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Early Carboniferous adakitic rocks in the area of the Tuwu deposit, eastern Tianshan, NW China: Slab melting and implications for porphyry copper mineralization

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Abstract: Existing geochronological and geochemical data for the Early Carboniferous magmatic rocks in the eastern Tianshan, Xinjiang, have been interpreted in a variety of theories regarding petrogenesis and geodynamic setting. The proposed settings include rift, back-arc basin, passive continental margin, island arc, ridge subduction, and post-collisional environment. To evaluate these possibilities, we present new SHRIMP zircon U–Pb geochronology and geochemical data, whole-rock geochemical, Hf isotope, and S isotope data for tonalitic rocks and ores associated with the Tuwu porphyry copper deposit located in the center of the late Paleozoic Dananhu–Tousuquan arc, eastern Tianshan. SHRIMP zircon U–Pb dating indicates that the magmatic activity and thus associated copper mineralization occurred

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ca.332 Ma. The tonalitic rocks are calc-alkaline granites with A/CNK values ranging from 1.16 to 1.58; are enriched in K, Rb, Sr, and Ba; and are markedly depleted in Nb, Ta, Ti, and Th. They show geochemical affinities similar to adakites, with high Sr, Al₂O₃, and Na₂O contents and La/Yb ratios; low Y and Yb contents; and slight positive Eu anomalies. In situ Hf isotopic analyses of zircons yielded positive initial \( \varepsilon_{\text{Hf}}(t) \) values ranging from 6.9 to 17.2. The \( \delta^{34}\text{S} \) values of the ore sulfides range from -3.0‰ to +1.7‰, reflecting a deep sulfur source. Our results indicate that the paleo-Tianshan oceanic slab was being simultaneously subducted northward beneath the Dananhu-Tousuquan arc, and southward beneath the Aqishan-Yamansu arc during the Early Carboniferous. The Tuwu adakitic tonalitic rocks were derived from the partial melting of the subducted paleo-Tianshan oceanic slab, which was subsequently hybridized by mantle wedge peridotites. The slab-derived magmas have considerably high copper contents and are highly oxidized, thus leading to porphyry copper mineralization. Such Early Carboniferous tonalitic rocks that are widespread in the eastern Tianshan define a province with high potential for copper mineralization.

**Keywords**: Eastern Tianshan; Tuwu porphyry Cu deposit; Subduction-related adakite; Tonalite; SHRIMP zircon U–Pb dating; Hf isotope; S isotope

1. **Introduction**

The Central Asian Orogenic Belt was formed by the amalgamation of various continental blocks, arc complexes, and accretionary wedges (Pirajno, 2010; Xiao et al., 2010; Rojas-Agramonte et al., 2011; Goldfarb et al., 2014; Mao et al., 2014). The eastern part of the Tianshan in northwestern China is part of the southern margin of the orogenic belt (Fig. 1a), and it separates the Junggar Basin to the north from the Tu-Ha Basin to the south (Fig. 1b). The
eastern Tianshan is characterized by widespread Carboniferous to Permian granitoids (Chen et al., 2005b; Wu et al., 2006a), and lesser Devonian granitoids (Li et al., 2006c; Zhou et al., 2010) and Triassic granitoids (Li et al., 2002; Zhang et al., 2005; Zhou et al., 2010). These eastern Tianshan granitoids have attracted much attention because they are often associated with Cu-Au-Fe-Ag mineralization. However, the petrogenesis and geodynamic setting of the granitoids are still a matter of 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 (Rui et al., 2002; Mao et al., 2005; Zhang et al., 2008), ridge subduction environment (Sun et al., 2010, 2011), or post-collision setting (Wang and Xu, 2006a; Gu et al., 2006; Zhou et al., 2008). Some studies suggest that the porphyry copper-related granitic intrusions in the eastern Tianshan may have an adakitic affinity (Wang et al., 2001; Liu et al., 2003; Han et al., 2006; Zhang et al., 2010). The intrusions are mostly tonalitic, granodiorite, and granodioritic porphyry in composition (Zhang et al., 2004). However, due to the lack of systematic, high-quality geochronological and geochemical data, the petrogenesis and geodynamic setting of the adakitic granitoids are poorly understood. As part of the magmatism research in the eastern Tianshan, this paper thus provides SHRIMP zircon U–Pb geochronological, whole-rock geochemical, Hf isotope, and S isotope data for the Tuwu intrusive rocks and ores, and discusses granitoid petrogenesis, the associated porphyry Cu mineralization, the crust–mantle interaction process, and eastern Tianshan geodynamic setting.

2. Geological setting and deposit geology

The eastern Tianshan region is one of the important producers of Cu (+/-Ni), Au, Fe, and Ag in China (Zhai et al., 1999; Mao et al., 2008; Deng et al., 2011). The eastern Tianshan may
be divided into three major tectonic units, the Dananhu–Tousuquan arc, the Kangguer–Huangshan ductile shear belt, and the Aqishan–Yamansu arc, which are separated by the regional-scale Kangguer and Yamansu crustal-scale faults (Fig. 1c). The Dananhu–Tousuquan arc is situated north of the Kangguer fault, is mainly composed of Devonian to Carboniferous volcanic and intrusive rocks, and contains several porphyry Cu deposits of different sizes, including the Tuwu, Yandong, Linglong, and Chihu deposits (Fig. 1c). The base of the Dananhu–Tousuquan arc is represented by basaltic to andesitic volcanic rocks, with locally overlying Lower Carboniferous carbonates and calcareous mudstones (Mao et al., 2005). The Kangguer–Huangshan ductile shear belt lies between the Kangguer and Yamansu faults, an area in which most rocks have undergone greenschist facies metamorphism and ductile deformation, and where there are a number of orogenic Au deposits (e.g., Kangguer) and magmatic Cu–Ni sulfide deposits (e.g., Huangshan and Huangshandong). The Aqishan–Yamansu arc is located between the Yamansu and Aqikuduke faults, mainly comprises Early Carboniferous basalt, andesite, dacite, and tuff of the Yamansu Formation and Late Carboniferous rhyolite of the Tugutubulake Formation (Ma et al. 1993). The arc hosts numerous Fe (-Cu) and Cu-Ag-Pb-Zn skarn deposits (e.g., Yamansu). The structural architecture of the eastern Tianshan is characterized by a series of E-W-trending regional faults, including the Dacaotan, Kangguer, Yamansu, and Aqikuduke faults (Qin et al., 2003).

