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Across-arc geochemical and Sr–Nd–Hf isotopic variations of mafic intrusive rocks at the southern Central Qilian block, China

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ABSTRACT

The cause of across-arc geochemical and isotopic variations above subduction zone is still controversial. The researches on petrogenesis of arc-type mafic intrusive rocks may give important insights into the cause of the variations. Here we undertakes an integrated study of U–Pb zircon dating, geochemical and Sr–Nd–Hf isotopic compositions for the rear-arc (Keqianyakou and Jinyuan plutons) and arc-front mafic intrusive rocks (Liushendong and Yishenchun plutons) in the southern Central Qilian block. These mafic rocks have magma crystallization ages of 454–465 Ma. Their evolved Sr–Nd–Hf isotopic compositions and relatively low Ba/Th, Sr/Th and high La/Sm ratios indicate that they were derived from mantle sources modified by slab sediment melt. Compared to the rear-arc mafic rocks (($^{87}Sr/^{86}Sr)_i$ = 0.7046–0.7054, $\varepsilon_{Nd}(t) = +0.8$ to $+2.4$ and $\varepsilon_{Hf}(t) = +8.4$ to $+11.9$), the arc-front mafic rocks are more enriched in strongly incompatible elements and have more evolved Sr–Nd–Hf isotopic compositions (($^{87}Sr/^{86}Sr)_i$ = 0.7092–0.7116, $\varepsilon_{Nd}(t) = -4.3$ to -5.4 and $\varepsilon_{Hf}(t) = -1.2$ to -0.1). Sr–Nd and Nd–Hf two-endmember (depleted mantle and slab sediment melt) mixing models reveal that ~0.7% slab sediment melt was incorporated into the magma sources of the mafic rocks in the rear arc, while up to 4.5% was incorporated into those in the arc front. This difference probably reflects release of hydrous fluid from the slab, which contributed to fluid-fluxed melting of the slab sediment. In response to the decreasing involvement of slab sediment melt with depth, degree of partial melting (F) of the modified mantle decreases across the arc (i.e. F = 9% in the arc front and F = 5% in the rear arc). The results indicate that the extent of slab sediment melting and the degree of partial melting of the mantle wedge can account for the across-arc geochemical and isotopic variations of arc-type mafic rocks. We thus suggest that the northward subduction of the South Qilian (North Qaidam–West Qinling) Ocean (a branch of the Proto-Tethys Ocean) is responsible for the Early Paleozoic arc-type mafic magmatism at the southern Central Qilian block.

1. Introduction

Arc magmatism has attracted great attention due to its significant contribution to continental crustal growth (Chu et al., 2006; Hawkesworth and Kemp, 2006; Lee et al., 2007) and to subducted slab material recycling (Pearce and Peate, 1995; Plank and Langmuir, 1993; Tatsumi, 2005). The ubiquitous overprinting of the slab signature in arc magmas arouses controversial topics on how the slab components contribute to magmatism and what causes result in spatial geochemical and isotopic variations for arc magmas (i.e. across arc, along arc, within segments of the arc and even within a single volcano) (Elburg et al., 2005; Martynov et al., 2010; Patino et al., 2000; Rychert et al., 2008; Sendjaja et al., 2009). The systematic variations in fluid-mobile elements (e.g. Ba, Pb and Sr) and their related elemental ratios (Hochstaedter et al., 2001; Patino et al., 2000), radioactive isotopic ratios, represented by $^{87}Sr/^{86}Sr$, $^{143}Nd/^{144}Nd$ and $^{206}Pb/^{204}Pb$ (Elburg et al., 2005; Martynov et al., 2010), elements and isotopes enriched in sediment/oceanic crust (such as ^{10}Be and B) (Ishikawa and Tera, 1997; Leeman et al., 1994) and stable isotopic fractionation like δ^7Li and $\delta^{11}B$ (Ishikawa and Nakamura, 1994; Moriguti and Nakamura, 1998) all have received great attention and have served as significant petrogenetic indicators.

