Late Carboniferous adakitic granodiorites in the Qiongkusitai area,
western Tianshan, NW China: Implications for partial melting of lower
crust in the southern Central Asian Orogenic Belt

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Abstract

Carboniferous granitic rocks are wide spread in the western Tianshan, but their tectonic contexts remain controversial. We present zircon U–Pb age, major element, trace element, and *in situ* zircon Hf isotopic data for the Qiongkusitai granodiorites from the southern part of the Yili block in the western Tianshan. The granodiorites were emplaced in the Late Carboniferous (ca. 314 Ma) and are characterized by high SiO₂ (62.1–65.7 wt.%), high Sr (376–485 ppm), low Y (13.7–17.7 ppm) and low Yb (1.34–1.81 ppm) with Sr/Y ratios of 23–34. Such characteristics imply adakitic affinities. Their low concentrations of Cr (3.85–6.75 ppm), Co (7.63–10.7 ppm) and Ni (2.94–6.80 ppm) suggest little, if any, interaction with a mantle source. Compared to the thickened lower crustal-derived adakitic rocks, the relatively low Nb/Ta ratios of the Qiongkusitai adakitic granodiorites indicate that they were probably generated by partial melting of amphibolite facies rocks, but not eclogite facies rocks. The Qiongkusitai adakitic granodiorites have positive zircon $\varepsilon_{\text{Hf}(t)}$ values of +0.7 to +5.1 and $T_{\text{DM}2}$ of 1.28 to 1.68 Ga, and they are interpreted as being derived from remelting of amphibolite facies Mesoproterozoic basement with an input of juvenile material. Late Carboniferous magmatism in the western Tianshan was possibly triggered by asthenospheric upwelling as a result of the roll-back of the subducted southern Tianshan oceanic lithosphere.

Keywords: Adakitic granodiorite; Slab roll-back; Partial melting of lower crust; West Tianshan; Carboniferous

1. Introduction

The Central Asian Orogenic Belt (CAOB) is one of the largest accretionary orogens and one of the most significant sites of Phanerozoic crustal growth on Earth (Sengör et al., 1993; Jahn et al., 2004; Windley et al., 2007; Xiao et al., 2010, 2013; Kröner et al., 2014). As a major part of the southwestern CAOB, the Tianshan orogenic belt consists of microcontinents, ophiolite and mélangé belts, continental island arcs, remnant seamounts and oceanic plateaus, all accreted together between the Neoproterozoic and Late Paleozoic (Windley et al., 1990; Allen et al., 1993; Xiao et al., 2004, 2008, 2009a, b; Gao et al., 2009).

An important feature of the Central Tianshan is the occurrence of voluminous, multi-stage granitoid intrusions (Tang et al., 2010; Dong et al., 2011; Long et al., 2011; Xu et al., 2013; Ma et al., 2014, 2015; Yin et al., 2016). However, the tectonic settings (arc, rift or post-collisional) (Xia et al., 2004; Wang et al., 2007a; Han et al., 2010, 2011; Tang et al., 2012, 2014; Xiao et al., 2013; Li et al., 2015) and geodynamic processes associated with the Late Paleozoic granitoid intrusions have been disputed (i.e. slab roll-back, slab break off or mantle plume) (Xia et al., 2004; Han et al., 2010; Long et al., 2011; Tang et al., 2014). In addition, the timing of collision of the Tarim Cratons and Central Tianshan arc is still controversial with Latest Silurian to Devonian (Dong et al., 2011; Xu et al., 2013); Late Devonian (Xia et al. 2004), Late Devonian–Early Carboniferous (Allen et al. 1992), Early Carboniferous (Gao et al. 1998, 2009; Han et al., 2010; Long et al., 2011), end of Carboniferous to Early Permian (Wang et al., 2007b; Yang et al., 2012; Li et al., 2015), or Permian–Triassic (Zhang et al., 2007; Xiao et al., 2009a) all having been proposed. Most of granitic intrusions were emplaced from the Silurian to Early Permian along the south margin of the Central Tianshan arc (Long et al., 2011; Ren et al., 2011; Xu et al., 2013).

These granitoids not only provide critical information on Phanerozoic crustal growth, but also place important constraints on the tectonic evolution of the Tianshan orogenic belt, since they were produced at different periods, under different tectonic process, and involved different magmatic sources (Han et al., 2010; Long et al., 2011; Ren et al., 2011; Xu et al., 2013; Ma et al., 2014). More importantly, some subduction-related and underplating-related adakitic rocks have been recognized in the Northern Tianshan and Central Tianshan, which were emplaced in the Ordovician, Early Carboniferous and Permian, respectively (Wang et al., 2007a; Zhao et al., 2008; Long et al., 2011; Xie et al., 2013). However, the Late Carboniferous adakitic granites are poorly described along the south margin of the Yili block, and their petrogenesis and geodynamic implications weakly constrained.

Our investigations into the geochronology and geochemistry of the Qiongkusitai adakitic granodiorites in the south margins of the Yili block not only constrain their age and petrogenesis, but also contribute to the Late Paleozoic tectonic evolution of the Tianshan Orogenic belt.