The Tuwu porphyry Cu deposit is located in the middle of the Dananhu-Tousuquan arc and is about 1–3 km north of the Kangguer fault (Fig. 2a). Tuwu, discovered in 1997, is the largest deposit in the eastern Tianshan, with total Cu reserves of 2.04 million tonnes (Zhang et al., 2006). The country rocks in the Tuwu area, have well-developed schistosity, strike
approximately E–W, and dip to the south at 43° to 63°. They can be divided into three lithologic sections of the Carboniferous Qieshan Group (Fig. 2b). The stratigraphically lowest section is composed of volcanioclastics and tuff; the middle section is composed of basalt and andesite, with intercalated dacite and basaltic andesite; and the upper section is composed of sandstone and polymictic conglomerate, intercalated with tuff and andesite (Wang et al., 2001). The overlying rocks of the Jurassic Xishanyao Formation consist chiefly of sandstone, siltite, mudstone, and conglomerate, and they form an angular unconformity with the strata of the Qieshan Group (Fig. 2b). Intrusive bodies, mostly tonalite and diorite porphyries (Fig. 2b and 3a), were emplaced into the Early Carboniferous volcanic rocks (Fig. 2b and 4b). The tonalitic rocks are associated with porphyry-style Cu mineralization and surrounding alteration (Zhang et al., 2004, 2006; Shen et al., 2012, 2014). Within the eastern Tianshan, 23 mineralized stocks and plugs have been identified, and the largest of these at Tuwu occupies a surface outcrop of ~0.03 km², with all other bodies occupying areas of <0.01 km². The intrusions are mostly irregular in shape where exposed (Fig. 2b).

The Tuwu porphyry Cu deposit consists of the Tuwu and Eastern Tuwu orebodies (Fig. 2b), which are situated <200 m apart from one another. The mineralization occurs as thick tabular bodies, and there is no distinct boundary between orebodies and subecononic wall rocks. Using a cut-off grade of 0.20% Cu to outline the orebodies, the Tuwu orebody has a continuous length of 1400 m, a width ranging from 7.6 to 125 m, and an average grade of 0.44% Cu. The Eastern Tuwu orebody is about 1300 m in length, its width varies from 8.0 to 87.1 m, and it has an average grade of 0.30% Cu (Zhang et al., 2006). The orebodies have a thick lenticular surface morphology, strike nearly E–W direction, and dip to the south at angles of 61°–67° (Fig. 4). The
orebodies extend down-dip for more than 600 m (Fig. 4), and the Cu mineralization occurs predominantly in tonalitic rocks (Liu et al., 2003; Zhang et al., 2004; Han et al., 2006).

Ore styles in the Tuwu porphyry Cu deposit mainly include disseminated (Fig. 5a), vein (Fig. 5b), veinlet and disseminated (Fig. 5c), and scaly (Fig. 5d). Hydrothermal alteration is zoned from the center of the tonalitic rocks to the margin with the wall rocks as follows: (1) quartz-core zone, (2) biotite zone, (3) phyllic zone, (4) chlorite – epidote – albite zone, and (5) argillite zone (Wang et al., 2001). Ore textures mainly include fine- to medium-grain sulfides or hypidiomorphic-xenomorphic granular textures (Fig. 5e and f). Chalcopyrite is the main ore mineral in the Tuwu deposit, with minor bornite, pyrite, molybdenite, chalcocite, digenite, and magnetite. Gangue minerals are quartz and plagioclase, which are associated with sericite, chlorite, and biotite (Wang et al., 2001).

3. Samples and analytical techniques

Tonalite samples for this study were collected from the Tuwu ore district (Fig. 2b). The porphyries were altered to variable degrees by formation of biotite, sericite, and propylitic assemblages. Thus, to best measure the chemical composition, the least altered samples were chosen for major element, trace element, SHRIMP zircon U–Pb, and Lu–Hf isotope analyses. These samples are defined as tonalite based on the IUGS classification, but they are also called plagiogranite porphyry in the literature (Rui et al., 2002; Zhang et al., 2004, 2006; Shen et al., 2012). They show porphyritic texture and massive structure, and mainly consist of plagioclase (30–45%), quartz (10–20%), and biotite (5–10%), with accessory minerals that include zircon and phosphates (Fig. 3b). Plagioclase is characterized by idiomorphic or hypidiomorphic tabular texture, showing superficial weak sericite alteration (Fig. 3c). Quartz shows xenomorphic
granular textures and distinct wavy extinction (Fig. 3d). Biotite was mainly yellow-brown in color, with a hypidiomorphic–xenomorphic flaky or fragmental texture (Fig. 3d).

Zircons were separated from rock samples using flotation and electromagnetic methods at the Hebei Regional Geological Survey located in Langfang. Zircons were documented with transmitted and reflected light micrographs as well as cathodoluminescence (CL) images to reveal their internal structures. The CL imaging was performed at the electronic probe lab of the Geological Institute of the Chinese Academy of Geological Sciences (CAGS), under an operating power of 15 kV and 4 nA. Under the guidance of zircon CL images, the zircons were analyzed for U–Pb isotopic composition and U, Th, and Pb concentrations using a SHRIMP II ion microprobe with a spot size of 30 μm at the Beijing Ion Probe Centre of the CAGS. Testing conditions and processes were after Liu et al. (2006). Common lead correction was performed using $^{204}$Pb, with a single testing error of 1σ and a $^{206}$Pb/$^{238}$U weighted average age error of 2σ. The zircon U–Pb isotope data are presented in Table 1.

Whole-rock compositions were analyzed at the test center of the Beijing Research Institute of Uranium Geology. Major element analysis was conducted using a Philips PW2404 XRF with testing precision greater than 1%. Trace element analysis was performed using a Finnigan MAT Element I ICP-MS, with RSD (10 min) < 1% and RSD (4h) < 5%. For the testing methods, refer to Gao et al. (2002). The whole-rock geochemical data are presented in Table 2.

