**Late Silurian-early Devonian adakitic granodiorite, A-type and
I-type granites in NW Junggar, NW China: Partial melting of mafic
lower crust and implications for slab roll-back**

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Abstract

Late Silurian-early Devonian magmatism of the NW Junggar region in the Central Asian Orogenic Belt provides a critical geological record that is important for unraveling regional tectonic history and constraining geodynamic processes. In this study, we report results of U-Pb zircon ages and systematic geochemical data for late Silurian-early Devonian largely granitic rocks in NW Junggar, aiming to constrain their emplacement ages, origin and geodynamic significance. The magmatism consists of a variety of mafic to felsic intrusions and volcanic rocks, e.g. adakitic granodiorite, K-feldspar granite, syenitic granite, gabbro and rhyolite. U-Pb zircon ages suggest that the granitoids and gabbros were emplaced in the late Silurian-early Devonian (420-405 Ma). Adakitic granodiorites are calc-alkaline, characterized by high Sr (407-532 ppm), low Y (12.2-14.7 ppm), Yb (1.53-1.77 ppm), Cr (mostly < 8.00 ppm), Co (mostly <11.0 ppm) and Ni (mostly <4.10 ppm) and relatively high Sr/Y (31-42) ratios, analogous to those of modern adakites. K-feldspar granites and rhyolites are characterized by alkali- and Fe-enriched, with high Zr, Nb and Ga/Al ratios, geochemically similar to those of A-type granites. Syenitic granites show high alkaline ($\text{Na}_2\text{O}+\text{K}_2\text{O}=8.39\text{-}9.34$ wt.%) contents, low $\text{Fe}^\#$ values (0.73-0.80) and are weakly peraluminous ($\text{A/CNK}=1.00\text{-}1.07$). Gabbros are characterized by low MgO (6.86-7.15 wt.%), $\text{Mg}^\#$ (52-53), Cr (124-133 ppm) and Ni (84.7-86.6 ppm) contents.

The geochemical characteristics of the gabbroic samples show affinity to both MORB- and arc-like sources. All granitoids have positive $\epsilon\text{Nd}(t)$ (+3.9 to +6.9) and zircon $\epsilon\text{Hf}(t)$ (+9.8 to +15.2) values and low initial $^{87}\text{Sr}/^{86}\text{Sr}$ ratios (0.7035-0.7043), with young $T_{\text{DM}}(\text{Nd})$ (605-791 Ma) and $T_{\text{DM}}(\text{Hf})$ (425-773 Ma) ages, suggesting significant addition of juvenile material. The adakitic granodiorites probably resulted from partial melting of mafic lower crust, leaving an amphibolite and garnet residue. The K-feldspar granites, rhyolites and syenitic granites probably formed from partial melting of the Xiemisitai mid-lower crust, while the gabbroic intrusion was probably generated by interactions between asthenospheric and metasomatized lithospheric mantle. Voluminous plutons of various types (adakites, A-type granites, I-type granites, and gabbros) formed during 420-405 Ma, and their isotopic data suggest significant additions of juvenile material. We propose that a slab roll-back model can account for the 420-405 Ma magmatic “flare up” in NW Junggar as well as an extensional setting.

Keywords: A-type granite; I-type granite; adakitic granodiorite; slab roll-back; NW Junggar; crustal growth

1. Introduction

The Central Asian Orogenic Belt (CAOB) is the largest Phanerozoic orogenic belt in the world, extending from the Urals in the west to the Pacific in the east and from Siberia in the north to the Tianshan in the south (Fig. 1a; Şengör et al., 1993; Windley et al., 2007; Xiao et al., 2008; 2014a; 2015). The CAOB is largely characterized by massive granitoids and their volcanic equivalents with positive $\epsilon\text{Hf}(t)$, $\epsilon\text{Nd}(t)$ values and young $T_{\text{DM-Nd}}$ model ages (Şengör et al., 1993; Chen and Jahn, 2004; Yuan et al., 2007; Geng et al., 2009; Tang et al., 2012; Yang et al., 2014a; Li et al., 2015a,b). Although the granitoids reflect crustal growth in West Junggar, the tectonic regimes where crustal growth takes place remain highly controversial. Şengör et al. (1993) proposed that the CAOB was chiefly formed by subduction-accretion processes during the Phanerozoic, while others stressed the role of vertical addition of juvenile material in the Phanerozoic crustal growth (Han et al., 2006; Jahn et al., 2000; Chen and Jahn, 2004). More recent views have suggested that an initial Paleozoic archipelago was formed by multiple, short-lived, subduction zones with different subduction polarities, a scenario similar to that in the present SW Pacific (Windley et al., 2007; Xiao et al., 2008; 2013; Xiao and Santosh, 2014). Granitoids in accretionary orogens can provide not only critical information on crustal growth, but also important constraints

on the tectonic evolution of the CAO. Previous studies, however, mainly concentrated on early Cambrian to early Silurian and Carboniferous to Permian plutons with little attention to plutons emplaced during the transitional period of late Silurian to early Devonian. This imbalance severely restricts a comprehensive understanding of the tectonic evolutionary history during the Paleozoic in West Junggar. Silurian-Devonian granitoids are widely distributed in the CAO and have been used to discriminate the geological evolution and crustal growth (Filippova et al., 2001; Yuan et al., 2007; Kröner et al., 2008; Sun et al., 2008; Gao et al., 2009; Chen et al., 2010; Cai et al., 2011; Shen et al., 2011). Chen et al. (2010a) reported late Silurian-early Devonian plutons in NW Junggar including A-type granite and associated diorites, K-feldspar granites, and subvolcanic rocks that indicate that middle Paleozoic magmatism was active in West Junggar. Recently, Chen et al. (2010a, 2015) proposed that the middle Paleozoic granitoids would form a post-collisional setting; However, Shen et al. (2012) and Yang et al. (2014b) considered that NW Junggar was in a normal arc-related setting in the middle Paleozoic from their study of the Xiemisitai volcanic rocks. Obviously, more work is needed and a correct model not only sheds light on the tectonic evolution of the area, but also helps understanding the crustal growth of CAO.

In this paper, we present new geochemical data, *in situ* zircon U-Pb

ages, zircon Hf isotopic data and whole-rock Nd-Sr isotopic data for representative granitic intrusions in NW Junggar. We recognize not only late Silurian-early Devonian A-type granites and I-type granites, but also contemporaneous adakitic granodiorites and gabbros in this region, which provide new constraints on the geodynamic background and crustal growth mechanism at this time.

