The geochemical evolution of the granitoid rocks in the South Qinling Belt: Insights from the Dongjiangkou and Zhashui intrusions, central China

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ABSTRACT

Widespread Late Triassic granitoid rocks in the South Qinling Belt (SQB) represent excellent subjects to study the geochemical and geodynamic evolution of magmatic rocks during the collision between the North China Craton and South China Block. In this study, we report new geological, geochemical, zircon U–Pb geochronology and zircon Hf isotopic data for the Dongjiangkou and Zhashui intrusions, two large igneous complexes typical of the SQB. We also summarize published geochemical data of similar granitoid rocks. Our results show that the Dongjiangkou intrusion is composed of ca. 223–214 Ma quartz diorites, tonalites and granodiorites with abundant coeval maﬁc magmatic enclaves (MME), and the Zhashui intrusion consists of ca. 203–197 Ma monzogranites and K-feldspar granites with rare MME. The Dongjiangkou granitoid rocks are characterized by high K2O, MgO, Rb, and Mg# values, but low TiO2, Sc, and A/CNK (molar Al2O3/(CaO + Na2O+K2O)) values, with εHf(t) values of −18.1 to −0.4 and TDM2(Hf) values of 1141–2117 Ma. We suggest that the Dongjiangkou granitoid rocks are formed by magma mixing between 70%–90% melts derived from partial melting of the Neoproterozoic basement rocks of the SQB and 10%–30% mantle-derived maﬁc melts with minor involvement of Archean to Paleoproterozoic old basement materials of the SQB. The Zhashui granitoid rocks exhibit high K2O, MgO, Rb, and Mg# values, but low TiO2, Sc, and A/CNK (molar Al2O3/(CaO + Na2O+K2O)) values, with εHf(t) values of −3.5 to +2.3 and TDM2(Hf) values of 979–1300 Ma, suggesting they are mainly produced by partial melting of Neoproterozoic metamorphic greywackes mixed with minor amounts of mantle-derived melts. The MME are characterized by low SiO2, Sr/Y ratio, but high MgO, K2O, and Rb contents, with εHf(t) values of −0.8 to +4.3 and TDM2(Hf) values of 732–905 Ma, suggesting they are produced by partial melting of metasomatized continental lithospheric mantle. A flare-up event is recognized during 225–205 Ma and the lower SiO2 and Sr/Y of the granitoid rocks during this period indicate prominent involvement of mantle-derived melts mixed with crustal melts. The granitoid rocks with higher SiO2 and Sr/Y during 225–205 Ma, however, suggest they are formed under a greater pressure than those of previous period (235–225 Ma) granitoid rocks. Few granitoid intrusions are formed after 205 Ma, and they display high SiO2 with low Sr/Y reﬂecting that they may be produced by low pressure partial melting of crustal materials or may represent highly fractionated magmas in the upper crust. These geochemical variations show a regular change with their formation ages, reﬂecting the possible variation in petrogenesis and crustal thickness. We propose that the granitoid rocks may have been formed in a transitional setting from subduction to collision during 235–225 Ma, and a slab break-off event followed during ca. 225–205 Ma. Slab detachment was completed during ca. 205–190 Ma. We propose that no intensive delamination/convective removal of lower crust occurred in the SQB.

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1. Introduction

Geochemical characteristics of granitoid rocks were used for decades to constrain their tectonic evolution (Atherton and Ghani, 2002; Barbarin, 1999; Batchelor and Bowden, 1985; Maniar and Piccoli, 1989; Pearce et al., 1984; Pitcher, 1983). Some recent studies proposed
that chemical indices, such as Ce/Y, Sr/Y and (La/Yb)$_N$ could be served as proxies for crustal thickness in magmatic arcs and further to evaluate the tectonic evolution of orogenic belts (Chapman et al., 2015; Chiaradia, 2015; Ducea et al., 2015; Mantle and Collins, 2008; Profeta et al., 2015). However, these studies focused mainly on subduction-related magmatism, and only few studies applied these indices to the continental collisional magmatism (e.g. Chung et al., 2009; Hou et al., 2012). Here, we apply these geochemical indices to granitoid rocks that formed during transition from subduction to continental collision in an ancient orogen and examine their implications for geodynamic evolution.

The Qinling Orogenic Belt (QOB) is one of the most important continental collisional orogens in east continental Asia. It connects the Qilian–Kunlun Orogens to the west and Dabie–Sulu Orogens to the east, and it is located between the North China Craton (NCC) and South China Block (SCB) (Diwu et al., 2012; Wu and Zheng, 2013). Widespread Mesozoic granitoid intrusions in the QOB, especially Early Mesozoic granitoids in the South Qinling Belt (SQB), provide targets to unravel the geodynamic evolution of the orogen by using petrologic and geochemical data (e.g. Dong and Santosh, 2016; Jiang et al., 2010; Zeng et al., 2014). In contrast, other researchers considered that chemical indices, such as Ce/Y, Sr/Y and (La/Yb)$_N$, could be served to evaluate the tectonic evolution of the orogen by using petrologic and geochemical data (e.g. Dong and Santosh, 2016; Jiang et al., 2010; N. Li et al., 2015; Wang et al., 2015; Yang et al., 2012a). A plethora of recently published chronological data from this region reveals that granitoids were intruded during 248–190 Ma time interval; the petrogenesis of these granitoid intrusions is still debated, especially for granitoids formed during the –225–190 Ma interval, which may hinder the use of geochemical indices (N. Li et al., 2015, and the references therein; Wang et al., 2015; Yang et al., 2012a). Scholars of this area usually considered that intrusions older than 235 Ma might be derived from partial melting of the subducted slab or mantle wedge during subduction (Li et al., 2013; Yang et al., 2014). As for the –225–205 Ma granitoid rocks, it is generally believed that most of them were formed by mixing between felsic and mafic magmas, although the sources of felsic magmas are debated. Some suggested that the felsic magma is derived from partial melting of subducted Yangtze continental crust (Qin et al., 2010a, 2013) or subducted sediments (Jiang et al., 2010; Zeng et al., 2014). In contrast, other researchers considered that felsic rocks formed by partial melting of lower crust or basalts of the SQB (Bao et al., 2015; Dong and Santosh, 2016; Gong et al., 2009a; Hu et al., 2016a; Wang et al., 2011). Granitoid rocks that were emplaced during –205–190 Ma are either highly fractionated I-type granites or may have been legitimate S-Type intrusions derived from partial melting of metasediments (Dong et al., 2012a; Lu et al., 2016; Xiao et al., 2014; Yang et al., 2012a).

Most researchers accept that the closure of Miawule ocean and collision between the NCC and SCB occurred during the Middle to Late Triassic based on the paleomagnetic data and the age of ultrahigh-pressure metamorphism in the Dabie–Sulu Orogenic Belt (AMES et al., 1996; Dong and Santosh, 2016; Dong et al., 2011; Lai et al., 2008; LI et al., 1993; MENG and ZHANG, 1999; WU and ZHENG, 2013; ZHANG et al., 2006; ZHAO and COE, 1987; ZHU et al., 1998), whereas the evolution of the QOB during Late Triassic to Early Jurassic is still unclear (Dong and Santosh, 2016; Ratschbacher et al., 2003; SUN et al., 2002; WANG et al., 2009). In contrast, N. LI et al. (2015) proposed oceanic subduction operated during the Triassic and into the Middle Jurassic. Some others argued that granitoid intrusions emplaced during 248–190 Ma in the SQB formed continuously from subduction to collisional environments (Bao et al., 2015; DENG et al., 2016; DONG and SANTOSH, 2016; JIANG et al., 2010; LIU et al., 2011a, 2011b; WANG et al., 2015; YANG et al., 2012a).

Recently, a new study proposed a slab tear tectonic model during –225–205 Ma based on regional structural and sedimentary geology, geochronology, petrochemistry and paleomagnetism (Hu et al., 2016a). Furthermore, it has been suggested that magmatism occurring during the –200–190 Ma period took place under a post-collisional setting, probably concomitant with a delamination event, because of the coeval deposition of redbeds and no deformation features in the upper crust (Dong and Santosh, 2016; DONG et al., 2012a; YANG et al., 2012a; ZHANG et al., 2008). Overall, the tectonic evolution of the QOB remains controversial and the magmatic rocks of the region provide the most continuous geologic archive available for its resolution.