In situ Hf isotope analysis was done on zircon grains using a Neptune MC-ICP-MS and a NewWave UP213 ultraviolet LA-MC-ICP-MS at the MLR Key Laboratory of Metallogeny and Assessment. During the analyses, He was used as the carrier gas. Depending on zircon size, the ablating diameter was set at either 55 or 40 μm. International standard zircon sample GJ1 was
used as a reference. Details of instrumental conditions and test process were given in Wu et al. (2006b) and Hou et al. (2007). The weighted average of $^{176}$Hf/$^{177}$Hf of the GJ1 zircon samples was 0.282015 ± 31 (2\textit{SD}, n = 10), which is in agreement with the values reported in the literature (Elhlou et al., 2006; Hou et al., 2007). The initial $^{176}$Hf/$^{177}$Hf ratios and $\varepsilon_{\text{Hf}}$ values were calculated with reference to the chondritic reservoir (CHUR) at the time of zircon growth from magmas. The decay constant for $^{176}$Lu of 1.867×10$^{-11}$ year$^{-1}$ (Soderlund et al., 2004), and the chondritic $^{176}$Hf/$^{177}$Hf ratio of 0.282772 and $^{176}$Lu/$^{177}$Hf ratio of 0.0332 (Blichert-Toft and Albarède, 1997) were adopted. The depleted mantle model ages ($T_{\text{DM}}$) used for basic rocks were calculated with reference to the depleted mantle at the present-day $^{176}$Hf/$^{177}$Hf ratio of 0.28325, which is similar to that of the average mid-ocean ridge basalt (MORB) (Nowell et al., 1998) and $^{176}$Lu/$^{177}$Hf=0.0384 (Griffin et al., 2000). Zircon Hf isotope crustal model ages ($T_{\text{cDM}}$) were calculated using an average continental crustal $^{176}$Lu/$^{177}$Hf ratio of 0.015 (Griffin et al., 2002). The zircon Hf isotopic data are presented in Table 3.

The $\delta^{34}$S values for sulfides were determined on SO$_2$ obtained by placing a sulfide–CuO composite (at weight ratio of 1/7) into a vacuum system heated to 980°C. Sulfur isotopes were measured using a Finnigan MAT251 mass spectrometer at the test center of the Beijing Research Institute of Uranium Geology. Isotopic data were reported in permil relative to the Canyon Diablo Triolite (CDT) standard for sulfur. Total uncertainties were estimated to be better than ± 0.2‰ for $\delta^{34}$S. The sulfur isotopic data are presented in Table 4.

4. Results

4.1. SHRIMP zircon U–Pb geochronology

Tonalite sample TW702-59 (N 42°06′57″, E 92°36′15″) from the Tuwu porphyry Cu
deposit was chosen for SHRIMP zircon U–Pb analysis. The analytical data are presented in Table 1. Zircons from the sample are colorless with no obvious inclusions. They are euhedral and elongate prismatic, with a length to width ratio from 2:1 to 4:1. In zircon CL images, all grains exhibit well-developed oscillatory zoning (Fig. 6a). The $^{238}\text{U}$ and $^{232}\text{Th}$ contents of analyzed zircons are 45–144 ppm and 21–91 ppm, respectively, with Th/U ratios ranging from 0.29 to 0.79. These ratios are higher than those of metamorphic zircons (typically $<$0.1), but consistent with those of magmatic zircons (Hoskin and Schaltegger, 2003). Therefore, the SHRIMP zircon U-Pb dating results are interpreted to provide the age of magma crystallization.

Fifteen spot analyses were carried out on zircon grains of the tonalite sample (TW702-59). Except for four older discordant data spots (9, 11, 12, and 15), the remaining 11 analyses have $^{206}\text{Pb}/^{238}\text{U}$ ages ranging from 320.3 to 348.6 Ma, with a weighted mean of $332.3\pm5.9\text{Ma}$ (MSWD = 1.5) (Fig. 6b). This is interpreted as the age of tonalite emplacement. In summary, the SHRIMP zircon U-Pb dating indicates that the tonalitic rocks in Tuwu were emplaced in the Early Carboniferous.

4.2. Whole-rock geochemistry

Whole-rock geochemical data for the Tuwu tonalite samples are presented in Table 2. The Tuwu tonalite samples are characterized by a limited range in SiO$_2$ (65.34%–68.21%), and plot in the granodiorite field on a Na$_2$O+K$_2$O vs. SiO$_2$ diagram (Fig. 7a). All tonalite samples record Al$_2$O$_3$ contents greater than 15% and high Na$_2$O concentrations (2.98%–4.65%). They have relatively low K$_2$O contents (1.28%–2.49%), and plot in the field of calc-alkaline granites (Fig. 7b). The A/CNK values of the samples (Al$_2$O$_3$/[CaO+Na$_2$O+K$_2$O], molratio) range from 1.16 to 1.58, which is characteristic of peraluminous granite (Fig. 7c). Most of tonalite samples have
slightly high Mg\# values of 40–42, except for two samples with low values of 36 and 37 (Table 2). The CaO, TFe$_2$O$_3$, and P$_2$O$_5$ contents of the tonalite samples range from 1.67% to 2.53%, 3.35% to 5.05%, and 0.13% to 0.15%, respectively. In the Harker diagrams for selected major oxides (Fig. 8), CaO, TFe$_2$O$_3$, MgO, MnO, P$_2$O$_5$, and TiO$_2$ contents are linearly correlated with SiO$_2$ contents.

The samples from the Tuwu deposits have steep heavy rare earth element (HREE) patterns (Fig. 9a) and display slight positive Eu anomalies (Eu/Eu* = 0.93–1.12). High (La/Yb)$_N$ ratios (8.24–10.87) indicate pronounced LREE/HREE fractionation. These features are observed in the chondrite-normalized REE distribution pattern (Fig. 9a). The samples show strong enrichment in large ion lithophile elements (K, Rb, Sr, and Ba) relative to high field strength elements (Nb, Ta, Ti, and Th), and pronounced positive U and Pb anomalies in primitive mantle-normalized trace element patterns (Fig. 9b). Tuwu tonalite samples also have low concentrations of Yb (0.84–1.15ppm) and Y (7.51–9.53 ppm). These characteristics, together with high Sr contents (261–669ppm) and Sr/Y ratios (35–82), indicate that the samples can be classified as adakites as defined by Defant and Drummond (1990) (Fig. 10a).

### 4.3. Zircon Hf isotopes

In situ Hf isotope analyses of zircons from the tonalite sample (TW702-59) are shown in Fig.6a. The zircon Hf isotopic data and calculated results are given in Table 3, and the Hf isotopic evolution diagram is shown in Fig. 11. Except for four older data spots (9, 11, 12, and 15), the remaining 11 analyses have variable Hf isotopic compositions, with $^{176}$Hf/$^{177}$Hf ratios of 0.282798–0.283081, $\varepsilon_{Hf(t)}$ values ranging from +6.9 to +17.2, and corresponding two-stage Hf isotopic crustal model ages ($T^{C}_{DM}$) values ranging from 239 to 902Ma.
4.4. S isotopes

Sulfur isotopic compositions for chalcopyrite and pyrite samples from the Tuwu deposit are presented in Table 4. The $\delta^{34}$S values of six pyrite samples range from +0.2‰ to +1.7‰, and the $\delta^{34}$S values of four chalcopyrite samples range from –3.0‰ to +0.4‰. In addition, Rui et al. (2002) and Han et al. (2006b) also obtained $\delta^{34}$S values for sulfides in Tuwu-Yandong ore field that ranged from –0.9‰ to +1.3‰. Therefore, sulfur isotopes in the Tuwu porphyry Cu deposit exhibit a narrow range, with an average $\delta^{34}$S value of 0.2‰, very close to meteoritic values, suggesting an upper mantle source for the sulfur in the Tuwu deposit.