2. Geological background

West Junggar is a triangular-shaped area in southwestern CAOB, surrounded by the Altay Orogen, Tianshan Orogen, Kazakhstan Plate and the Junggar Basin (Fig. 1b; Windley et al., 2007; Xiao et al., 2008; Xiao and Santosh, 2014). West Junggar is divided into northern and southern parts by the Xiemisitai Fault (Fig. 1c). NW Junggar is mainly characterized by two EW-trending faults (Xiemisitai Fault and Sawur Fault) and six EW-striking mountain belts, i.e. Tarbgatay, Sawur, Saier, Xiemisitai, Sharburti and Wuerkashier Mountains (Fig. 1c; Chen et al., 2010a). Many ophiolitic blocks in NW Junggar occur along the Xiemisitai and Sawur faults (Fig. 1b; Zhang et al., 2003; Jian et al., 2005; Zhu and Xu et al., 2006); they mainly consist of Ordovician to late Devonian mafic to ultramafic rocks. Zhao et al. (2013) reported an early Cambrian Chagantaolegai ophiolite in the southern Xiemisitai Mountains

(Fig. 2). The distribution of volcanic rocks in NW Junggar is governed by the Zharma-Sawur and Boshchekul-Chingiz arcs (Fig. 1b). The former mainly consists of Devonian-early Carboniferous arc volcanic rocks, whereas the latter is characterized by many Silurian to early Carboniferous arc volcanic rocks (Fig. 1c). Zircon LA-ICP-MS U-Pb ages indicate that the Xiemisitai volcanic rocks were all emplaced in the early Silurian-early Devonian (429 Ma-411 Ma) indicating that the volcanic rocks and intrusions were coeval (Shen et al., 2012; Yang et al., 2014b). Common granitic plutons in NW Junggar were emplaced from early Cambrian to Permian (Han et al., 2006; Zhou et al., 2008; Chen et al., 2010a; Xu et al., 2012, 2013; Ren et al., 2014). Four pulses of granitic magmatism have been distinguished, i.e. the early Cambrian to early Silurian (517 to 452 Ma; Xu et al., 2012, 2013; Ren et al., 2014), the late Silurian-early Devonian (ca. 422 to 405 Ma; Chen et al., 2010a), the Early Carboniferous (ca. 346 to 321 Ma, Han et al., 2006; Zhou et al., 2008; Yin et al., 2013a), and the latest Carboniferous-middle Permian (ca. 304 to 263 Ma, Han et al., 2006; Zhou et al., 2008; Yin et al., 2013a). The early Cambrian to early Silurian plutons, composed of gabbro, diorite, granodiorite and granite with calc-alkaline characteristics, are mainly in the Mayile and Saleinuohai mountains in SW Junggar (Xu et al., 2012, 2013; Ren et al., 2014). The late Silurian-early Devonian granitoids mainly occur in the Ximisitai and Saier Mountains including A-type

granites and associated diorites, K-feldspar granites and subvolcanic rocks (Fig. 2; Chen et al., 2010a). The early Carboniferous granitoids are dominated by I-type granitoids mainly in the Tarbgatay and Sawur Mountains (Zhou et al., 2008; Chen et al., 2010b; Yin et al., 2013a, 2015a). The latest pulse of granitic magmatism was in the Wuerkashier, Tarbgatay and Sawur Mountains between the latest Carboniferous and middle Permian, and is dominated by alkaline granites, some of which show strong affinity to A-type granites (Han et al., 2006; Zhou et al., 2008; Chen et al., 2010a, b).

Samples from NW Junggar located in the Xiemisitai and Saier mountains (Fig. 1c). The sampling locations are labelled in Figure 2 and the GPS coordinates of all the samples are listed in Appendix 2.

3. Petrography

Four groups of intrusive rocks and one group of extrusive rock were identified in NW Junggar, i.e. adakitic granodiorites, K-feldspar granites, rhyolites, gabbros and syenitic granites. The intrusive rocks intrude the Xiemisitai and Saier mountains volcanic rocks (Fig. 2). Recent zircon U-Pb ages of volcanic rocks in the Xiemisitai and Saier mountains in NW Junggar suggest that they erupted in the early Silurian-early Devonian (Shen et al., 2012; Yang et al., 2014b) rather than in the middle

Devonian, as previously considered (BGMRXUAR, 1993).

Adakitic granodiorites from the Xiemisitai Mountains (Figs. 3a, g, j) consist of plagioclase (45-50 vol.%), alkali feldspar (10-15 vol.%), quartz (20-25 vol.%), biotite (5-15 vol.%), and amphibole (5 vol.%), with minor Fe-Ti oxides (Fig. 4a). K-feldspar granites in the Xiemisitai Mountain are pinkish and composed of K-feldspar (68 vol.%), quartz (20 vol.%), amphibole (10 vol.%), and biotite (2 vol.%); accessory minerals are mainly opaque oxides, apatite, and titanite, and amphiboles are arfvedsonites (Figs. 3b, c, i, k, l; Figs. 4b, c). Rhyolites in the Xiemisitai Mountains contain phenocrysts up to 4.5 mm in a 65 vol.% groundmass (Fig. 3d) that consist of orthoclase (22 vol.%), plagioclase (3 vol.%), quartz (8 vol.%), mafic minerals (2 vol.%), and accessories (Fig. 4e). Syenitic granites from the Saier and Xiemisitai Mountains (Fig. 3h) are massive and consist of plagioclase (20 vol.%; An₂₉), perthite (55 vol.%), quartz (22 vol.%), biotite (3 vol.%), and accessory zircon, apatite, titanite and opaque oxides (Fig. 4d). The gabbroic rocks from the Xiemisitai Mountains have a gabbroic texture (Figs. 3c, f) and mainly contain plagioclase (~62 vol.%; An₅₀) and clinopyroxene (35 vol.%) with amphibole and biotite (3 vol.%), and accessory zircon, apatite, and opaque oxides (Fig. 4f). Clinopyroxene and amphibole occur as subhedral to euhedral grains, and locally as large poikilitic (up to 5 mm) crystals, while plagioclase usually forms subhedral crystals some of which show

zonal structure.

4. Analytical methods

Major elements were analyzed by X-ray fluorescence spectrometry (XRF) on fused glass beads using a Rigaku 100e spectrometer at the Guangzhou Institute of geochemistry, Chinese Academy of Sciences (GIGCAS). Details of the procedures are described by Yuan et al. (2010).

Trace elements, including rare earth elements (REE), were determined with a Perkin-Elmer ELAN 6000 inductively-coupled plasma source mass spectrometer (ICP-MS) at GIGCAS, following the procedures of Li et al. (2002).

Rb-Sr and Sm-Nd isotope analyses were performed in the Laboratory for Isotope Analysis, Institute of Geology, CAGS; The Sr isotope compositions were measured by isotope dilution on a Finnigan MAT-262 mass spectrometer. The Nd isotope compositions were acquired with a Nu Plasma HR multi-collector inductively coupled plasma mass spectrometry (MC-ICP-MS) (Nu Instruments). Procedural details are described by He et al. (2007).

Zircon U-Pb isotopic compositions were analyzed with a VG PQ Excell ICP-MS equipped with a New Wave Research UV213 laser ablation system in the Department of Earth Sciences, the University of

Hong Kong. The laser system delivers a beam of 213 nm UV light from a frequency quintupled Nd: YAG laser. Most analyses were carried out with a beam diameter of 30 μ m, 6 Hz repetition rate. The instrumental settings and detailed analytical procedures are described by Xia et al. (2004).

Hf isotopic analyses were undertaken with a Nu Plasma HR MC-ICP-MS (Nu Instruments, UK), coupled to a 193 nm excimer laser ablation system (RESOLUTION M-50, Resonetics LLC, USA), installed in the Department of Earth Sciences, University of Hong Kong. Hf isotopic data were acquired by ablating 55 μ m in beam diameter, and a 6 hz repetition rate was used. Detailed analytical procedures are described by Geng et al. (2009).

5. Results

5.1. Zircon U-Pb geochronology

Eight samples in the Xiemisitai and Saier Mountains were selected for zircon separation. All the zircons from these rocks possess clear magmatic oscillatory zoning in cathodoluminescence (CL) images and possess Th/U ratios higher than 0.2, suggesting a magmatic origin. The results of U-Pb single zircon analysis are presented in Appendixes 1 and

2 and plotted in Fig. 5.

