al. 2010; Qin et al. 2011; Wang et al. 2015b, 2015c). The Central Tianshan Terrane comprises the Precambrian basement (Bgmrxuar 1993; Shen et al. 2014).
The Jueluotage belt may be subdivided into the Xiaorequanzi–Wutongwozi and Dananhu–Tousuquan arcs in the north, the Kanggur–Huangshan ductile shear zone in the middle, and the Aqishan–Yamansu arc in the south, which are separated by the Kanggur and Yamansu faults (Figure 1(C); Xiao et al. 2004; Qin et al. 2011; Wang et al. 2016). The Xiaorequanzi–Wutongwozi and Dananhu–Tousuquan arc belts mainly consist of Lower Devonian volcanic and clastic sedimentary rocks of the Dananhu Formation, lower Carboniferous turbidites of the Gandun Formation, Carboniferous basaltic to andesitic volcanic rocks and sedimentary rocks of the Qi’eshan group, Permian calc-alkaline volcanic, pyroclastic, and clastic rocks, Jurassic sandstone, and Cenozoic cover (Mao et al. 2005; Zhou et al. 2010; Shen et al. 2014; Gao et al. 2015). The Kanggur–Huangshan ductile shear belt is mainly composed of Devonian–Carboniferous volcanioclastic rocks, basalt, tuff, limestone, sandstone, and ophiolitic slices (Zhang et al. 2008; Xiao et al. 2013; Mao et al. 2014). The Aqishan–Yamansu arc belt is characterized by 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).

The main structures of Eastern Tianshan are characterized by a series of approximately E–W-trending faults, including the regional-scale Dacaotan, Kanggur, Yamansu, and Aqikuqduke faults, and some small-scale faults (Figure 1(C); Mao et al. 2005, 2008; Qin et al. 2011; Huang et al. 2013). The Eastern Tianshan intrusive rocks mainly formed in late Palaeozoic time and include diorite porphyry, plagiogranite porphyry, and granodiorite associated with Cu mineralization, and mafic–ultramafic bodies mainly associated with Cu–Ni mineralization (Zhang et al. 2008; Pirajno et al. 2011; Wang et al. 2015a, 2015b, 2015c).

3. Petrography of the Chihu granitoids

The Chihu area is located along a regional E–W-striking fault at the south margin of the Dananhu–Tousuquan arc belt (Figure 2(A) and (B)). The main lithostratigraphic units include the Carboniferous Qi’eshan Group, consisting of basalt (Figure 3(A)), andesite, and brecciated andesite, intercalated with tuff and lithic sandstone (Wang et al. 2006a).

Figure 2. (A) Geological map of the Yandong–Chihu region showing the distribution of porphyry deposits (modified from Gao et al. 2015); (B) simplified geological map of the Chihu porphyry Cu deposit (modified from Wang et al. 2006b).
Chihu granitoids are predominantly porphyritic granodiorite and granodiorite, which intruded the intermediate to mafic volcanic rocks of the Qi’eshan Group (Figure 2(B)).

The porphyritic granodiorite rock is mainly distributed in the central part of the Chihu area near the main ore body (Figure 2(B)). It is grey-green coloured and exhibits a porphyritic texture (Figure 3(B)–(D)). It contains 40–50% phenocrysts mainly comprising quartz (30–40%), plagioclase (20–30%), and biotite (5–10%). Its groundmass mainly comprises quartz, plagioclase, K-feldspar, and biotite, with accessory minerals that include zircon, apatite, and magnetite. Some quartz grains exhibit distinct corroded textures, and plagioclase shows a hypidiomorphic tabular texture that is partly replaced by sericite (Figure 3(C)). The granodiorite was emplaced as batholith or stock in the southern part of the Chihu area (Figure 2(B)). It is grey-green coloured, and is characterized by a medium-coarse grain texture, massive structure, and a weak alteration. The granodiorite typically contains plagioclase (30–40%), quartz (15–20%), K-feldspar (10–15%), hornblende (5–10%), and biotite (3–5%) with weak silicification (Figure 3(E) and (F)). Its accessory minerals are dominated by titanite, apatite, zircon, and magnetite. Plagioclase generally appears as hypidiomorphic with polysynthetic twins (Figure 3(E)). K-feldspar generally appears as xenomorphic or hypidiomorphic (Figure 3(F)), and quartz is xenomorphic and granular.