2. Geological setting and sampling

The Chinese Tianshan is geographically subdivided into the Western Tianshan, Middle Tianshan, and Eastern Tianshan from west to east (Dong et al., 2011). The Chinese Western Tianshan is further divided into the Northern Tianshan, Central Tianshan and Southern Tianshan (Fig. 1). The Central Tianshan can be further divided into Western and Eastern parts with different rock assemblages (Dong et al., 2011). The Western part, namely the Yili block, is dominated by a thick sequence of Proterozoic–Paleozoic sedimentary rocks (Wang et al., 2007b; Dong et al., 2011). The

basement rocks of the Yili Block, consists of mainly Paleoproterozoic metamorphic rocks (i.e. Wenquan Group and Muzart Group) and Mesoproterozoic to Devonian strata (Long et al., 2011). They are unconformably overlain by upper Paleozoic volcanic and sedimentary rocks (Xia et al., 2004; Xu et al., 2013). The upper Paleozoic volcanic rocks on the southern margin of the Yili block represent the continental arc formed by northward subduction of southern Tianshan oceanic crust, and have been dated as 363–313 Ma by the zircon U–Pb super high-resolution ion microprobe (SHRIMP) method (Zhu et al., 2005, 2009). Two Paleozoic granitic belts occur along the south and north margins of the Yili block and have been interpreted as related to southward subduction of the northern Tianshan ocean (Tang et al., 2010, 2012, 2014; Li et al., 2015; Yin et al., 2016) and northward subduction of the southern Tianshan ocean (Gao et al., 2009; Zhu et al., 2009; Dong et al., 2011), respectively. They intruded the Meso–Neoproterozoic gneisses and sedimentary rocks, Cambrian–Lower Ordovician and Silurian sedimentary rocks (Gao et al., 1998; Wang et al., 2007b). These granitoid intrusions were dated at 497–296 Ma in the south margins of the Yili block and 390–287 Ma in the north margins of the Yili block by the zircon U–Pb LA-ICP MS and SHRIMP method (Wang et al., 2007b; Han et al., 2010; Long et al., 2011; Ren et al., 2011; Xu et al., 2013). Some high pressure to ultrahigh pressure (HP/UHP) metamorphic rocks have been identified within Paleozoic ophiolitic mélanges along the South–Central Tianshan suture. They include meta-sedimentary and basic meta-volcanic rocks containing blueschist-, eclogite- and greenschist-facies assemblages. The geochemistry of these rocks suggest N–MORB, E–MORB, OIB and arc basalt affinities (Gao et al., 1998, 2009; Zhang et al., 2013). The HP/UHP metamorphism was likely associated with the subduction of the South Tianshan Ocean (Gao et al., 2009).

Our study area is located in the Qiongkusitai area at the south margins of the Yili block in a region characterized by NNE-trending thrusts (Fig.2). The southeast parts of area consist mainly of high-pressure/low-temperature metamorphic rocks, whereas the most common units to the northwest are Cenozoic strata. The granodiorites that are the focus of this study intruded mainly Silurian strata (Fig.2). They have medium- to fine-grained granoblastic texture. Their mineral assemblage includes plagioclase (~45vol.%), alkali-feldspar (20 vol.%), quartz (20 vol.%), amphibole(10 vol.%) and biotite (5% vol.%) (Figs.3a, b, c). Accessory minerals include apatite, zircon, titanite and Fe-Ti oxides (Figs.3b, d).

3. Methods

Major elements were analyzed by X-ray fluorescence spectrometry (XRF) on fused glass beads using a Rigaku 100e spectrometer at the State Key Laboratory of Isotope Geochemistry, Guangzhou Institute of geochemistry, Chinese Academy of Sciences (GIGCAS). All samples were crushed into small chips after removal of weathered rims. Fresh chips were selected and washed using distilled water in an ultrasonic bath. The chips were then powdered to 200 mesh in a Tungsten carbide mill to avoid contamination. Loss on ignition (LOI) was determined at 980°C for 90 min. Details of the procedures are described by Yuan et al. (2010) and analytical uncertainties are less than 2%.

Trace elements, including rare earth elements (REE), were determined with a Perkin-Elmer ELAN-DRC-e inductively-coupled plasma mass spectrometry (ICP-MS) at the State Key Laboratory of Ore Deposit Geochemistry (SKLOG), Institute of Geochemistry, Chinese Academy of Sciences (IGCAS). The powdered

samples (50 mg) were dissolved in high-pressure Teflon bombs using HF+HNO₃ mixture for 48 h at ~195 °C (Qi et al., 2000). Rh was used as an internal standard to monitor signal drift during counting. The international standards GBPG-1, OU-6, and the Chinese National standard GSR-1 were used for analytical quality control. The analytical precision is generally better than 5% for trace elements. Details of the procedures are described by Qi et al. (2000).

Zircon U–Pb isotopic compositions were analyzed with a Agilent 7700e ICP–MS equipped with 193nm Excimer Laser–Ablation system (Geolas Pro) at the CAS Key Laboratory of Crust–Mantle Materials and Environments, University of Science and Technology of China, Hefei (USTC). Zircon 91500 (1065.4 ± 0.3 Ma, Wiedenbeck et al., 1995) was used as the external standard for U–Pb dating, and NIST SRM 610 glass as the standard for trace element analysis. The instrumental settings and detailed analytical procedures are described by Wang et al. (2014).

