Continuity of the North Qilian and North Qinling orogenic belts, Central Orogenic System of China: Evidence from newly discovered Paleozoic adakitic rocks


1. Introduction

China is tectonically composed of the South China block and Tibet Plateau on the south and the North China and Tarim blocks on the north (Fig. 1a). Between these northern and southern tectonic units is the WNW trending Central Orogenic System (COS) extending from the eastern Sulu through Dabie, Tongbai, Qinling, and Qilian to the western Kunlun orogenic belts (Fig. 1a; Yang et al., 2003). The relationships between these orogenic belts provide critical constraints for reconstructing the tectonic evolution of eastern Asia and the Gondwana continent (e.g., Metcalfe, 2006; Han et al., 2009). The tectonic framework of the Sulu and Dabie orogenic belts is well established on the wide occurrence of ultrahigh pressure eclogites and gneisses resulted from the collision between the North and South China blocks at ∼220 Ma (e.g., Ayers et al., 2002; Katsube et al., 2009; Zhang et al., 2009). Based on SHRIMP zircon ages and tectono-stratigraphy, Zhai et al. (2004; Tung et al., 2007) extended the Sulu–Dabie orogenic belt to the Korean Peninsula. In contrast, tectonic models for the western COS are mostly limited to individual orogenic belts (e.g., Ratschbacher et al., 2003; Wang et al., 2003; Li et al., 2007; Ye et al., 2008). An important result is that the Kunlun and Qilian orogenic belts represent a suture zone from the closure of the “Proto-Tethyan Ocean” (Bian et al., 2004; Tung et al., 2007). However, the eastern extension of this suture zone remains unclear due to insufficient geological, petrological and geochronological constraints on the relationships between...
these western orogenic belts, hindering the development of an integrated tectonic model.

In this paper we identify adakitic rocks from the North Qilian orogenic belt and propose that they are petrogenetically and geochronologically related to the adakitic rocks from the easterly adjacent North Qinling orogenic belt. This result together with similarities in tectonic configurations and major constituent lithological assemblages leads to an interpretation that the North Qilian and North Qinling orogenic belts were an undivided tectonic unit formed by the northward subduction of the "Proto-Tethyan Ocean" during Early Paleozoic time.

2. Geological setting

The Qilian Mountain System forms a ~300 km wide and ~1200 km long WNW-trending belt at the northern margin of the Tibetan Plateau (Fig. 1a). It is composed of the North Qilian orogenic belt and the South Qilian block (Fig. 1a). The South Qilian block consists of Precambrian basement overlain by Paleozoic sedimentary sequence (Song et al., 2006). The North Qilian orogenic belt has been proposed to be an island arc system formed by northward subduction of an ancient ocean, the Paleo-Qilian ocean (Xu et al., 1994; Yang et al., 2002). Its eastern section, which bounds to the western end of the

Fig. 1. (a) Simplified geological map of the north Qilian and Qinling orogenic belts, NW China (modified from Wang et al., 2005a; Chen et al., 2006), and sampling localities. (b) Detailed geological map enlarged from the rectangular area in (a). The contact zone (described in text) that separates the Northern and Southern terranes is roughly in between the Precambrian–Paleozoic contact at the south and the Leigonshan–Laohushan–Shenmutou lineament at north.
Qinling orogenic belt with an ambiguous tectonic relationship (Fig. 1a), is divided into the Northern and Southern terranes by a <10 km wide contact zone (Fig. 1b; Yang et al., 2002; Wang et al., 2005a). The Southern terrane represents the remnant of oceanic lithosphere, whereas the Northern terrane is composed of arc assemblages (Yang et al., 2002). The contact zone consists mainly of Early Paleozoic volcanic and sedimentary assemblages, which underwent epidote–amphibolite facies metamorphism (Yang et al., 2002).

The studied samples were collected from three felsic intrusive bodies at the east of the Northern terrane (Fig. 1b). Among them, the Shenmutou outcrop is the largest with an area of ∼50 km², whereas the Leigongshan and Daiqiangou outcrops are ∼10 km². These outcrops are lithologically homogeneous without obvious mineral layering.

3. Sample descriptions

Samples were collected from Daiqiangou, Leigongshan, and Shenmutou along the Laohushan range (Fig. 1b). All the rocks are coarse-grained. The Daiqiangou and Leigongshan samples are tonalites, consisting of 40–50% quartz and 60–50% plagioclase. The plagioclase grains (An33–42) are euhedral and slightly saussuritized.