4. Samples and analytical methods
4.1. Sample preparation
Granitoid samples for this study were collected from the Chihu area. Owing to pervasive alteration, the granitoids
were more or less affected by sericitization, silicification, and chloritization. Thus, to better measure and understand the chemical composition, the least altered samples were selected for major and trace element, SIMS zircon U–Pb dating, and in situ zircon Hf–O isotopic analyses. They are composed of eight granodiorite and seven porphyritic granodiorite samples, and the sampling locations are shown in Figure 2(B).

4.2. Analytical methods

Zircons grains were separated using conventional heavy liquids, magnetic separation techniques, and handpicking under a binocular microscope at the Langfang Regional Geological Survey in Hebei Province, China. Zircon grains, together with zircon standard Penglai Plesovice (Black et al. 2004) and Qinghu (Li et al. 2009a), were mounted in epoxy, which were subsequently polished to section the crystals in half for analysis. Zircons were imaged with transmitted and reflected light micrographs as well as cathodoluminescence (CL) to reveal their internal structures, and the mount was vacuum coated with high-purity gold prior to O isotopic analyses.

Zircon oxygen isotopic analyses were conducted using the Cameca IMS–1280 SIMS at the Institute of Geology and Geophysics, Chinese Academy of Sciences. The detailed analytical procedure and operating conditions are described by Li et al. (2009b, 2010b). The measured oxygen isotopic data were first normalized relative to the Vienna Standard Mean Ocean Water (VSMOW) and then corrected for instrumental mass fractionation using the zircon Penglai and Qinghu standards with a δ18O value of 5.3 ± 0.1‰ (2α) and 5.4 ± 0.2‰ (2α), respectively (Li et al. 2010b, 2013b). The corrected δ18O values for the samples were reported in the standard per mil notation with 2α errors (Li et al. 2010b).

SIMS zircon U–Pb analyses were conducted at the same domain of the O isotope analytical spots using the same Cameca IMS–1280 SIMS at the Institute of Geology and Geophysics, Chinese Academy of Sciences. Detailed analytical and data acquisition and processing procedures are documented by Li et al. (2009a). A long-term uncertainty of 1.5% (1 RSD) for 206Pb/238U measurements of the standard zircons was propagated to the unknowns (Li et al. 2010a), despite the fact that the measured 206Pb/238U error in a specific session was generally approximately 1% (1 RSD) or less. Measured compositions were corrected for common Pb using the non-radiogenic 204Pb method, and data processing was conducted using the ISOPLOT 3.0 program (Ludwig 2003). Corrections were sufficiently small to be insensitive to the choice of common Pb composition, and an average of present-day crustal composition (Stacey and Kramers 1975) was used for the common Pb composition, assuming that the common Pb was largely because of surface contamination introduced during sample preparation. Uncertainties on individual analyses in data tables were reported at the 1σ level; mean ages for pooled 206Pb/238U results were quoted at the 95% confidence level.

In situ Hf isotopic analyses were performed on a Newwave UP 213 laser-ablation microprobe attached to a Neptune MC-ICP-MS at the MLR Key Laboratory of Metallogeny and Assessment in Chinese Academy of Geological Sciences, Beijing. Depending on the zircon size, a stationary beam spot of approximately 60 μm diameter was employed for the analyses, and the international standard zircon sample GJ1 was used as a reference. Details on the instrumental conditions and data acquisition are given in Wu et al. (2006b). The measured values of the well-characterized zircon standard (GJ1) agreed with the recommended values to within 2σ. The weighted average of the 176Hf/177Hf ratio of the GJ1 zircon samples was 0.282000 ± 0.000011 (2σ, n = 31), consistent with the recommended values (Elhrou et al. 2006) to within 2σ. The initial 176Lu/177Hf ratios were calculated using a decay constant of 1.867 × 10−11 year−1 for 176Lu (Söderlund et al. 2004). The chondritic 176Lu/177Hf ratio of 0.0332 and the 176Hf/177Hf ratio of 0.282772 (Blichert-Toft and Albarède 1997) were adopted to calculate the εHf(t) values. The depleted mantle model age (TDM) was measured with reference to the depleted mantle at a present-day 176Lu/177Hf ratio of 0.0384 and 176Hf/177Hf ratio of 0.28325 (Griffin et al. 2002). The crustal model age (TDM) was calculated using an average continental crustal 176Lu/177Hf ratio of 0.015 (Griffin et al. 2002).

