Petrogenesis of Early Carboniferous adakitic dikes, Sawur region, northern West Junggar, NW China: Implications for geodynamic evolution

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A B S T R A C T

Adakitic dikes are widespread in the Sawur region, northern West Junggar, northwestern China. Zircon U–Pb analyses of the dikes have yielded consistent ages of ca. 334 Ma. The dikes are characterized by relatively high SiO 2 (55.5–61.8 wt.%), Al 2 O 3 (14.5–16.3 wt.%), and Sr (468–1005 ppm), and low Y (10.1–14.1 ppm) and Yb (0.93–1.39 ppm) contents, with high Sr/Y (34–74) ratios and slight Eu anomalies, which are analogous to those of slab-derived adakites. In addition, the dikes are relatively MgO-rich (1.75–3.57 wt.%; Mg° = 44–56), with high Th/Yb ratios and positive ε Nd (334 Ma) (+6.2 to +6.5) and ε H f (334 Ma) (+11.3 to +15.8) values. The data suggest that the dikes were generated by partial melting of subducted oceanic crust and overlying sediments. However, these Early Carboniferous adakitic rocks and associated I-type granites in the northern part of West Junggar are petrochemically distinct from the Late Carboniferous adakitic plutons from the southern part of West Junggar. The latter are associated with charnockites, A-type granites, tholeiites, and Nb-enriched, alkaline basalts, as well as magnesian dikes, which were generated by ridge subduction during the Late Carboniferous. The distinct lithological association of the Early Carboniferous adakites is consistent with flat slab subduction, which was characterized by anomalous heating of the slab and consequential partial melting to generate adakitic magma. After generation of the Early Carboniferous adakites, the subducting slab cooled, reverted to a more normal subduction angle in the late Early Carboniferous, and was associated with more typical I-type granite arc magmatism.

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1. Introduction

Adakite was originally proposed to define intermediate- to high-silica (≥ 56 wt.% SiO 2 ), high Sr/Y (>40), and high La/Yb (>20) volcanic and plutonic rocks derived from melting of the basaltic portion of oceanic crust subducted beneath volcanic arcs (Defant and Drummond, 1990). Emphasis for adakite generation has recently shifted from the arc setting to subduction, with high Sr/Y ratios and slight Eu anomalies, which are analogous to those of slab-derived adakites. In addition, the dikes are relatively MgO-rich (1.75–3.57 wt.%; Mg° = 44–56), with high Th/Yb ratios and positive ε Nd (334 Ma) (+6.2 to +6.5) and ε H f (334 Ma) (+11.3 to +15.8) values. The data suggest that the dikes were generated by partial melting of subducted oceanic crust and overlying sediments. However, these Early Carboniferous adakitic rocks and associated I-type granites in the northern part of West Junggar are petrochemically distinct from the Late Carboniferous adakitic plutons from the southern part of West Junggar. The latter are associated with charnockites, A-type granites, tholeiites, and Nb-enriched, alkaline basalts, as well as magnesian dikes, which were generated by ridge subduction during the Late Carboniferous. The distinct lithological association of the Early Carboniferous adakites is consistent with flat slab subduction, which was characterized by anomalous heating of the slab and consequential partial melting to generate adakitic magma. After generation of the Early Carboniferous adakites, the subducting slab cooled, reverted to a more normal subduction angle in the late Early Carboniferous, and was associated with more typical I-type granite arc magmatism.

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Lasite Formation and younger Wenggeerkoula Formation, with an unconformable contact between the two. The Lasite Formation is comprised of pillow basalts, intercalated with radiolarian bedded chert, and lesser volcanoclastic sedimentary rocks. The Wenggeerkoula Formation consists of shallow marine and paralic clastic sediments and well-stratified tuffaceous conglomerates, interbedded with minor tuff, limestone, volcanic breccia, tuffaceous mudstone, and sandstone. Along the northwestern margin of the Junggar basin, Early Carboniferous sedimentary rocks consist mainly of imbricated turbidite (Li and Jin, 1989). The Pre-Late Permian sedimentary rocks, in the Sawur region show green schist facies regional metamorphism.

In the Sawur region, there are widespread late Paleozoic intrusions, which are I-type or A-type granitoids with highly depleted isotopic signatures (εNd(t) = +5.9 to +7.6) (Zhou et al., 2008a; Chen et al., 2010b). The I-type granitoids formed between 338 Ma and 321 Ma (Han et al., 2006; Zhou et al., 2008a; Chen et al., 2010a), whereas the A-type granites were emplaced between 298 Ma and 291 Ma (Zhou et al., 2008a). Early Carboniferous (338–332 Ma) I-type granites from the Sawur and Tarbogatay Mountains exhibit geochemical features of typical adakites, characterized by high Sr, low heavy rare earth elements (REE), and high Sr/Y ratios (Fig. 2a; Defant et al., 1991; Chen et al., 2010b). Temporally, these granites exhibit an evolutionary trend from calc-alkaline to alkaline, suggesting that the tectonic setting of the Sawur region gradually shifted from compressional to extensional in the Early Permian (Zhou et al., 2008a).