The Shenmutou samples contain 20–30% quartz, 40–50% alkali feldspar and 40–30% plagioclase; therefore, are classified as quartz monzonite. The plagioclase (An13–18) is euhedral to subhedral and is commonly replaced by chlorite. The rim of titanomagnetite is sometimes altered to titanite and chlorite. Samples were analyzed for bulk major and trace element abundances (Table 1) and Sr and Nd isotope ratios (Table 2). In addition, zircon grains in two samples were separated for U–Pb age determination (Table 3).

4. Analytical methods

4.1. Bulk major and trace element abundances

Major element concentrations were determined by X-ray fluorescence (XRF). Abundances of trace elements were measured by

<table>
<thead>
<tr>
<th>Sample</th>
<th>SMT-01</th>
<th>SMT-02</th>
<th>SMT-05</th>
<th>SMT-07</th>
<th>SMT-12</th>
<th>LGS-07</th>
<th>LGS-10</th>
<th>LGS-15</th>
<th>D38</th>
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<td>66.88</td>
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<td>62.59</td>
<td>63.51</td>
<td>64.19</td>
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<tr>
<td>TiO₂</td>
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<td>0.40</td>
<td>0.40</td>
<td>0.36</td>
<td>0.31</td>
<td>0.35</td>
<td>0.40</td>
<td>0.28</td>
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<tr>
<td>Al₂O₃</td>
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<td>16.12</td>
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<tr>
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<td>2.59</td>
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<tr>
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<tr>
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<tr>
<td>K₂O</td>
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<td>1.50</td>
<td>1.50</td>
<td>1.50</td>
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<tr>
<td>P₂O₅</td>
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</tr>
<tr>
<td>Total</td>
<td>98.59</td>
<td>99.92</td>
<td>99.27</td>
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<td>99.32</td>
<td>95.30</td>
<td>98.45</td>
<td>96.66</td>
<td>99.07</td>
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</table>

L.O.I. indicates loss on ignition. Shenmutou samples are SMT-01, -02, -05, -07, and -12. Leigongshan samples are LGS-07, -10, and -15. D38 is a Daiqiangou sample.
inductively-coupled plasma mass spectrometry (ICP-MS), except for Ni, Cr and V concentrations, which were analyzed by XRF. All analyses were carried out at the Washington State University, U.S.A. following the procedures of Johnson et al. (1999). The accuracy and precision are <1% for XRF analysis and ~5% for ICP-MS analysis.

4.2. Sr and Nd isotope analyses

For Sr and Nd isotopic analyses, approximately 70 mg of sample powder was decomposed by HF–HNO₃ mixture. After dryness, samples were re-dissolved in 2 ml HCl (2 N), then, loaded onto the column containing AG50W-X8 resin (100–200 mesh) to separate Sr and REE. The Sr aliquot was purified by eluting through the Sr-Spec column containing AG50W-X8 resin to extract Nd. Approximately 250 ng of Sr and 50–200 ng Nd were loaded onto double filaments (Re–Ta), and measured by Thermal Ionization Mass Spectrometer (TIMS; Finnigan MAT262 at National Cheng-Kung University). The total procedural blanks for Sr and Nd were both <200 pg. Mass fractionations were corrected using ¹⁴⁷Sr/¹⁴⁴Nd = 0.7219 and ⁸⁶Sr/⁸⁸Sr = 0.1194. During the course of this study, the mean ⁸⁷Sr/⁸⁶Sr ratio was 0.710245 ± 0.000111 (n = 10) for NBS 987 and 0.705011 ± 0.000124 (n = 12) for BCR-1, whereas the mean ¹⁴³Nd/¹⁴⁴Nd ratios for LaJolla and BCR-1 were 0.511855 ± 0.000124 and 0.511855 ± 0.000124, respectively.

4.3. Zircon SHRIMP U–Pb dating

Two samples, SMT-05 and LGS-07 were crushed and sieved. Zircon grains were separated by heavy liquids and magnetic separator and finally purified by hand-picking. They were mounted with epoxy and ground to half of their original grain sizes then polished. Reflecting-light and transmitted-light photomicrographs and cathodoluminescence images show that most zircon grains are euhedral with long axis of 80–200 μm and aspect ratios of 2–3. The separated zircon grains were dated using in-situ U-Pb isotope data obtained from SHRIMP II at Beijing SHRIMP Centre (Williams, 1998). Radiogenic lead