Major and trace element analyses of the granitoid samples were conducted at the test centre of the Beijing Research Institute of Uranium Geology. The samples were shipped 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. Analytical precision was better than 1%, and the detailed analytical procedures were as described by Norrish and Hutton (1969). Sample powders for trace element analyses were weighed (25 mg) into Savillex Teflon beakers within a high-pressure bomb, and then were digested using HF + HNO3 + HClO4 acid to assure the complete dissolution of refractory minerals. Trace elements, including rare earth elements (REEs), were determined using an Element-I plasma mass spectrometer (Finnigan-MAT Ltd. Geram), 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%, with analytical procedures being described by Qi et al. (2000).

5. Results

5.1. SIMS zircon U–Pb dating

Chihu granodiorite sample (CH-9) and porphyritic granodiorite sample (CH001-12) were selected for SIMS zircon U–Pb dating, and the analytical data are listed in Supplementary Table 1 (see http://dx.doi.org/10.1080/00206814.2015.1136800 for supplementary tables). Most zircons are euhedral–subhedral and show long prismatic forms (90–200 μm long) with an aspect ratio of 2:1–3:1, and exhibit clear oscillatory growth zoning in CL images (Figure 4(A) and (C)). Analysed zircons have varying U (93–323 ppm) and Th (49–342 ppm) contents, with Th/U ratios ranging from 0.31 to 1.18 (Supplementary Table 1), which is consistent with a magmatic origin (Hoskin and Schaltegger 2003). Therefore, the SIMS zircon U–Pb dating results are interpreted to represent the timing of zircon crystallization and thus the age of magma emplacement. Fifteen analyses from the granodiorite sample (CH-9) yielded concordant 206Pb/238U ages varying from 311.8 to 327.5 Ma (Figure 4(B)), with a weighted mean age of 320.2 ± 2.4 Ma (MSWD = 0.82, n = 15). Except for two discordant spots (CH001-12@01 and CH001-12@15), the remaining 13 analytical spots from porphyritic granodiorite CH001-12 had 206Pb/238U ages ranging from 308.1 to 324.5 Ma (Figure 4(D)), with a weighted mean age of 314.5 ± 2.5 Ma (MSWD = 0.82, n = 13). Thus, we interpret the two weighted mean ages as emplacement ages of the granodiorite and porphyritic granodiorite, respectively.

5.2. Major and trace element geochemical analyses

Seven granodiorite (CH001-16, CH-15, CH001-14, CH-14, CH001-15, CH-21, and CH001-6) and six porphyritic granodiorite samples (CH001-5, CH001-4, CH001-3, CH-4, CH-5, and CH001-7) were analysed for whole-rock geochemistry (Supplementary Table 2). These samples plot in the granodiorite area on the quartz-alkali feldspar-plagioclase (QAP) diagram (Figure 5; Le Maitre 1989), and span across the granodiorite to granite fields on the Na2O + K2O versus SiO2 diagram (Figure 6(A); Le Maitre 2002).

The granodiorite samples are characterized by high SiO2 (63.27–71.25 wt.%), Al2O3 (11.77–16.01 wt.%), and Na2O + K2O (3.61–6.21 wt.%), and low MgO (1.30–2.65 wt.%), TiO2 (0.27–0.85 wt.%), P2O5 (0.09–0.20 wt.%), and MnO (0.02–0.08 wt.%). These rocks belong to the calc-alkaline series (Figure 6(B); Rollinson 1993) and display low A/CNK values (Al2O3/(CaO+Na2O+K2O), mole ratio) of 0.92–1.58, indicating metaluminous to weakly peraluminous compositions (Figure 6(C); Maniar and Piccoli 1989). The porphyritic granodiorite samples are more siliceous, with SiO2 = 71.98–78.43 wt.%, Al2O3 = 11.08–13.71 wt.%, MgO = 0.79–1.08 wt.%, and Mg# = 37–53 (100 × molar Mg2+/[Mg2+ + Fe2+]); Supplementary Table 2). These rocks have low K2O (0.78–1.70 wt.%), K2O/Na2O (0.18–0.54), and variable...
A/CNK (1.04–1.57) values, similar to low-K tholeiite peraluminous granites (Figure 6(B) and (C)).