5.1.1 Adakitic granodiorite

Seventeen spots from sample WJ1132 of adakitic granodiorite from the Xiemisitai Mountains show similar apparent $^{206}\text{Pb}/^{238}\text{U}$ ages, and form a coherent group (Fig. 5a; Appendix 1), which yields a weighted mean $^{206}\text{Pb}/^{238}\text{U}$ age of 420.4 ± 2.2 Ma (MSWD=0.056) (Fig. 5a). The well-preserved magmatic zoning (Fig. 6) and relatively high Th/U ratios (0.55-1.07) of these zircons suggest that 420.4 ± 2.2 Ma can be interpreted as the age of crystallization of the adakitic granodiorite in the Xiemisitai Mountains.

Eighteen zircons from sample WJ1311, an adakitic granodiorite from the Xiemisitai Mountains, show well-defined magmatic zoning, suggesting a magmatic origin (Fig. 6). Eighteen analyses that plot on the Concordia (Fig. 5e) form a tight cluster yielding a weighted mean $^{206}\text{Pb}/^{238}\text{U}$ age of 418.8 ± 1.7 Ma (MSWD=0.099) (Fig. 5g), consistent with the age of sample WJ1132 (Appendixes 1 and 2, Fig. 5a).

5.1.2 K-feldspar granite

Ten spots were analyzed on 10 zircons separated from K-feldspar granite from the Xiemisitai Mountains (sample WJ1125). The ten

analyses yield a weighted mean $^{206}\text{Pb}/^{238}\text{U}$ age of 419.6 ± 1.5 Ma (MSWD=0.35) (Fig. 5b). The well-preserved magmatic zoning (Fig. 6) and relatively high Th/U ratios (0.18-3.19) of these zircons suggest that the above age represents the best estimate for the time of crystallization of this K-feldspar granite.

Twenty zircons from sample WJ1312, a K-feldspar granite in the Xiemisitai Mountains, form a tight cluster yielding a weighted mean $^{206}\text{Pb}/^{238}\text{U}$ age of 419.4 ± 1.8 Ma (MSWD=0.13) (Fig. 5h). The $^{206}\text{Pb}/^{238}\text{U}$ age of 419.4 ± 1.8 Ma from the K-feldspar granite is similar to the age of the adakitic granodiorite (419-420 Ma) in the Xiemisitai Mountains.

5.1.3 Rhyolite

Sample WJ1128 was collected from the Xiemisitai Mountains and sixteen spots were analyzed on 16 zircons. The sixteen analyses plot on the Concordia (Fig. 5c) with a tight cluster yielding a weighted mean $^{206}\text{Pb}/^{238}\text{U}$ age of 419.0 ± 2.3 Ma (MSWD=0.098) (Fig. 5c). Based on the magmatic oscillatory zoning and rather high Th/U ratios (0.46-1.00) of the zircons, we consider the 419.0 ± 2.3 Ma age to be the crystallization age of the rhyolite.

5.1.4 Syenitic granite

Eighteen spots from 18 zircons of a syenitic granite (WJ1126) from the Xiemisitai Mountains plot on or near the Concordia (Fig. 5d) forming a tight cluster with a weighted mean $^{206}\text{Pb}/^{238}\text{U}$ age of 418.2 ± 2.1 Ma (MSWD=0.106) (Fig. 5d). The magmatic oscillatory zoning and rather high Th/U ratios (0.65-1.07) of these zircons suggest that 418.2 ± 2.1 Ma can be interpreted as the age of crystallization of this syenitic granite.

Fourteen zircons from sample WJ1136, a syenitic granite in the Saier Mountains, show well-defined magmatic zoning and high Th/U ratios (0.65-1.00), suggesting a magmatic origin. Fourteen analyses plot on the Concordia (Fig. 5e) and form a tight cluster yielding a weighted mean $^{206}\text{Pb}/^{238}\text{U}$ age of 406.6 ± 2.5 Ma (MSWD=0.17) (Fig. 5e). We consider the 406.6 ± 2.5 Ma age to be the crystallization age of the syenitic granite.

5.1.5 Gabbro

Eighteen spots for 18 zircons from a Xiemisitai gabbro (sample WJ1122) plot on the Concordia (Fig. 5f) and yield a weighted mean $^{206}\text{Pb}/^{238}\text{U}$ age of 419.8 ± 2.5 Ma (MSWD = 0.09) (Fig. 5f), which is similar to the age of the adakitic granodiorite (420.4 ± 2.2 Ma). These samples are dark gray, translucent, and form subhedral, stubby to

prismatic crystals (Fig. 6). Based on their high Th/U ratios (0.8-2.6), the weighted mean $^{206}\text{Pb}/^{238}\text{U}$ age of 419.8 ± 2.5 Ma is interpreted as the intrusion age of the gabbro.

5.2. Major and trace element geochemistry

5.2.1 Adakitic granodiorite

The adakitic granodiorite samples have moderate SiO_2 (60.9-65.6 wt.%) contents and calc-alkaline characteristics (Figs. 7a, b), straddling the boundary between trachydacite and andesite (Appendix 3; Fig. 7c). They are relatively low MgO contents (mostly 1.26-1.84 wt.%) and $\text{Mg}^\#$ (mostly 41-43) (Appendix 3; Fig. 7d), with relatively high Al_2O_3 (14.8-15.5 wt.%) and alkalis ($\text{Na}_2\text{O} + \text{K}_2\text{O} = 5.7-7.7$ wt.%). Their relatively high $\text{K}_2\text{O}/\text{Na}_2\text{O}$ (mostly 0.9-1.2) ratios imply a potassium-rich composition. The adakitic samples display coherent REE patterns characterized by relative enrichment of LREE ($(\text{La}/\text{Yb})_N = 7.8-9.2$) and nearly flat HREE ($(\text{Gd}/\text{Yb})_N = 1.3-1.4$), with weak negative Eu anomalies ($\text{Eu}^*/\text{Eu} = 0.80-0.92$) (Fig. 8a). The adakitic granodiorites have low Cr (mostly 3.50-7.81 ppm), Co (mostly 6.91-10.8 ppm) and Ni (mostly 2.12-4.04 ppm) contents (Figs. 9a, b). They are enriched in Sr (407-532 ppm) and Ba (639-903 ppm), depleted in HREE (e.g. $\text{Yb} = 1.53-1.77$ ppm) and have high Sr/Y ratios (31-42), which are comparable to those of

modern adakites (Appendix 3; Fig. 9c; Defant et al., 1991). In a primitive mantle normalized spider diagram, they show remarkable enrichments of LILE (such as Ba, Sr, Rb and U) and LREE relative to HFSE, with negative Ta, Nb and Ti anomalies (Fig. 8b), consistent with the geochemical characteristics of subduction-related magmas.

5.2.2 *K-feldspar granite and rhyolite*

Samples of the K-feldspar granite and rhyolite from the northern and southern Xiemisitai Mountains, respectively show similar geochemical characteristics. They have high SiO₂ (72.7-76.7 wt.%), total alkali (Na₂O+K₂O=8.16-10.7 wt.%) contents (Appendix 3; Fig. 7a, c) and high Fe[#] (FeO^{tot}/(FeO^{tot}+MgO)=0.88-0.94) values (Appendix 3; Figs. 7b; 9b). They have low MgO (0.12-0.27 wt.%), CaO (0.13-0.32 wt.%), and P₂O₅ (< 0.04 wt.%) (Appendix 3). The samples have high total REE (221-343 ppm) contents and show similar chondrite-normalized REE patterns characterized by relative enrichments of LREE ((La/Yb)_N=4.7-9.3) and nearly flat HREE ((Tb/Yb)_N=1.2-1.4) as well as pronounced negative Eu anomalies (Eu/Eu*=0.09-0.24) (Fig. 8c). On a primitive-mantle normalized diagram, they show prominent negative Ba, Sr, P, Eu, and Ti anomalies, and slightly negative Nb and Ta anomalies (Fig. 8d). Their high Zr, Nb contents and 10000×Ga/Al ratios make these samples

geochemically akin to A-type granites (Figs. 10a, b).