Dikes are widespread in the southern part of the West Junggar (Qi, 1993; Li et al., 2004; Xu et al., 2008; Yin et al., 2010; Feng et al., 2012; Ma et al., 2012; Tang et al., 2012a; Yin et al., 2012), and they trend NW (280°–310°), NE (210°–230°), and N–S (360°) (Yin et al., 2013a). Dikes dated by whole-rock Rb–Sr isochron, whole-rock K–Ar, and 40Ar/39Ar methods have yielded ages between 271 Ma and 241 Ma (Qi, 1993; Li et al., 2004; Xu et al., 2008; Zhou et al., 2008b). Thus, the dikes were suggested to have formed in a post-collisional setting (Qi, 1993; Li et al., 2004; Han et al., 2006; Xu et al., 2008; Zhou et al., 2008b). However, using conventional Rb–Sr, K–Ar and 40Ar/39Ar dating to achieve high quality data is difficult due to high background values and low K content in the dike. Recent laser whole rock 40Ar/39Ar and laser-ablation inductively-coupled-plasma mass spectrometer (LA-ICP-MS) zircon U–Pb dating results demonstrated that the dikes in the southern West Junggar mainly formed between 321 Ma and 284 Ma (Tang et al., 2010; Yin et al., 2010, 2012, 2013a). Moreover, an association of Nb-rich doleritic dikes, MgO-rich dioritic dikes, charnockites, A-type granites, tholeiites, adakites, and alkaline basalts was suggested to indicate that a ridge subduction regime probably prevailed in West Junggar in the Late Carboniferous–Early Permian (Tang et al., 2010; Yin et al., 2010; Tang et al., 2012a; Yin et al., 2013a).

Dikes in the Sawur region of the northern part of West Junggar, however, have not been extensively studied. Our study area is located in the northern part of the Sawur region (Fig. 2b), characterized by an E–W-trending anticline and numerous dikes. The core and southern limb of the anticline consist mainly of Devonian strata, whereas most of the northern limb is composed of rocks of the Early Carboniferous Lasite Formation and subordinate Devonian strata. Dikes, mainly intruding rocks of the Lasite Formation (Fig. 3), trend either NW (230°–320°) or NE (230°–250°) (Figs. 3 and 4). They range in width from 0.4 to 10 m, and in length from 1 to 5 km. The most common dikes are altered diorite porphyrites, with phenocrysts of plagioclase (20 vol.%) and hornblende (7 vol.%) (Table 1). The rocks are generally fresh, although some sericitization, chloritization, and kaolinization can be locally observed. In places, the dikes crosscut each other, but their compositions are similar. Their ages, geochemical features, and petrogenesis are still poorly constrained. Therefore, both the NE- and NW-trending dikes were selected for zircon U–Pb dating and geochemical analysis. In this study, we present geochronological data for two dikes and geochemical data for twelve samples of three representative dikes in the region, aiming to further elucidate the geodynamic history of the region.

Fig. 1. Simplified tectonic divisions of the Central Asian Orogenic Belt. After Jahn et al. (2000).
3. Analytical methods

3.1. Major and trace element analyses

Major element compositions were obtained 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). Details of procedures are described by Yuan et al. (2010). Trace elements, including REE, were determined using a Perkin-Elmer ELAN 6000 ICP-MS at GIGCAS, following procedures described by Li et al. (2002). Selected rocks were first crushed into small chips and ultrasonically cleaned in distilled water, then powdered after drying and handpicked to remove visible contamination. The powdered samples (50 mg) were dissolved in screw-top Teflon beakers using an HF + HNO3 mixture for 7 days at ~100 °C. An internal standard solution containing the single element Rh was used to monitor drift in mass response during counting. U.S. Geological Survey (USGS) standard BCR-1 was used to calibrate the elemental concentrations of the measured samples. Precision for REE and other incompatible elements is estimated to be better than 5% from the
international USGS reference samples BIR-1 and laboratory standard (ROA-1). In-run analytical precision for Nd is less than 2.5% RSD (relative standard deviation). The Sm/Nd ratios measured by ICP-MS are within 2% uncertainty, and calculation of εNd(t) values for the samples of the present study using these Sm/Nd ratios will result in uncertainties of less than 0.25 units, which are negligible for petrogenetic discussions.

3.2. Whole-rock Sr–Nd isotope analyses

The Rb–Sr and Sm–Nd isotope analyses were performed in the Laboratory for Isotope Analysis, Institute of Geology, CAGS. Details of the procedures are described by He et al. (2007). The Sr isotope compositions were measured by isotope dilution on a Finnigan MAT-262 mass spectrometer.