In the chondrite-normalized REE diagram (Figure 7(A); Boynton 1984), the granodiorites are moderately fractionated ((La/Yb)\text{N} = 3.46–8.02), with light rare earth element (LREE) enrichment and heavy rare earth element (HREE) depletion and modest negative Eu anomalies (Eu/Eu* = 0.69–0.92). In the N-MORB-normalized trace element spider diagram (Figure 7(B); Bevins et al. 1984), the granodiorites are characterized by negative Nb, Ta, and Ti anomalies and enrichment in large ion lithophile elements (LILEs) (e.g. K, Rb, and Pb). Moreover, the chondrite-normalized REE diagram of the porphyritic granodiorite rocks exhibits moderate LREE enrichment and nearly flat HREE segments that lack significant Eu anomalies (Figure 7(A)). They also show coherent N-MORB-normalized trace element patterns, with clear depletion in Nb, Ta, P, and Ti, and enrichment in K, Rb, Ba, and Pb (Figure 7(B)).

5.3. Zircon Hf–O isotopic analyses

In situ Hf–O isotopic results for zircons from CH-9 (granodiorite) and CH001-12 (porphyritic granodiorite) are shown in Figures 8 and 9, and the zircon Hf–O isotopic data and calculation results are presented in Supplementary Table 3. Fifteen spots on zircon grains from the granodiorite (320.2 ± 2.4 Ma) have δ18O values ranging from 4.80 to 5.85 ‰ (Figure 8(A)), with a weighted mean value of...
5.40 ± 0.14 ‰ (2σ; n = 15). They exhibit variable Hf isotopic compositions, with \(^{176}\text{Hf}/^{177}\text{Hf}(t)\) ratios ranging from 0.282901 to 0.282991 and positive \(\varepsilon_{\text{Hf}}(t)\) values and DM ages ranging from +11.5 to +14.9 and from 383 to 594 Ma, respectively (Supplementary Table 3; Figure 9(A)). Fifteen magmatic zircons from the porphyritic granodiorite (314.5 ± 2.5 Ma) have \(\delta^{18}\text{O}\) values ranging from 3.78 to 4.71 ‰, with a weighted mean value of 4.36 ± 0.15 ‰ (2σ; n = 15). They have \(^{176}\text{Hf}/^{177}\text{Hf}\) ratios varying from 0.282939 to 0.283059, and show positive \(\varepsilon_{\text{Hf}}(t)\) values (+11.9 to +17.2) that corresponded to the Hf isotopic DM value of 232–509 Ma (Supplementary Table 3; Figure 9(B)).

6. Discussion

6.1. Geochronology

According to previous studies, widespread magmatism took place in Eastern Tianshan, and abundant granitoids, including granodiorite, monzogranite, biotite granite, quartz diorite, diorite porphyry, granite porphyry, rhyolite porphyry, and tonalite (Qin et al. 2002; Ru et al. 2002; Mao et al. 2005; Zhou et al. 2008, 2010; Gao et al. 2015; Wang et al. 2015a, 2015b, 2015e), are mainly divided into four magmatic stages: Late Devonian (386–369 Ma) (Li et al. 2006; Tang et al. 2007), Carboniferous (353–297 Ma) (Liu et al. 2003; Li and Chen 2004; Mao et al. 2005; Zhou et al. 2008, 2010; Gao et al. 2015; Wang et al. 2015a, 2015b, 2015e), Permian (290–251 Ma) (Qiu et al. 2011; Hou et al. 2014), and Early to Middle Triassic (246–228 Ma) (Han et al. 2014; Zhang et al. 2015a).