5. Discussion

5.1. Geochronology

Previous studies of most granites in the eastern Tianshan reported that they were formed between 386 Ma and 228Ma (Fig. 1c; Table 5), and magmatic activity in this region can be divided into four stages (Zhou et al., 2010; Wang et al., 2014): Late Devonian (386–369 Ma) (Li et al., 2006c; Tang et al., 2007; Zhou et al., 2010), Early Carboniferous (349–329 Ma) (Sun et al., 2012; Wang et al., 2014), Late Carboniferous–Late Permian (322–252 Ma) (Mao et al., 2002; Wu et al., 2006c;) and Early and Middle Triassic (246–228 Ma) (Li et al., 2006a; Yang et al., 2011). The Late Devonian granitic intrusions mainly occur on the eastern margin of the Tu-Ha Basin in the eastern Tianshan. They are represented by Jingerquan, Xianshuiquan, and Sidingheishan bodies, mainly consisting of biotite granite and granodiorite. The Early Carboniferous granitic intrusions are widely distributed in the middle and western parts of the eastern Tianshan. They include the Hongshi, Shiyingtan, Xifengshan, Hongyuntan, Yandong and Tuwu intrusions, mainly consisting of moyite, syenogranite, granodiorite, dioritic
porphyrite, and tonalite. The Late Carboniferous–Late Permian granites are mainly distributed in Kangguer-Huangshan ductile shear belt, and include Bailingshan, Kangguer, Weiquan, Chihu, Huangshan, Sanchakou, and Shuangchagou, which comprise granite porphyry, rhyolite porphyry, quartz-syenite porphyry, granodiorite, and tonalite. The Early and Middle Triassic granites are locally exposed as the Weiya, Donggebi, Baishan, and Tudun bodies, and they are notably less common than the earlier three stages. There is an overall trend in the magmatic activity in the area, with more of the older intrusions being emplaced in the east and younger bodies in the middle and west along the length of the Kangguer ductile shear zone.

The internal structure of the large zircon grains from the Tuwu tonalite shows that they possess good crystal form, uniform composition, and clear oscillatory zoning, which is typical of magmatic zircons (Fig. 6a). This suggests that zircons were formed by crystallization in the magmatic system. Our calculated SHRIMP zircon U–Pb age for the Tuwu tonalite of 332.3±5.9 Ma (MSWD = 1.5) is interpreted to represent the age of Tuwu tonalitic body emplacement and is consistent with ages for the Tuwu–Yandong porphyry Cu mineralization of ca.340–330 Ma (Liu et al., 2003; Chen et al., 2005a).

Rui et al. (2002) previously obtained a Re–Os isochron age of 323Ma for molybdenite from the Tuwu porphyry Cu deposit. Qin et al. (2002) used K–Ar and $^{39}$Ar–$^{40}$Ar methods to determine the ages for hydrothermal sericite and copper sulfide-bearing quartz from the Tuwu–Yandong region and obtained age of 341 Ma and 347 Ma, respectively. Zhang et al. (2004) obtained a Re–Os isochron age of 343 Ma for veinlet-hosted and disseminated molybdenite from the Yandong area. Zhang et al. (2010) obtained a Re–Os isochron age of 326 Ma for molybdenite from the Yanxi porphyry Cu deposit. In summary, these isotopic age data
suggest that the mineralization ages for the Tuwu–Yandong porphyry Cu deposits range from 340 Ma to 320 Ma. Therefore, the mineralization at the Tuwu porphyry Cu deposit occurred simultaneously with intrusion of the tonalitic host rock or slightly later.

5.2. Petrogenesis

The petrochemical signature of magmatic rocks records significant information on magma source region, magmatic process, and tectonic setting (Pearce et al., 1984; Sylvester, 1998; Barbarin, 1999); therefore, it is important to have a clear understanding of the petrogenetic history of the Tuwu tonalitic rocks. Apatite is typically assumed to provide a reliable criterion to distinguish magma types (e.g. S-, I-type) (Chappell and White, 1992; Wolf and London, 1994; Wu et al., 2003; Li et al., 2006b, 2007). Apatite reaches saturation in metaluminous and weekly metaluminous magmas and the apatite solubility will reduce with the decrease of temperature and the increase of SiO$_2$ content, but it remains highly soluble in highly peraluminous magmas (Wolf and London, 1994). These studies indicate that P$_2$O$_5$ and SiO$_2$ in I–type and A–type granites are negatively correlated, whereas the P$_2$O$_5$ in S–type granite increases or remains unchanged with an increase in SiO$_2$ (Li et al., 2007, Wu et al. 2007a; Cheng and Mao, 2010). The P$_2$O$_5$ content of the Tuwu tonalite ranges from 0.13% to 0.15%, and decreases with increasing SiO$_2$. The results are consistent with an I-type granite (Fig. 13a). The Y vs. Rb and Th vs. Rb diagrams (Fig. 13c and d) also show the same trend. The Th- and Y-rich minerals will not crystallize from a metaluminous I-type granite during early stages of magmatic differentiation, consequently resulting in high Th and Y abundances and a positive correlation between Y and Rb, and Th and Rb in differentiated I-type granites (Li et al., 2007; Zhu et al., 2009b). Based on the above interpretations, we suggest that the Tuwu tonalite is an
I-type granite.

The term adakite was introduced by Kay (1978) and has been used to describe high-Al (Al₂O₃ > 15%) and Na-rich andesitic to dacitic, extrusive or intrusive rocks with a high Sr content (>600 ppm), strongly fractionated REE patterns (HREE depleted, LREE enriched), and positive Sr and Eu anomalies (Defant and Drummond, 1990). Based on the whole rock geochemical data, the Tuwu tonalitic rocks display an adakitic major and trace element geochemical affinity. They have high Al₂O₃ and Na₂O contents ranging from 15.53% to 16.83%, and 2.98% to 4.65%, respectively. They also have a high Sr concentration (261–669 ppm), and low Y and Yb concentrations (7.51–9.53 ppm and 0.84–1.15 ppm, respectively). Therefore, the above data indicate that the Tuwu tonalitic rocks display characteristics similar to adakites. Furthermore, in (Sr/Y) vs. Y and (La₈/Yb₈) vs. Yb₈ discrimination diagrams (Fig. 10a and b), the Tuwu tonalitic rocks also plot well within the adakitic field.