![Fig. 3. Geological maps of the study area showing distribution of dikes and sample locations.](image)

![Fig. 4. Photos of dikes in Sawur region, Lasite Formation is intruded by dikes.](image)
spectrometer. The Nd isotope compositions were acquired by a Nu Plasma HR multi-collector inductively coupled plasma mass spectrometry (MC-ICP-MS) (Nu Instruments). The Nd and Sr measurements were corrected for mass fractionation by normalization to $^{146}\text{Nd}/^{142}\text{Nd} = 0.7219$ and $^{88}\text{Sr}/^{86}\text{Sr} = 0.1194$. External precisions during this period of measurement for Sr and Nd isotopic compositions are ±0.000010 (n = 18), and ±0.000011 (n = 18), respectively. The $^{87}\text{Sr}/^{86}\text{Sr}$ ratio for the NBS987 standard is 0.710250 ± 10 (2σ) and $^{143}\text{Nd}/^{144}\text{Nd}$ for

### Table 1

Summary of sample localities and zircon U–Pb ages of dikes in the Sawur region.

<table>
<thead>
<tr>
<th>Sample no</th>
<th>Lithology</th>
<th>GPS</th>
<th>Mineral assemblage</th>
<th>Age (Ma)</th>
<th>Method</th>
</tr>
</thead>
<tbody>
<tr>
<td>WJ1138</td>
<td>Altered diorite porphyrite</td>
<td>47° 13' 45.2&quot;</td>
<td>Phenocrysts: Pl (20%), Hbl (5%); and matrix: Pl (57%), Hbl (10%), Kfs (5%) and Qtz (3%)</td>
<td>334.3 ± 1.9</td>
<td>Zircon LA-ICP MS</td>
</tr>
<tr>
<td>WJ1138-1</td>
<td>Altered diorite porphyrite</td>
<td>47° 13' 45.2&quot;</td>
<td>Phencrys: Pl (24%), Hbl (10%); and matrix: Pl (56%), Hbl (5%), Kfs (10%) and Qtz (5%)</td>
<td>334.6 ± 1.8</td>
<td>Zircon LA-ICP MS</td>
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<td>47° 13' 45.2&quot;</td>
<td>Phencrys: Pl (21%), Hbl (7%); and matrix: Pl (58%), Hbl (8%), Kfs (4%) and Qtz (2%)</td>
<td>334.3 ± 1.9</td>
<td>Zircon LA-ICP MS</td>
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<td>Altered quartz diorite porphyrite</td>
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<td>Phenocrysts: Pl (20%), Hbl (5%); and matrix: Pl (57%), Hbl (10%), Kfs (5%) and Qtz (3%)</td>
<td>334.3 ± 1.9</td>
<td>Zircon LA-ICP MS</td>
</tr>
<tr>
<td>WJ1139-1</td>
<td>Altered quartz diorite porphyrite</td>
<td>47° 14' 11.3&quot;</td>
<td>Phencrys: Pl (24%), Hbl (10%); and matrix: Pl (56%), Hbl (5%), Kfs (10%) and Qtz (5%)</td>
<td>334.6 ± 1.8</td>
<td>Zircon LA-ICP MS</td>
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<td>47° 14' 11.3&quot;</td>
<td>Phencrys: Pl (21%), Hbl (7%); and matrix: Pl (58%), Hbl (8%), Kfs (4%) and Qtz (2%)</td>
<td>334.3 ± 1.9</td>
<td>Zircon LA-ICP MS</td>
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<td>47° 15' 23.1&quot;</td>
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<td>334.3 ± 1.9</td>
<td>Zircon LA-ICP MS</td>
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<td>334.6 ± 1.8</td>
<td>Zircon LA-ICP MS</td>
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<td>334.3 ± 1.9</td>
<td>Zircon LA-ICP MS</td>
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</table>

Notes: Hbl, hornblende; Kfs, K-feldspar; Pl, plagioclase and Qtz, quartz.

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Table 2
LA-ICP-MS U–Pb isotopic analysis for zircons from the dikes in Sawur region of northern West Junggar.

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<th>Sample No.</th>
<th>U/Pb</th>
<th>Pb/206Pb</th>
<th>±1σ</th>
<th>Pb/207Pb</th>
<th>±1σ</th>
<th>Pb/208Pb</th>
<th>±1σ</th>
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JMC Nd standard 0.511125 ± 10 (2σ). An age of 334 Ma was assigned to the initial Sr and Nd ratios for the dikes based on their U/Pb zircon age (this study, see below).