Magmatic activities during these four episodes showed a close temporal and spatial relationship with Cu (Ni), Mo, Au, Fe, and Ag mineral systems, and the Carboniferous episode (353–297 Ma) is the most important magmatic-metallogenic episode in the region (Table 1; Chen et al. 1999, 2009; 2012).
Figure 8. Zircon Hf and O isotopic compositions of the Chihu granitoids. (A, B) The cumulative probability histogram of zircon $\delta^{18}O$ values for the Chihu granitoids; (C) zircon $\delta^{18}O$ versus $\varepsilon_{Hf}(t)$ diagram for the Chihu granitoids. The dotted lines denote the two-component mixing trends between the depleted mantle and the supercrust-derived magmas. $Hf_{pm}/Hf_{lc}$ is the Hf concentration ratio between the parental mantle magma (pm) and the lower crustal (lc) components indicated for each curve, and the small open circles on the curves represent 10% mixing increments by assuming the mantle zircon has $\varepsilon_{Hf}(t) = +12$ and $\delta^{18}O = 5.3$‰; the lower crustal zircons have $\varepsilon_{Hf}(t) = -13$ and $\delta^{18}O = 7.5$‰ (Kempton and Harmon 1992). The field of the depleted mantle is from Valley et al. (2005).

Figure 9. (A) Histogram of zircon $\varepsilon_{Hf}(t)$ values; (B) histogram of zircon Hf-isotope crust model age ($T_{C,DM}$); (C, D) correlation diagrams of zircon Hf isotopes versus U–Pb ages of the Eastern Tianshan intrusions. The concentration of Hf in N-type MORB from Sun and McDonough (1989) is used to represent the composition of melt derived from the depleted mantle. Data for the Donggebi intrusions are from Zhang et al. (2015a). Data for the Huangshan, Xiangshan, and Tulaergen intrusions are from Su et al. (2011). Data for the Tuwu and Yandong intrusions are from Wang et al. (2015a, 2015b).
Carboniferous magmatic rocks in the orogen are represented by Xiaorequanzi monzogranite (353 ± 4 Ma; Li and Chen 2004), Hongshi syenogranite (344 ± 4 Ma; Sun et al. 2012), Shiyingtian granodiorite (342 ± 11 Ma; Zhou et al. 2010), Yandong diorite porphyry and tonalite (340 ± 3 and 335 ± 3.7 Ma, respectively; Shen et al. 2014; Wang et al. 2015b), Tuwu tonalite (332.3 ± 5.9 Ma; Wang et al. 2015a), Xiaoabaishitou biotite granite (322 ± 5 Ma; Li et al. 2011); Bailingshan granodiorite (317.7 ± 3.7 Ma; Zhou et al. 2010), and Baishiquan granodiorite (303 ± 18 Ma; Zhou et al. 2010). These geochronological data indicate that the Carboniferous magmatic activity was widely distributed in the middle and western parts of Eastern Tianshan (Figure 1C). In addition, Chen et al. (1999) reported that the K–Ar age of the Xiaorequanzi Cu–Zn deposit is 339.1 Ma; Rui et al. (2002) obtained a Re–Os isochron age of 322.7 ± 2.3 Ma for molybdenite from the Tuwu porphyry Cu deposit; Zhang et al. (2004) reported a Re–Os isochron age of 343 Ma for veined-hosted and disseminated molybdenite from the Yandong area; and Zhang et al. (2010) obtained a Re–Os model age of 326.2 ± 4.5 Ma for molybdenite from the Yanxi porphyry Cu deposit. These isotopic age data suggest that Carboniferous magmatism and Cu–dominant mineral system are significant in the Eastern Tianshan orogenic belt, which are considered to be related to subduction tectonism (e.g. Mao et al. 2005; Han et al. 2006).

Precise dating of host rocks can be used to constrain the timing and duration of magmatic hydrothermal events, which is crucially important in understanding the rock-forming process and geodynamic setting (Stacey and Kramers 1975; Leng et al. 2013; Deng et al. 2014a; Zhang et al. 2015b; Wang et al. 2015d). Based on new SIMS zircon U–Pb data presented herein, the timing of granitoid intrusions in the Chihu area is well constrained. The Chihu granodiorite was emplaced at 320.2 ± 2.4 Ma (Figure 4B)), whereas the porphyritic granodiorite was formed at 314.5 ± 2.5 Ma (Figure 4D)), thereby confirming that they were intruded in the Late Carboniferous. This episode is coeval with Late Palaeozoic (354–297 Ma) large-scale magmatic-metallogenesis in Eastern Tianshan (Zhang et al. 2002, 2008; Wu et al. 2006a, 2006c; Sun et al. 2012; Shen et al. 2014; Wang et al. 2015a, 2015b), and this episode was also responsible for producing the Chihu Cu deposit.