In situ zircon Hf isotopic composition analyses were obtained using a Neptune multicollector ICP-MS, equipped with a 193-nm laser at the at the Institute of Geology and Geophysics, Chinese Academy of Science. A spot size of 32 μ m was used for analysis, with a laser repetition rate of 10 Hz at 100 mJ. Detailed analytical procedures are described by Xie et al. (2008). During the analytical period, the $^{176}\text{Hf}/^{177}\text{Hf}$ and $^{176}\text{Lu}/^{177}\text{Hf}$ ratios of the standard zircon (91500) were 0.282294 ± 15 ($2\sigma_n$, $n=20$) and 0.00031, similar to the low peaks of $^{176}\text{Hf}/^{177}\text{Hf}$ ratios of 0.282284 ± 22 measured by Griffin et al. (2006).

4. Results

4.1 Whole-rock geochemistry

The granodiorite samples are characterized by uniform geochemical compositions and show moderate SiO₂ contents ranging from 62.1 wt.% to 65.8 wt.% (Table 1). They have low K₂O (2.03–3.00 wt.%) and slightly higher Na₂O (2.91–3.21 wt.%) contents, accordingly low K₂O/Na₂O ratios (0.63–0.99), indicating that they are calc-alkaline magmas (Gill, 1981; Fig. 4a; Table 1). Aluminum saturation indices A/CNK (Al₂O₃/(CaO + Na₂O + K₂O) molar ratios) range from 0.92 to 0.99, defining a metaluminous character (Maniar and Piccoli, 1989, Fig. 4b). In the TAS diagram (Fig. 4c), all samples are sub-alkaline and mostly plot in the granodiorite field except for two in the diorite field. Compared with the Early Carboniferous subducted oceanic slab-derived adakitic rocks in the northern Tianshan Orogen (Wang et al., 2007a), these rocks display slightly lower MgO (1.47–2.12 wt.%) and Mg numbers (39–42) (Fig. 4d; Table 1).

All samples have similar REE patterns characterized by relative enrichment of LREE ((La/Yb)_N=3.91–18.2) and nearly flat HREE ((Gd/Yb)_N=1.2–1.5), with weak negative or positive Eu anomalies (Eu^{*}/Eu=0.82–1.06) (Fig. 5a), pronounced negative Nb and Ta anomalies, and marked positive Pb anomalies (Figs. 5b,c). The samples have relatively high Sr (376–485 ppm) and low Y (13.7–17.7 ppm) concentrations, and thus show high Sr/Y ratios (23–34), which implies adakitic affinities as defined by Defant et al. (1991) (Fig. 6a; Table 1). They have low Cr (3.85–6.75 ppm), Co (7.63–10.7 ppm) and Ni (2.94–6.80 ppm) contents, similar to those of Permian adakitic rocks (Zhao et al., 2008), but lower than those of Early Carboniferous adakitic rocks in the northern Tianshan Orogen (Figs. 6b, c; Wang et al., 2007a).

4.2 Zircon U–Pb dates and Hf isotopic compositions

Fifteen zircons from the granodiorite sample TS1375 were analyzed in order to constrain the crystallization age. The analyzed zircons were prismatic, transparent, and colorless with lengths ranging from 80 to 160 μm and widths from 60 to 100 μm . In cathodoluminescence (CL) images, they display well-preserved oscillatory zoning. Their high Th/U ratios (1.6–2.4) are indicative of a magmatic origin (Belousova et al., 2002). Fifteen zircons yielded a relatively tight cluster of $^{206}\text{Pb}/^{238}\text{U}$ ages between 308 Ma and 318 Ma (Table 2), with a weighted mean value of 313.9 ± 1.8 Ma (MSWD=0.64) (Fig. 7). We interpret this as the crystallization age of the granodiorite. *In situ* zircon Lu–Hf data show that the zircons have relatively high initial $^{176}\text{Hf}/^{177}\text{Hf}$ ratios (0.282602–0.282727) and positive $\varepsilon_{\text{Hf}(t)}$ values (+0.7 to +5.1), with T_{DM2} ages ranging from 1.28 to 1.68 Ga (Fig. 8; Table 3).

5. Discussion

5.1. Petrogenesis of the Qiongkusitai adakitic granodiorites

Several petrogenetic models have been proposed for the origin of adakitic rocks, including: (1) melting of subducted oceanic crust, followed by interaction with the overlying mantle wedge (Rapp et al., 1999; Moyen et al., 2001; Martin et al., 2005; Wang et al., 2007a); (2) melting of delaminated lower crust (Gao et al., 2004; Wang et al., 2007c); (3) partial melting of thickened lower crust (Petford and Atherton, 1996; Chung et al., 2003); (4) assimilation and low-pressure fractional crystallization from parental basaltic magmas (Castillo et al., 1999); (5) high-pressure fractional crystallization (involving garnet) of mafic magmas derived from mantle wedge

peridotites (Macpherson et al., 2006); (6) magma mixing between felsic and basaltic magmas (Streck et al., 2007). We can evaluate these different possibilities based on the new major, trace element, and Hf isotopic data presented here.