5.2.3 Syenitic granite

The syenitic granites from the northern Xiemisitai and Saier Mountains have similar geochemical characteristics. They have high SiO_2 (70.5-73.4 wt.%), K_2O (4.92-6.16 wt.%), $\text{Na}_2\text{O}+\text{K}_2\text{O}$ (8.39-9.34 wt.%) contents (Appendix 3; Fig. 7a) and low $\text{Fe}^\#$ (0.73-0.80) values (Fig. 9d) and display alkaline characteristics (Fig. 7b). In addition, they are weakly peraluminous ($\text{A/CNK}=1.00$ to 1.07) and possess I-type granite characteristics (Figs. 10c, d).

The samples have relatively higher MgO (0.38-0.86 wt.%), $\text{Mg}^\#$ values (32-39) and CaO (0.85-1.87 wt.%) than the K-feldspar granite and rhyolite (Appendix 3), and relatively lower total REE (110-137 ppm) contents than the K-feldspar granite and rhyolite and display coherent REE patterns characterized by relative enrichments of LREE ($(\text{La/Yb})_N=5.4-9.7$) and nearly flat HREE ($(\text{Gd/Yb})_N=1.0-1.3$; Appendix 3), with obvious negative Eu anomalies ($\text{Eu/Eu}^*=0.51-0.58$) (Fig. 8e). In a primitive mantle normalized spider diagram, the syenitic granites show remarkable enrichments of LILE (such as Ba, Th, Rb, U and K) relative to HFSE and LREE, with negative Ta, Nb and Ti anomalies (Fig. 8f) consistent with the geochemical characteristics of subduction-related

magmas. Their relatively low Zr, Nb contents and $10000 \times \text{Ga}/\text{Al}$ values plot within the I, S and M-type granite fields (Figs. 10a, b).

5.2.4 Gabbros

The gabbros are characterized by moderate SiO_2 (46.0-46.6 wt.%), MgO (6.86-7.15 wt.%), Cr (124-133 ppm) and Ni (84.7-86.6 ppm) contents. On a TAS diagram (Fig. 7c), data plot within the alkaline basalt field. The gabbros also define a typical tholeiitic compositional trend on the $\text{SiO}_2\text{-FeO}^{\text{T}}/\text{MgO}$ diagram (Fig. 9e), they have very uniform chondrite-normalized REE patterns ($(\text{La}/\text{Yb})_{\text{N}}=3.25\text{-}3.29$) with weak positive Eu anomalies ($\text{Eu}/\text{Eu}^*=1.08\text{-}1.16$) (Fig. 8g), and they are characterized by the enrichment of highly incompatible elements (e.g. K, Rb, Sr, Ba) and LREE, but depletion of moderately incompatible elements (e.g. Nb, Ta and Ti) and HREE relative to those of E-MORB (Fig. 8h). In addition, trace-element distribution patterns of the gabbros are different from those of arc volcanics (Fig. 8h). The major and trace element abundances show that the gabbros are obviously influenced by subduction processes.

5.3. *Sr-Nd-Hf isotopic compositions*

In spite of their lithological diversity, all the rocks (i.e. adakitic

granodiorite, K-feldspar granite, rhyolite, syenitic granite and gabbro) display similar $^{87}\text{Sr}/^{86}\text{Sr}$ ratios (0.7035 to 0.7043) and $\epsilon\text{Nd}(t)$ values (+3.9 to +6.9), with two-stage depleted mantle Nd model ages (605-791 Ma) (Appendix 4; Fig. 11a).

Hf isotope compositions from five zircon samples are listed in Appendix 5 and shown on Fig. 11b. Sixteen zircon grains from the adakitic granodiorite (WJ1132) were analyzed for Lu-Hf isotopic compositions and yielded $\epsilon\text{Hf}(t)$ values between +13.0 and +15.2, with young $T_{2\text{DM}}$ model ages from 447 to 645 Ma. Nine zircon grains from the K-feldspar granite (WJ1125) yielded $\epsilon\text{Hf}(t)$ values of +10.1 to +15.1, and young $T_{2\text{DM}}$ model ages (433 to 610 Ma). Eighteen zircon grains from the syenitic granite (WJ1126) yielded variable $\epsilon\text{Hf}(t)$ values (+9.8 to +15.2) and young $T_{2\text{DM}}$ model ages (425 to 642 Ma). Analyses of fourteen zircon grains from the syenitic granite (WJ1136, $t=407$ Ma) yielded $\epsilon\text{Hf}(t)$ values ranging from +10.7 to +15.1, with $T_{2\text{DM}}$ model ages from 445 to 845 Ma. Analyses of fifteen zircon grains from gabbros (WJ1122) yielded lower $\epsilon\text{Hf}(t)$ values (+11.6 to +14.6), with similarly young $T_{2\text{DM}}$ model ages (503 to 773 Ma) .

All the samples have high positive $\epsilon\text{Hf}(t)$ values and young $T_{2\text{DM}}$ model ages, indicating depleted mantle characteristics.

6. Petrogenesis

6.1 *The adakitic granodiorite*

The adakitic granodiorites have geochemical characteristics comparable to those of modern adakites (Fig. 9c; Defant and Drummond, 1990; Martin et al., 2005). Adakites were initially interpreted as products of partial melting of subducted young, hot oceanic crust (e.g., Defant and Drummond, 1990). Recently, more petrogenetic mechanisms have been proposed to account for the origin of adakites, such as partial melting of slab-melt-modified peridotitic mantle wedge (Moyen et al., 2001; Martin et al., 2005); melting of delaminated lower crust (Gao et al., 2004; Wang et al., 2007), partial melting of thickened lower crust (Petford and Atherton, 1996; Chung et al., 2003); melting of subducted continental crust (Wang et al., 2008), assimilation and fractional crystallization processes involving basaltic magma (Castillo et al., 1999; Macpherson et al., 2006), and magma mixing involving multiple end-members (Guo et al., 2007; Streck et al., 2007).

The adakitic granodiorites are characterized by medium to high SiO₂ contents (60.9–67.8 wt.%), high K₂O contents (1.79–4.22 wt.%) and low Mg[#] values (mostly 41–43) and MgO (1.26–1.84 wt.%) contents, which are different from those of typical slab-derived adakites (Fig. 7d; Martin et al., 2005). In addition, they have very low Cr (mostly < 8.00 ppm), Co

(mostly <11.0 ppm) and Ni (mostly <4.10 ppm) contents that exclude melt–mantle interaction, which commonly occurs when a slab-derived melt or delaminated lower crust melt interacts with mantle peridotite (Figs. 9a, b; Martin, 1999; Rapp et al., 1999; Wang et al., 2007). The adakitic granodiorites in the Xiemisitai Mountains have high positive $\epsilon_{\text{Hf}}(t)$ (+10.2 to +15.8) and $\epsilon_{\text{Nd}}(t)$ (+5.0 to +5.2) values that are clearly different from adakites generated by partial melting of subducted continental crust, which normally show low and negative $\epsilon_{\text{Hf}}(t)$ and $\epsilon_{\text{Nd}}(t)$ values in central Tibet (Wang et al., 2008). Additionally, the adakitic granodiorites are unlikely to be the product of high-pressure or low-pressure crystallization, because the adakitic granodiorites exhibit no compositional trends associated with low pressure or high pressure assimilation fractional crystallization (AFC) from parental basaltic magmas (Figs. 12a-d). Likewise, magma mixing of felsic and basaltic magma cannot account for the genesis of the adakitic granodiorites. The gabbros and K-feldspar granites in the Xiemisitai Mountain stand for mantle-derived basaltic and crust-derived felsic end members in the area. The adakitic granodiorites have lower $\epsilon_{\text{Nd}}(t)$ value of (+5.0 to +5.2) than those of the K-feldspar granites (+5.3 to +5.9) and the gabbros (+6.6 to +6.9) (Fig. 11a), suggesting that the adakitic granodiorites are not products of mixing between felsic and basaltic magmas.