Data were obtained using SHRIMP at Beijing Centre. Radiogenic lead Pb⁎ corrected for common Pb using ²⁰⁶Pb⁰. The average ²⁰⁶Pb/²³⁸U ages for samples LGS-07 and SMT-05 are 453.4 ± 5.8 Ma and 429.9 ± 6.1 Ma, respectively. These Paleozoic ages are interpreted to be the emplacement ages. Some zircon grains from sample SMT-05 have inherited cores with ²⁰⁶Pb/²³⁸U ages of 1011–2935 Ma, which were not included in the average age.
was corrected for common Pb using measured $^{206}\text{Pb}/^{238}\text{U}$. Zircon standard SL 13 (572 Ma, 238 ppm U) was used to calibrate U, Th and Pb concentrations of samples and TEMORA standard. Then, the TEMORA standard (417 Ma) was used to calibrate the Pb/U and UO/U values (Black et al., 2003). The ages of the analyzed zircons were calculated using SQUID and ISOPLOT program (Ludwig, 2000). Two sigma uncertainties are reported for the mean weighted ages (Table 3).

5. Results

The analyzed samples have SiO$_2$ contents ranging from 62.6 to 68.4%, high Al$_2$O$_3$ concentrations of $\sim$15.9% and K$_2$O/Na$_2$O ratios $<$0.5 (Table 1). Their [Al$_2$O$_3$/(CaO + Na$_2$O + K$_2$O)] ratios are $<$1.10 indicating magmatic origin, except for the high value of 1.28 for sample LGS-15, which is relatively enriched in secondary minerals and a high L.O.I. content. All the samples are characterized by LREE enrichments (Fig. 2a) with depletions in Nb and Ti (Fig. 2b). Most importantly, these granitoid samples are high in Sr ($>$654 ppm) and La ($>$9.8 ppm) abundances (Table 1). Their high Sr/Y of $>$65 and (La/Yb)$_N$ of $>$11.2 reflect the role of residual garnet and are characteristic of adakites (Defant and Drummond, 1990; Fig. 3). However, some of the analyzed samples have Mg# lower than that of adakites ($<$42 vs. $>$50). In a strict sense, we refer our samples to as “adakitic rocks”.

Most zircon grains exhibit well-developed crystal faces and magmatic oscillatory zoning (Fig. 4). Except for four data, the measured $^{206}\text{Pb}/^{238}\text{U}$ ages vary within the range of 413–462 Ma with weighted averages of 453.4±5.6 Ma (MSWD=0.5) for the Leigongshan tonalite sample (RGS-07) and 429.9±6.1 Ma (MSWD=1.4) for the Shennmutou quartz monzonte sample (SMT-05) (Table 3). These ages represent the time of magma emplacement. The four older ages of 1011–2935 Ma were measured from cores of inherited zircon grains from sample SMT-05 (Table 3).

The bulk rocks have $^{87}\text{Sr}/^{86}\text{Sr}$ and $^{143}\text{Nd}/^{144}\text{Nd}$ ratios varying in the ranges of 0.70692–0.70834 and 0.51228–0.51235, respectively (Table 2). If the zircon emplacement ages and the measured Rb/Sr and Sm/Nd ratios are considered, the initial $^{87}\text{Sr}/^{86}\text{Sr}$ ratios are 0.70546–0.70677 and the $^{143}\text{Nd}/^{144}\text{Nd}$ values range from $\sim$1.4 to $\sim$1.9 (Table 2). Using the present-day (147Sm/144Nd)$_{DM}$ of 0.2137 and (143Nd/144Nd)$_{DM}$ of 0.51315, the $T_{DM}$ values were calculated to be 1.16–1.49 Ga (Table 2).

6. Petrogenesis of the Qilian adakitic rocks

Both subducted oceanic slab and lower continental crust can be the sources for adakitic melts (e.g., Condie, 2005; Martin et al., 2005). The Qilian adakitic rocks have $^{87}\text{Sr}/^{86}\text{Sr}$ ratios of 0.7055–0.7068 and $^{143}\text{Nd}/^{144}\text{Nd}$ values of $\sim$1.4 to $\sim$1.9, which are more radiogenically enriched than that of mid-ocean-ridge basalt (MORB), consistent with derivation from lower continental crust rather than oceanic slab (Fig. 5). Although some segments of the subducting Chile ridge show crustal signatures due to source contamination (Klein and Karsten, 1995; Sturm et al., 1999), they are distinct from the Qilian adakitic rocks for higher $^{143}\text{Nd}/^{144}\text{Nd}$ and lower $^{87}\text{Sr}/^{86}\text{Sr}$ values (Fig. 5). Moreover, the Qilian adakitic rocks have Nb/U, Ce/Pb, Ti/Eu, and Nd/Sm ratios differing from that of...
these source-contaminated ocean ridges but resembling the crustal values (Fig. 6), further strengthening their continental affinity.