In this study, we study two sizable intrusive suites (Dongjiangkou and Zhashui intrusions), which formed during the second half of the Triassic, and show common characteristics with other coeval previously studied intrusions (GONG et al., 2009a, 2009b; QIN et al., 2010a; YANG et al., 2009). We report new geological, petrological, whole-rock geochemical, and zircon U–Pb and Lu–Hf isotopic data on these intrusions, and compile previously published geochemical data of other granitoid intrusions in the SQB. We conclude that the Dongjiangkou granitoid rocks are formed by magma mixing between 10–30% melts from metamorphic lithospheric mantle and 70–90% melts from Neoproterozoic basalts, whereas the Zhashui granitoid rocks are mainly formed by partial melting of Neoproterozoic crustal materials. The systematic changes between ages and geochemical characteristics of granitoids are also observed and it can reflect geochemical and geodynamic evolution in the QOB.

2. Geological setting and sampling

2.1. The South Qinling Belt

The QOB is separated from the NCC by the Lingbao–Lushan–Wuyang fault (LLWF) in the north, and from the YZC by the Mianlue–Bashan–Xiangguang fault (MBXF) in the south (Fig. 1; Diwu et al., 2012; Dong and Santosh, 2016). There are three well-documented sutures in the area: the Kuanping suture, Shandang suture and Mianlue suture from the north to south (Dong and Santosh, 2016; Dong et al., 2014). Therefore, the QOB is subdivided into four tectonic domains: the southern margin of the NCC, North Qinling Belt (NQB), South Qinling Belt (SQB), and northern margin of the YZC, respectively (Fig. 1B; Diwu et al., 2013; Dong and Santosh, 2016; Dong et al., 2014).

The SQB, bounded by the Shandang suture zone to the north and the MBXF to the south, comprises some Precambrian basements which were unconformably overlain by Proterozoic (Sinian) carbonates, Cambrian–Ordovician limestones, Silurian shales, Devonian–Carboniferous limestones, and Permian–Triassic sandstones (Dong and Santosh, 2016; Yang et al., 2012b). These sedimentary sequences, together with the Precambrian basements, were intruded by Mesozoic granitoid intrusions (DENG et al., 2016; DONG and SANTOSH, 2016; HU et al., 2016a; YANG et al., 2012b). Early Paleozoic ophiolitic mélange and subduction-related volcanic and sedimentary rocks in the Shandang suture zone also named as Danfeng Group, represent the remnants of Proto-Tethyan oceanic crust (Dong et al., 2011; Y. LI et al., 2015). The Mianlue suture zone consists chiefly of Paleozoic to Triassic ophiolites and arc-related volcanic rocks, which marks a Triassic collision event (LAI et al., 2008; LI et al., 2007). The middle Triassic and pre-Triassic strata in the Mianlue suture underwent intense deformation, which is dominated by folds with brittle thrusting, suggesting the collision began at Late Triassic (Li et al., 2007). The ~223 Ma ductile-brittle left-lateral strike-slip shear deformation and ~227–219 Ma metamorphic ages of ophiolite mélanges indicated the collision should be occurred during 230–220 Ma (CHEN et al., 2010; LI et al., 1999). Recently, some discrete Neoproterozoic volcanic rocks were also found in the Mianlue suture zone, which are the products of another subduction process (Dong and Santosh, 2016; LIN et al., 2013). The main Precambrian basement blocks in the SQB comprise the Foping block, Douling Group, Wuguan Group, Yuolingly Group, and Wudangshan Group (SHI et al., 2013; ZHANG et al., 2001). Except for the Neoarchean TTG assemblages exposed in the Douping Group (WU et al., 2014), most other Precambrian basement blocks are composed mainly of Meso- to Neoproterozoic greenschist facies metamorphosed volcano-sedimentary rocks (Dong et al., 2011, 2012b; LING et al., 2008; SHI et al., 2013). A recent study reported a series of Neoproterozoic
basement blocks containing mafic to felsic intrusive rocks in the SQB (Hu et al., 2016b).

Early Mesozoic granitoid intrusions are widely exposed in the SQB (Fig. 1B). They include the Zhongchuan–Wenquan–Heijiazhuang–Mishuling intrusions and the Guangtoushan granitoid suite in the western segment of SQB, as well as the Huayang–Wulong and Dongjiangkou granitoid suites in the eastern SQB (Fig. 1B; e.g. Deng et al., 2016; Dong et al., 2011; Liu et al., 2011a, 2011b; Yang et al., 2012a). Triassic granitoid intrusions also outcrop in the NQB (e.g. Baoji–Taibai–Cuihuashan intrusions) and south of the Mianlue suture zone (e.g. Yangba–Da’an intrusion) (Dong and Santosh, 2016; Liu et al., 2011a). Geochronological data indicate that these granitoid intrusions were emplaced during ca. 248–190 Ma, mainly ca. 225–200 Ma (Deng et al., 2016; Dong and Santosh, 2016; Hu et al., 2016a; Liu et al., 2011a, 2011b; Qin et al., 2010a, 2013; Wang et al., 2015; Yang et al., 2011, 2012a, 2014; Zhang et al., 2011, 2012). The ~235 Ma granitoids are mainly subduction-related andesites (~246–234 Ma) and adakites (245–238 Ma) (Li et al., 2013; Qin et al., 2008; Yang et al., 2014). The 235–225 Ma granitoids show significant ductile deformation and gneissic textures (Deng et al., 2016; Qin et al., 2013), whereas the ~225 Ma granitoids display mainly massive structures, and limited to no gneissic textures especially for rocks formed ~220 Ma (Deng et al., 2016; Dong and Santosh, 2016; Hu et al., 2016a; Qin et al., 2013). Subsequently, Late Mesozoic granitoid stocks, formed during ca. 160–140 Ma distributed sporadically in the eastern SQB, which are thought to be formed by partial melting of lower basaltic crust (Yan et al., 2014).

2.2. Dongjiangkou intrusion

The Dongjiangkou intrusion, ca. 60 km south of the Xi'an city, is mainly composed of porphyritic and coarse to medium-grained tonalites, granodiorites, and monzogranites, showing weak gneissic to massive structures (Figs. 2 and 3A–C; Gong et al., 2009a; Qin et al., 2010a). The intrusion emplaced into the sandy slates of the Devonian Liuling Group in the south, with exposed area of ca. 400 km² (Fig. 2; Qin et al., 2010a). Locally, the granitoid intrusion shows EW-trending gneissic foliation, which is consistent with the NEE–SWW-trending of the long axis of the intrusion and to the regional structural trending (Figs. 2 and 3A). Abundant mafic magmatic enclaves (MME) are preserved in the Dongjiangkou intrusion. They are round or elliptical ranging from centimeter to meter in long dimension. The MME are characterized by fine-grained hypidiomorphic granular texture and massive structure (Fig. 3C). Some of the MME contain plagioclase phenocrysts and scarce K-feldspar phenocrysts, suggesting possibly phenocryst transfer from host granitoid rocks to the MME (Fig. 2; Barbarin, 2005; Pietranik and Koepeke, 2014).

We collected 21 samples from Dongjiangkou intrusion, including 6 mafic magmatic enclaves (MME), and 2 tonalities, 12 granodiorites and 1 monzogranite (Table 1). The granodiorite consists of quartz (24–27%), K-feldspar (9–11%), plagioclase (33–36%), hornblende (5–10%), biotite (4–8%), with accessory mineral association of titanite, magnetite, apatite and zircon (Fig. 3G and H). The monzogranite sample contains more quartz (29–32%) and hornblende (23–25%), biotite (6–10%) and quartz (8–14%). Tonalites show relatively less amount of quartz (21–23%) and K-feldspar (6–8%), but have more plagioclase (42–45%) and hornblende (13–15%).

The MME are mainly composed of hornblende (23–29%), biotite (18–31%), plagioclase (33–36%), K-feldspar (2–10%), and quartz (3–11%), with accessory minerals of magnetite, apatite, titanite, and zircon (Fig. 3I and J). Some apatites in the MME have an acicular shape, suggesting quenching of the mafic melt globules trapped in granitoid magma (Fig. 3J; Kocak et al., 2011).