We suggest that the adakitic granodiorites were most probably

generated by partial melting of lower crust. In such a case, the rocks would have relatively high SiO_2 and K_2O contents and low MgO , Cr , and Ni because of the lack of interaction with a mantle source (Atherton and Petford, 1993). As we mentioned above, the geochemical characteristics of adakitic granodiorites in the Xiemisitai Mountain are similar to those of lower crust -derived adakitic melts (Fig. 7d; Figs. 9a,b; Petford and Atherton, 1996; Chung et al., 2003) indicating that the magmas might not have interacted with mantle wedge peridotites. In addition, the adakitic granodiorites have depleted Nd isotope compositions comparable to those of the late Silurian-early Devonian Xiemisitai arc volcanic rocks (Fig. 11; Shen et al., 2012) suggesting that the mafic lower crust, which consisted of the Xiemisitai arc volcanic rocks, was a possible source of the adakitic granodiorites. Therefore, we conclude that the adakitic granodiorites were most probably generated by partial melting of lower crust.

6.2 K-feldspar granite and rhyolite

The K-feldspar granites and rhyolites are characterized by high alkali, Fe, Zr and Nb contents (Fig. 7b; Figs. 10a, b). They contain arfvedsonite and display prominent negative Ba, Sr, P, Eu, and Ti anomalies (Fig. 4c; Figs. 8c, d), which, together with their high $10000 \times \text{Ga}/\text{Al}$ ratios, are distinct from highly fractionated granites, but

similar to typical A-type granites (Figs. 10a, b; Whalen et al., 1987; Eby, 1990, 1992). On the Nb-Y-3×Ga and Nb-Y-Ce triangular diagrams of Eby (1992), the K-feldspar granites and rhyolites plot in the A₂ field (Figs. 13a, b), which represents magmas derived from continental crust or underplated crust that has been through a cycle of continent-continent collision or island arc magmatism (Eby, 1992). However, the depleted Nd-Hf isotopic compositions ($\epsilon\text{Nd}(t)=+4.9$ to $+5.7$; $\epsilon\text{Hf}(t)=+10.9$ to $+15.1$, Appendixes 4 and 5) of the K-feldspar granites and rhyolites imply that they were unlikely to have been generated by partial melting of Neoproterozoic basement in northern Xinjiang, which has distinctly negative $\epsilon\text{Nd}(t)$ (Hu et al., 2000). Instead, the rocks might be derived by partial melting of the mid-lower crust of the Xiemisitai island arc. The interference is supported by the similar depleted Sr-Nd isotope composition between the K-feldspar granites and rhyolites and the Silurian basaltic rocks ($+5.0$ to $+6.7$) (Figs. 11a, b; Shen et al., 2012) from the Xiemisitai arc, which represent the juvenile lower crust beneath it.

6.3 Syenitic granite

The syenitic granites have relatively lower SiO₂ (70.5-73.4 wt.%) and higher MgO (0.38-0.86 wt.%), Mg[#] (32-39), CaO (0.85-1.87 wt.%)

than the Xiemisitai K-feldspar granites and rhyolites, and they are weakly peraluminous comparable to I-type granites (Figs. 10c, d). They are characterized by relative enrichments of LREE and depletion of HFSE (e.g., Nb, Ta and Ti), consistent with the geochemical characteristics of subduction-related magmas (Figs. 8f). The syenitic granites are characterized by depleted Sr-Nd-Hf isotopic compositions and young Hf model ages (T_{2DM}) of 425-642 Ma (Fig. 11b), indicating that they were derived from a juvenile source. However, it is unlikely that the syenitic granites were generated by direct melting of a mantle source, given that their silica contents are as high as 70 wt.% and their $Mg^\#$ are as low as 40. Moreover, it is unlikely that they were generated by direct melting of a subducting slab, because they are geochemically different from typical adakites. As a result, Sr-Nd-Hf isotopic compositions of the syenitic granites are similar to those of the Xiemisitai K-feldspar granites and rhyolites, suggesting that they are likely of the same origin. Thus, the Xiemisitai syenitic granites were also probably generated by partial melt of the mid-lower crust.

6.4 Gabbro

The gabbros have relatively low $Mg^\#$ (52-53), Cr (124-133 ppm) and Ni (84.7-86.6 ppm), in comparison to magmas in equilibrium with typical

upper mantle mineral association ($\text{Mg}^\# > 70$, $\text{Cr} > 400$ ppm, and $\text{Ni} > 1000$ ppm, respectively) (Wilson, 1989). The low Mg, Cr, and Ni contents of the gabbros indicate that they formed after fractionation of mafic phases. The gabbros have high positive $\epsilon_{\text{Hf}}(t)$ and $\epsilon_{\text{Nd}}(t)$ values with negligible negative Nb and Ta anomalies, indicating crustal contamination has not played a major role in their evolution. In addition, They not only have more slightly higher Nb/La ratios (0.34-0.36), and Zr (78.5-93.2 ppm) and Nb contents (3.06-3.33 ppm) relative to arc basalts but low $^{87}\text{Sr}/^{86}\text{Sr}$ (0.7035-0.7036) and La/Sm (2.21-2.40) suggesting that asthenospheric mantle is one of possible source. Their Nb/Yb and Th/Yb ratios plot near the mantle array of N-MORB-OIB and between an E-MORB and subduction component (Fig. 8h; Fig. 9f). Even though the gabbros show subduction-related geochemical characteristics, several lines of evidence demonstrate that they were not formed under a normal slab subduction system. The evidence includes: (1) Sr-Nd-Hf isotopic characteristics more depleted than previously documented for the Xiemisitai arc volcanic rocks; (2) typical tholeiitic features were obviously different from calc-alkaline volcanic rocks in the Xiemisitai volcanic arc; (3) the gabbro rocks were simultaneously generated with the Xiemisitai adakitic granodiorites and A-type granites.

As a result, the gabbros were probably generated by interactions between asthenospheric and metasomatized lithospheric mantle.

7. Discussion

7.1. Silurian-early Devonian magmatism in West Junggar

Our new zircon U-Pb ages as well as previous isotopic dates of both intrusive and extrusive rocks in the region (Fig. 14; Appendix 2; Chen et al., 2010a; 2015; Shen et al., 2012) suggest that there was a late Silurian-early Devonian (ca. 420-405 Ma) magmatic “flare up” in the Xiemisitai and Saier Mountains in NW Junggar. In this study, the adakitic granodiorites were dated at 420-419 Ma, coeval with the nearby gabbros (420 Ma). The A-type granites were also emplaced between 420 Ma and 419 Ma, while the syenitic granites were intruded between 419 Ma and 405 Ma (Appendix 2; Chen et al., 2010a and this study). The volcanic rocks erupted from 429 Ma to 411 Ma (Shen et al., 2012; Yang et al., 2014b). From their temporal distribution, the K-feldspar granites, calc-alkaline granites and arc volcanic rocks were almost contemporaneous (Fig. 14). However, from their spatial distribution, the late Silurian-early Devonian magmatic rocks are linear and parallel to the Xiemisitai fault (Fig. 2). The geochronological data suggest a northeasterly trend migration of the magmatism during 420-405 Ma (Fig. 2).

