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Crustal contamination versus an enriched mantle source for intracontinental mafic rocks: Insights from early Paleozoic mafic rocks of the South China Block

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A B S T R A C T

Several recent studies have documented that the silicic rocks ($SiO_2 > 65$ wt.%) comprising Silicic Large Igneous Provinces are derived from partial melting of the crust facilitated by underplating/intraplating of "hidden" large igneous province-scale basaltic magmas. The early Paleozoic intracontinental magmatic rocks in the South China Block (SCB) are dominantly granitoids, which cover a combined area of ~22,000 km^2. In contrast, exposures of mafic rocks total only ~45 km^2. These mafic rocks have extremely heterogeneous isotopic signatures that range from depleted to enriched (whole rock initial $^{87}Sr/^{86}Sr = 0.7041–0.7102$; $\varepsilon_{Nd}(t) = -8.4$ to $+1.8$; weighted mean zircon $\varepsilon_{Hf}(t) = -7.4$ to $+5.2$), show low Ce/Pb and Nb/U ratios (0.59–13.1 and 3.5–20.9, respectively), and variable Th/La ratios (0.11–0.51). The high-MgO mafic rocks (MgO > 10 wt.%) tend to have lower $\varepsilon_{Nd}(t)$ values (<−4) and Sm/Nd ratios (<0.255), while the majority of the low-MgO mafic rocks (MgO < 10 wt.%) have higher $\varepsilon_{Nd}(t)$ values (>−4) and Sm/Nd ratios (>0.255). The differences in geochemistry between the high-MgO and low-MgO mafic rocks indicate greater modification of the compositions of high-MgO mafic magmas by crustal material. In addition, generally good negative correlations between $\varepsilon_{Nd}(t)$ and initial $^{87}Sr/^{86}Sr$ ratios, MgO, and K_2O, along with the presence of inherited zircons in some plutons, indicate that the geochemical and isotopic compositions of the mafic rocks reflect significant crustal contamination, rather than an enriched mantle source. The results show that high-MgO mafic rocks with fertile isotopic compositions may be indicative of crustal contamination in addition to an enriched mantle source, and it is more likely that the lithospheric mantle beneath the SCB during the early Paleozoic was moderately depleted than enriched by ancient subduction processes.

1. Introduction

In recent years, Silicic Large Igneous Provinces (SLIPs) have attracted attention because they consist of >80 vol.% silicic magmatic rocks ($SiO_2 > 65$ wt.%) and are considered to be unrelated to subduction (Bryan, 2007; Bryan and Ferrari, 2013; Ernst, 2014; Zincone et al., 2016). In contrast to typical intraplate magmatic rocks, which are linked to mantle plumes, mantle upwelling, and/or edge-driven convection (Davies and Rawlinson, 2014; Hanson et al., 2006; Pirajno, 2007; Pirajno and Santosh, 2014), silicic magmatic rocks in SLIPs are believed to be derived from the partial melting of the crust triggered by underplating/intraplating of "hidden" large volumes of basaltic magmas (Ernst, 2014). Therefore, mantle-derived mafic magmas are crucial to the formation of SLIPs. Unfortunately, our understanding of the evolution of mantle-derived mafic magmas has been hindered by the paucity of mafic rocks in SLIPs, which is most likely due to the density barrier of low-density felsic magmas encountered by mafic magmas (Ernst, 2014).

The South China Block (SCB) contains ~22,000 km^2 of early Paleozoic intracontinental felsic magmatic rocks (Fig. 1), compared with ~45 km^2 of early Paleozoic mafic rocks. The extensive felsic rocks are generally considered to have been generated by melting of the lower to middle crust, triggered by underplating and/or intraplating of mantle-derived magmas (Huang et al., 2013; Xu and Xu, 2015). Previous petrogenetic studies of the mafic rocks indicate they were derived from the partial melting of an ancient subduction-modified lithospheric mantle (Wang et al., 2013; Yao et al., 2012; Zhang et al., 2015; Zhong et al., 2013).