3.3. U–Pb zircon geochronology

Zircon grains were separated using conventional magnetic and heavy liquid techniques, followed by hand-picking. Representative grains were mounted in epoxy, polished, and photographed in transmitted and reflected light, followed by cathodoluminescence (CL) imaging to study the internal structure of the grains. The U–Pb isotopic compositions of zircon grains were analyzed on a VG PQ Excell ICP-MS equipped with a NewWave 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-tripled Nd:YAG laser. Most analyses were carried out with a beam diameter of 30 μm, at a 6 Hz repetition rate. This gave a 238U signal of 3 × 10^4 to 2 × 10^5 counts per s, depending on U contents. Typical ablation time was 30–60 s, resulting in pits 20- to 40-μm-deep. Before measurement, samples were ablated for 10 s to eliminate common lead contamination on sample surfaces. In addition, 202Hg was monitored to control the isobaric interference of 204Hg on 204Pb. Data acquisition started with a 15 s measurement of a gas blank during the laser warm-up time. The 204Pb signal was so small that the common lead correction is therefore.
regarded as unnecessary (Xia et al., 2004). The standard zircon 91500 was used to evaluate the magnitude of mass bias and inter-elemental fractionation. The instrumental settings and detailed analytical procedures are described in Xia et al. (2004). The U–Pb ages were calculated using the U decay constants of $^{238}\text{U} = 1.55125 \times 10^{-10}$ year$^{-1}$ and the Isoplot 3 software (Ludwig, 2003). Individual analyses are presented with 1σ errors, and uncertainties in pooled age results are quoted at the 95% confidence level (2σ). $^{206}\text{Pb}/^{238}\text{U}$ ages are adopted in this study because the relatively small amount of $^{207}\text{Pb}$ accumulated in Earth Sciences, The University of Hong Kong. Each analytical spot was subjected to 20 ablation cycles, resulting in pits 20- to 40-μm deep. Atomic masses 172 to 179 were simultaneously measured in static-collection mode. The measured isotopic ratios of $^{176}\text{Hf}/^{177}\text{Hf}$ were normalized to $^{176}\text{Yb}/^{172}\text{Yb} = 0.7325$, using exponential correction for mass bias. The in-situ measured $^{173}\text{Yb}/^{172}\text{Yb}$ ratio was used for mass bias correction for both Yb and Lu because of their similar physicochemical properties. Ratios used for the corrections were 0.5886 for $^{176}\text{Yb}/^{172}\text{Yb}$ (Chu et al., 2002) and 0.02655 for $^{176}\text{Lu}/^{172}\text{Lu}$ (Machado and Simonetti, 2001). External corrections were applied to all unknowns, and standard zircons 91500 and GJ were used as external standards and were analyzed twice before and after every 10 analyses.

3.4. Zircon Hf isotope analysis

Hafnium isotope analyses were performed using a Nu Plasma HR MC-ICP-MS (Nu Instruments), coupled to a 193 nm excimer laser ablation system (Resolution M-50, Resonetics LLC), installed in the Department of Earth Sciences, The University of Hong Kong. Each analytical spot was used to evaluate the magnitude of mass bias and inter-elemental fractionation. The instrumental settings and detailed analytical procedures are described in Xia et al. (2004). The U–Pb ages were calculated using the U decay constants of $^{238}\text{U} = 1.55125 \times 10^{-10}$ year$^{-1}$ and the Isoplot 3 software (Ludwig, 2003). Individual analyses are presented with 1σ errors, and uncertainties in pooled age results are quoted at the 95% confidence level (2σ). $^{206}\text{Pb}/^{238}\text{U}$ ages are adopted in this study because the relatively small amount of $^{207}\text{Pb}$ accumulated in

Table 3

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4. Results

4.1. Zircon U–Pb geochronology

Zircon samples WJ1138 and WJ1139 from NE- and NW-trending dikes, respectively, were analyzed for zircon U–Pb isotopic compositions.
Zircon grains from both samples are light brown in color, transparent to translucent, and occur as euhedral, stubby to prismatic crystals. The CL images show that all of the grains have good oscillatory zoning and lack visible inherited cores (Fig. 5). Zircon grains from the dikes are 40- to 150-μm-long, with length to width ratios of 1.5–3 (Fig. 5). Their Th/U ratios are relatively high (0.42–1.08 and 0.67–1.45, respectively), consistent with a magmatic origin (Hanchar and Rundnick, 1995). Eighteen zircon grains were analyzed for sample WJ1138, and the data are concordant or nearly concordant. Their 206Pb/238U ages range from 332 Ma to 335 Ma and form a coherent group with a weighted mean 206Pb/238U age of 334.3 ± 1.9 Ma (Table 2; Fig. 6a). Sixteen zircon grains were analyzed for sample WJ1139, and all the data are concordant and form a cluster as a single population in the concordia diagram. The 206Pb/238U ages for sample WJ1139 range from 331 Ma to 336 Ma and give a weighted mean of 334.6 ± 1.8 Ma, consistent with the age of sample WJ1138 (Table 2; Fig. 6b).