The moderate SiO₂, low MgO and Mg numbers, low Cr, low Co, and low Ni characteristics of these rocks are unlike those typically reported for subducted oceanic slab-derived adakites or delaminated lower crust-derived adakites (Martin, 1999; Wang et al., 2007c), thus arguing against the possibility that slab-derived melt or delaminated lower crust melt (Figs. 6b, c; Martin, 1999; Rapp et al., 1999; Wang et al., 2007c).

It is also unlikely that the Qiongkusitai adakitic granodiorites were generated by the mixing of felsic and basaltic magmas. Generally, magma mixing produces straight arrays on binary plot on major and trace elements (Macpherson et al., 2006), but the La and Na₂O versus SiO₂ plots of the adakitic rocks (Figs. 9a, b) do not. Further, the absence of mafic xenoliths suggest that magma mixing between felsic and basaltic magmas is also not favored for the formation of the Qiongkusitai granodiorites.

High-pressure fractional crystallization involving garnet will cause a decrease in HREE and Y contents, therefore, the Sr/Y and Dy/Yb ratios in the residual magmas will increase with increasing SiO₂ contents (Macpherson et al., 2006; Davidson et al., 2007). However, the Qiongkusitai granodiorites do not exhibit such trends in their chondrite-normalized rare earth element patterns (Fig. 5a), or on Dy/Yb and Sr/Y vs. SiO₂ diagrams (Figs. 9c, d).

Castillo et al. (1999) proposed that adakitic rocks could be formed by crustal assimilation and low-pressure fractional crystallization process (involving olivine + clinopyroxene + plagioclase + hornblende) from parental basaltic magmas. However, the Mg[#], Cr, Ni values of the adakitic granodiorites studied here are relatively

constant (Figs.6b, c) and do not show clearly negative trends with the increasing SiO₂ contents. In addition, they do not show low-pressure fractional crystallization trends on La and Na₂O versus SiO₂ plots (Figs.9a, b). Fractionation of olivine and pyroxene is also not consistent with the depletion of HREE (e.g., Yb). These samples display slightly negative or positive Eu and positive Sr anomalies (Figs.5a, b) as well as high Al₂O₃ and Sr content indicating that fractional crystallization of plagioclase did not play an important role in their formation. The lack of correlation in (Dy/Yb)_N and (La/Yb)_N diagrams (Fig.10a) suggests that fractional crystallization of amphibole and garnet was not a significant process for these rocks. Moreover, La/Sm ratios exhibit strong positive correlation with Sm, suggesting that magma evolution is controlled by partial melting rather than fractionation (Fig.10b). Therefore, it is unlikely that the Qiongkusitai adakitic rocks could have been generated by high- or low-pressure fractional crystallization from basaltic parental magmas.

By process of elimination, we suggest that the Qiongkusitai adakitic rocks were most probably generated by partial melting of lower crust. In such a case, the rocks would have relatively high SiO₂ contents and low MgO, Cr, and Ni because of the lack of interaction with a mantle source (Atherton and Petford, 1993). As shown above, the geochemical characteristics of the adakitic granodiorites in the Qiongkusitai area are similar to those of other lower crust-derived adakitic melts (Petford and Atherton, 1996; Chung et al., 2003).

5.2 Source of the Qiongkusitai adakitic granodiorites

The low A/CNK ratios, medium-K to high-K characteristics, and apparent calc-alkaline affinity of these rocks – as well as their negative correlation between

SiO₂ and P₂O₅ (Fig.10c) –suggest that the Qiongkusitai granodiorites may be I-type bodies produced by partial melting of an igneous source. Trace-element modeling of partial melting of eclogite and amphibolite shows that melts of eclogite bearing rutile lie in the upper right quadrant, and eclogites without rutile have unfractionated Nb/Ta, while rocks in the lower right quadrant may originate by 1–15% batch melting of amphibolite (Fig. 10d; Foley et al., 2002). The relatively low Nb/Ta ratios and high Zr/Sm ratios of the Qiongkusitai granodiorites indicate partial melting of amphibolite but not eclogite (Fig.10d). Trace element characteristics of melt with low Nb/Ta and high Zr/Sm ratios, can be explained by melting of relatively low Mg[#] amphibolite, but not by melting of Mg-rich amphibolites or eclogites (Foley et al., 2002). Thickened lower crustal–derived adakitic rocks from the Tibetan Plateau exhibit much higher Nb/Ta ratios (Fig.10d). The remarkable difference between the Tibet an adakitic rocks and the Qiongkusitai adakitic rocks implies that the crustal source of the Qiongkusitai adakitic granodiorites was the low Mg[#] amphibolites and did not undergo significant thickening. In fact, some studies have demonstrated that an adakitic signature can be achieved at relatively low pressures (10–12.5 kbar) at 800–950°C (Johnson et al., 1997; Zellmer et al., 2012). This suggests that an adakitic signature can be generated in unthickened crust, and it is unnecessary to presume that an adakitic signature unambiguously demonstrates partial melting of an over-thickened crust (Qian and Hermann, 2013).