In this paper, we combine pre-existing and new data from the early Paleozoic mafic (49 samples of 10 plutons from previous studies and new data from the Yonghe hornblende gabbro), intermediate (22 samples of 6 plutons from previous studies and new data from the Shima quartz diorite), and felsic rocks (239 samples of 26 plutons from previous studies) to constrain the petrogenesis of the early Paleozoic intracontinental magmatic rocks of the SCB. In particularly, we focus on evidence for crustal contamination of the early Paleozoic mafic rocks, the petrogenetic relationship between the mafic and felsic rocks

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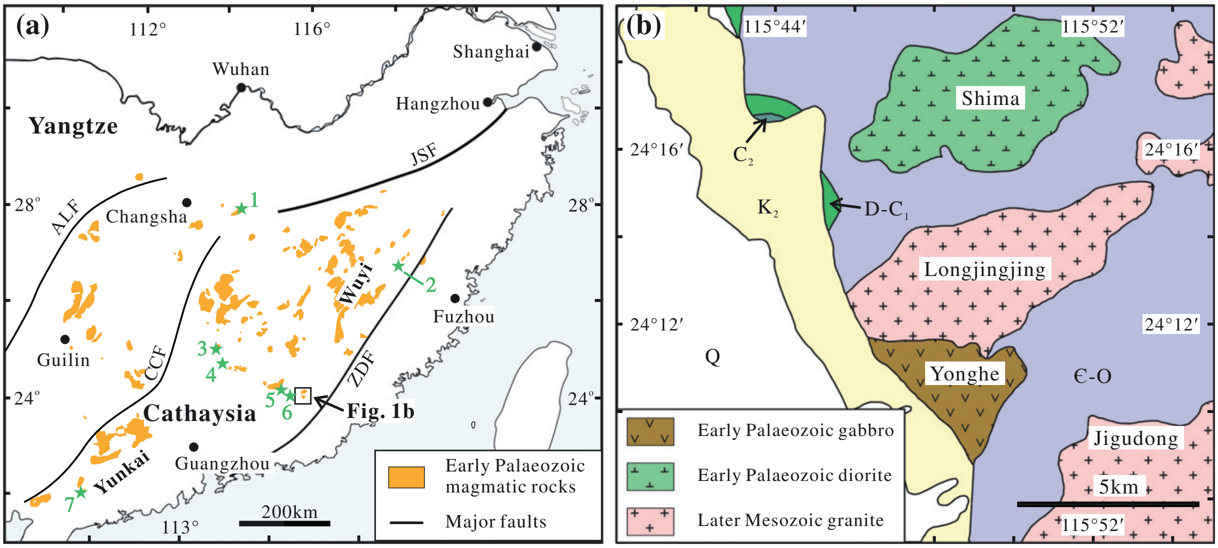

Fig. 1. (a) Schematic map showing the distribution of early Paleozoic igneous rocks in the SCB (modified after Sun, 2006). Most of the mafic rocks are not drawn to scale due to their limited extent; details are provided in the text. Known early Paleozoic mafic rocks in the SCB: (1) Taoyuan hornblende gabbro; (2) Dakang hornblende gabbro; (3) Fuxi monzonorite; (4) Chayuanshan basalt; (5) Xinchuan gabbro; (6) Xinsi gabbro; and (7) gabbros from the Xinyi district (Longhugang, Shiban, Yunlu, and Zhuya). Abbreviations: ALF, Anhua–Luocheng Fault; CCF, Chaling–Chenzhou Fault; JSF, Jiangshan–Shaoxing Fault; ZDF, Zhenghe–Dapu Fault. (b) Simplified geological map of the study area showing the distribution of plutons. Abbreviations of country rock ages: Є, Cambrian; O, Ordovician; D, Devonian; C, Carboniferous; K, Cretaceous; and Q, Quaternary.

(which has been largely overlooked in previous studies), and the nature of the lithospheric mantle beneath the SCB during the early Paleozoic.

2. Distribution and previous studies of early Paleozoic intracontinental mafic rocks in the SCB

The SCB is a major continental block in East Asia, formed by the amalgamation of the Yangtze (in the northwest) and Cathaysia (in the southeast) blocks during the early Neoproterozoic (Charvet et al., 1996; Guo et al., 1989; Li et al., 2009). The late Neoproterozoic successions in both blocks consist of slaty sandstone, siltstone, and mudstone (Shu et al., 2014). In contrast, the Cambrian to Ordovician lithofacies and biofacies of the Yangtze Block are distinct from those of the Cathaysia Block (Chen et al., 2010; Shu et al., 2014). The Yangtze Block contains carbonate sequences, whereas graptolite-bearing sandy-muddy sequences dominate the Cathaysia Block. Carbonate-siliceous sequences occur between the two blocks. Silurian deposits are absent due to uplift and erosion of the crust triggered by extensive magmatism (Rong et al., 2003). In the Middle Devonian, the SCB rapidly switched to a littoral-neritic depositional environment (Xun et al., 1996). During the early Paleozoic, an intracontinental depositional environment prevailed in the SCB, as inferred from paleocurrent data, stratigraphic records, paleographic reconstructions, and the similarity of detrital zircon age spectra of Cambrian-Silurian sandstone samples from the Yangtze and Cathaysia blocks (Charvet et al., 2010; Ren, 1990; Shu, 2006; Wang et al., 2010).