Therefore, we conclude that extensive arc magmatism took place in

the Xiemisitai and Saier Mountains in NW Junggar during the late Silurian-early Devonian.

7.2 *P-T conditions*

A-type granites are anhydrous, alkaline, anorogenic and high temperature magmas that generally reflect an extensional environment (Clemens et al., 1986; Eby, 1990, 1992; Bonin, 2007). Zircon saturation temperatures (T_{Zr}) of K-feldspar granites and rhyolites range from 884 °C to 940 °C. Although the zircon saturation temperature ($T_{Zr}=810^{\circ}\text{C}$ – 874°C) of syenitic granites is lower than that of K-feldspar granites and rhyolites, it is higher than that of early Carboniferous I-type granites in NW Junggar (Fig. 15), suggesting that NW Junggar was under a high temperature regime during the late Silurian-early Devonian. These rocks have relatively low $\text{Al}_2\text{O}_3/(\text{Fe}_2\text{O}_3+\text{MgO}+\text{TiO}_2)$ and $\text{CaO}/(\text{MgO}+\text{TiO}_2+\text{FeO})$ ratios, suggesting melting at relative low-pressure conditions (Figs. 16a, b, Patiño Douce, 1999). On the other hand, experimental work has demonstrated that adakitic signatures can be achieved by dehydration and hydrous partial melting of a basaltic source at P-T conditions of >1.0 GPa and $>650^{\circ}\text{C}$ (Hastie et al., 2010 and references therein). Some studies have demonstrated that an adakitic signature can be achieved at relatively low pressures (~ 1.0 GPa) (Johnson

et al., 1997; Zellmer et al., 2012). This suggests that an adakitic signature can be attained under a normal crustal thickness, and it is unnecessary to assign an adakitic signature exclusively to an over-thickened crust (Guan et al., 2014). The adakitic granodiorites in the Xiemisitai mountain have significantly higher SiO_2 and K_2O contents and lower MgO , Cr , and Ni contents than those of typical adakites (Martin et al., 2005; Moyen, 2009) suggesting a K-rich mafic source. The adakitic granodiorites have depleted Nd isotope compositions comparable to those of the late Silurian-early Devonian Xiemisitai arc volcanic rocks (Figs. 11a,b; Shen et al., 2012) suggesting that the mafic lower crust could consist of the Xiemisitai arc volcanic rocks. In the Dy/Yb vs. La/Yb diagram (Fig. 17a), the adakitic granodiorites likely underwent fractionation or residue of amphibole and garnet. More importantly, in a Nb/Ta vs. Zr/Sm diagram, their relatively low Nb/Ta ratios and negative Nb-Ta anomalies indicate that the Xiemisitai adakitic granodiorites were probably generated by partial melting of amphibolite in the garnet stability field (Fig. 17b). All plots of the adakitic granodiorites are very close to the modeled melt of amphibolite, whereas thickened lower crustal-derived adakitic rocks from the Tibetan Plateau exhibit much higher Nb/Ta ratios (Fig. 17b). The remarkable difference between the thickened lower crustal-derived adakitic rocks and the Xiemisitai adakitic granodiorites implies that a common crustal source in the garnet stability field of the Xiemisitai

adakitic granodiorites may not undergo significant thickening. Therefore, the appearance of adakitic granodiorites, A-type granites and gabbros in NW Junggar indicates high temperature-low pressure and an extensional setting in the late Silurian-early Devonian.

7.3. Tectonic setting

The area of West Junggar is triangular and surrounded by the Altay Orogen, Tianshan Orogen, Kazakhstan Plate and East Junggar. In these regions late Silurian-early Devonian plutons are widespread (Filippova et al., 2001; Yuan et al., 2007; Kröner et al., 2008; Sun et al., 2008; Gao et al., 2009; Cai et al., 2011; Shen et al., 2011). Recently, Chen et al (2010a; 2015) recognized late Silurian-early Devonian plutons in the Xiemisitai and Saier Mountains. They proposed that the middle Paleozoic granitoids would form a post-collisional setting (Chen et al., 2010a; 2015). However, from their study of the Xiemisitai volcanic rocks, Shen et al. (2012) and Yang et al. (2014b) considered that NW Junggar was in a normal arc-related setting in the middle Paleozoic, but that cannot reasonably explain the petrogenesis of coeval adakitic granodiorites and A-type granites in the region.

A-type granites can form in a variety of extensional regimes, e.g. slab roll-back; post-collisional extension; within-plate; slab break-off, and

ridge subduction (e.g. Eby, 1992; Whalen et al., 1996; King et al., 1997; Förster et al., 1997, 2006; Tang et al., 2010; Yuan et al., 2010; Shen et al., 2011; Li et al., 2012; Li et al., 2014). Eby (1992) subdivided A-type granites into two sub-types, of which A₁-type granites are restricted to anorogenic settings (e.g. hot spots, plumes and continental rifts), while A₂-type granites are derived from partial melting of continental crust or underplated mafic crust in post-collision extensional settings (Eby, 1992). On the Nb-Y-3×Ga and Nb-Y-Ce triangular diagrams of Eby (1992), the K-feldspar granites and rhyolites plot in the A₂ field (Figs. 13a, b) and thus are classified as A₂-type granites. We can thus rule out an origin related to a hot spot, plume or continental rift located in an anorogenic setting. In West Junggar, there are widespread late Paleozoic A₂-type granites that were envisaged as post-collisional granites (Chen and Arakawa, 2005; Han et al., 2006; Zhou et al., 2008; Chen et al., 2010a). Recently, many authors proposed that they may be related to ridge subduction during the late Carboniferous-early Permian (Geng et al., 2009; Tang et al., 2010, 2012; Xiao et al., 2014a; Yin et al., 2010, 2013b, 2015b; Zhang et al., 2011a,b). In the Xiemisitai and Saier mountains there are widespread late Silurian-early Devonian volcanic rocks and their sub-volcanic equivalents (Shen et al., 2012; Yang et al., 2014b). These rocks are LREE-enriched, with a negative Nb, Ta and Ti anomaly suggesting that the volcanic rocks formed in a subduction-related setting

(Shen et al., 2012; Yang et al., 2014b). Moreover, continent-continent collision and post-collision extensional settings are not supported by the following geological evidence: (1) in NW Junggar there were mainly marine volcanic and clastic rocks from Silurian Shaerbuer Formation (S_{2s}) to the Devonian Mangkelu Formation (D_{1m}), and Carboniferous Lasite Formation (C_{1l}), which is a suite of marine volcanic rocks intercalated with pillow basalts and radiolarian bedded cherts (XBGMR, 1986); (2) geotectonic reconstructions show that the Paleo-Asian Ocean was still in existence during the middle Paleozoic (Xiao et al., 2010); (3) a paleomagnetic study shows that the Junggar Ocean and Irtysh-Zaysan Ocean consumed continuously beneath the Boshchekul–Chingiz arc in the late Carboniferous (Filippova and Bush, 2001; Windley et al., 2007; Abrajevitch et al., 2008; Yi et al., 2015); (4) paleogeographic data suggest that West Junggar was in a deep sea environment in the late Carboniferous (Wang, 2006; Xiao et al., 2014b); (5) the A_2 -type granites were generated synchronously with the adakitic granodiorites (Wang et al., 2013 and this study). The above lines of evidence strongly indicate that West Junggar was in a subduction-dominated setting instead of a continent-continent collision or a post-collision extensional setting during the late Silurian-early Devonian. In addition, slab break-off is commonly triggered by attempted continental subduction (Chung et al., 2005; Yuan et al., 2010), so that the environment is not available for consideration

according to above evidence. In any case, a high temperature and extensional subduction setting should be required for the formation of the Xiemisitai A₂-type granites, adakitic granodiorites.