2.3. Zhashui intrusion

The Zhashui intrusion is located to the east of the Dongjiangkou intrusion (Fig. 2), and intruded into felsic gneisses of the Qinling Group in the north and Devonian Liuling Group in the south, with an outcrop area of ca. 260 km² (Fig. 2; Gong et al., 2009b). The Zhashui intrusion consists mainly of porphyritic and coarse to medium-grained monzogranites and K-feldspar granites, with massive structures (Figs. 2 and 3D–F; Gong et al., 2009b). The Zhashui intrusion also shows the similar trending to the long axis of the Dongjiangkou intrusion (Fig. 2).
We collected 12 samples from Zhashui intrusion, including 8 monzogranites and 4 K-feldspar granite (Table 1). The monzogranite samples are composed of quartz (30–33%), K-feldspar (27–31%), plagioclase (22–27%), hornblende (4–6%), biotite (7–11%), together with titanite, magnetite, zircon and apatite as accessory minerals (Fig. 3K). The K-feldspar granite samples contain more quartz (34–36%) and K-feldspar (30–34%), but less plagioclase (12–18%) and hornblende (2–3%).

The MME are extremely rare in the Zhashui intrusion and much smaller relative to those of Dongjiangkou intrusion (Fig. 3D and F). The MME have round or elliptical shapes, and are a few centimeters to more than ten centimeters in dimension, and are characterized by fine-grained hypidiomorphic granular texture (Fig. 3D). Some of the MME contain either plagioclase or K-feldspar phenocrysts, suggesting possibly phenocryst transfer from host granitoid rocks to MME (Fig. 3F; Barbarin, 2005; Pietranik and Koepke, 2014).

3. Analytical methods

Chemical analyses of major and trace elements were conducted upon a total of thirty-three representative whole-rock samples including six MME, fifteen porphyritic and coarse to medium-grained granitoid rocks that were collected from the Dongjiangkou intrusion, and twelve porphyritic and coarse to medium-grained granitoid rocks from the Zhashui intrusion (Table 1). Among these samples, zircon U–Th–Pb and Lu–Hf isotopic analyses were performed on one MME, three porphyritic and coarse to medium-grained granitoid rocks.

3.1. Major and trace elements

Whole-rock samples were washed and trimmed in order to remove weathered surfaces. The fresh portions were then pulverized and powdered in an agate mill to about 200 mesh for major and trace elements analyses. Volatile contents (e.g., CO₂ and H₂O) were determined by measuring the weight loss after heating the samples at 1050 °C for 30 min. Major oxides were determined using an automatic X-ray fluorescence (XRF) spectrometry at the Key Laboratory of Orogenic Belts and Crustal Evolution, Ministry of Education, School of Earth and Space Sciences, Peking University. The analytical precision is at 0.5% for major element oxides, and detailed analytical procedures were given by Liu et al. (2004).

The trace elements, including rare earth elements, were analyzed at the Key Laboratory of Orogenic Belts and Crustal Evolution, Ministry of Education, School of Earth and Space Sciences, Peking University. Pre-treatment of the sample powders was performed at Peking University, with procedures described as follows (Guo et al., 2015). Firstly, powders were weighed (25 mg) into Savillex Teflon beakers loaded into high-pressure bombs, with HF and HNO₃ mixing at 1:1 added. The beaker was heated for 24 h at 80 °C, and evaporated. Then, 1.5 ml HNO₃ and 1.5 ml HF accompanied by 0.5 ml HClO₄ were added after the evaporation, and the beakers were capped for digestion within a high-temperature oven at 180 °C for 48 h or longer, until powders were completely digested. Finally, the residue was diluted with 1% HNO₃ to 50 ml for determination. Trace elements, including rare earth elements (REEs), were measured using an Agilent 7500 ICP–MS at the Key Laboratory of Orogenic Belts and Crustal Evolution, Ministry of Education, School of Earth and Space Sciences, Peking University. The international standards GSR-1 (granite), GSR-2 (andesite) and GSR-9 (granodiorite) were used for analytical control. The measurement precision of trace elements is better than 0.5‰.

3.2. Zircon U–Pb and Lu–Hf analyses

Four representative samples, including one MME sample (14QL28–1 from Dongjiangkou intrusion), one sample of granodiorite (14QL38–1 from Dongjiangkou intrusion), and two samples of monzogranites (14QL39–1 and 15QL12–1 from Zhashui intrusion), were selected for in-situ zircon U–Th–Pb and zircon Lu–Hf isotopic analyses. Zircon grains were separated from the samples using conventional heavy liquid and magnetic techniques and the grains were handpicked under a binocular microscope to ensure purity. The sample zircons, together with a zircon U–Pb isotopic standard Qinghu, were cast in an epoxy mount, and were...
then polished to approximately a half of the average zircon grain thickness. Prior to analysis, cathodoluminescence (CL) images were obtained using a FEL Quanta 200 FEG environmental scanning electron microscope (ESEM) at the Electron Microscopy Laboratory of Peking University, based on which internal structures were characterized and potential target sites for U–Pb dating and Lu–Hf analyses were determined.

U–Th–Pb elements and isotopes analyses for zircons were conducted on quadruple-based inductively coupled plasma mass spectrometry (ICP-QMS), equipped with a 193 nm laser. All four samples (14QL28–1, 14QL38–1, 14QL39–1 and 15QL12–1) at the Key Laboratory of Orogenic Belts and Crustal Evolution, Ministry of Education, Peking University. Detailed descriptions for analytic procedures were documented by Liu et al. (2012). The laser beam is of 32 μm and ablated depth is 20–40 μm. Harvard zircon 91500 was used as the external standard and NIST610 as the reference standard for zircon U–Pb geochronological and trace element (U and Th) analyses. $^{207}\text{Pb}/^{206}\text{Pb}$, $^{207}\text{Pb}/^{235}\text{U}$ and $^{206}\text{Pb}/^{238}\text{U}$ ratios were calculated using the GLITTER program (van Achterbergh et al., 2001) and common Pb was corrected using the method proposed by Anderson (2002). Age calculations and concordia plots were made using Isoplot (ver 3.0) (Ludwig, 2003). The 91500 standard zircon has been dated at 1061.9 ± 3.8 Ma (2σ, n = 26; $^{206}\text{Pb}/^{238}\text{U}$ age) in this study (the recommended $^{206}\text{Pb}/^{238}\text{U}$ age is 1065.4 ± 0.6 Ma (2σ); Wiedenbeck et al., 1995).

In-situ Lu–Hf analyses for zircons were carried out using a Neptune MC–ICPMS, equipped with a 193 nm laser. All four samples (14QL28–1, 14QL38–1, 14QL39–1 and 15QL12–1) were analyzed at the State Key Laboratory of Geological Process and Mineral Resources (GPMR),
<table>
<thead>
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<th>Intrusion</th>
<th>Sample no.</th>
<th>Latitude</th>
<th>Longitude</th>
<th>Lithology</th>
<th>Texture</th>
<th>Mineral association</th>
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<td>Dongjiangkou</td>
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<tr>
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<td>33°44′37″N</td>
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<td>MME Fine-grained</td>
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<td></td>
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<td>108°46′11″E</td>
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<td>Tonalite Coarse to medium-grained</td>
<td>Qtz (21%) + KF (6%) + PI (45%) + HB (15%) + Bi (9%) + Ttn + Ap + Zr + Mag</td>
<td></td>
</tr>
<tr>
<td>Zhashui</td>
<td></td>
<td></td>
<td></td>
<td></td>
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<tr>
<td>14QL39-1</td>
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<td>109°10′45″E</td>
<td></td>
<td>Monzogranite Coarse to medium-grained</td>
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<tr>
<td>14QL39-2</td>
<td>33°41′33″N</td>
<td>109°10′22″E</td>
<td></td>
<td>Monzogranite Porphyritic</td>
<td>Phenocryst: KF (5%) + PI (1%) + Matrix: Qtz (33%) + KF (24%) + PI (21%) + HB (40%) + Bi (10%) + Ttn + Ap + Zr + Mag</td>
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<td>K-feldspar granite Porphyritic</td>
<td>Phenocryst: KF (55%) + PI (3%) + Matrix: Qtz (35%) + KF (26%) + PI (16%) + HB (3%) + Bi (11%) + Tnn + Ap + Zr + Mag</td>
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</table>

Abbreviation: Qtz, quartz; KF, K-feldspar; PI, plagioclase; HB, hornblende; Bi, biotite; Ttn, titanite; Ap, apatite; Zr, zircon; Mag, magnetite.
China University of Geosciences, Wuhan. The instrumental conditions and data acquisition were described by Hu et al. (2012). The analyses were conducted with a spot size of 44 μm, a hit rate of 8 Hz and laser energy density of 5.3 J/cm². Harvard zircon 91500, TEM and GJ-1 were used as references during analysis, and Harvard zircon 91500 was used as the external standards for analyses. Off-line selection and integration analytic signals, as well as isobaric interference and mass fractionation correction of Lu–Hf isotopic ratios were performed by ICPMS–DataCal (Liu et al., 2010). The 176Hf/177Hf isotopic ratios of standard zircons are 0.282308 ± 5 for 91500 (1σ, n = 22; the recommended value is 0.282308 ± 3; Bliechert-Toft, 2008).