4.2. Major and trace element geochemistry

The dikes show intermediate SiO2 (55.5 to 61.8 wt.%), and relatively high Al2O3 (14.5–16.3 wt.%) and alkali elements (K2O + Na2O = 5.5–7.7 wt.%), with high-K to medium-K calc-alkaline characteristics (Table 3; Fig. 7a). The dikes are relatively magnesium enriched, with Mg# between 44 and 56 (Table 3; Fig. 7b). In the Nb/Y vs Zr/Y classification diagram, most of the dikes plot in andesite fields (Fig. 7c). The dikes display coherent REE patterns characterized by relative enrichment of light rare earth elements ((La/Yb)N = 10.2–11.8), with fractionated heavy rare earth element (HREE) patterns ((Gd/Yb)N = 1.9–2.5) and weak negative Eu anomalies (Eu/Eu* = 0.92–0.98) (Fig. 8a, b). The rocks are enriched in Sr (467–1005 ppm) and Ba (296–652 ppm), depleted in HREE (e.g. Yb = 0.93–1.39 ppm), which, together with their high Sr/Y ratios (34–74), are analogues to those of modern adakites (Table 3; Fig. 9; Defant et al., 1991; Moyen, 2009). In a primitive mantle normalized spider diagram, the samples show remarkable enrichment of large ion lithophile elements (LILE) (such as Ba, Sr, Re, and U) relative to high field strength elements (HFSE) and LREE, with negative Ti, Nb, and Ta anomalies (Fig. 8b), consistent with the geochemical characteristics of subduction-related magmas.

4.3. Sr-Nd-Hf isotopic compositions

The Sr-Nd isotope compositions of the representative dikes are shown in Table 4. The dikes possess initial 87Sr/86Sr ratios (0.7036–0.7041), εNd (334 Ma) values (+6.2 to +6.5), and TNd model ages (596–567 Ma) that are comparable to those of Late Carboniferous adakitic rocks in the southern part of the Western Junggar (Table 4, Fig. 10, Geng et al., 2009). The dikes have slightly higher εNd(t) values than the Early Carboniferous (340 Ma) volcanic rocks in the area (Fig. 10; Shen et al., 2007).

Seventeen zircon grains from sample WJ1138 were analyzed for Lu-Hf isotopic compositions (Table 5), which all exhibit positive εHf(t) values (+11.3 to +15.8) and relatively juvenile TDM model ages (516–333 Ma) (Table 5). Sixteen zircon grains from sample WJ1139 were analyzed for Lu-Hf isotopic compositions (Table 5), which yielded similar εHf(t) values (+10.2 to +15.1, respectively) and TDM model ages (362 Ma and 565 Ma, respectively) (Table 5).
5. Discussion

5.1. Formation of the adakitic dikes

5.1.1. Crustal contamination

To evaluate the effect of crustal contamination of the magmas, we examined correlations among selected trace element ratios such as La/Sm, Nb/La, Th/Ta, Sm/Nd, SiO₂/MgO, and Nb/U. The correlations between these ratios are sensitive to crustal contamination. No significant correlation is found in the variation diagrams of Sm/Nd vs. Nb/La, La/Sm, Nb/La, Th/Ta, Sm/Nd, SiO₂/MgO, and Nb/U. The correlations between the trace element ratios indicate that the magmas are not significantly contaminated by crustal materials.

5.1.2. Petrogenesis

Adakites were originally recognized in Cenozoic island arcs where they are associated with the subduction of young (≤25 Ma) oceanic lithosphere (Defant and Drummond, 1990). Compared with andesites, dacites, and rhyolites (ADR), adakites have high concentrations of Na and Sr; low MgO (<3 wt.%), Y, and HREE; and high Sr/Y ratios (Defant and Drummond, 1990, 1993). Slab melting of oceanic crust had been proposed to account for the genesis of adakitic rocks (Kay, 1978; Stern and Kilian, 1996; Rapp et al., 1999; Wang et al., 2007c). Several other mechanisms have also been proposed to account for the origin of adakitic rocks, such as assimilation and fractional crystallization (AFC) processes from parental basaltic magmas (Castillo et al., 1999; Macpherson et al., 2006; Moyen, 2009; Rooney et al., 2011); magma mixing of felsic and basaltic magmas (Guo et al., 2007; Streck et al., 2007); melting of thickened or delaminated lower crust (Chung et al., 2003; Gao et al., 2004; Wang et al., 2005, 2007a,b), and melting of subducted continental crust (Wang et al., 2008, 2010). The dikes in the Sawur region exhibit geochemical characteristics of typical adakites (Fig. 8; Kay, 1978; Defant and Drummond, 1990; Martin et al., 2005). Because the dikes do not exhibit significant compositional trends indicative of low-pressure or high-pressure assimilation and fractional crystallization (AFC) from parental basaltic magmas (Fig. 11a–d), such a process seems unlikely. Moreover, the dikes show higher εNd(t) values than those of the coeval basalts in the area (Fig. 10; Shen et al., 2007), implying that the dikes may have a distinct source.