Several hypotheses have been suggested for the origin of rocks with geochemical characteristics similar to those of adakitic rocks. The various processes proposed for the genesis of adakitic rocks include: (1) partial melting of a subducted oceanic slab (Rapp et al., 1999; Escuder et al., 2007); (2) partial melting of thickened or delaminated lower crust (Gao et al., 2004; Hou et al., 2004); (3) assimilation and fractional crystallization processes involving basaltic magma (Macpherson et al., 2006; Richards and Kerrich, 2007); (4) mixing of felsic and basaltic magmas (Streck et al., 2007); and (5) partial melting of subducted continental crust (Wang et al., 2008, 2010). We suggest that the Tuwu adakitic tonalitic rocks were most likely generated by partial melting of subducted oceanic slab based on both geochemical and isotopic data. This interpretation is supported by the following lines of evidence:
(1) The Tuwu tonalitic rocks are geochemically similar to slab-derived adakites. Most samples may be defined as calc-alkaline granites with relatively low $\text{K}_2\text{O}$ contents (1.28%–2.49%) (Fig. 7b), similar to slab-derived adakites in the northern Tianshan (Wang et al., 2007) formed by partial melting of subducted oceanic crust. The Tuwu tonalitic rocks also have slightly high $\text{Mg}^#$ values of 40–59, and this characteristic is consistent with those of adakites derived by partial melting of a subducted slab (Defant and Drummond, 1993). Melts from basaltic lower crust are characterized by $\text{Mg}^#$ less than 40 regardless of degree of melting, whereas those with $\text{Mg}^# > 40$ can be obtained only with a mantle component (Rapp and Watson, 1995). Therefore, the slightly high $\text{Mg}^#$ values indicate that interaction between subducted oceanic crust and mantle wedge peridotite could have formed the Tuwu adakitic magmas.

(2) The trace element signatures of the Tuwu tonalitic rocks are compatible with the partial melting of a subducted oceanic slab. The assimilation and fractional crystallization of parental basaltic magmas would result in positive correlation between $\text{Sr}/\text{Y}$, and particularly $\text{Dy/Yb}$ ratios with increasing $\text{SiO}_2$ (Macpherson et al., 2006; Tang et al., 2010), but there are no such obvious correlations in our data (Fig. 13a and b). The data clearly plot along a partial melting trend in the $\text{La}/\text{Sm}$ versus $\text{La}$ and $\text{La/Yb}$ versus $\text{La}$ diagrams (Fig. 13c and d), indicating that partial melting of the source, rather than fractional crystallization, was the dominant process. Moreover, the Tuwu tonalitic rocks have low $\text{Y}$ and $\text{Yb}$ concentrations, and a geochemical affinity to MORB in the $\text{Sr/Y}$ versus $\text{Y}$ diagram (Fig. 10a), which is consistent with other ore-forming adakitic rocks from the Tuwu–Yandong porphyry Cu belt (Zhang et al., 2006).

(3) The Tuwu tonalitic rocks have slight positive Eu anomalies ($\text{Eu/Eu}^* = 0.93–1.12$) and
positive zircon $\varepsilon_{\text{Hf}}(t)$ values (+6.9 – +17.2), similar to a subducted oceanic slab (Mo et al., 2005; Zhu et al., 2009a). Additionally, the zircons from all samples show an inhomogeneous Hf isotopic composition, with variations of as much as 10.3 $\varepsilon$ units, indicating interaction between the subducted crust with less radioactive Hf geogenesis and mantle sources with more radioactive Hf geogenesis (Bolhar et al., 2008). This is because the zircon Hf isotope system has a high closure temperature (Patchett, 1983; Cherniak and Watson, 2003), and the isotope ratio remains unchanged during partial melting or fractional crystallization. This is consistent with the explanation from various workers regarding Hf isotopic inhomogeneity in zircon (Griffine et al., 2002; Li et al., 2007; Bolhar et al., 2008). Therefore, the Tuwu tonalitic magmas likely reflected interaction between a subducted slab and mantle wedge peridotite.

In summary, the hypothesis of partial melting of a subducted oceanic slab is our favored interpretation for the genesis of the Tuwu tonalitic rocks, although there might have been minor interaction between slab-derived magmas and mantle wedge peridotite during magma ascent. Moreover, based on the formation conditions for adakites (Martin, 1999; Rapp et al., 1999; Defant et al., 2002), we suggest that the Tuwu ore-bearing tonalitic rocks formed during fast and oblique convergence between the paleo-Tianshan oceanic plate and the Dananhu-Tousuquan island arc (Defant and Drummond, 1990; Oyarzun et al., 2001).

5.3. Implications for Cu mineralization

Different mineral deposit types are associated with different geodynamic environments, and thus have distinct distribution in time and space (Meyer and Saager, 1985; Deng et al., 2013, 2014; Mao et al., 2014; Santosh et al., 2014). With respect to porphyry copper deposits, the relationship between subduction environments and adakitic rocks is well documented
Numerous porphyry and other hydrothermal base and precious metal deposits are shown to be associated with adakitic rocks in various parts of the world, such as the late Miocene Los Pelambres porphyry Cu deposit in the Andes (Reich et al., 2003), the Eocene-Oligocene Yulong porphyry Cu-Mo belt in eastern Tibet (Hou et al., 2003; Cooke et al., 2005), and the mid-Miocene Gangdese porphyry Cu belt in southern Tibet (Hou and Cook, 2009). The three largest porphyry Cu deposits in the world, El Teniente, Chuquicamata, and Río Blanco–Los Bronces, are considered by many workers to be related to adakites derived by partial melting of a subducted oceanic slab (Reich et al., 2003; Jiang et al., 2012).

The adakites derived from partial melting of a subducted slab have been shown to be fertile for Cu mineralizations (Thiéblemont et al., 1997; Defant et al., 2002; Mungall, 2002), so that a very favorable tectonic setting for the generation of porphyry Cu deposits is above subduction zones (Sillitoe, 1972; Defant et al., 2002; Reich et al., 2003; Yang et al., 2012, 2014). The adakitic magmas derived from slab melting in the Tuwu area were favorable melts for the generation of porphyry Cu mineralization as evidenced by:

1. The $\delta^{34}$S values of sulfides from the Tuwu porphyry Cu deposit range from –3.0 to +1.7‰, with an average value of +0.2‰, which is very close to that of meteorite, implying that the sulfur was probably derived from a mantle source. Thus, we suggest that the mantle probably played an important role in providing water and sulfur to the Tuwu magma.