4. Results

4.1. Zircon geochronology and Lu–Hf isotopes

Four representative samples, comprising one MME sample (14QL28–1 from Dongjiangkou intrusion), one granodiorite sample (14QL38–1 from the Dongjiangkou intrusion), and two samples of monzogranites (14QL39–1 and 15QL12–1 from the Zhashui intrusion), were chosen for zircon U–Pb and Lu–Hf isotopic analyses (Figs. 4 and 5). The analytical results of the U–Pb isotopes and calculated ages are listed in Appendix Table S1, and the Lu–Hf isotopes and calculated relevant parameters are listed in Appendix Table S2. Analyses that fall below the concordia curve, which could be the results of Pb loss influenced by later thermal events, are not shown in the figures entirely but are listed in Appendix Table S1.

As shown in representative CL images (Fig. 4), zircon grains from these four samples exhibit similar morphological characteristics. They are generally round to long-prismatic shapes, with lengths between 100 and 350 μm and length/width ratios of 1:1 to 3:1 (Fig. 5). CL images of zircon grains from the MME samples show mainly chaotic textures and poorly-developed oscillatory zoning (Fig. 3A; Corfu et al., 2003). CL images of zircon grains from granodiorite rocks show clear oscillatory zoning textures (Fig. 3C, E and G; Corfu et al., 2003). These analyses of zircons from granodiorite rocks exhibit Th and U contents ranging from 72 to 2075 ppm and 69 to 2679 ppm, respectively, with Th/U ratios of 0.19–2.18 (Appendix Table S1). Zircons grains from MME sample exhibit higher Th (578–10,569 ppm) and U (737–185 ppm), but low Th contents (3.64–8.38 ppm), but high Th/U ratios of 0.39–2.34 (Appendix Table S2). Synthesis of their morphologies, inner structures and Th/U ratios, indicate their magmatic origin (Corfu et al., 2003; Rubatto, 2002).

A total of thirty zircon spots were analyzed for a granodiorite sample 14QL38–1 from Dongjiangkou intrusion (Appendix Table S1). Among these, two analyses (spot # 22 and 26) fall below the concordia curve, indicating probably Pb loss. Four analyses yield older apparent 206Pb/238U ages of 697 ± 14 Ma, 453 ± 9 Ma, 349 ± 7 Ma, and 232 ± 5 Ma (Fig. 4B). The remaining twenty-four analyses yield a weighted mean 206Pb/238U age of 232 ± 1 Ma (MSWD = 0.32) (Fig. 4F), which is taken as the magmatic crystallization age of this sample. This weighted mean 206Pb/238U age of 232 ± 1 Ma exhibit εHf(t) values of −0.6 to +1.7, and TDM2(Hf) values of 979–1300 Ma (Appendix Table S2; Fig. 5).

A total of thirty zircon spots were analyzed for a monzogranite sample 15QL12–1 from Zhashui intrusion, and seven analyses fall below the concordia curve, implying possible Pb loss (Appendix Table S1; Fig. 4H). Four analyses yield apparent 206Pb/238U ages of 932 ± 15 Ma, 231 ± 4 Ma, 224 ± 4 Ma, and 191 ± 3 Ma, respectively, and these analyses yield a weighted mean 206Pb/238U age of 216 ± 2 Ma (MSWD = 0.19) (Fig. 4H). The remaining thirteen analyses yield a weighted mean 206Pb/238U age of 201 ± 1 Ma (MSWD = 0.48) (Fig. 4H), which is taken as the crystallization age of this sample. This weighted mean 206Pb/238U age of 201 ± 1 Ma exhibit εHf(t) values of +12.5, with TDM2(Hf) values of 978 Ma, and five analyses with ages of 231 Ma and 216 Ma have the εHf(t) values of +0.8 to +1.7, with TDM2(Hf) values of 1024–1074 Ma. Nine Lu–Hf isotopic analyses are corrected to their magmatic crystallization age of 201 Ma, and give the εHf(t) values of +0.3 to +2.3, with TDM2(Hf) values of 981–1091 Ma (Appendix Table S2; Fig. 5).

4.2. Whole-rock geochemistry

4.2.1. Dongjiangkou intrusion

The major and trace element data of fifteen host granitoid rock samples and six MME samples from the Dongjiangkou intrusion are shown in Appendix Table S3. The host granitoid rocks have intermediate SiO2 (64.0–69.4 wt.%), and mainly plot in the quartz monzonite, tonalite and granodiorite fields and in the sub-alkaline field in the SiO2 vs. Na2O + K2O diagram (Fig. 6A). The three samples vs. K2O diagram, they plot in the high-K calc-alkaline rock series (Fig. 6B). These samples display high MgO (2.19–3.69 wt.%), Mg# (58–64) and Sr/Y (38.48–78.94 ppm) values, with metaluminous to weakly peraluminous features (A/CNK = 0.87–1.05). (Appendix Table S3; Fig. 6). As shown in Fig. 6, they define a negative correlation between SiO2 and MgO, CaO, P2O5, TiO2 and Sc contents, but positive correlations between SiO2 and K2O, Rb and Th concentrations. They are characterized by steep chondrite-normalized REE patterns with high (La/Yb)N, (La/Sm)N, and (Gd/Yb)N ratios of 12.43, 1.05, 5.86, and 2.38 (Appendix Table S3). In the primitive mantle-normalized multi-element patterns (Fig. 7B), all of these samples show obviously negative Nb–Ta anomalies, and moderately negative Ti anomalies.

The MME samples have lower SiO2 contents of 55.5 to 61.7 wt.% and higher K2O contents of 3.45 to 4.89 wt.% relative to host granitoid rocks, falling in the monzonites field in the SiO2 vs. Na2O + K2O classification diagram (Fig. 6A), belonging to high-K calc-alkaline to shoshonite series in the SiO2 vs. K2O diagram (Fig. 6B). These MME samples also show high concentrations of MgO (4.90–7.36 wt.%), CaO (4.45–6.75 wt.%), P2O5 (0.22–0.38 wt.%), TiO2 (0.62–0.81 wt.%), Sc (13.3–22 ppm), and Rb (122–185 ppm), but low Th contents (3.64–14.44 ppm) and Sr/Y (18.89–50.11) ratios (Appendix Table S3; Fig. 6). In the chondrite-normalized REE diagrams (Fig. 7A), these samples are enriched in LREEs and depleted in HREEs, which are similar to those of the granitoid rocks, with mainly negative Eu anomalies ((La/Yb)N = 4.91–21.05, (La/Sm)N = 1.76–5.28, (Gd/Yb)N = 1.89–2.73, δEu = 0.75–0.93). In the primitive mantle-normalized multi-element patterns (Fig. 7B), all
MME samples show enrichment in large ion lithospheric elements (LILEs, such as Ba and Rb) and are characterized by negative Nb-Ta anomalies and slightly negative Ti anomalies without P anomalies, which are similar to the trace element distribution patterns of host granitoid rocks.