Magma mixing typically is supported by linear trends on major and trace element plots (Macpherson et al., 2006). On La and Na₂O diagrams, however, the dikes do not display such trends (Fig. 11a and d). In addition, Nd isotopic compositions (average εNd(t) = +6.3) of the dikes are similar to those of contemporaneous I-type granite in the area, but are significantly higher than those of the contemporaneous basalt (Fig. 10), suggesting that the dikes were not produced by mixing between the felsic and basaltic magmas.

It is possible that the adakitic magmas were derived from partial melting of the lower crust without passing through the mantle wedge. In such a case, the rocks would have relatively low MgO, Cr, and Ni because of the lack of interaction with the mantle source (Atherton and Petford, 1993; Smithies, 2000). Melts from basaltic lower crust are characterized by low MgO (<40) regardless of degree of melting, whereas those with high MgO values (>40) can be attributed to the involvement of a mantle component (Rapp and Watson, 1995). The adakitic dikes have high MgO (1.75–5.37 wt.%; MgO = 44–56), Cr (40.1–128 ppm), and Ni (24.1–58.8 ppm) (Table 3), which are distinct from partial melts of a thickened mafic lower crust.

Alternatively, adakitic rocks may be generated by partial melting of delaminated lower crust or subducted continental crust (Chung et al., 2003; Gao et al., 2004; Wang et al., 2008, 2010). Because the basement beneath western Junggar is likely dominated by early Paleozoic oceanic crust and parts of arc complexes that were deeply subducted during the late Paleozoic (Chen and Jahn, 2004; Chen and Arakawa, 2005; Tang et al., 2012c), it is difficult to distinguish partial melting of delaminated lower crust from subducted oceanic crust in terms of geochemical characteristics. However, the Sawur region was a part of the Zharma–Sawur arc in the Early Carboniferous (Shen et al., 2008; Chen et al., 2010a; Shen et al., 2012), and the crust experienced only limited thickening; hence making it difficult to generate the adakitic dikes.
Based on an extensive adakite geochemical database (~340 analyses), Martin et al. (2005) identified two distinct groups of adakite, which may be discriminated on the basis of their SiO₂ and MgO contents. High-SiO₂ adakite (HSA; SiO₂ > 60 wt.%; MgO = 0.5–4 wt.%) is considered to represent melts from subducted basaltic slabs that have variably reacted with peridotite during ascent through the mantle wedge, whereas low-SiO₂ adakite (LSA; SiO₂ < 60 wt.%, MgO = 4–9 wt.%) is formed by melting of peridotitic mantle wedge modified by interaction with felsic slab-melts (Martin et al., 2005). On the discrimination diagrams for low-SiO₂-adakites (LSA) and high-SiO₂-adakites (HSA) of Martin et al. (2005) (Fig. 12a–d), the dikes mainly plot in the HSA field, suggesting an interaction between slab-derived melts and mantle peridotites. Therefore, the dikes resulted from interaction between mantle peridotite and slab melts during their ascent (Rapp et al., 1999; Martin et al., 2005).

5.1.3. Source

The adakitic dikes have high MgO, Cr, and Ni contents and depleted Sr, Nd, and Hf isotope compositions, suggesting the involvement of a mantle source. Isotopic characteristics of the Early Carboniferous arc-related basalt and basaltic andesite in the area indicate an origin from mantle sources in the northern West Junggar (εNd(t) = +3.5 to +4.8; Shen et al., 2008). However, the isotopic compositions are different from those of the dikes in Sawur because these dikes have much higher εNd(t) (+6.2 to +6.5) values than those of the Early Carboniferous basalts and basaltic andesite in the region (Table 4; Fig. 10). In addition, these dikes show Sr–Nd–Hf isotope compositions that differ from those of adakitic rocks generated by partial melting of underplated lower crust in the North Tianshan (Zhao et al., 2008). This indicates that dikes in the Sawur region may not be derived from melting of the middle and lower crust (Fig. 10; Zhao et al., 2008; Zhou et al., 2008a).

The Bayingou ophiolite, dated at 344.0 ± 3.4 Ma by zircon U–Pb, is the youngest ophiolite in northern Xinjiang and can provide information about the isotopic composition of the Carboniferous Paleo-Asian Ocean crust (Xu et al., 2006). The isotopic compositions of the adakitic dikes are similar to those of the l-type granites in Sawur region and gabbro and dolerite in the Bayingou ophiolite in the Tianshan (Xu et al., 2006; Zhou et al., 2008a), suggesting that subducted oceanic lithosphere could be the dominant source of the dikes and adakitic pluton in the area (Fig. 10).

Generally, high Th/Yb ratios in arc lavas indicate involvement of sediments and/or sediment-derived melts, whereas high Ba/La ratios normally reflect the involvement of slab-derived fluids in arc magma generation (Woodhead et al., 2001). In the Th/Yb versus Ba/La diagram (Fig. 13), the adakitic dikes plot parallel to the Th/Yb axis, indicating a significant involvement of subducted sediments. Consequently, compared with the Late Carboniferous adakites of the southern part of Western Junggar, the adakitic dikes originating from melting of subducted basaltic oceanic crust and minor sediments tend to have slightly lower εNd(t) values (Fig. 10; Geng et al., 2009).