Many studies have discussed the causes of geochemical and isotopic variations of arc magmas in space. Generally, the along-arc variations are attributed to discrepancies in (1) subducted components (Elburg et al., 2005; Peate and Pearce, 1998) and/or mantle source composition (Peate and Pearce, 1998); (2) subducted slab geometry (Patino et al., 2000) and/or physical conditions (Leeman et al., 1994); (3) thermal structure of the overriding wedge (Rychert et al., 2008) and (4) crustal contamination (Hildreth and Moorbath, 1988). For the across-arc variations, two prevalent but opposite phenomena have been reported. Firstly, incompatible elemental contents, $^{87}Sr/^{86}Sr$ and $^{207}Pb/^{204}Pb$ ratios increase and $^{143}Nd/^{144}Nd$ ratios decrease from the arc front (AF)

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to the rear arc (RA) (Sendjaja et al., 2009; Whitford et al., 1979). This phenomenon was interpreted as increasing involvement of slab fluids or melts (Whitford et al., 1979), and/or decreasing degree of partial melting of metasomatized mantle wedge with depth (Sendjaja et al., 2009; Whitford et al., 1979), and/or heterogeneity of mantle wedge (Whitford et al., 1979), and/or discrepancy in fluid composition (Sendjaja et al., 2009). Secondly, δ^7Li, δ^{11}B, ^{207}Pb/^{204}Pb and ^{87}Sr/^{86}Sr ratios decrease, whereas ^{143}Nd/^{144}Nd ratio increases with increasing depth (Ishikawa and Nakamura, 1994; Moriguti and Nakamura, 1998; Shibata and Nakamura, 1997). This was attributed to continuously decreasing involvement of subducted components with increasing depth. In addition, other complex situations have also been reported (e.g. Martynov et al., 2010; Tatsumi et al., 1992). Although widespread attention has been drawn to the spatial variations of the modern arcs, spatial variations in paleo-subduction zones are rarely identified due to the lack of knowledge of the slab geometry and of the precise compositions of subducted slab and mantle wedge.

As mentioned above, the causes of across-arc variations are diverse and complex. Among them, the differences in slab fluid/melt flux rate and the extent of mantle wedge partial melting are ubiquitous across the arcs. Generally, higher fluid/melt flux rate would lead to higher partial melting extent of the mantle wedge. Higher proportion of fluid/melt incorporated into the mantle source could enhance the overprinting of the slab signature in the resultant magma, while higher partial melting extent has an opposing effect. Thereby, in order to evaluate which role dominates the process, quantitative geochemical models need to be set up. For partial melting in an open system, the arc basalt simulator (ABS) model has been proposed by Sendjaja et al. (2009). As for in a closed system, Sr–Nd–Hf isotopic compositions of arc-type mafic rocks can be employed to constrain the incorporated proportion of slab material, and incompatible element compositions may be used to estimate the partial melting extent of the mantle wedge.

The Hualong–Lajishan area, as a segment of the Early Paleozoic tectono-magmatic belt in the southern Central Qilian block, NW China (Fig. 1), witnessed the northward subduction of the South Qilian (North Qaidam–West Qinling) Ocean (Fu et al., 2014; Wang et al., 2016; Zhang et al., 2014). Recently, it has drawn great attention due to the discovery of several magmatic Cu–Ni–(PGE) sulfide deposits in small mafic-ultramafic intrusions (Zhang et al., 2014). The mafic-ultramafic intrusive rocks, along with the coeval intermediate-acid intrusive rocks and relevant volcanics, display arc-type magmatic geochemical signatures. The crystallization ages of these rocks mainly range from 450 to 465 Ma (Guo et al., 2015; Yu et al., 2012; Zhong, 2015), which are earlier than the prevalent eclogite-facies peak metamorphism ages (i.e. 430–450 Ma) in the North Qaidam belt, on the south of the Qilian block (Fig. 1a) (Mattinson et al., 2006; Zhang et al., 2010). Therefore, the coeval arc-type magmatism from Hualong (AF) to Lajishan (RA), on the north of Hualong, provides a good opportunity to study the across-arc variations in a paleo-subduction zone. In this study, we present an integrated study of U–Pb zircon chronology, geochemistry and Sr–Nd–Hf isotopic compositions for the mafic intrusive rocks in Hualong–Lajishan area. Our objectives are (1) to delineate their petrogenesis; (2) to establish the geochemical and Sr–Nd–Hf isotopic variations across the arc; and (3) to discuss the causes of the across-arc variations and the tectonic evolution of the Qilian Orogenic belt.

2. Geologic setting and sample description

2.1. Geologic setting

The Qilian Orogenic belt, located in northwest China, extends ~1200 km in length and ~300 km in width (Tseng et al., 2009). To the north and northeast of the belt are the Alxa and Ordos blocks, respectively, and to the south are the North Qaidam and West Qinling belts. To the west, the orogen is separated from the Tarim block by the Altyn Tagh fault. Internally, the Qilian Orogenic belt is divided into the South Qilian belt, the Central Qilian block and the North Qilian belt (Fig. 1a) (Feng and He, 1996).