7.4 Geodynamic model

Based on the lines of evidence and arguments listed above, we conclude that a slab window model is viable for West Junggar. Slab windows are gaps in subducted plates that allow the upwelling of asthenospheric mantle and have been documented during spreading ridge-trench interactions (Thorkelson, 1996; Sisson et al., 2003; Cole et al., 2006; Tang et al., 2010). In this case, a slab window can impart dramatic changes along convergent margins, including near-trench high heat flow (DeLong et al., 1979; Sisson et al., 2003) accompanied by magmatism and/or high-temperature-low pressure metamorphism, leading to the formation of alkaline magmatic rocks or A-type granites (Mortimer et al., 2006; Anma et al., 2009; Geng et al., 2009; Tang et al., 2010; Yin et al., 2013b), and it can cause an extensional stress field between subducting and overriding plates (Sisson et al., 2003; Cole et al., 2006). From the presence of adakites, boninites, near-trench magmatism, Alaskan-type mafic-ultramafic complexes, andesite dykes and high-temperature metamorphic belts, a ridge subduction model with

associated slab window was first proposed by Windley et al. (2007) in the CAO, the evolution of which was similar to that of modern western Pacific accretionary orogens (Wakita et al., 2013). Recently, many types of diagnostic rock associations have been found in West Junggar strongly suggesting that ridge subduction was in operation during the late Carboniferous-early Permian (Geng et al., 2009; Tang et al., 2010, 2012; Yin et al., 2010, 2013a, b, 2015b; Ma et al., 2012; Zhang et al., 2011a, b; Yang et al., 2012). In Japan, ridge subduction has occurred every 100 Ma in the last 450 Ma. At a similar rate, there could have been at least seven ridge subductions in the evolution of the CAO (Windley et al., 2007). As an important part of the CAO, West Junggar could have experienced ridge subduction many times.

Therefore, we consider that a slab window model is a viable mechanism to explain the late Silurian to early Devonian magmatic “flare up” in the area. During late Silurian to early Devonian times, the Irtysh-Zaysan Ocean ridge was subducting beneath the Boshchekul-Chingiz volcanic arc. As the slab window opened, the asthenosphere upwelling heated and then melted the overlying mafic lower crust, leaving an amphibole and garnet residue to generate adakitic rocks. The tholeiites can be interpreted as the product of decompression melts of asthenospheric mantle upwelling and subsequent metasomatized lithospheric mantle interaction. When asthenosphere upwelling brings a

high heat flux, the overriding mantle within the slab window tends to be hotter and less hydrated (Thorkelson, 1996; Sisson et al., 2003), and the mid-lower crust may be heated and melted to generated A-type granites. As a result, the formation of this extensive high-temperature magmatic association may indicate that ridge subduction associated with slab window opening was in operation between 420 to 405 Ma in NW Junggar.

Slab roll-back is another alternative model. Slab roll-back tends to form where relatively old oceanic crust is subducted. Such a lithosphere is negatively buoyant, which causes the subducting slab to sink vertically (Garfunkel et al., 1986; Hamilton 2007). The subducting slab can sink into the mantle faster than it converges with the overriding plate. In this case, the trench is said to ‘roll back’ from the overriding plate (Elsasser, 1971). Slab roll-back may induce upwelling of asthenosphere to compensate for the loss in volume of the mantle wedge (Uyeda and Kanamori, 1979). During the late Silurian to early Devonian, the Irtysh-Zaysan Ocean was being consumed beneath the Boshchekul-Chingiz volcanic arc (Xu et al., 2012) (Fig. 18). With ongoing extension during the roll-back of the Irtysh-Zaysan slab, the crust and lithospheric mantle become progressively thinned. The upwelling of asthenosphere can trigger partial melting of crustal rocks, generating granitic magmas (i.e. A-type granitic magmas and I-type granitic magmas)

(Jiang et al., 2006; 2011). Decompression melting of the asthenospheric mantle generates gabbros (Stern, 2010). The mafic lower crust was partial melted by compulsive heating from the injected hot asthenosphere, forming adakitic magmas (Guan et al., 2014; Liu et al., 2014b). The temporal and spatial distribution of magmatism suggests a NE-trend migration after 420 Ma (Fig. 2), which is consistent with a roll-back of the subducting Irtysh-Zaysan slab. Therefore, the formation of extensive high-temperature magmatic associations suggests that a slab roll-back model is the most likely explanation for the late Silurian to early Devonian magmatic “flare up” in NW Junggar (Fig. 18).

Accordingly, we are inclined to favor this second explanation and propose that there was a slab roll-back during late Silurian-early Devonian time in NW Junggar. The reasons are chiefly as follows: (1) late Silurian-early Devonian magmatism shows a NE-trending migration (Fig. 2). (2) Intermediate to acid magmas are dominant, whereas mafic-ultramafic complexes are rare in NW Junggar in the late Silurian-early Devonian. (3) The adakitic gabbros and A-type granites were almost simultaneously accompanied by arc volcanic rocks in NW Junggar. (4) The adakitic rocks in a slab window are characterized by high MgO, $Mg^\#$, Cr, Co, Ni contents, whereas the Xiemisitai adakitic gabbro show lower MgO, $Mg^\#$, Cr, Co, Ni contents.

Evidently, more work is required to understand whether a slab

roll-back or slab window was existed in the late Silurian-early Devonian in NW Junggar. In any case, a slab roll-back model is a possible mechanism to explain the middle Paleozoic magmatic “flare up” in the NW Junggar. Moreover, there is little doubt that a high temperature and extensional subduction setting was present in NW Junggar during the period 420-405 Ma.

8. Conclusions

The petrological, geochemical and geochronological data presented in this study lead to the following general conclusions.

(1) The magmatic rocks in NW Junggar are divisible into adakitic granodiorites, A-type granites, I-type granites and gabbros, which were emplaced in the period 420-405 Ma.

(2) The adakitic granodiorites were likely generated by partial melting of mafic lower crust, leaving an amphibole and garnet residue. The A-type granites and I-type granites were likely formed by partial melting of the Xiemisitai mid-lower crust. The gabbros were probably generated by interactions between asthenospheric and metasomatized lithospheric mantle..

(3) Voluminous plutons of adakitic granodiorites, A-type granites and gabbros were emplaced at 420-405 Ma, and their isotopic data

suggest significant additions of juvenile material. A slab roll-back model can account not only for the geochemical characteristics of these granitoids, but also for the necessary coeval high-T, low-P and extensional setting. Therefore, the middle Paleozoic magmatic “flare up” in NW Junggar of the CAOBS was likely related to a slab roll-back model, which played an important role in the crustal growth of the CAOBS.

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Supplementary data to this article can be found online.

Appendix 1. LA-ICP–MS U–Pb isotopic analysis for zircons from the granitic batholiths in NW Junggar.

Appendix 2. Summary of sample localities and zircon U–Pb ages of the intrusions in the Xiemisitai-Saier Mountain.

Appendix 3. Major (wt.%) and trace (ppm) element compositions of the granitic batholiths in NW Junggar.