5.2. Geodynamic implications

5.2.1. Paleozoic magmatism in West Junggar: Temporal and spatial distribution

Intrusions in the West Junggar were emplaced mostly between the Late Silurian and Middle Permian, as defined by numerous SHRIMP and LAICP-MS zircon U–Pb dating studies (Han et al., 2006; Zhou et al., 2008a; Chen et al., 2010a; Yin et al., 2013b). Three pulses of granitic magmatism have been recognized (Fig. 14), e.g. ca. 422 to 405 Ma (Chen et al., 2010a), ca. 346 to 321 Ma (Han et al., 2006; Zhou et al., 2008a; Chen et al., 2010a; Yin et al., 2013b), and ca. 316 to 283 Ma (Han et al., 2006; Zhou et al., 2008a; Geng et al., 2009; Chen et al., 2010a; Tang et al., 2011; Yin et al., 2013b). The Late Silurian–Early Devonian plutons mainly occur in the Boshchekul–Chingiz volcanic arc, and include A-type granites and associated diorite, K-feldspar granite and subvolcanic rocks (Chen et al., 2010a). The Early Carboniferous plutons are mainly distributed in the Zharma–Sawur volcanic arc and consist of l-type granites, adakitic granites, and adakitic dikes (Zhou et al., 2008a; Chen et al., 2010b, and this study). The youngest plutons, widespread in the northern and southern parts of western Junggar, mostly consist of A-type and l-type granites, adakites, charnockites, sanukites, Nb-enriched and magnesian dikes, and tholeiitic and alkaline basalts (Chen and Jahn, 2004; Chen and Arakawa, 2005; Geng et al., 2009; Tang et al., 2010; Yin et al., 2010; Zhang et al., 2011a,b; Tang et al., 2012a; Yin et al., 2012, 2013a,b). The plutons in the south of West Junggar (316 Ma–283 Ma) were emplaced earlier than those in the north (303 Ma–283 Ma) (Fig. 14). It is quite clear that there were two periods of magmatic quiescence (405–346 Ma and 321–303 Ma) in the northern West Junggar. The adakitic intrusions with contemporaneous l-type granites in the northern West Junggar formed between the two periods of quiescence.

5.2.2. Implications for the Early Carboniferous geodynamic evolution of the northern Western Junggar

The adakitic dikes show strong depletion of HREE and Y contents, a positive Sr spike, negligible to negative Eu anomalies, and negative Nb,
Table 5
Lu–Hf isotopic compositions of zircons from the dikes in Sawur region of northern West Junggar.

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Fig. 11. Plots of (a) SiO$_2$ versus La; (b) SiO$_2$ versus Ba; (c) SiO$_2$ versus Dy/Yb; (d) SiO$_2$ versus Na$_2$O; 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).

The Sawur basalt is from Shen et al. (2008).
Ta, and Ti anomalies, which together suggest that partial melting of source rocks took place in the garnet and rutile stability field, where garnet and rutile, rather than plagioclase, were left behind as residual minerals in the source region (Xiong, 2006) (Fig. 8a, b). Thus, the pressure–temperature (P–T) conditions for the adakitic dike formation was constrained to 1.5–2.5 GPa and 850–1050 °C by the P–T stability boundaries of amphibole and rutile in the basalt system (Xiong, 2006). Under normal circumstances, subducted ocean crust is too cold to melt when it lies beneath the volcanic arc of most modern subduction zones (Schmidt and Pollard, 1998), while slab melting would most likely occur when young and hot lithosphere is being subducted (Defant and Drummond, 1990) or the lithosphere is being under abnormal tectonic setting, such as ridge subduction or flat subduction (Tuena et al., 2003; Mori et al., 2007; Geng et al., 2009; Tang et al., 2010). Because the dikes possess adakitic characteristics, a thermal regime must have been invoked in the Early Carboniferous.

Windley et al. (2007) proposed ridge–trench interactions to explain some key features of the CAOB (e.g., adakites, boninites, near-trench magmatism, Alaskan-type mafic–ultramafic complexes, and high-temperature metamorphic belts). Ridge subduction can readily provide enough heat for generating widespread magmatic activity, metamorphism, and mineral deposit formation (Defant and Drummond, 1990; Aguillon-Robles et al., 2001; Kelemen et al., 2003; Sisson et al., 2003; Windley et al., 2007). The Sawur region is characterized by calc-alkaline volcanic rocks and I-type granitic intrusions formed in the Early Carboniferous. Zircon saturation temperature calculations for the Early Carboniferous plutons (689–857 °C) are significantly lower than those for Late Carboniferous–Middle Permian granites (833–1032 °C) (Zhou et al., 2008a; Chen et al., 2010b). The occurrence of Late Carboniferous–Early Permian granites, together with the coeval charnockites, sanukites, tholeiites, and adakite–magnesian diorites (Geng et al., 2009; Tang et al., 2010; Yin et al., 2012; Yin et al., 2013a), implies that the western Junggar had been affected by a hot, subduction-related regime, which gave rise not only to abundant magmatism in the Late Carboniferous, but also to Cu–Au mineralization in the area (e.g. Baogutu copper deposit). These studies strongly support a ridge subduction regime in the western Junggar during Late Carboniferous–Early Permian. However, such a thermal regime is not feasible in the Early Carboniferous in the Sawur region.