Although all the samples have similar trace element abundances and Sr and Nd isotope ratios, they are discernible in some other compositional parameters. Specifically, the Shenmutou samples have higher MgO, SiO2, Na2O, Cr, and Ni contents than the Leigongshan and Daiqiangou samples (Table 1). Were these differences caused by fractional crystallization as postulated for lavas from the Negros arc of the Philippines (Solidum et al., 2003)? If so, the evolved melts should contain low MgO contents for amphibole and biotite removal and low Sr contents for feldspar removal. However, Sr contents of the low MgO and high MgO samples are comparable (Table 1), inconsistent with the control of fractional crystallization.

Compositions of experimental melts provide constraints on the petrogenesis of the Qilian adakitic rocks. In the MgO–SiO2 plot, the Leigongshan and Daiqiangou samples plot within the field of partial melts from eclogites, typical of adakitic rocks derived from thickened lower crust (Fig. 7). In contrast, the Shenmutou samples deviate from the experimental melts to higher MgO at a given SiO2 content falling within the field for slab-derived adakites (Fig. 7). The high MgO, Ni and Cr contents in slab-derived adakites relative to that of experimental melts have been attributed to interaction with mantle peridotite upon ascent (e.g., Condie, 2005; Martin et al., 2005). Applying this interpretation to the Shenmutou samples requires migrating shallow crustal melts through deep mantle peridotite. This apparent contradiction can be resolved by invoking lower crust delamination. At converging margins, the overlying continental crust was thickened by compression from subducted slab. As the lower mafic crust was metamorphosed to eclogites, it became denser and could be detached from crust, sinking into the mantle regime. In response to increases in pressure and temperature, the delaminated eclogites were then partially melted, generating adakitic melts (Kay and Kay, 1993). Upon ascent, the adakitic melts interacted with mantle peridotites, resulting in higher MgO, Ni and Cr contents. The Shenmutou samples do plot within the field for adakitic rocks derived from delaminated lower crust in the MgO–SiO2 plot (Fig. 7) and their Ni and Cr contents are comparable to the slab-derived adakites (≥ 20 and 50, respectively; Condie, 2005). Deviation from delaminated lower crust, however, cannot explain the high SiO2 and Na2O contents in the Shenmutou samples relative to that of the Leigongshan and Daiqiangou samples. Such differences were also shown by the comparison between the tonalites and granites from the Cordillera Blanca batholith, Peru, and were attributed to distinct sources (Petford and Atherton, 1996).

The proposed petrogenetic model for the Qilian adakitic rocks can be justified by geochronological data. The occurrence of ophiolites,
oceanic basalts and eclogites in the North Qilian orogenic belt indicates the existence of Paleo-Qilian ocean (Song et al., 2006). These ophiolites and oceanic basalts represent the \( \sim 490 \)–\( 550 \) Ma Qilian oceanic crust (Shi et al., 2004; Tseng et al., 2007), which subducted to the eclogite stability field at \( \sim 460 \) Ma (Song et al., 2006). Subsequently, the adakitic melts were generated during \( \sim 430 \)–\( 450 \) Ma (Table 3; Fig. 4). This evolutionary sequence is consistent with deriving adakitic melts from lower crust thickened by subduction-related compression. If the overriding lower crust extended to the depths where its adjacent subducted slab dehydrated, the slab-derived fluids could migrate to the lower crust to trigger melting (Wang et al., 2005b). Alternatively, heat for lower crust melting could be provided by underplating of earlier (\( \sim 450 \) Ma) mantle-derived arc magmas (Wang et al., 2005a).

Being the source of the adakitic magmas, the lower crust must be mafic and deeper than the eclogite stability field at \( \sim 460 \) Ma (Song et al., 2006). Subsequently, the adakitic melts were generated during \( \sim 430 \)–\( 450 \) Ma (Table 3; Fig. 4). This evolutionary sequence is consistent with deriving adakitic melts from lower crust thickened by subduction-related compression. If the overriding lower crust extended to the depths where its adjacent subducted slab dehydrated, the slab-derived fluids could migrate to the lower crust to trigger melting (Wang et al., 2005b). Alternatively, heat for lower crust melting could be provided by underplating of earlier (\( \sim 450 \) Ma) mantle-derived arc magmas (Wang et al., 2005a).