4.2.2. Zhashui intrusion

The granitoid rocks from Zhashui intrusion exhibit higher SiO2 contents than the other intrusion (68.38 to 72.2 wt.%), and plot into granodiorite and granite field in the TAS classification diagram, mostly belonging to high-K calc-alkaline rock series (Fig. 6A and B). They exhibit relatively high A/CNK ratios of 0.97 to 1.10, most of them belonging to peraluminous. These samples also display low MgO (0.51–1.42 wt.%), CaO (1.65–2.61 wt.%), P2O5 (0.07–0.16 wt.%), TiO2 (0.25–0.46 wt.%), Sc (3.88–5.55 ppm) concentration and Sr/Y (18.89–40.64) ratios, but high K2O (3.40–5.60 wt.%), Rb (102–182 ppm) and Th (11.6–27) contents, with wide range of Mg# (34–55) values. In the chondrite-normalized REE diagrams (Fig. 7E), these samples are characterized by steep REE patterns with weakly negative to positive Eu anomalies (\(\text{La/Yb}_N = 14.45–24.45\), \(\text{La/Sm}_N = 4.47–7.57\), \(\text{Gd/Yb}_N = 1.83–2.42\), \(\delta\text{Eu} = 0.62–1.11\)). In the primitive mantle-normalized multi-element patterns, these samples show negative Nb-Ta anomalies, and prominently negative P and Ti anomalies, and enrichment of Ba, Rb, Th, and K (Fig. 7F).

5. Discussion

5.1. Ages of the Dongjiangkou and Zhashui intrusions

The granitoid rocks of the Dongjiangkou intrusion preserve inherited zircons with ages of ~697 Ma, ~453 Ma, ~349 Ma, and ~232 (Fig. 4B), and the granitoid rocks of Zhashui intrusion contain inherited zircons with ages of ~932 Ma, ~231 Ma, ~224 Ma, and ~216 Ma (Fig. 4F and H), whereas the MME sample from Dongjiangkou intrusion also preserves some inherited zircons with the age of ~235 Ma (Fig. 6B and E). The ~932 Ma and ~697 Ma ages from the inherited populations may be connected to the emplacement ages of the Neoproterozoic magmatism in the SQB (e.g. Hu et al., 2016b). The zircon ages of ~453 Ma and ~349 Ma may be captured from Paleozoic crustal materials during magma transfer and emplacement (Deng et al., 2016; Qin et al., 2010a). The ~232–231 Ma ages of the inherited zircons are consistent with the emplacement ages of the Triassic Carnian magmatism in the SQB (Jiang et al., 2010; Qin et al., 2013). The inherited zircon ages of ~224 Ma and ~216 Ma from Zhashui intrusion are consistent with widespread Triassic Norian magmatism in the SQB (N. Li et al., 2015; Wang et al., 2015). Therefore, these older zircons are considered to be inherited from either the source regions or captured from the wall-rocks of the intrusions and ascending channels of the magmas.

The magmatic zircons from the Dongjiangkou granitoid rocks and MME show similar ages of 217 ± 1 and 218 ± 1 Ma. Previous studies...
obtained the zircon $^{238}$U/$^{206}$Pb ages of 223 Ma, 222 Ma, 220 Ma, 214 Ma, 211 Ma and 209 Ma for these granitoid rocks, and zircon $^{238}$U/$^{206}$Pb ages of 222 Ma and 219 Ma for the MME from Dongjiangkou intrusion, which are basically consistent with our new zircon U–Pb chronological data (Gong et al., 2009b; Jiang et al., 2010; Liu et al., 2011a). Whereas the biotite 40Ar/39Ar age of 198 Ma was also obtained by previous study, which may be related to the later thermal event (Zhang et al., 2006). Therefore, we suggest the Dongjiangkou granitoid rocks were mainly emplaced during 223–214 Ma, which were approximately coeval with mafic magmas (MME). Our new zircon U–Pb chronological data reveal that the Zhashui intrusion mainly emplaced at ~200 Ma. Previous studies obtained a biotite 40Ar/39Ar age of 197 Ma and the zircon $^{238}$U/$^{206}$Pb ages of 225 Ma, 213 Ma, 203 Ma, and 199 Ma from the granitoid rocks in the Zhashui intrusion, which were similar to our data except for the ages of 225 Ma and 213 Ma that may stand for early magmatisms (Gong et al., 2009b; Hu et al., 2016a; Jiang et al., 2012; Laumonier et al., 2015; Vernon, 1984). Therefore, we suggest the Zhashui granitoid rocks were mainly emplaced during 203–197 Ma.

5.2. Petrogenesis

5.2.1. MME

Mafic enclaves are present in virtually all intermediate volcanic rocks and granitoid batholiths formed in classic Andean subduction systems such as those along the western margins of the Americas (Ducea et al., 2015). They usually represent a signature feature of subduction related magmas in the Phanerozoic and late Proterozoic. The petrogenesis of the MME in the granitoid rocks has long been debated, and three models were proposed as: (1) cogenetic cumulates or early segregation (autolith) from the host magma (Chen et al., 2016; Dahlquist, 2002; Donaire et al., 2005); (2) residual material from the partial melting of the source rocks (restite) (Chappell et al., 1987, 2000); and (3) products of magma mingling, i.e. globules of mafic magma that were injected into a felsic magma chamber (Barbarin, 2005; Hu et al., 2016a; Jiang et al., 2012; Laumonier et al., 2015; Vernon, 1984). The magma mingling model is widely accepted as the origin of enclaves in North America Cordilleran geology (Ducea et al., 2015).
The MME studied here contain acicular shape apatites and K-feldspar phenocrysts, suggesting that the MME were formed by mixing between mafic magma and felsic magma (Fig. 3). Moreover, their magmatic textures further indicate that they were formed by magma mixing but not cumulates or restites (Fig. 3). Their relative wide range of zircon $\varepsilon_{\text{Hf}}(t)$ values ($-17.7$ to $+13.3$) also indicate magma mixing/mingling process (Fig. 5). Some elements (e.g., K$_2$O and Rb) of the MME from the Dongjiangkou intrusion displaying nonlinear trends with host granitoid rocks also argue against a cumulate or restite origin (Fig. 6; Chen et al., 2016). Therefore, we suggest that the MME represent injected magmatic globules of a mantle-derived magma into the felsic host magma.

The MME from the Dongjiangkou show mainly low SiO$_2$ (55.48–61.74 wt.%) and Th (3.64–14.4 wt.%) contents, but high MgO (4.90–7.36 wt.%), TiO$_2$ (0.62–0.81 wt.%), Sc (13.3–22 ppm) contents, and Mg# values (62.18–69.27), indicating they are derived from a mantle source (Figs. 6 and 8; Chen et al., 2009). However, because of the magma mixing process, the geochemical characteristics of the MME are inevitably modified by felsic magmas (Blundy and Sparks, 1992). Compared with published MME data of Dongjiangkou intrusion and adjacent Caoping and Shahewan intrusions, our MME samples from the Dongjiangkou intrusion show basically the same geochemical characteristics but have slightly higher SiO$_2$ relative to the most mafic MME sample (Figs. 6 and 7). Additionally, MME show mainly lower Sr/Y ratios (average 37.43) relative to the host granitoid rocks (average 53.51), although few samples with higher SiO$_2$ display higher Sr/Y ratios (e.g., ZS03–04), reflecting the MME are not altered by magma mixing significantly (Appendix Table S3; Fig. 8B and C). In spite of some samples are affected by magma mixing process, the MME samples display relatively uniform geochemical features with low SiO$_2$, Th and Sr/Y but high MgO, K$_2$O, Sc, and Rb contents, and distinct evolution trend relative to host granitoid rocks (e.g., Rb vs. SiO$_2$), indicating these geochemical features of the MME are not modified and could be used to trace their source. Zircons are early crystallization phase during magmatism and could retain their original geochemical information (Hoskin and Ireland, 2000). The zircons from the MME in this study exhibit higher $\varepsilon_{\text{Hf}}(t)$ values ($-0.8$ to $+4.3$) than the host granitoid rocks ($-18.1$ to $-0.4$) and their relative consistent $\varepsilon_{\text{Hf}}(t)$ values further indicate these MME are not significantly altered by magma mixing (Fig. 5). Previous studies obtained wide range of zircon $\varepsilon_{\text{Hf}}(t)$ values ($-17.7$ to $+13.3$) suggesting part of their samples are altered by mixing and it is obvious that the majority of zircons from the MME show chondritic-like $\varepsilon_{\text{Hf}}(t)$ values (Fig. 5). Therefore, we suggest that our samples are not significantly altered by magma mixing processes and their geochemical features could be used to trace their source.