2. Slab-derived adakitic magmas, together with the metasomatized mantle wedge, provide relatively large amounts of chalcophile elements (Cu) and volatiles, such as H$_2$O and Cl, to a porphyry Cu magmatic-hydrothermal system (McDonough and Sun, 1995; Rudnick.
and Gao, 2003; Ling, et al. 2009; Sun et al. 2010, 2011). Such magmas resulted in the favorable conditions for porphyry Cu mineralization in the Tuwu area (Liu et al., 2010; Sun et al., 2010).

(3) As chalcophile elements are mainly hosted in sulfides in the mantle (Fleet et al., 1996; Ballard et al., 2002; Mungall, 2002), the removal of chalcophile elements from the mantle and their incorporation into magmas can only occur if sulfides are absent in the melted source rocks. This requires a high oxygen fugacity, with values of log $f_O^2$ > FMQ+2 (FMQ represents fayalite–magnetite–quartz oxygen buffer; Mungall, 2002). The biotite in the Tuwu tonalitic rocks is rich in magnesium, with Mg/(Mg + Fe + Mn) values ranging from 0.35 to 0.60, and abundant hematite and magnetite are observed in the ores (Rui et al., 2002; Zhang et al., 2004, 2006). The mineralized porphyries are cut by numerous quartz-sulfide and chlorite-sulfide veinlets, and locally by carbonate veinlets with minor amounts of sulfides. Therefore, the adakitic magmas derived from partial slab melting in the Tuwu area are considered to have had a high oxygen fugacity that was particularly favorable for porphyry Cu mineralization.

5.4. Geodynamic setting

SHRIMP zircon U–Pb dating and geochemical data obtained in this study and by previous workers show that widespread granitic intrusions occurred in the eastern Tianshan at ca. 340-320 Ma. Magmatism and mineralization in the Tuwu area occurred in the period at ca. 332 Ma, with the mineralization being coeval with or slightly younger than emplacement of the Tuwu tonalite.

Studies on Carboniferous andesites and granitoids in northern Xinjiang have revealed that these rocks display an obvious subduction-related component as evidenced by positive bulk
\[ \varepsilon_{\text{Nd}}(t) \text{ and } \varepsilon_{\text{Hf}}(t) \] values (Sun et al., 2008; Tang et al., 2010; Su et al., 2012; Wang et al., 2014). There is also a broad consensus that the northern part of Xinjiang experienced post-collisional magmatism in the latest Paleozoic (Wang and Xu, 2006b; Zhou et al., 2008; Chen et al., 2012; Yang et al., 2012). The eastern Tianshan is suggested to have been in a post-collision extensional setting since Early Permian, as supported by an ophiolite as young as \(~310 \text{ Ma}\) and widespread bimodal volcanic rocks (Qin et al., 2002, 2003; Su et al., 2012). A few workers, however, favor subduction until Late Permian and Early Triassic based on the presence of Permian mafic-ultramafic complexes suggested to have formed in an island arc setting (Xiao et al., 2004; Ao et al., 2010; Su et al., 2012). In the Rb vs. (Y+Nb), Rb vs. (Ta+Yb), and Nb vs. Y tectonic discrimination diagrams (Pearce et al., 1984), and Rb–Hf–Ta diagram, all granitoid samples plot within the oceanic arc field (Figs. 10a, b, and c), indicating that the Tuwu tonalitic rocks have characteristics of island arc granites that were formed in a subduction-related setting.

Subduction zones have been considered as very favorable tectonic settings for the generation of porphyry Cu deposits (Sillitoe, 1972; Defant et al., 2002; Reich et al., 2003). Previous studies have shown that the simultaneous southward and northward subduction of the paleo-Tianshan oceanic plate in the Carboniferous formed the Aqishan–Yamansu and the Dananhu-Tousuquan arcs, respectively (Wang et al., 2006a; Han et al., 2006b; Zhang et al., 2010). In the Aqishan–Yamansu arc belt, the Fe (-Cu) and Cu-Ag-Pb-Zn skarn deposits are widely distributed, including Yamansu, Hongyuntan, Bailingshan, and Weiquan. These deposits formed during emplacement of granitic intrusions, with associated hydrothermal activity resulting in the replacement of Carboniferous and Neoproterozoic carbonate and calcic
clastic rocks (Mao et al., 2005). The Aqishan–Yamansu arc belt formed throughout the Carboniferous (Li et al., 2003) along the northern margin of the Central Tianshan (Mao et al., 2005). The Carboniferous Dananhu-Tousuquan arc was generated by the northward subduction of the paleo-Tianshan plate (Xiao et al., 2004; Mao et al., 2005; Chen et al., 2012). During the Early Carboniferous dual subduction, the Tuwu adakitic magma were generated by partial melting of the paleo-Tianshan slab and subsequent hybridization of the mantle wedge peridotites (Fig. 16). Such slab melts initially have high Cu contents and are highly oxidized, and thus play a crucial role for generating deposits such as the Tuwu porphyry Cu system (Sun et al., 2011). Given that adakitic rocks can only form at temperatures above 700°C and at depths greater than 70–85 km, regardless of whether subduction occurs at normal dips or shallower angles (Sajona et al., 1993; Gutscher et al., 2000; Zhu et al., 2009a), the paleo-Tianshan oceanic slab must have subducted beneath the Dananhu-Tousuquan sub-arc mantle to depths of at least 70–85 km during the Early Carboniferous. In such an environment, generation of Cu-rich adakitic magmas is favored. We therefore speculate that the widespread Carboniferous–Permian magmatic rocks in the eastern Tianshan hold more potential for Cu mineralization than is presently recognized.

6. Conclusions

(1) SHRIMP zircon U–Pb dating indicates that magmatic events occurred at ca.332 Ma in the Tuwu area, and the associated Tuwu porphyry Cu deposit formed during the same period.

(2) The Tuwu tonalite is calc-alkaline; enriched in K, Rb, Sr, and Ba; markedly depleted in Nb, Ta, Ti, and Th; and shows geochemical affinities similar to those of adakites. The Tuwu tonalitic rocks have positive $\varepsilon_{Hf}(t)$ values ranging from +6.9 to +17.2, and these $\varepsilon_{Hf}(t)$ values are
inhomogeneous, with variations of as much as 10.3ε units. The geochemical and isotopic data for the tonalitic rocks indicate that they were probably derived from the partial melting of a subducted oceanic slab, and subsequently hybridized by peridotite in the mantle wedge.

(3) The Tuwu adakitic rocks and associated porphyry Cu mineralization in the eastern Tianshan were generated in an arc setting, and they likely resulted from the northward subduction of the paleo-Tianshan ocean plate beneath the Dananhu-Tousuquan island arc during the Early Carboniferous.