Magmatism in the northern West Junggar allows us to propose a flat subduction regime that can produce the temperature and pressure conditions required for generating adakitic magma by partial melting of moderately old oceanic crust (Fig. 15a). There was a magmatic quiescence in the northern West Junggar between ca. 405 Ma and 346 Ma, which has been attributed to a period of flat-subduction (Fig. 15a). The formation of the adakitic intrusions at 338–332 Ma, and their

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**Fig. 12.** Comparison between the geochemical characteristics of the adakitic dikes and the key geochemical parameters used by Martin et al. (2005) to highlight the differences between high-SiO₂ (HSA) and low-SiO₂ (LSA) adakites. (a) MgO versus SiO₂; (b) Cr/Ni versus TiO₂; (c) Sr versus CaO + Na₂O; (d) Sr/Y versus Y.

**Fig. 13.** Diagram of Th/Yb vs Ba/La for the adakitic dikes in the western Junggar. Woodhead et al. (2001).
emplacement after a magmatic quiescence, are consistent with a flat subduction geometry that favored slab melting at relatively low pressures (Fig. 15a). Thermal modeling for slab melting has suggested that during flat subduction, the leading edge of the slab can be anomalously overheated and allow partial melting to generate adakitic magma (Gutscher et al., 2000). Thus, adakite can serve as a powerful magmatic marker of geodynamic changes in active margins. Many modern adakitic rocks are associated with flat subduction, such as the Trans-Mexican Volcanic Belt and the Northern Volcanic Zone (NVZ) in Ecuador (Bourdon et al., 2003; Tuena et al., 2003; Mori et al., 2007). Therefore, the adakitic intrusions in northern West Junggar may be related to partial melting of the subducting Irtysch–Zaysan oceanic lithosphere. On the other hand, numerical models have also shown that the high temperatures of this configuration can only be sustained for relatively short periods of time, after which both the subducting and overriding lithospheres will produce a gradually cooler thermal structure in the subduction zone, hindering slab melting, and instead favoring slab dehydration and fluid fluxing of the mantle wedge. Such a mechanism would form the more typical calc-alkaline volcanic rocks and granitic intrusions of the northern West Junggar (e.g., 332–321 Ma I-type granites) (Fig. 15b). Finally, the oldest stitching plutons (307 Ma, Kuibida et al., 2009) within the Irtysch–Zaysan suture zone place an upper age limit for the formation of the Irtysch–Zaysan suture zone and abundant Late Devonian–Early Carboniferous conodonts and radiolarians were obtained from siliceous rocks of ophiolites within the Irtysch–Zaysan suture zone, suggesting that the Irtysch–Zaysan Ocean was closed in the Late Carboniferous (Iwata et al., 1994, 1997; Han et al., 2010).

The 338–332 Ma adakite were generated by the southward flat subduction of the Irtysch–Zaysan ocean crust beneath the northern West Junggar (Fig. 15a). The available data suggest that the western Junggar underwent a long process of accretion/subduction in the late Paleozoic (Sengör et al., 1993; Windley et al., 2007; Kröner et al., 2008; Xiao et al., 2008). During such an event, flat slab subduction may have played an important role in the crustal growth of this part of the CAOB.

6. Conclusions

(1) The adakitic dikes (both NW- and NE-trending) in the Sawur region of the northern West Junggar were formed contemporaneously at ~334 Ma.

(2) The dikes are geochemically similar to slab-derived adakites, generated by partial melting of a subducted oceanic slab and overlying sediments, and subsequent melt–mantle interaction.

![Fig. 14. Histograms zircon U–Pb ages for plutons in the western Junggar. Age data are from Chen et al. (2010a), Han et al. (2006), Feng et al. (2012), Geng et al. (2009), Tang et al. (2010, 2012a), Song et al. (2011), Zhou et al. (2008a), Wei (2010), Yin et al. (2013b), and this study.](https://example.com/image1)

![Fig. 15. Schematic presentations of flat slab subduction model to explain the generation of adakitic intrusions from northern West Junggar.](https://example.com/image2)
(3) The formation of the adakitic dikes was probably associated with the flat subduction during Early Carboniferous.

Acknowledgments

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References