6.2. Petrogenesis and source of magma

Petrogeochemical signature of intrusive rocks records important information on magma source region, magmatic process, and tectonic setting (Pearce et al. 1984; Sylvester 1998; Barbarin 1999; Sillitoe 2010); therefore, it is important to have a clear understanding of the petrogenetic history of the Chihu granitoid rocks. Aluminous minerals such as muscovite, tourmaline, and garnet, as diagnostic minerals in S-type granites (Barbarin 1999), were not identified in the Chihu granodiorite and porphyritic granodiorite. All granitoid samples in the Chihu area show positive correlation between P₂O₅ and SiO₂ contents (Figure 10A), and negative correlation between Y and Rb values (Figure 10B), which are typical I-type granite evolution trends (Wu et al. 2003; Li et al. 2007). Furthermore, Chihu granitoids have low 10000 Ga/Al (1.26–1.87), Zr + Nb + Y + Ce (73.93–245.95 ppm), and Fe₂O₃/TiO₂/MgO (1.69–3.44) values, falling into the non-fractionated granite field (Figure 10C) and (D); Whalen et al. 1987). Therefore, the Chihu granitoid rocks are considered as non-fractionated I-type granites, rather than S-type or A-type granites. In addition, the Chihu granitoid rocks are characterized by low Sr/Y (10.64–25.73) ratios, low (La/Yb)N (3.46–8.02) values, and high Y (12.1–22.0 ppm) and HREE concentrations (Yb = 1.61–2.55 ppm), showing geochemical signatures comparable to typical island arc rocks (Figure 11A) and (B); Defant and Drummond 1990). However, the Chihu porphyritic granodiorites exhibit relatively high Sr/Y (28.13–36.97) ratios, and low Y (6.87–11.70 ppm) and HREE (Yb = 0.98–1.49 ppm) concentrations, different in normal island-arc magma, suggesting an adakite-like source (Figure 11A) and (B); Defant and Drummond 1990).

Geochemically, the Chihu granitoids are characterized by moderate HREE depletion, slightly negative Eu anomalies, and negative Nb, Ta, and Ti anomalies on the N-MORB normalized plots (Figure 7B)), reflecting clear subduction signatures. Moreover, the adakite-like porphyritic granodiorites at Chihu have moderate LREE enrichment and weak HREE depletion, with positive or no Eu anomalies (Figure 7A)). They also show clear depletion in high field strength elements (HFSEs), such as Nb, Ta, and Ti (Figure 7B)), similar to those of modern subduction-related plutonic rocks (Wood et al. 1979; Briqueu et al. 1984; Shen et al. 2014), formed by the partial melting of subducted oceanic slab.

Experimental studies have shown that Mg# is a useful criterion in distinguishing melts purely derived from the crust from those involved in the mantle. Melts from the basaltic lower crust are characterized by low Mg# less than 40 regardless of the melting degree, whereas those with Mg# greater than 40 can only be obtained when a mantle component is involved (Rapp and Watson 1995; Rapp et al. 1999; Zhu et al. 2009; Guan et al. 2012). All of the Chihu granodiorite rocks show features of somewhat elevated MgO contents (1.30–2.65 wt.%) and Mg# values (45–54) (Supplementary Table 2), implying the involvement of mantle components. In comparison, the adakite-like porphyritic granodiorites at Chihu have...
slightly high Mg# values (37–53) (Supplementary Table 2), indicating that the source for their magma was partially derived from the mantle-derived material.