The T_{DM2} ages of 1.28 to 1.68 Ga (peak at 1.40–1.60 Ga) for the Qiongkusitai adakitic granodiorites indicated that these rocks were likely generated by partial melting of Mesoproterozoic crust. Previous studies showed that such crust existed in the Central Tianshan and its surrounding areas, such as a 1.4 Ga granitic gneiss in Bingdaban of Central Tianshan (Chen et al., 2009), a 1.46-1.45 Ga Xingxingxia

granitic gneiss in the eastern segment of the Central Tianshan (Shi et al., 2010), and an inherited zircon with age of ~1.4 Ga from the Xingxingxia granodiorite (Lei et al., 2011). In addition, their $\varepsilon_{\text{Hf}(t)}$ of +0.7 to +5.1 (peak at +2 to +4) as well as $\varepsilon_{\text{Nd}(t)}$ of -0.87 (Long et al., 2011) imply that newly underplated mafic rocks were involved in the formation of the Qiongkusitai adakitic granodiorites. Therefore, the Qiongkusitai adakitic granodiorites were probably generated by partial melting of amphibolite facies Mesoproterozoic basement and a contribution from juvenile material.

5.3 Tectonic implications

Many studies have concluded that the Tianshan orogenic belt was formed by the subduction and collision of the northern Tianshan Ocean and southern Tianshan Ocean (Gao et al., 2009; Long et al., 2011; Xu et al., 2013). However, the timing of closure is still debated. Interpretations vary from latest Silurian to Triassic (Allen et al. 1992; Gao et al. 1998, 2009; Zhang et al., 2007; Xu et al., 2010, 2013; Xiao et al., 2004, 2008, 2009). The overall structure of South Tianshan is characterized by high- to ultrahigh-pressure rocks thrust over an accretionary complex that was located along the southern margin of the Yili block in the Late Paleozoic (Xiao et al., 2013). Zircon and rutile U–Pb ages of ~319 Ma from eclogites of the Chinese Tianshan have been interpreted to record the closure of the South Tianshan Ocean and the collision between the Yili and Tarim blocks at ca. 319 Ma (Su et al., 2010; Gao et al., 2011; Li et al., 2011). However, based on studies in Japan, Xiao et al. (2013) showed that a thrust accretionary wedge orogen can be overlain by its own trench slope basins and by its own forearc basins long before continental collision. The Tianshan HP/UHP rocks may have become involved in a forearc accretionary complex due to northward

subduction of the South Tianshan ocean plate. Therefore, all these ages of HP/UHP rocks could be closely associated with the northward subduction of the South Tianshan ocean plate rather than the collision between the Yili block and Tarim craton. Additionally, the southern margin of the Yili block contains voluminous, mainly I-type granitoid intrusions with ages ranging from 437 to 313 Ma (Long et al., 2011; Xu et al., 2013). They are characterized by the enrichment of light rare earth elements (LREE) and depletion of high field strength elements (e.g., Nb, Ta and Ti) (Long et al., 2011; Xu et al., 2013) similar to typical arc geochemical affinities. In addition, the Late Palaeozoic volcanic rocks (361–313 Ma) in the southwestern Tianshan Mountains, mainly consisting of basalt, trachyte, trachy-andesite, andesite and rhyolite, represent a continental arc formed during the subduction of the Palaeo-southern Tianshan Ocean (Zhu et al., 2009). Therefore, the multiple lines of evidence strongly indicate that the Yili block was in a subduction-dominated setting in the Late Carboniferous.

Adakitic rocks provide significant information on magma sources and geodynamic mechanisms and form in a variety of settings, such as flat subduction, ridge subduction and slab roll-back (Tuena et al., 2003; Mori et al., 2007; Geng et al., 2009). It is unlikely that the Qiongkusitai adakitic rocks were generated by a flat subduction. Generally, a period of magmatic quiescence would appear during a flat subduction episode (e.g., Gutscher et al., 2000). However, many intrusions and volcanic rocks from Devonian to Permian have been reported (Zhu et al., 2009; Long et al., 2011; Xu et al., 2013) and no period of magmatic quiescence has been identified on the southern margin of the Yili block. Ridge subduction is also a viable mechanism to form the adakitic rocks. In this study, the ridge subduction model is not favored because (1) In the ridge subduction setting, arc-type magmatic activities

above slab window will be replaced by alkaline magma (Sisson et al., 2003). However, in the western part of the Tianshan, widely distributed Late Carboniferous arc-type magmas, e.g., the Dahalajunshan Formation trachy-andesites-rhyolites formed between 361 Ma and 313 Ma (Zhu et al., 2009). (2) The adakitic rocks in a ridge subduction setting are characterized by high MgO, Mg[#], Cr, Co, Ni contents, whereas the Qiongkusitai adakitic granodiorite show lower MgO, Mg[#], Cr, Co, Ni contents. (3) The Devonian -Carboniferous granitoids in the western Tianshan define a narrow, linear zone of magmatism parallel to the subduction zone, which is inconsistent with a ridge subduction model.