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Figure Captions:

Fig. 1. (a) Location of the study area in the Central Asia Orogenic Belt (modified from Zhang et al., 2009). (b) Sketch map showing geologic units of the Tianshan (modified from Chen et al., 2012). (c) Simplified geological map of the eastern Tianshan (modified from Huang et al., 2013).

Fig. 2. (a) Geological map of the Tuwu–Yandong district (modified from Shen et al., 2012). (b) Geological sketch map of the Tuwu porphyry Cu deposit (modified from Pan et al., 2013).

Fig. 3. (a) Field photograph of diorite porphyrite and tonalite. (b) Hand specimen of tonalite. (c) Photomicrographs of tonalitic rock, showing mineral components and alteration, under crossed-polarized light. (d) Tonalitic rock with porphyritic texture, under crossed-polarized light. Abbreviations: Bt-biotite; Pl-plagioclase; Ser-sericite; Q-quartz; Kf-K-feldspar.

Fig. 4. Cross section along section Line 7 with orebody (a) and lithologies (b) in the Tuwu porphyry deposit (modified from Han et al., 2006).

Fig. 5. Mineralization in the Tuwu porphyry deposit. (a) Disseminated chalcopyrite with xenomorphic granular texture. (b) Chalcopyrite veins. (c) Pyrite with enterolithic structure. (d) Scaly molybdenite. (e) Chalcopyrite replacing early pyrite. (f) Chalcopyrite. Photomicrographs are taken under reflected light (a, b, c, d, e, f). Abbreviations: Ccp-Chalcopyrite; Py-Pyrite; Mo-Molybdenite.
Fig. 6. Cathodoluminescence (CL) image of representative zircons (a) and Concordia diagram (b) for zircons from the Tuwu granites.

Fig. 7. Classification and series diagrams of the Tuwu granites. (a) Na$_2$O+K$_2$O vs. SiO$_2$ plot diagram (Rickwood, 1989). (b) K$_2$O vs. SiO$_2$ diagram (Rollinson, 1993). (c) A/NK vs. A/CNK plot diagram (Maniar and Piccoli, 1989).

Fig. 8. Harker diagram of granites in the Tuwu porphyry Cu deposit.

Fig. 9. (a) Chondrite-normalized REE and (b) primitive mantle-normalized trace element abundance spider diagram for the Tuwu granites (normalized data are from Boynton, 1984, and Sun and McDonough, 1989).

Fig. 10. Plots of (a) Sr/Y vs. Y and (b) (La/Yb)$_N$ vs. Yb$_N$ for the Tuwu granites (modified after Defant and Drummond, 1990). Data sources: Li et al., 2002; Han et al., 2006; Zhang et al., 2004, 2006.

Fig. 11. (a) $\varepsilon_{Hf}(t)$ vs. U-Pb age diagram. (b) Histograms of zircon $\varepsilon_{Hf}(t)$ values. (c) Histograms of zircon Hf-isotope crust model age ($T^C_{DM}$).

Fig. 12. Histogram of sulfur isotope composition of sulfides from the Tuwu porphyry copper deposit.

Fig. 13. Diagrams for granitoid classification for samples from the Tuwu granites. (a) P$_2$O$_5$ vs. SiO$_2$ diagram. (b) Na$_2$O vs. K$_2$O diagram. (c) Th vs. Rb diagram (Li et al., 2007). (d) Y vs. Rb diagram (Li
et al., 2007).

Fig. 14. Dy/Yb vs. SiO$_2$, Sr/Y vs. SiO$_2$, La/Sm vs. La and La/Yb vs. La diagrams for the Tuwu granites. Data sources: Li et al., 2002; Han et al., 2006; Zhang et al., 2004, 2006.

Fig. 15. Tectonic discrimination diagrams for the Tuwu granites. (a) Rb vs. (Y+Nb) diagram (Pearce et al., 1984). (b) Rb vs. (Yb+Ta) diagram (Pearce et al., 1984). (c) Nb vs. Y diagram (Pearce et al., 1984). (d) Rb/30-Hf-3×Ta diagram (Harris et al., 1986). WPG, within-plate granites; VAG, volcanic arc granites; Syn-COLG, syn-collision granites; Post-COLG, post-collision granites; ORG, ocean ridge granites. Data sources: Li et al., 2002; Han et al., 2006; Zhang et al., 2004, 2006.

Fig. 16. Schematic showing the geodynamic setting of the Tuwu porphyry Cu deposit in the eastern Tianshan.

Table Captions:
Table 1. SHRIMP zircon U-Pb data of the Tuwu granites in the eastern Tianshan\(^a\).

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\(^a\)206Pb\(^\%\) (%) represents the percentage of common 206\(^{\text{Pb}}\) in total 206\(^{\text{Pb}}\)

\(^*\)denotes radioactivity lead. Common Pb corrected using measured 204\(^{\text{Pb}}\).

Table 2. Whole-rock geochemical data of the Tuwu granites in the eastern Tianshan (Major elements: wt%; Trace elements: ppm).
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| Value   | 27.7| 6.66| 31.1| 10.2 | 356  | 162  | 11.4| 56.3| 261 | 7.51| 43   | 2.49 | 3.31 | 433 | 10.9| 22.5| 2.42| 11.2 | 1.95| 0.621| 1.55 | 0.258| 1.43 | 0.271| 0.874 | 0.134| 0.134| 1.5 | 0.223| 15.5 | 1.59 | 0.923 |

| Value   | 68.8| 8.83| 31.5| 6.74 | 204  | 162  | 16.7| 49.1| 566 | 9.53| 53.6 | 2.41 | 3.04 | 461 | 14.8| 29.3| 3.73| 15.3 | 2.71| 0.878| 2.23 | 0.35 | 1.96 | 0.362| 1.1  | 0.164| 1.82 | 0.203| 5    | 1.44 | 0.972 |

| Value   | 46.5| 31.7| 28.4| 6.62 | 249  | 34.2 | 13.4| 32.5| 608 | 8.08| 43.6 | 2.33 | 2.22 | 339 | 13.4| 26.5| 3.35| 13.6 | 2.47| 0.674| 1.98 | 0.306| 1.63 | 0.293| 0.9  | 0.136| 1.51 | 0.186| 5.52 | 1.45 | 0.805 |

| Value   | 52.6| 6.39| 26.2| 4.37 | 1102 | 28.2 | 13.4| 39.5| 669 | 8.18| 41.5 | 2.18 | 2.64 | 426 | 10.7| 21.6| 2.7 | 11.6 | 2.15| 0.737| 1.88 | 0.199| 1.71 | 0.307| 0.945 | 0.080| 1.15 | 0.884| 5.52 | 1.39 | 0.709 |

| Value   |      |     |     |      |      |      |     |     |     |      |      |      |     |     |     |     |     |     |     |     |     |     |     |     |     |     |     |     |     |     |     |     |     |     |     |     |