These results are supported by the zircon Hf–O isotopic data (Supplementary Table 3). The Hf isotopic compositions of the granitoids from the Chihu area are characterized by positive εHf(t) values, which range from +11.5 to +14.9 of magmatic zircons from a granodiorite sample (CH-9), and from +11.9 to +17.2 of zircons from a porphyritic granodiorite sample (CH001-12) (Supplementary Table 3; Figure 9(A)). They also show young Hf model ages (TDM), which are between 383 and 594 Ma (granodiorite), and between 232 and 509 Ma (porphyritic granodiorite) (Supplementary Table 3; Figure 9(B)). In the εHf(t) versus U–Pb age diagram (Figure 9(C)), zircons from these samples show a spread of εHf(t) values close to the depleted mantle evolution line, which are higher than those of the Triassic within-plate granitoids in the Eastern Tianshan (e.g. Donggebi) (Han et al. 2014; Zhang et al. 2015a). In contrast, the Chihu εHf(t) values are more similar to those of the Carboniferous to Permian intrusions in Eastern Tianshan (Figure 9(D)), such as the subduction-related granites (e.g. Tuwu and Yandong) (Shen et al. 2012, 2014; Wang et al. 2015a, b), and the mantle-derived mafic–ultramafic complexes (e.g. Xiangshan, ...
Huangshan, and Tulaergen) (Chen et al. 2011; Su et al. 2011; Tang et al. 2012), indicating the same origin by partial melting of a subduction slab or lithospheric mantle materials. Based on the geochemical affinities and the relatively inhomogeneous Hf isotopic composition (3.4e and 5.3e units, respectively) recorded in the Chihu granodiorites and porphyritic granodiorites, we infer that they were most likely derived from the subduction-modified mantle rocks. The interpretation is also supported by the presence of coeval intermediate to mafic volcanic rocks in the Chihu area (Wang et al. 2006b; Wu et al. 2006c).

Zircons are highly retentive of the magmatic O isotopic compositions. It is known that zircons in equilibrium with mantle-derived magmas have a very consistent δ18O value of 5.3 ± 0.3‰ (Valley 2003; Valley et al. 2005; Li et al. 2009b). The δ18O value of igneous zircons is relatively insensitive to magmatic differentiation, because the increase in the bulk rock δ18O value is compensated by an increase in zircon/liquid δ18O fractionation, so their O isotopes can be used to trace the parental magma source (Valley et al. 2005). In this study, the zircon δ18O values of the granodiorites vary from 4.80 to 5.85 ‰, indicating depleted isotopic signatures close to the depleted mantle (DM) reservoir (δ18O = 5.3 ± 0.3‰; Li et al. 2009b). However, zircons from the porphyritic granodiorites have significantly lower δ18O values between 3.78 and 4.71 ‰. The lower O isotopic features recorded in the porphyritic granodiorites might be attributed to the interaction with strongly modified mantle wedge peridotite by subduction-related processes beneath the Eastern Tianshan (Su et al. 2012) or reflect high-level hydrothermal activity associated with Cu mineralization.

Taking the whole data set into consideration, it is proposed that the Chihu granodiorite and porphyritic granodiorite intrusions share the same signatures as I-type granites formed in the Dananhu–Tousuquan arc, and have broadly similar formation mechanisms and magmatic sources. The primary magmas for the granodiorite (320.2 ± 2.4 Ma) and porphyritic granodiorite (314.5 ± 2.5 Ma) were most likely generated by the partial melting of subduction-modified mantle components followed by fractionation to more felsic compositions.

6.3. Geodynamic setting

The Eastern Tianshan orogenic belt occupies the middle part of the CAOB, which is considered an important poly-metallic ore province in China (Goldfarb et al. 2001, 2014; Han et al. 2006; Mao et al. 2008; Huang et al. 2013; Pirajno 2013; Deng and Wang 2015). Previous studies have revealed that the Eastern Tianshan orogenic belt experienced a long and complex geodynamic evolution, involving subduction of the Palaeo-Tianshan Ocean, collision-accretionary, strike-slip motion, post-collisional, and intracontinental extension between the Siberian and Tarim Cratons (Pirajno et al. 2011; Santosh et al. 2011; Xiao et al. 2013; Deng et al. 2014a, 2014b), during which widespread late Palaeozoic volcanic rocks and granitoids were emplaced (Figure 1C; Zhou et al. 2010; Wang et al. 2015a, 2015b). Studies on Carboniferous andesites and granitoids in Eastern Tianshan have shown that these rocks display a subduction-related component, as evidenced by positive bulk εNd(t) and zircon εNd(t) values (Sun et al. 2008; Tang et al. 2010; Su et al. 2012). Southward and northward subduction of the Palaeo-Tianshan oceanic plate could have occurred during the Carboniferous, with ages constrained by the subduction-related Yandong–Tuwu intrusions (335–332 Ma; zircon U–Pb; Wang et al. 2015a, 2015b) and Yamansu volcanics (324.4 ± 0.9 Ma; zircon U–Pb; Hou et al. 2014). There is a broad consensus that the Palaeo-Tianshan ocean was closed in the end of Carboniferous and the Eastern Tianshan entered into a post-collisional setting since the Early Permian, as supported by the presence of the youngest ophiolite of ~310 Ma and widespread bimodal volcanic rocks of ~290 Ma (Qin et al. 2002; Zhang et al. 2008; Chen et al. 2011; Su et al. 2012; Huang et al. 2013). Furthermore, Mao et al. (2005) and Zhang et al. (2008) also suggested that the extensive porphyry Cu mineralization and associated magmatism that occurred in Eastern Tianshan were genetically related to the island-arc accretionary processes during the period of Carboniferous.