The South Qilian belt, between the North Qaidam belt and the Central Qilian block, is composed of Cambrian–Ordovician lavas, pyroclastic rocks as well as abyssal and bathyal deposits, Silurian flysch, Devonian molasse and Late Paleozoic granitoids (Fig. 1a) (Xu et al., 2006). The North Qilian belt, sandwiched between the Alxa and Central Qilian blocks, comprises Neoproterozoic and Early Paleozoic ophiolites, Early Paleozoic arc-related volcanics and intrusive rocks, high-pressure metamorphic rocks, Silurian flysch and Devonian molasse (Fig. 1a) (BGMRGP, 1989; Song et al., 2013). This belt had witnessed subduction of the North Qilian oceanic slab and subsequent continental collision during the Early Paleozoic (Song et al., 2013). The Central Qilian block mainly consists of Precambrian metamorphic basements, Early Paleozoic granitoids and Paleozoic sedimentary sequences (Fig. 1a) (Feng and He, 1996). The basements had experienced high greenschist-facies to amphibolite-facies metamorphism and consist of schist, gneiss, amphibolite and marble (Tung et al., 2007). The granitoids with magma crystallization ages of 482–415 Ma resulted from the northward subduction of the South Qilian (North Qaidam-West Qinling) oceanic slab (Xu et al., 2006) and subsequent syn- and/or post-collisional processes (Li et al., 2010; Yang et al., 2016), although some researchers argued that the southward subduction of the North Qilian Oceanic slab is responsible for their generation (Cowgill et al., 2003; Gehrels et al., 2003; He et al., 2008).

The Hualong arc terrane, in the southern margin of the Central Qilian block, is a NW–SE trending elongated mountain range with width of ~20 km and length of ~160 km (Fig. 1b). It consists of Precambrian metamorphic basement (the Hualong Group), Early Paleozoic felsic to ultramafic intrusions and Tertiary terrestrial sandstones and conglomerates. The Hualong Group, dated as Neoproterozoic (He et al., 2011; Xu et al., 2007; Yan et al., 2015), mainly consists of quartzite, amphibolite and gneiss. It was intruded by large-volume Early Paleozoic granitoids and numerous 440–455 Ma dike-like mafic–ultramafic rocks (Guo et al., 2015; Yu et al., 2012; Zhang et al., 2012a; Zhang et al., 2012b).

The E-W-trending Lajishan tectonic belt, on the north of the Hualong arc terrane, extends from Riyue Mountain in the west to Guanting in the east. It is 200 km in length and 10–30 km in width and bordered by two faults on both the south and north sides (Fig. 1b) (Yang et al., 2002). The belt consists of Early Paleozoic acid-basic volcanic strata and subordinate contemporaneous felsic to ultramafic intrusive rocks (Yang et al., 2002). These strata are unconformably overlain by Silurian flysh and Devonian mollasse (BGMRQP, 1991). The mafic-ultramafic intrusive rocks together with some basic volcanic and siliceous sedimentary rocks have been considered to represent an ophiolite suite in the past few decades (Yang et al., 2002). However, the tectonic setting for the ophiolite and associated igneous rocks is debated. Competing hypotheses include (1) they were related to the spreading of a small oceanic basin evolved from a continental rift (Yang, 2000), (2) they represent the suture zone of the northward subducted South Qilian ocean (Y. Zhang et al., 2017), and (3) they recorded opening of the Lajishan back-arc basin (Pan et al., 1997). The widespread Early Paleozoic arc-type magmatic rocks in Hualong (Wang et al., 2016; Zhang, 2013), on the south of Lajishan, absolutely contradicts the second viewpoint. Recently, Fu et al. (2014) reported the MORB-like and ca.491 Ma OIB-like diabases in western Lajishan (Fig. 1b), and Wang et al. (2017) reported ca. 493 Ma arc-type ultramafic intrusion in the northern margin of central Lajishan (Fig. 1b). These, together with the ca.494 Ma arc-type pillow basalt and ca.471 Ma OIB-like basalt (our unpublished data), suggest that the Lajishan belt could develop from rifting of an arc to opening of a back-arc basin.

2.2. Sample description

As shown in Fig. 1b, samples from four plutons, including the Keqianyakou and Jinyuan plutons in Lajishan area (RA) and the