Qian and Hermann (2013) reported experimental results suggesting that adakite can be produced by melting of mafic lower crust at surprisingly low pressures (equivalent to ca. 30 to 40 km depth) that might be found in normal thickness continental crust with an elevated geotherm. This result challenges the widespread assumption that adakite formation requires crustal overthickening. In our study, the relatively low Nb/Ta and high Zr/Sm ratios of the Qiongkusitai adakitic granodiorites support amphibolite melting, not eclogite melting, implying that an overthickened crust was not present in Late Carboniferous in the western Tianshan. Recently, the association of Fe-rich basalt-rhyolite, mafic and granitoid dikes, Nb-rich doleritic dikes, MgO-rich dioritic dikes, and A-type rhyolite in the central Tianshan has been interpreted as indicative of an extensional setting in western Tianshan in the Late Carboniferous (Liu et al., 2012; Tang et al., 2014; Li et al., 2015). Yang et al. (2012) and Li et al. (2015) proposed that a slab roll-back model could account for the geochemical characteristics of A-type rhyolite as well as coeval arc mafic and felsic magmas from the Awulale Mountains in the western Tianshan. Taking into account all available data from Late Paleozoic magmatic rocks, our data support a slab

roll-back model during the Late Carboniferous in western Tianshan (Fig. 11). At that time, we infer that the southern Tianshan Ocean slab was being consumed beneath the Yili block. Slab roll-back may have induced asthenospheric upwelling. This process not only could have provided a mechanism for melting overlying metasomatized lithospheric mantle, but it also could have led to decompression melting of the asthenospheric mantle to generate mafic magmas (Liu et al., 2012; Li et al., 2015). Subsequently, the underplating of mafic magmas could have resulted in partial melting of lower crust, producing felsic rocks (i.e. A-type granitic magmas, I-type granitic magmas and adakitic rocks; Li et al., 2015). The temporal and spatial distribution of magmatism suggests a northeastward migration of melting, which is consistent with rollback of the subducting southern Tianshan ocean slab (Xu et al., 2013 and references therein). An analogous geodynamic process has been proposed for the Trans-Mexican Volcanic Belt (Ferrari et al., 2001; Gómez-Tuena et al., 2003), for western North America (Smith et al., 2014), for northern Luzon (Hollings et al., 2011), for the southern Lhasa block of Tibet (Ma et al., 2013a, b), for West Junggar (Yin et al., 2015a, b), and for western Tianshan (Tang et al., 2010; 2012; 2014).

6. Conclusion

The Qiongkusitai granodiorites were emplaced in the Late Carboniferous (314 Ma) in the western Tianshan. They are characterized by high SiO₂ (62.1–65.7 wt.%), high Sr (376–485 ppm) and low Y (13.7–17.7 ppm) and Yb (1.34 – 1.81 ppm) with high Sr/Y ratio of 23–34, which imply adakitic affinities, whereas their low Cr (3.85–6.75 ppm), Co (7.63–10.7 ppm) and Ni (2.94–6.80 ppm) contents suggest the lack of interaction with a mantle source. The Qiongkusitai adakitic granodiorites were

most likely derived from the melting of amphibolite facies Mesoproterozoic basement and an input of juvenile material. The Late Carboniferous magmatism in the western Tianshan was possibly triggered by the asthenospheric upwelling as a result of the rollback of the subducted southern Tianshan oceanic lithosphere.

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Figures and captions

Fig.1. The distribution of major suture zones and Paleozoic granitic rocks in the Chinese Tianshan (after Gao et al., 2009 and Long et al., 2011).

Fig.2. Geological map in the Qiongkushitai region with sampling locations; modified after Long et al.(2011) and Xu et al.(2012)). The granite ages are from: (1) This study; (2) Xu et al.(2012); (3) Long et al.(2011).

Fig.3. Photo-micrographs of rocks from the Qiongkusitai granodiorites in the Yili block. Apm=Amphibole, Pl=Plagioclase, Kf=K-feldspar, Titanite=Ti, Bi=Biotite, Q=Quartz.

Fig.4. (a) K_2O - SiO_2 classification diagram is after Gill (1981);(b) $Al/(Na+K)$ vs $Al/(Ca+Na+K)$, molecular ratio (Maniar and Piccoli, 1989); (c) SiO_2 -(Na_2O+K_2O) diagram (Middlemost, 1994);(d) SiO_2 - MgO diagram, reference fields are from Wang et al. (2006) and references therein. Qiarbahete adakitic rocks (354 Ma) in the western Tianshan (Xie et al., 2013); Alataw adakitic rocks (320 Ma) in the western Tianshan (Wang et al., 2007); Awulale adakitic rocks (260 Ma) in the western Tianshan (Zhao et al., 2008).

Fig.5. (a) Chondrite-normalized REE patterns and (b, c) primitive mantle-normalized spider diagrams for the Qiongkusitai granodiorites. Normalizing values are from Sun and McDonough (1989). Data source for other adakitic rocks are as in Fig.4.

Fig.6. (a) Sr/Y versus Y (after Defant et al. (1992));(b) and (c) SiO_2 versus Cr and Ni diagram. Reference fields are from Wang et al. (2006) and references therein. Data source for other adakitic rocks are as in Fig.4.