The early Paleozoic intracontinental felsic magmatic rocks have been intensively studied (e.g., Huang et al., 2013; Li et al., 1989, 2010; Xu and Xu, 2015; Zhang et al., 2012; Zhao et al., 2013). However, it was not until more recently that coeval mafic rocks have been identified (Peng et al., 2006; Wang et al., 2013; Yao et al., 2012; Zhang et al., 2015; Zhong et al., 2013). Table 1 provides a summary of the early Paleozoic intracontinental mafic rocks in the SCB.

The first study of early Paleozoic mafic rocks in Xinyi was undertaken by Peng et al. (2006). Based on Nb–Ta depletions, enrichments in U–Th, and low $\varepsilon_{Nd}(t)$ values, Peng et al. (2006) asserted that the mafic rocks were the products of subduction–collision processes. However, it is widely accepted that during the early Paleozoic the SCB occupied an intracontinental geodynamic setting. Consequently, the hypothesis that the mafic rocks were generated in a subduction setting was not widely accepted by subsequent studies.

Yao et al. (2012) presented the first Nd–Hf–O isotope study of the Chayuanshan high-MgO basalt–dacite from Shaoguan, which profoundly influenced subsequent studies. The Chayuanshan basalt samples are characterized by high MgO contents (12.3–19.2 wt.%) and low Nb/La ratios (0.4–0.8) and $\varepsilon_{Nd}(t)$ values (−8.4 to −8.0), despite their variable SiO_2 contents (44.8–51.5 wt.%). The Chayuanshan dacite samples are characterized by their high MgO contents (1.9–4.6 wt.%) and low Nb/La ratios (0.3–0.4) and $\varepsilon_{Nd}(t)$ values (−9.8 to −9.4). Zircon grains

Table 1
A brief summary of lithology and isotope compositions of the early Palaeozoic mafic rocks in the SCB.

Pluton	Location	Lithology	Size (km^2)	Initial $^{87}Sr/^{86}Sr$ ratios	$\varepsilon_{Nd}(t)$ values	Average zircon $\varepsilon_{Hf}(t)$ values	Reference
Taoyuan	Yichun, Jiangxi	hornblende gabbro	<1	0.7053 to 0.7058	+0.2 to +1.6	+5.2 ± 0.4	Zhong et al. (2013)
Dakang	Nanping, Fujian	hornblende gabbro	8.1	0.7066 to 0.7098	−7.0 to −3.3	−5.0 ± 0.6	Zhang et al. (2015)
Fuxi	Shaoguan, Guangdong	monzonorite	~1	0.7087 to 0.7098	−6.8 to −6.3	−7.4 ± 0.4	Xu and Xu (2017)
Chayuanshan	Shaoguan, Guangdong	basalt–dacite	<1	–	−9.8 to −9.4	−9.4 ± 0.3	Yao et al. (2012)
Xinchuan	Longchuan, Guangdong	gabbro	1.5	0.7092 to 0.7102	−7.8 to −4.2	+0.1 ± 0.7	Wang et al. (2013)
Xinsi	Longchuan, Guangdong	gabbro	8	0.7076 to 0.7101	−5.7 to −4.1	–	Wang et al. (2013)
Longhugang	Xinyi, Guangdong	gabbro	~2	0.7041 to 0.7095	−3.5 to −0.6	+2.8 ± 0.3	Wang et al. (2013)
Yunlu	Xinyi, Guangdong	gabbro	<1	–	−8.4 to −4.3	–	Peng et al. (2006)
Zhuya	Xinyi, Guangdong	gabbro	<1	–	−6.1 to −3.6	–	Peng et al. (2006)
Shiban	Xinyi, Guangdong	gabbro	2	–	−7.3 to −7.1	–	Peng et al. (2006)
Yonghe	Xingning, Guangdong	hornblende gabbro	20	0.7053 to 0.7060	−2.9 to −1.5	+0.9 ± 0.5, −0.6 ± 0.7	this study