SIMS zircon U–Pb dating (320.2–314.5 Ma) of the granodiorite and porphyritic granodiorite obtained in this study indicates that the igneous activities that occurred in the Chihu Cu deposit of Eastern Tianshan correspond to the subduction-island arc stage as defined by Zhang et al. (2008). During subduction tectonism, the largest Tuwu and Yandong porphyry Cu deposits were formed in the Eastern Tianshan orogenic belt, with the emplacement of subduction-related granitoid intrusions, represented by the quartz diorite, diorite porphyry, and tonalite (Zhang et al. 2004, 2008; Gao et al. 2015; Wang et al. 2015a, 2015b). These intrusions and associated mineral systems were closely related to the northward subduction of the Palaeo-Tianshan oceanic plate beneath the Dananhu–Tousuquan arc (Shen et al. 2014; Wang et al. 2015a, 2015b), further suggesting the subduction environment for Carboniferous metallogeny and magmatism. In addition, on the Ta versus Yb, and Rb versus (Y + Nb) tectonic discrimination diagrams (Figure 12A and B; Pearce et al. 1984), both the granodiorite and porphyritic granodiorite samples plot within the oceanic arc field, indicating that
the Chihu intrusive rocks have characteristics of island arc granites that were formed in a subduction-related setting. Combined with regional tectonic evolution, and our new isotopic age and geochemical studies, we suggest that the Palaeo-Tianshan oceanic plate subducted northward beneath the Dananhu–Tousuquan arc belt during the Carboniferous (Figure 13), and that the Chihu granodiorite and porphyritic granodiorite intrusions were derived from partial melting of the mantle components, induced by the subduction processes.

7. Conclusions

(1) SIMS zircon U–Pb dating indicates that the Chihu granodiorite was emplaced at ca. 320 Ma, and the porphyritic granodiorite was emplaced at ca. 314 Ma. These granitoids were precisely dated in the Chihu area, corresponding to late Carboniferous magmatism in the Eastern Tianshan orogenic belt.

(2) Geochemistry indicates that the Chihu granodiorite and porphyritic granodiorite are calc-alkaline to low-K tholeiite rocks and show moderate enrichment in LREEs with I-type granite affinity. The geochemical and zircon Hf–O isotopic data indicate that these granitoids share a broadly common origin, probably derived from partial melting of the subduction-modified mantle components followed by fractionation.

(3) Based on the regional geological history, and new geochronological and isotopic data, we suggest that the Chihu granitoid intrusions in Eastern Tianshan were generated in an arc setting, and they most likely resulted from the northward subduction of the Palaeo-Tianshan ocean plate beneath the Dananhu–Tousuquan island arc during the Carboniferous.

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Figure 12. Tectonic discrimination diagrams for the Chihu granitoids. (A) Ta versus Yb diagram (Pearce et al. 1984); (B) Rb versus (Y+Nb) diagram (Pearce et al. 1984). Syn-COLG, syn-collision granites; WPG, within-plate granites; VAG, volcanic arc granites; ORG, ocean ridge granites.

Figure 13. A tectonic model for the formation of the late Carboniferous granitoids in the Chihu area of Eastern Tianshan.
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