Fig.7. U-Pb concordia diagrams showing zircon ages obtained by LA-ICP-MS for the Qiongkusitai granodiorite in the Yili block.

Fig.8. Plots of $\epsilon_{Hf(t)}$ values versus Zircon U-Pb age of the Qiongkusitai granodiorite.

Fig.9. Plots of (a) SiO_2 versus La ; (b) SiO_2 versus Na_2O ; (c) SiO_2 versus Dy/Yb ; (d) SiO_2 versus Sr/Y ; Fractional crystallization trends in a-d: HPFC, high-pressure fractional crystallization involving garnet (Macpherson et al., 2006); LPFC: Low pressure crystal fractionation of island arc tholeiitic series basalt (Castillo et al., 1999). Data source for other adakitic rocks are as in Fig.4.

Fig.10. (a) Plots of $(La/Yb)_N$ vs. $(Dy/Yb)_N$; (b) Plots of La/Sm vs Sm ; (c) P_2O_5 vs. SiO_2 diagram, the trend of I- and S-type granites follows Chappell (1999); (d) Nb/Ta vs. Zr/Sm diagram for the adakitic granodiorites. Reference fields are from Foley et al. (2002) and Guan et al. (2014) and references therein. Data source for other adakitic rocks are as in Fig.4.

Fig.11. A suggested model to produce the Late Carboniferous adakitic granodiorites of the western Tianshan, triggered by slab roll-back of subducted southern Tianshan ocean, which provides the required high thermal regime for partial melting of lower crust.

Table 1 Major (wt.%) and trace element (ppm) composition of the Qiongkusitai granodiorites.

Table 2 LA-ICP-MS U-Pb isotopic analysis for zircons from the Qiongkusitai granodiorites.

Table 3 Lu-Hf isotopic compositions of zircons from the Qiongkusitai granodiorites.

Figure 1

Figure 2

Figure 3

Figure 4

Figure 5

Figure 6

Figure 7

Figure 8

Figure 9

Figure 10

Figure 11

Table 1

Table 1 Major (wt.%) and trace element (ppm) composition of 1

Sample	TS1375-1	TS1375-2	TS1375-3	TS1375-4	TS1375-5	TS1375-6	TS1376-1	TS1376-2
SiO ₂	62.2	63.3	64.0	63.1	63.0	63.5	66.1	65.1
TiO ₂	0.53	0.49	0.51	0.54	0.51	0.57	0.41	0.40
Al ₂ O ₃	16.4	16.8	16.5	16.5	16.5	16.2	15.8	16.0
Fe ₂ O _{3T}	5.90	5.32	5.08	5.64	5.36	5.35	4.53	4.71
MnO	0.15	0.12	0.12	0.13	0.13	0.13	0.12	0.12
MgO	2.13	1.78	1.72	1.95	1.83	1.92	1.48	1.52
CaO	5.47	5.75	5.04	5.61	5.25	5.05	4.54	4.65
Na ₂ O	2.91	3.36	2.95	3.18	3.04	3.01	3.05	3.12
K ₂ O	2.88	2.12	2.50	2.03	2.76	2.71	2.97	2.83
P ₂ O ₅	0.21	0.19	0.19	0.20	0.19	0.18	0.16	0.16
L.O.I	0.90	0.70	0.76	0.74	0.80	0.85	0.82	0.90
Total	99.6	100.0	99.3	99.6	99.4	99.5	100.0	99.5
Mg [#]	42	40	40	41	40	42	39	39
Na ₂ O+K ₂ O	5.80	5.50	5.50	5.20	5.80	5.70	6.00	6.00
K ₂ O/Na ₂ O	0.99	0.63	0.84	0.64	0.91	0.90	0.97	0.91
A/CNK	0.92	0.92	0.99	0.94	0.94	0.95	0.96	0.96
Li	19.6	17.7	21.0	21.3	14.5	17.4	19.9	20.0
Be	1.64	1.40	1.22	1.46	0.90	1.17	2.22	1.18
Sc	14.9	12.5	11.8	12.7	11.1	9.87	11.1	12.1
V	109	97.7	101	105	98.7	95.7	82.2	86.3
Cr	3.97	4.41	3.85	5.40	6.52	5.10	3.89	3.98
Co	10.7	9.40	9.96	10.4	9.14	9.53	7.88	7.78
Ni	3.62	3.60	3.57	3.79	4.43	5.75	2.94	2.82
Cu	13.8	11.7	11.3	15.1	11.4	11.1	17.5	27.9
Zn	94.3	79.1	84.9	97.7	83.6	74.9	77.3	78.3
Ga	15.8	16.2	15.8	16.3	15.1	15.3	15.6	15.9
Ge	1.67	1.71	1.79	1.83	1.50	1.66	1.82	2.09
As	0.51	0.58	0.86	0.50	0.86	0.26	0.87	0.77
Rb	86.4	70.1	87.2	75.9	86.2	92.5	99.7	99.5
Sr	437	467	468	445	485	483	376	386
Y	17.7	15.8	16.0	13.7	15.5	14.2	16.7	15.7
Zr	32.2	31.9	41.9	25.4	49.2	50.3	38.4	43.1
Nb	7.74	7.82	8.80	7.29	6.49	8.51	9.36	8.80
Cd	0.05	0.04	0.05	0.04	0.05	0.05	0.02	0.05
In	0.04	0.04	0.03	0.03	0.07	0.05	0.03	0.04
Sn	0.74	0.63	0.79	0.74	0.85	0.87	0.67	0.94
Sb	0.05	0.01	3.69	0.05	0.11	0.35	0.11	0.23
Cs	2.60	2.33	2.66	2.79	2.64	3.03	4.89	5.03
Ba	1060	723	1050	692	1050	929	619	632
La	9.87	11.1	9.47	7.91	11.0	7.97	20.0	12.8
Ce	22.8	25.0	21.8	18.0	25.0	17.8	37.4	23.2
Pr	3.08	3.07	2.76	2.38	2.91	2.25	4.16	3.00
Nd	13.5	12.7	11.4	10.1	12.2	9.36	15.0	11.8
Sm	2.88	2.80	2.77	2.29	2.75	2.34	2.98	2.52
Eu	0.95	0.91	0.92	0.79	0.85	0.78	0.83	0.76
Gd	3.02	2.84	2.66	2.27	2.65	2.19	2.72	2.58
Tb	0.42	0.41	0.38	0.33	0.42	0.38	0.41	0.38