The somewhat surprisingly higher K$_2$O and Rb concentrations of the MME than those of their host granitoid rocks indicate that these MME are not greatly affected by felsic magma, but come from a distinct mantle source. Similarly, the MME in the adjacent intrusions also show higher K$_2$O and Rb contents, e.g., MME in the Caoping and Shahewan intrusions (Hu et al., 2016a; Jiang et al., 2012; Qin et al., 2010a), and Wang et al. (2011). Therefore, such distinct feature may not be from their alterations.
during the magmatic mixing but are likely to be inherited from their source. The MME show high Rb/Sr ratios (0.12–0.30) and low Ba/Rb ratios (5.29–12.89) that conform to melts in equilibrium with phlogopite, which are expected to exhibit high K2O, Rb/Sr (>0.1) and low Ba/Rb (<20) features (Furman and Graham, 1999). Although the MME have wide range of εHf(t) values suggesting magma mixing or crustal contamination, most MME show relatively concentrated range with near-chondritic εHf(t) values and their Neoproterozoic TDM(Hf) ages imply that they were mainly formed from a metasomatized continental lithospheric mantle (Fig. 5; Hu et al., 2016a). The MME also display similar Sr–Nd isotopic compositions to the lamprophyres and mafic dikes from the QOB, which were thought to be formed by partial melting of a metasomatized mantle source (Qin et al., 2010a; Wang et al., 2011). Therefore, we suggest that the MME are formed by partial melting of phlogopite-bearing metasomatized continental lithospheric mantle and contaminated by or mixed with felsic melts or crustal material subsequently.

5.2.2. Granitoid rocks of the Dongjiangkou intrusion

The granitoid rocks from the Dongjiangkou intrusion display medium to high SiO2, and high K2O, MgO, Rb, and Th contents, and low TiO2, P2O5, Sc contents, and A/CNK values (Appendix Table S3; Fig. 6). These granitoid rocks are typical I-type granites (Chappell et al., 1987, 2000; Figs. 3H and 6F). The abundance of the MME in the Dongjiangkou intrusion suggest mantle-derived melts are involved during the formation of the granitoid rocks. They show higher MgO and Mg# values than the experimental melts that are derived from the partial melting of pure crustal materials or basalts and amphibolites, and the granitoid rocks plot along the trajectory of magma mixing process in the Th/La versus Th, Th versus Th/Sc, and 1/Sc versus Th/Sc diagrams, all of these indicate the these granitoid rocks were formed by a magma mixing between mafic and felsic melts (Figs. 6C, 8A and 9A–C; Martin et al., 2005; Rapp and Watson, 1995; Schiano et al., 2010). The granitoid rocks show similar evolutionary trends to the fractional crystallization of plagioclase in Sr/Y versus Y and (La/Yb)N versus YbN diagrams, suggesting they may underwent plagioclase fractionation after the initial granitoid magma was formed (Fig. 8B–C; Castillo, 2012). However, these granitoid rocks don’t show positive correlation between Eu/Eu* and Sr indicating the fractional crystallization of plagioclase is not a major process in their petrogenesis (Fig. 8D).

Previous studies focused in the petrogenesis of the Dongjiangkou granitoid rocks and proposed four models (1) interaction between subducted Yangtze continental crust and the overlying mantle wedge (Qin et al., 2010a); (2) partial melting of subducted sediments with subsequent melts interacting with the overlying mantle wedge (Jiang et al., 2010); (3) the magma mixing between depleted mantle melts and
crustal melts that were derived from partial melting of Meso- to Neoproterozoic lower crust materials (Gong et al., 2009a); and (4) the magma mixing between metasomatized mantle melts and Proterozoic mafic lower crust melts (Bao et al., 2015; Zeng et al., 2014). Because the MME represent products of mantle-sourced melts and inject into the felsic magma chamber, contrasting to the situation of felsic melts that are derived from subducted continental crust and interacted with overlying mantle wedge. Additionally, the subducted sediments usually show high radiogenic Sr composition (generally $^{87}\text{Sr}/^{86}\text{Sr} > 0.71000$; GLOSS: $^{87}\text{Sr}/^{86}\text{Sr} = 0.71730$; Plank and Langmuir, 1998), which are quite different with Dongjiangkou granitoid rocks according to previous studies ($^{87}\text{Sr}/^{86}\text{Sr} = 0.70411–0.70672$; Jiang et al., 2010; Liu et al., 2011b; Qin et al., 2010a; Zhang et al., 2006). Taking into consideration their mainly metaluminous compositions and absence of coeval subduction-related adakites and related volcanic rocks, subducted sediments are unlikely the source of the felsic melts (Hermann and Spandler, 2008; Stern et al., 2006).

Previous studies have found out the presence of the Proterozoic inherited zircons and these inherited zircons show a wide $\varepsilon_{\text{Hf}}(t)$ range from $-24.1$ to $+12.5$ (Fig. 5; Gong et al., 2009a; Jiang et al., 2010; Ping et al., 2013; Qin et al., 2010a). As shown in the Fig. 5, the inherited zircons with negative $\varepsilon_{\text{Hf}}(t)$ values plot into the evolutionary region of the old basements of the SQB, which is defined by the Douling Neoarchean TTG gneisses and detrital zircons from the Wudangshan and Yaolinghe Groups in the SQB. On the other hand, the inherited zircons with positive $\varepsilon_{\text{Hf}}(t)$ values plot into the evolutionary region of the Neoproterozoic basement blocks of the SQB, defined by the newly found Neoproterozoic rocks and detrital zircons from the Wudangshan and Yaolinghe Groups (Fig. 5). In this case, the magmatic sources of the Dongjiangkou granitoid rocks may be heterogeneous in isotopic compositions. However, the involvement of the old basement is limited because only few zircons exhibit $\varepsilon_{\text{Hf}}(t)$ values that are lower than $-15$. Thus, the Neoproterozoic basement blocks of the SQB is the major magmatic sources of the Dongjiangkou granitoid rocks.

To further understand magmatic sources of the granitoid rocks, we use Neoproterozoic hornblende gabbro samples as the source rock to model partial melting process and obtain the partial melts (Appendix Table S4; Fig. 10). The residual mineral assemblages and the melting degrees are employed from the experimental results of Qian and Hermann (2013). As shown in the Fig. 10A and B, the trace element patterns of all the modelling melts are extremely similar to those of Dongjiangkou granitoid rocks. Moreover, according to our modeling results, the compositions of the source rocks are the primary control factor for the granitoid melts, which is consistent with previous study (Fiannacca et al., 2015). For instance, the Th is an easily mobile element, especially for those Precambrian rocks, hence the model results of Th display large uncertainty due to the different compositions of the source rocks. We further calculate the mixing results of these pure partial melts

Fig. 9. Petrogenetic discrimination diagrams for porphyritic to coarse to medium-grained granitoid rocks from the Dongjiangkou and Zhashui intrusions. (A) Th/La versus Th diagram for Dongjiangkou and Zhashui granitoid rocks. (B) Th versus Th/Sc diagram for Dongjiangkou granitoid rocks. (C) 1/Sc versus Rb/Sc diagram Dongjiangkou granitoid rocks. (D) Th versus Th/Sc diagram Zhashui granitoid rocks. The inset in A is a schematic C$^\ast$/C$^\ast$ versus C$^\ast$/C$^\ast$ diagram (C$^\ast$, highly incompatible element concentration; C$^\ast$, moderately incompatible element concentration). The inset in B is a schematic C$^\ast$/C$^\ast$ versus C$^\ast$/C$^\ast$ diagram (C$^\ast$, incompatible element concentration; C$^\ast$, compatible element concentration). The inset in C is a schematic C$^\ast$/C$^\ast$ versus C$^\ast$/C$^\ast$ diagram. The curves are calculated melt compositions produced by partial melting, magma mixing, and fractional crystallization processes (after Schiano et al., 2010). Legends as for Fig. 6.
Fig. 10. Trace element modeling for the petrogenesis of Dongjiangkou granitoid rocks. (A) The calculated melts with degrees of melting from 10% to 40% as source rocks is 08LY2-14. (B) The calculated melts with degrees of melting from 10% to 40% as source rocks is 08LY2-9. (C) Mixing of 10% MME with 90% calculated melts as source rock is 08LY2-14. (D) Mixing of 30% MME with 70% calculated melts as source rock is 08LY2-14. Detailed parameters and calculations of models see Appendix Table S4. The MME is the lowest SiO2 MME sample published by Jiang et al. (2012).