Being the source of the adakitic magmas, the lower crust must be mafic and deeper than the eclogite stability field, \( > 40 \) km (Rapp and Watson, 1995; Petford and Atherton, 1996). The present-day lower crust beneath the eastern Qilian area does extend to the depth of \( \sim 45 \) km but is composed of andesitic layers (Liu et al., 2006), apparently inconsistent with the requirement of mafic sources. However, it should be noted that the present-day crustal thickness and constituent lithologies do not reflect that in the Paleozoic time.

7. Tectonic continuity between the Qilian and Qinling orogens

Prior to our discovery of the Qilian adakitic rocks, Li et al. (1998, 2001) reported 437 Ma adakitic rocks with \( T_{DM} \) ages of 1.0–1.1 Ga from Huichizi in the North Qinling orogenic belt, which is on the southeast of the North Qilian orogenic belt (Fig. 1a). In addition, Zhang et al. (2006) found 434 Ma adakitic rocks with \( T_{DM} \) ages of 1.1–1.3 Ga from Caochuanpu at the boundary of Qilian and Qinling orogenic belts. These emplacement and model ages resemble that of the Qilian adakitic rocks (Tables 2 and 3). The Huichizi and Caochuanpu adakitic rocks also have Sr and Nd isotopic ratios indicating lower crust origin (Fig. 5). As the Leigongshan and Daiajiangou samples, the Huichizi and Caochuanpu adakitic rocks are compositionally comparable to
experimental melts with low MgO, Ni, and Cr abundances, precluding interaction with peridotites (Fig. 7). The petrogenetical similarities between the Qilian and Qinling adakitic rocks suggest that these two orogenic belts, even the two larger scale mountain systems, were subjected to similar tectonomagmatic processes during Early Paleozoic time. This inference is supported by the general similarities in their tectonic configurations and lithological assemblages. Specifically, the Qilian and Qinling Mountain Systems were both formed by northward subduction of oceanic lithospheres. They are both divided into northern and southern parts by narrow ophiolitic belts (Fig. 1a), which had active margins on the north and passive margins on the south during Early Paleozoic time (Meng and Zhang, 2000; Zhang et al., 2001; Yang et al., 2002). The southern parts of these two mountain systems consist of Precambrian basement overlain by Paleozoic sedimentary–volcanic sequence (Zhang et al., 2001; Song et al., 2006). The northern parts known as the North Qilian and North Qinling orogenic belts are characterized by the occurrence of strongly deformed and slightly-moderately metamorphosed volcanic–sedimentary sequences together with mafic–ultramafic complexes, intermediate-felsic plutons, Precambrian basalts and the 700–800 Ma granitoid fragments (Zhang et al., 2001; Ratschbacher et al., 2003; Wang et al., 2005a; Chen et al., 2006; Tseng et al., 2006). In summary, the overall consistencies in tectonic configurations and constituent lithological assemblages with the occurrence of adakitic rocks of similar ages and petrogenesis are an unlikely coincidence but suggest the continuity between eastern Qilian and western Qinling forming a >1000 km Early Paleozoic orogenic belt. The apparent topographic discontinuity between these two orogenic belts might reflect later (<420 Ma) tectonic activities.

The developments of the Qilian and Qinling orogens were closely related to the subduction of ancient oceanic lithospheres. Although the existence of the Paleo–Qilian and Qinling oceans has long been recognized, the tectonic architectures of these ocean basins have been debated. Xia et al. (1996) suggested that the Qilian ocean was a small oceanic basin, while Zhang et al. (1997) argued that it was a mature large ocean, probably comparable to the modern West Pacific. Following the recognition of the continuity between the Qilian and Qinling orogens, it is inferred that the adjacent ~500 Ma Qilian and Qinling oceans (Shi et al., 2004; Pei et al., 2005; Tseng et al., 2007) were parts of a large ocean basin rather than two separated small ones. This inference is consistent with palaeontological evidence. Cambrian–Ordovician fossil biota from the North Qilian orogenic belt contain coral and trilobite specimens from North China, South China, North America, Siberian, Baltic Sea, and Australia (Zhou et al., 1996). The occurrence of southern continent specimens implies that the inferred ~500 Ma large ocean might correspond to the “Proto-Tethyan Ocean” that separated several small continents in the north from the larger Gondwana continent in the south. While we propose that the North Qilian and North Qinling orogenic belts were an un-divided tectonic unit during ~550–430 Ma, it is emphasized that post 400 Ma volcanic rocks occur in the North Qinling orogenic belt but are absent in the North Qilian orogenic belt. Apparently, these two orogenic belts underwent distinct evolution history since the closure of the Proto-Tethyan Ocean (~420 Ma; Stampfli and Borel, 2002).

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