Table 2 LA-ICP–MS U-Pb isotopic analysis for zircons from the Qiongkusitai granodiorites.

Isotopic ratios								
Analysis	²⁰⁷ Pb/ ²⁰⁶ Pb	1σ	²⁰⁷ Pb/ ²³⁵ U	1σ	²⁰⁶ Pb/ ²³⁸ U	1σ	²⁰⁷ Pb/ ²⁰⁶ Pb	1σ
1	0.055096	0.001669	0.377843	0.010982	0.050286	0.000569	0.015883	0.000345
2	0.06126	0.002195	0.416048	0.014908	0.050024	0.000633	0.014877	0.000430
3	0.056837	0.002301	0.386418	0.015037	0.050045	0.000647	0.015221	0.000469
4	0.052214	0.001461	0.352071	0.009258	0.049642	0.000510	0.014741	0.000395
5	0.057956	0.003001	0.399063	0.018402	0.050601	0.00049	0.017248	0.002227
6	0.062127	0.00481	0.416610	0.028875	0.050144	0.000637	0.014534	0.000584
7	0.062068	0.002282	0.432119	0.015481	0.050704	0.000577	0.016855	0.000468
8	0.05585	0.002162	0.376685	0.014538	0.050148	0.000671	0.015062	0.000401
9	0.059061	0.002026	0.399901	0.013548	0.049463	0.000594	0.015505	0.000403
10	0.057146	0.001925	0.377498	0.011533	0.049382	0.000615	0.015414	0.000403
11	0.055545	0.001978	0.370074	0.012362	0.049731	0.000602	0.015204	0.000407
12	0.058006	0.002342	0.400745	0.016252	0.050296	0.000608	0.015065	0.000457
13	0.054158	0.001716	0.366135	0.011324	0.048981	0.000557	0.014074	0.000294
14	0.057381	0.001964	0.392486	0.011968	0.049973	0.000536	0.014752	0.00045
15	0.053314	0.001858	0.359308	0.011723	0.049702	0.000598	0.013727	0.000432

Table 3 Lu-Hf isotopic compositions of zircons from the Qiongkusitai granodiorites.

Sample	Age (Ma)	$^{176}\text{Yb}/^{177}\text{Hf}$	2σ	$^{176}\text{Lu}/^{177}\text{Hf}$	2σ	$^{176}\text{Hf}/^{177}\text{Hf}$	2σ	ϵ_{Hf}
1	314	0.018253	0.000528	0.000882	0.000017	0.282638	0.000020	1.98
2	314	0.016241	0.000210	0.000798	0.000010	0.282602	0.000020	0.74
3	314	0.017189	0.000370	0.000843	0.000017	0.282679	0.000018	3.44
4	314	0.01334	0.000151	0.000702	0.000009	0.282664	0.000017	2.95
5	314	0.016401	0.000178	0.000829	0.000008	0.282669	0.000023	3.10
6	314	0.011999	0.000298	0.000619	0.000015	0.282678	0.000018	3.44
7	314	0.017724	0.000391	0.000891	0.000020	0.282685	0.000019	3.65
8	314	0.015226	0.000074	0.000746	0.000004	0.282636	0.000017	1.95
9	314	0.01369	0.000178	0.000688	0.000009	0.282622	0.000019	1.44
10	314	0.022543	0.000286	0.001061	0.000012	0.282638	0.000027	1.96
11	314	0.021771	0.000284	0.001084	0.000013	0.282727	0.000019	5.10
12	314	0.017517	0.000400	0.000821	0.000013	0.282683	0.000019	3.58
13	314	0.014422	0.000160	0.000727	0.000009	0.282685	0.000021	3.67
14	314	0.010951	0.000184	0.000566	0.000008	0.282724	0.000024	5.08
15	314	0.011625	0.000150	0.000599	0.000007	0.282677	0.000015	3.43