Fig. 11. Petrogenetic discrimination diagrams for porphyritic to coarse to medium-grained granitoid rocks from the Zhashui intrusion. (A) Molar Al2O3/(MgO + FeOT) (AFM) versus CaO/(MgO + FeOT) (CMF) diagram showing the source composition for the granitoid rocks from the Zhashui intrusion, modified after Altherr et al. (2000). (B) CaO/(FeOT + MgO + TiO2) versus CaO + FeOT + MgO + TiO2 diagram, modified after Patiño Douce (1999). (C) CaO/Na2O versus Al2O3/TiO2 diagram, after Sylvester (1998). (D) Rb/Ba versus Rb/Sr diagram, after Sylvester (1998). Legends as for Fig. 6.
with a MME sample with SiO$_2$ of 50.02 wt.% reported by Jiang et al. (2012) (Fig. 10C and D). The results show that 10 to 30% MME melts may mix with the felsic melts and the mixed melts also display similar trace element patterns to those of Dongjiangkou granitoid rocks. Additionally, the mixing of 10 to 30% MME melts also enable to acquire the similar Mg# of the Dongjiangkou granitoid rocks (Fig. 8A). Therefore, we suggest that the Dongjiangkou granitoid rocks were formed by magma mixing of mainly two sources: 70–90% melts derived from the Neoproterozoic basement rocks of the SQB and 10–30% mantle-derived mafic melts, with minor involvement of older basement materials (as old as Archean) of the SQB.

5.2.3. Granitoid rocks of the Zhashui intrusion

The granitoid rocks of the Zhashui intrusion, showing quite different geochemical characteristics from the granitoid rocks of the Dongjiangkou intrusion, have higher SiO$_2$, K$_2$O, Rb contents, and A/CNK values, but lower MgO, TiO$_2$, P$_2$O$_5$, Sc contents, Mg# and Sr/Y values (Appendix Table S3; Fig. 6). These granitoid rocks are also I-type granites (Figs. 3K and 6F; Chappell et al., 1987). Nevertheless, the rare MME in the Zhashui intrusion and all samples plot within the region of the experimental melts that derived from the partial melting of pure crustal materials or basalts and amphibolites in the MgO versus SiO$_2$ diagram, suggesting the involvement of mantle-derived melts are insignificant (Fig. 6C; Martin et al., 2005; Rapp and Watson, 1995). According to our modeling calculation, less than 10% MME melts may be involved into the crustal melts (Fig. 8A). The geochemical modeling also reveals that the granitoid rocks array along the trend line of partial melting in the Th/Sc versus Th and Th versus Th/Sc diagrams, indicating the these granitoid rocks were formed by a partial melting process (Fig. 9A and D; Schiano et al., 2010). The granitoid rocks show similar evolution trends to the fractional crystallization in Sr/Y versus Y and (La/Yb)$_N$ versus Yb$_N$ diagrams, indicating they might undergo plagioclase fractionation (Fig. 8B–C; Castillo, 2012). Some samples also show negative Eu anomalies in the chondrite-normalized REE diagrams but no clear positive correlation between Eu/Eu* and Sr, reflecting that the negative Eu anomalies are due to formed by partial melting process with plagioclase as one of the residue minerals (Figs. 7E and 8D).

Previous researchers studied the petrogenesis of the Zhashui granitoid rocks and they proposed that the Zhashui granitoid rocks were formed by mixing between crustal-derived melts and mantle-derived melts (Gong et al., 2009b; Liu et al., 2013). Gong et al. (2009b) also suggest that the felsic end member might be derived from Neoproterozoic or older mafic lower crustal material. However, we propose here that magma mixing is not a major petrogenetic process, and chemical diversity of these granitoid rocks is mainly due to partial melting process of a heterogeneous source. On the basis of the zircon $\varepsilon_{Hf}(t)$ values that plot within the range of Neoproterozoic basalts of the SQB, we suggest that the Neoproterozoic basement blocks of the SQB may be their main source (Fig. 5). Also, the Neoproterozoic inherited zircons from the Zhashui intrusion also exhibit similar $\varepsilon_{Hf}(t)$ values to those of the zircons from the Neoproterozoic rocks, which further supports that the granitic magma may be derived from partial melting of the Neoproterozoic crustal materials (Fig. 5). Additionally, the zircon $\varepsilon_{Hf}(t)$ values of the Zhashui granitoid rocks display less variations than those of the Dongjiangkou granitoid rocks, suggesting their source rocks are relative homogeneous in isotopic compositions, which are mainly Neoproterozoic basalts (Fig. 5).

The Zhashui granitoid rocks plot within the field of partial melting of metamorphic greywackes in the AMF (Al$_2$O$_3$/MgO + FeOT) versus CMF (CaO/(MgO + FeOT)) diagram, indicating that metamorphic greywackes may be the major source materials of these granitoid rocks.

Fig. 12. Plotting of compiled data of granitoid rocks from the middle SQB. (A) MgO versus SiO$_2$ diagram of unfiltered data showing differentiation trend. (B) Sr/Y versus SiO$_2$ diagram of unfiltered data reflecting variations of Sr/Y. (C) Rb/Sr versus SiO$_2$ diagram of unfiltered data reflecting the influence of fractional crystallization on Rb/Sr. The grey area shows the limits to data filters used for Sr/Y analysis in this study. (D) Sr/Y versus SiO$_2$ diagram of filtered data. The triangles represent the experimental results of partial melting of basaltic rocks at different pressures, after Qian and Hermann (2013).
rocks (Fig. 11A; Altherr et al., 2000). Similarly, these granitoid rocks plot within the range of the partial melting of metamorphic greywackes and amphibolites in the CaO/(FeOT + MgO + TiO2) versus CaO + FeOT + MgO + TiO2 diagram (Fig. 11B; Patiño Douce, 1999). These rocks also plot within the field of strongly peraluminous granites in the CaO/Na2O versus Al2O3/TiO2 diagram, and show similar Rb/Ba and Rb/Sr ratios to the greywackes (Fig. 11C and D; Sylvester, 1998). Nevertheless, these rocks do not belong to strongly peraluminous granites, because of their relatively low A/CNK value (<1.1) and the absence of primary highly-aluminous minerals (e.g. muscovite, cordierite, garnet) (Sylvester, 1998). On the other hand, Zhashui granites show I-type trend in P2O5 versus SiO2 diagram (Fig. 6F; Wu et al., 2003). Metamorphic greywackes also has been proposed for a potential source of I-type granite on the basis of experimental and regional studies (Altherr et al., 2000; Kemp et al., 2007; Patiño Douce, 1999). However, it should be noted that these samples also exhibit similar signatures of melts derived from partial melting of basaltic rocks, e.g. low AMF values and high (CaO + FeOT + MgO + TiO2) values, which may be influenced by MME melts as evidenced by their elevated Mg# values. In view of their zircon Hf isotopic feature, the metamorphic greywackes may be mainly Neoproterozoic volcanic rocks (Figs. 5 and 7F). Therefore, in consideration of geochemical characteristics, we suggest that granitoid magmas of the Zhashui granitoid rocks may be mainly derived from partial melting of Neoproterozoic metamorphic greywackes with some additions of mantle-derived mafic melts.

5.3. Geochemical evolution in the SQB

To investigate the geochemical evolution in the SQB, we compiled the geochemical and chronological data of ca. 230–190 Ma granitoid rocks and associated MME in the SQB (Appendix Tables S5–S7; Figs. 12–14). The SiO2 content could somewhat reflect the extent of the involvement of crustal melts and mantle-derived melts, and could further indicate the melting temperature of the crust because less mantle-derived melts will lead to lower partial melting temperature. The Sr/Y ratio could reflect the depth of partial melting because of the different geochemical character of Sr and Y as many studies have proved (Chapman et al., 2015; Drummond and Defant, 1990; Lee and Morton, 2015; Lu et al., 2015).