Appendix 4. Sr-Nd isotope compositions of the granitic batholiths in NW Junggar.

Appendix 5. Lu-Hf isotopic compositions of zircons from the granitic batholiths in NW Junggar.

Fig.1. (a) Simplified tectonic divisions of the Central Asian Orogenic Belt (after Jahn et al., 2000). (b) Tectonic map showing the main units separated by major suture zones in the West Junggar and adjacent regions (modified after Xu et al., 2012). IZAC: Irtysh-Zaysan Accretionary Complex; ZhSA: Zharma-Saur arc; BCA: Boshchekule-Chengiz Arc; DBA: Dulate-Baytag arc; YA: Yemaquan arc; NWJ: Northern West Junggar; SWJ: Southern West Junggar; NTSAC: North Tian Shan accretionary complex. (c) Simplified geological map of the West Junggar (modified after Xu et al., 2012). 1, Chen et al. (2010a); 2, Han et al.

(2006); 3, Zhou et al. (2008); 4, Feng et al. (2012); 5, Geng et al. (2009); 6, Tang et al. (2012); 7, Tang et al. (2010); 8, Song et al. (2011); 9, Wei et al. (2010); 10, Yin et al. (2013b); 11, Zhu and Xu, (2006); 12, Zhao et al. (2013a); 13, Zhang and Guo, 2010.

Fig.2. Geological map of the Xiemisitai and Saier Mountains in NW Junggar (modified after Chen et al., 2010a). 1, Chen et al. (2010a); 10, Yin et al. (2013b); 12, Zhao et al. (2013a); 14, this study.

Fig.3. Field photos of rocks from the granitic batholiths in NW Junggar. (a, j) Outcrop of granodiorite; (b, k) Outcrop of K-feldspar granite; (c) Gabbro intruded by K-feldspar granite; (d) Outcrop of rhyolite; (e) K-feldspar granite intruded by doleritic dyke; (f) Outcrop of gabbro; (g) hand specimen of granodiorite; (h) hand specimen of syenitic granite; (i, l) hand specimen of K-feldspar granite.

Fig.4. Microscopic photos of rocks from the granitic batholiths in NW Junggar. (a) Mineral compositions and texture of granodiorite; (b) and (c) Mineral compositions and texture of K-feldspar granite; (d), (e) and (f) Mineral compositions and texture of syenitic granite, rhyolite and gabbro, respectively. Cpx=clinopyroxene, Apm=Amphibole, Pl=Plagioclase, Kf=K-feldspar, Ar=Arfvedsonite, Bi=Biotite, Q=Quartz.

Fig.5. U-Pb concordia diagrams showing zircon ages obtained by LA-ICP-MS for the granitic batholiths in NW Junggar.

Fig.6. Representative CL images of zircons for the granitic batholiths in NW Junggar. Green circles indicate the locations of age and Hf isotope analysis sites, respectively.

Fig.7. (a) K_2O-SiO_2 classification diagram is after Gill (1981); (b). $A.R.-SiO_2$ diagram, $A.R.=(Al_2O_3+CaO+Na_2O+K_2O)/(Al_2O_3+CaO-Na_2O-K_2O)$; (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.

Fig.8. Chondrite-normalized rare earth element patterns and Primitive Mantle (PM) normalized trace element diagrams for the granitic batholiths in NW Junggar. The chondrite, Primitive mantle, OIB, N-MORB and E-MORB data are from Sun and McDonough (1989). Arc volcanics are from Luhr and Haldar (2006).

Fig.9. (a) and (b) SiO_2 versus Cr and Ni diagram. Reference fields are from Wang et al. (2006) and references therein.(c) Sr/Y versus Y (after

Defant et al. (1992)); (d) $\text{SiO}_2\text{--Fe}_2\text{O}_{3\text{T}}/(\text{Fe}_2\text{O}_{3\text{T}}+\text{MgO})$ diagram. Ferroan and magnesian division is after Frost et al. (2001); (e) Tholeiitic and calc-alkaline rocks division on the $\text{SiO}_2\text{--FeO/MgO}$ plot is from Miyashiro (1974), note that this diagram shows only those rocks with $\text{SiO}_2 \leq 65$ wt.%; (f) Trace element diagrams showing Nb/Yb-Th/Yb variations for gabbros from Xiemisitai region; Values of N-MORB, E-MORB and OIB are from Sun and McDonough (1989).

Fig.10 (a) Nb versus 10000 Ga/Al discrimination diagram (Whalen et al., 1987); (b) Zr vs 10000 Ga/Al discrimination diagrams (Whalen et al., 1987); (c) $\text{Al}/(\text{Na}+\text{K})$ vs $\text{Al}/(\text{Ca}+\text{Na}+\text{K})$, $\text{Al}/(\text{Na}+\text{K}) = \text{Al}_2\text{O}_3/(\text{Na}_2\text{O} + \text{K}_2\text{O})$, $\text{Al}/(\text{Ca}+\text{Na}+\text{K}) = \text{Al}_2\text{O}_3/(\text{CaO} + \text{Na}_2\text{O} + \text{K}_2\text{O})$, molecular ratio; (d) P_2O_5 vs SiO_2 diagram, the trend of I- and S-type granites follows Chappell (1999).

Fig.11. (a). $(^{87}\text{Sr}/^{86}\text{Sr})_i\text{--}\epsilon\text{Nd}(t)$ diagram. (b). Age- $\epsilon\text{Hf}(t)$ diagram. The late Carboniferous adakites in SW Junggar are after Geng et al.(2009) and Tang et al.(2010); The data of Xiemisitai arc volcanic rocks in the figure is recalculated from Shen et al.(2012); Underplating-related adakites in Tianshan are from Zhao et al.(2008); Dalabute ophiolites are after Liu et al. (2014a).

Fig.12. Plots of (a) SiO₂ versus La; (b) SiO₂ versus Ba; (c) SiO₂ versus Dy/Yb; (d) SiO₂ versus Na₂O; Fractional crystallization trends in a-d: HPFC, high-pressure fractional crystallization involving garnet (Macpherson et al., 2006); LPFC, low-pressure fractional crystallization involving olivine + clinopyroxene + plagioclase + hornblende + titanomagnetite (Castillo et al., 1999).

Fig.13. Discrimination diagrams for the subdivision of the A-type granites by Eby (1992). (a) Nb-Y-3Ga; (b) Nb-Y-Ce.

Fig.14. Chronodiagram showing successive magmatism recognized in NW Junggar region during 429-405 Ma. The widespread magmatism occurred in NW Junggar since 429 Ma. Age data are from: Chen et al. (2010a), Shen et al. (2012), Wang et al., (2013), Yang et al., (2014a) and this study.

Fig.15. Diagram for variations in zircon saturation temperatures in NW Junggar region. Data for the early Carboniferous I-type granite in NW Junggar are from Chen et al.(2010b).

Fig.16 (a) and (b) Composition diagrams of the granitic batholiths in the northern West Junggar. The dashed lines are reaction curves that model

the melt compositions that would be produced by hybridization of high-Al olivine tholeiite with metapelite. The area between the high pressure (12-15 kbar) and low pressure (≤ 5 kbar) curves encompasses the range of depths at which mantle-crust interaction takes place (Patiño Douce, 1999).

Fig.17 (a) La/Yb vs. Dy/Yb diagram for the adakitic granodiorites; (b) Nb/Ta vs. Zr/Sm diagram for the adakitic granodiorites. Reference fields are from Guan et al. (2014) and references therein.

Fig.18. Tectonic model for slab roll-back in the middle Paleozoic in the Chingiz volcanic arc.