LOI = loss on ignition; A/NK = molecular Al₂O₃/ (Na₂O + K₂O); A/CNK = molecular Al₂O₃/ (CaO + Na₂O + K₂O); Mg²⁺ = 100×molar Mg²⁺/(Mg²⁺ + Fe³⁺), calculated by assuming TFeO = 0.9 × TFe₂O₃; Data sources: a-this study, b-Zhang et al., (2004), c-Li et al., (2002)

Table 5. Summary of geochronological data for granitoids in the eastern Tianshan.
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\[^{a}\varepsilon_{\text{Hf}}(0) = 10000 \times \left[ \left( \frac{\text{^{176}Hf}}{\text{^{177}Hf}} \right)_{\text{CHUR},0} - \left( \frac{\text{^{176}Hf}}{\text{^{177}Hf}} \right)_{\text{S}} \right] \left( \frac{\text{^{176}Lu}}{\text{^{177}Hf}} \right)_{\text{CHUR}} \right] - 1 \right] \left( \frac{\text{^{176}Lu}}{\text{^{177}Hf}} \right)_{\text{CHUR}} - 1 \right], \quad \varepsilon_{\text{Hf}}(t) = 10000 \times \left[ \left( \frac{\text{^{176}Hf}}{\text{^{177}Hf}} \right)_{\text{CHUR},0} - \left( \frac{\text{^{176}Hf}}{\text{^{177}Hf}} \right)_{\text{S}} \right] \left( \frac{\text{^{176}Lu}}{\text{^{177}Hf}} \right)_{\text{CHUR}} - 1 \right] - 1, \quad T_{\text{DM}} = T_{\text{DM}}^{0} \times \frac{\left( \frac{\text{^{176}Lu}}{\text{^{177}Hf}} \right)_{\text{CHUR}}}{\left( \frac{\text{^{176}Lu}}{\text{^{177}Hf}} \right)_{\text{CHUR},0}}, \quad T_{\text{DM}}^{0} = T_{\text{DM}} \times \frac{\left( \frac{\text{^{176}Lu}}{\text{^{177}Hf}} \right)_{\text{CHUR}}}{\left( \frac{\text{^{176}Lu}}{\text{^{177}Hf}} \right)_{\text{CHUR},0}}.\]

\[^{a}\text{CHUR(T)} = \text{CHUR} \times \text{CHUR(T)} / \text{CHUR}.\]

\[^{a}\text{DM} = \text{DM} \times \text{DM} / \text{DM} \times \text{DM}.\]

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Table 4
Sulfur isotopic data of the Tuwu porphyry Cu deposit in the eastern Tianshan

<table>
<thead>
<tr>
<th>Sample no.</th>
<th>Minerals</th>
<th>$\delta^{34}$S (‰)</th>
</tr>
</thead>
<tbody>
<tr>
<td>TW-9</td>
<td>Pyrite</td>
<td>1.7</td>
</tr>
<tr>
<td>TW-10</td>
<td>Pyrite</td>
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<td>TW-11</td>
<td>Pyrite</td>
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<tr>
<td>TW-005-522-5</td>
<td>Chalcopyrite</td>
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<tr>
<td>TW-005-522-5</td>
<td>Pyrite</td>
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<tr>
<td>TW-005-510-8</td>
<td>Chalcopyrite</td>
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</tr>
<tr>
<td>TW-15</td>
<td>Chalcopyrite</td>
<td>1.9</td>
</tr>
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<td>TW-16</td>
<td>Pyrite</td>
<td>1.0</td>
</tr>
<tr>
<td>TW-14</td>
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</tr>
<tr>
<td>TW-12</td>
<td>Chalcopyrite</td>
<td>-3.0</td>
</tr>
</tbody>
</table>
Fig. 3. (a) Field photograph of diorite porphyrite and tonalite. (b) Hand specimen of tonalite. (c) Photomicrographs of tonalitic rock, showing mineral components and alteration, under crossed-polarized light. (d) Tonalitic rock with porphyritic texture, under crossed-polarized light. Abbreviations: Bt-biotite; Pl-plagioclase; Ser- sericite; Q-quartz; Kf- K-feldspar.
Fig. 5. Mineralization in the Tuwu porphyry deposit. (a) Disseminated chalcopyrite with xenomorphic granular texture. (b) Chalcopyrite veins. (c) Pyrite with enterolithic structure. (d) Scaly molybdenite. (e) Chalcopyrite replacing early pyrite. (f) Chalcopyrite. Photomicrographs are taken under reflected light (a, b, c, d, e, f). Abbreviations: Ccp-Chalcopyrite; Py-Pyrite; Mo-Molybdenite.
Fig. 6. Cathodoluminescence (CL) image of representative zircons (a) and Concordia diagram (b) for zircons from the Tuwu granites.
Fig. 8. Harker diagram of granites in the Tuwu porphyry Cu deposit.
Fig. 11. (a) $\varepsilon_{\text{Hf}}(t)$ vs. U-Pb age diagram. (b) Histograms of zircon $\varepsilon_{\text{Hf}}(t)$ values. (c) Histograms of zircon Hf-isotope crust model age ($T_{\text{DM}}^C$).
Fig. 12. Histogram of sulfur isotope composition of sulfides from the Tuwu porphyry copper deposit.
Fig. 16. Schematic showing the geodynamic setting of the Tuwu porphyry Cu deposit in the eastern Tianshan.
Highlights:

1) Zircon U–Pb dating data indicate that the magmatic events might have occurred around 332 Ma in the Tuwu region, and the Cu mineralization occurred during the same period as that of the magmatic rocks formation in the region or slightly later.

2) All the Tuwu tonalitic rocks are calc-alkaline or high–k calc–alkaline, enriched in K, Rb, Sr, and Ba, makedly depleted in Nb, Ta, Ti, and Th, and show geochemical affinities similar to those of adakites.

3) The adakitic tonalitic rocks geochemical and isotopic data indicate that they were probably derived from the partial melting of a subducted oceanic slab, and subsequently hybridized by peridotite in the mantle wedge.

4) The Tuwu adakitic tonalitic rocks and associated Cu mineralization were generated in an arc setting, and resulted likely from the northward subduction of the paleo-Tianshan ocean crust beneath the Dananhu-Tousuquan island arc belt during the Early Carboniferous.