According to our compilation, all granitoid rocks show differentiation trends in MgO–SiO2 diagram (Fig. 12A). However, the Sr will decline in highly fractionated magmas, which may cause the decrease of Sr/Y ratios (Fig. 12B; Lee and Morton, 2015). We used elevated Rb/Sr ratio as an indicator of highly fractionated magmas because Rb will increase in highly fractionated magmas (Fig. 12; Lee and Morton, 2015). The samples with Rb/Sr ratios higher than 0.3 were discarded. Additionally, to obtain more reliable results, we further filtered the data by SiO2 (58–71 wt.%), but we did not filter MME samples due to their low SiO2 (Appendix Tables S6–S7).

Based on our compilation, the most conspicuous feature is that a distinct magmatic flare-up event was happened during ca. 225–205 Ma and abundant MME were associated with coeval granitoid rocks that some of them show very high Sr/Y ratios (>100) with variable SiO2 (Fig. 13). According to the experimental studies of partial melting, the pressure would be higher than 1.35 GPa to obtain the melts with such high Sr/Y (Fig. 12D; Qan and Hermann, 2013; Rapp et al., 1999). As for the granitoid rocks formed during ca. 235–225 Ma, they are accompanied with some MME but rare in outcrop, and show mainly lower SiO2 and Sr/Y than those of ca. 225–205 Ma granitoid rocks (Deng et al., 2016; Qin et al., 2013). The granitoid rocks after ca. 205 Ma that are associated with no or rare MME, show consistent high SiO2 content with low Sr/Y ratios. Roughly, such variations reflect that the 225 to 205 Ma granites may be formed at the time that crust reached to the thickest level along with a great quantity of mantle-derived melts. The crust may not become thinner after 205 Ma although no high Sr/Y granitoid rocks are formed. We suggest that partial melting of crustal materials at shallow level after ca. 205 Ma due to lack of heat from mantle-derived melts.

There are also some variations in the same period. The Sr/Y ratios of samples with Rb/Sr < 0.3 exhibit positive correlations with their SiO2 contents during 225–205 Ma (Fig. 14). We consider that those high Sr/Y granitoid rocks are relatively pure crustal melts that are formed at a deeper crustal level and the low Sr/Y of some granitoid rocks are results of the mixing with low Sr/Y MME (Figs. 13 and 14). By combining with previous studies, we consider those high SiO2 and Rb/Sr (>0.3) but low Sr/Y rocks were derived from partial melting of metasedimentary rocks at relatively shallow crustal level or highly fractionated magmas (Dong et al., 2012a; Meng et al., 2013; Yang et al., 2012a).

5.4. Implications for geodynamic evolution

A consensus has been achieved that the QOB was developed as a result of consumption of an ocean and ultimate collision between the SCB and NCC during Triassic era (Dong and Santosh, 2016). Paleomagnetic and sedimentary studies suggest that the initial collision between the NCC and YZC occurred at the location of the Dabie Orogenic Belt in the Early Triassic or Late Permian and a clockwise rotation of the SCB to the northwest was followed (Zhao and Coe, 1987; Zhu et al., 1998). During the entire collision process, extensive magmatism was produced in the SQB from ca. 248 Ma to 190 Ma, and mostly between ~225–205 Ma (N. Li et al., 2015, and the references therein).
Prior to ca. 235 Ma magmatism in the SQB was formed in a subduction-related setting (Li et al., 2013; Liu et al., 2011a, 2011b; Qin et al., 2008; Yang et al., 2014). Flysch deposition lasted until the Carnian and nonmarine molasses deposition (post-tectonic) started in the Norian in the foreland basin (Liu et al., 2005). Ca. 235–225 Ma granitoid rocks were only exposed in the middle and western SQB (Wulong and Guangtoushan intrusions), perhaps suggesting a transitional period from subduction to the later collisional magmatic flare-up event (Deng et al., 2016; Hu et al., 2016a; Qin et al., 2013). The ~224 Ma outer zone of Guangtoushan granitoid complex was emplaced into the Mianlune suture zone, which could be regarded as stitching intrusion (Deng et al., 2016). Whereas ~230 Ma Xinyuan, Zhangjiaba granitoid intrusions and outer zone of Wulong granitoid intrusion all situated in the north of the Mianlune suture zone (Deng et al., 2016; Qin et al., 2013). Therefore, combined with regional geology (see geological setting), the collision in the western SQB should have started before ~225 Ma. Based on the Sr/Y (median value <70) of granitoid in this period, the crust was still not greatly thickened. The 235–225 Ma granitoid rocks are mainly the crustal materials, primarily metasedimentary rocks, in a relatively low pressure setting (Dong et al., 2012a). Cooling rates of granitoid rocks in the SQB decreased significantly after ca. 200 Ma, suggesting a tardiness uplift event was followed afterwards (Wang et al., 2007, 2014). Therefore, we proposed that the slab break-off was finished in this period resulting in lacking heat and limited melts derived from the continental lithospheric mantle. Because of the low melting point, partial melting of the metasedimentary rocks where situated at higher crustal level is plausible, which leads to high SiO2 melts with low Sr/Y. Some researchers proposed that the delamination of thickened lower crust is responsible for the formation of granitoid rocks in this period (Deng et al., 2016; Dong et al., 2012a; Yang et al., 2012a). However, no massive high-Mg adakitic rocks are exposed in the SQB during ca. 205–190 Ma, which are quite common production of intensive delamination of thickened lower crust in the southern Tibet and eastern NCC (Chung et al., 2009; Gao et al., 2004). Therefore, intensive delamination is not appropriate for explaining the fact of observation and geochemical evidence, but regional small-scale

![Sr/Y versus SiO2 showing geochemical variations of granitoid rocks and MME in the SQB. The MME display low SiO2 contents with low Sr/Y values. The granitoid rocks with Rb/Sr higher than 0.3 show high SiO2 contents with low Sr/Y ratios, suggesting they are high fractionated magmas or formed by partial melting of metasedimentary rocks at shallower depth. The granitoid rocks with Rb/Sr lower than 0.3 display positive correlation between SiO2 and Sr/Y, and more MME are formed from 235 to 225 Ma to 225–205 Ma, suggesting the increase of the partial melting depth and increase of involvement of mantle-derived magmas. The ca. 205–190 Ma granitoid rocks with Rb/Sr lower than 0.3 show high SiO2 contents and low Sr/Y ratios with no coeval MME, indicating the decrease of partial melting depth and less involvement of mantle-derived magmas. Compiled and plotted data are included in Appendix Table S7.](image)
detachment is completed in the SQB during ca. 205–190 Ma and no in-
tensive delamination of lower crust is occurred.

6. Conclusion

(1) The Dongjiangkou intrusion is composed of ca. 223–214 Ma quartz diorites, tonalites and granodiorites with abundant ca. 222–219 Ma coeval MME. The Zhashui intrusion consists of ca. 203–197 Ma monzogranites and K-feldspar granites with minor MME.

(2) The MME in the SQB are produced by partial melting of plagioclase-bearing metasomatized continental lithospheric mantle.

(3) The Dongjiangkou granitoid rocks are formed by magma mixing between 70–90% melts derived from the Neoproterozoic basement rocks of the SQB and 10–30% mantle-derived mafic melts with less Archean to Paleoproterozoic old basement mate-
rials of the SQB. The Zhashui granitoid rocks were produced by partial melting of the Neoproterozoic metamorphic greywackes with minor assimilation of mantle-derived melts.

(4) A temporal evolution of granitoid rocks is observed in the SQB during ca. 235–190 Ma period. The SiO2 and Sr/Y of granitoid rocks show a change with their formation ages, reflecting the temperature and partial melting depth of the crust may increase from 235–225 Ma to 225–205 Ma and decrease significantly after ca. 205 Ma. The granitoid rocks showing low SiO2 contents and Sr/Y ratios are result from mixing with low Sr/Y MME, however, the granitoid rocks having high SiO2 contents and low Sr/Y ratios are derived from either partial melting of metasedimentary rocks at a shallower crustal level or highly fractionated magmas.


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