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The source of Mesozoic granitoids in South China: Integrated geochemical constraints from the Taoshan batholith in the Nanling Range

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ABSTRACT

A combined study of zircon U–Pb ages and Lu–Hf isotopes, whole-rock major-trace elements and Sr–Nd isotopes as well as whole-rock and mineral O isotopes was carried out for Mesozoic granitic intrusions from the Taoshan batholith in the Nanling Range, South China. The results not only place constraints on the origin of granitoids but also provide insights into the effect of melting temperature on granitoid compositions. LA-ICPMS zircon U–Pb dating yields weighted $^{206}Pb/^{238}U$ ages of 230 ± 2 Ma for the Caijiang intrusion, 167 ± 2 Ma for the Huangpi intrusion, 152 ± 3 Ma for the Daguzhai intrusion, and 146 ± 3 Ma for the Luobuli intrusion. Relict zircon cores with older Mesozoic to Paleozoic U–Pb ages are present in some samples. These Mesozoic granitoids are weakly to strongly peraluminous with A/CNK ratios of 1.05 to 1.23. They exhibit arc-like trace element distribution patterns, with enrichment of LREE and LILE (e.g., Rb, K, Pb) but depletion of HFSE (e.g., Nb, Ta, Ti). They show high whole-rock initial $^{87}Sr/^{86}Sr$ ratios of 0.7101 to 0.7156 and low $\varepsilon_{Nd}(t)$ values of −11.2 to −8.8 as well as negative zircon $\varepsilon_{Hf}(t)$ values of −14.3 to −4.8 and Paleoproterozoic Nd-Hf model ages. These results suggest their derivation from partial melting of ancient continental crust. Furthermore, they have high zircon $\delta^{18}O$ values of 8.6 to 10.6‰ and calculated whole-rock $\delta^{18}O$ values of 10.8 to 12.5‰. Along with their peraluminous features, high K_2O/Na_2O ratios, arc-like trace element distribution patterns and enriched Sr–Nd–Hf isotope compositions, these Mesozoic granitoids are unambiguously derived from partial melting of metasedimentary rocks and thus are of S-type affinity. There are significant differences in both major and trace elements between the Caijiang intrusion of Triassic age and the Huangpi, Daguzhai and Luobuli intrusions of Jurassic age. While the Triassic granites exhibit high $(Fe_2O_3)_T$ + MgO, P_2O_5, Th, LREE and Zr + Nb + Ce + Y contents but low Al_2O_3/TiO_2, Rb/Ba and Rb/Sr ratios in association with high zircon saturation temperatures, the Jurassic granites have low $(Fe_2O_3)_T$ + MgO, P_2O_5, Th, LREE and Zr + Nb + Ce + Y contents but high Al_2O_3/TiO_2, Rb/Ba and Rb/Sr ratios in association with low zircon saturation temperatures. These correlations indicate that melting temperature and thus extent of partial melting have played an important role in dictating the compositions of granitoids. Therefore, the geochemical compositions of S-type granitoids are dictated not only by the composition of source rocks but also by the temperature of partial melting.

1. Introduction

Granite is one of the most common magmatic rocks in the continental crust, providing an important target to investigate reworking of crustal rocks in the Earth's history. It also has bearing on crust–mantle geochemical differentiation and thus on the generation and evolution of continental crust (e.g., Kemp et al., 2007; Hawkesworth et al., 2010). However, granite petrogenesis has been enigmatic and its relation to the origin of continental crust is controversial. There are various kinds of granites, varying significantly in mineralogical assemblages and geochemical compositions (Pitcher, 1997; Clemens and Stevens, 2012). This has led to longstanding discussion of the classification systems, source nature and differentiation mechanism of granites. The classification of granites is mainly based on mineralogical and geochemical characteristics that are linked either to the nature of source rocks or to the tectonic setting (Pitcher, 1997). I- and S-type granites are two of the most common types (e.g., Chappell and White, 1974, 1992; Clemens and Stevens, 2012), whereas A-type granites are spectacular in their geochemical compositions and are genetically linked to extensional tectonics (e.g., Loiselle and Wones, 1979; Whalen et al., 1987; Eby, 1992; Bonin, 2007).

Different types of Mesozoic granitoids widely occur in South China (e.g., Chen and Jahn, 1998; Zhou et al., 2006; Wang et al., 2013). They are related to hydrothermal ore deposits, particularly in the Nanling Range. However, their petrogenesis has been enigmatic despite many studies of these granitoids in the past four decades (e.g., Zhou and Li, 2000; Wang et al., 2002, 2007; Li and Li, 2007; Chen et al., 2008; Li et al., 2012). In view of their petrology and geochemistry, Zheng et al. (2013) advocate that these granitoids would be primarily produced by

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reworking of preexisting crustal rocks in the Mesozoic. However, there is a hot debate on the nature of source rocks for these granitoids (Zhou et al., 2006; Gao et al., 2014), which has bearing on reasonable discrimination between I- and S-type granites by geochemical parameters. Because the granitoids are one of the most important rock types in South China, deciphering their petrogenesis is very important to understanding the formation and evolution of continental crust in South China.

The Taoshan granitic batholith in the Nanling Range is composed of many plutons with emplacement ages from early to late Mesozoic. It exhibits relatively homogeneous Sr–Nd isotope compositions but variable lithochemical compositions among different plutons (e.g., Zheng et al., 1986, 1992; Shen et al., 1988; Zhao et al., 2011, 2013). This provides us with an opportunity to decipher the source nature of these plutons. This study presents a combined study of zircon U–Pb ages and Lu–Hf isotopes, whole-rock major-trace elements and Sr–Nd isotopes as well as whole-rock and mineral O isotopes for the Taoshan granitoids of Mesozoic age. The results place constraints on the origin of these granitoids and provide insights into the effect of melting temperature on their geochemical variations.

2. Geological setting and samples

The South China Block (SCB) is located in southeastern China (insert in Fig. 1a), and is surrounded by the Qinling-Dabie orogenic belt in the north, the Tibetan plateau in the west and the Indochina Block in the south (Wang et al., 2013; Zheng et al., 2013). The SCB is composed of the Yangtze craton in the northwest and the Cathaysia terrane in the southeast (Fig. 1a), with the Jiangnan orogen of Neoproterozoic age in between (Charvet, 2013; Zhang and Zheng, 2013). In the literature, the Yangtze Block was defined as being composed of the Yangtze craton and its surrounding Neoproterozoic orogens, only including the northwestern part of the Jiangnan orogen. In comparison, the Cathaysian Block was defined as being composed of the Cathaysian terrane and the southeastern part of the Jiangnan orogen. As such, the Yangtze Block is separated from the Cathaysian Block by the Jiangshan–Shaoxing fault in the northeast and by the Chenzhou–Linwu fault in the southwest. In the SCB, there are few occurrences of pre-Neoproterozoic crystalline basement rocks. As summarized by Zhang and Zheng (2013), Archean rocks only outcrop in the Kongling complex in the Yangtze craton, and are composed of TTG (tonalite, trondhjemite and granodiorite) gneisses and migmatites. Paleoproterozoic magmatic and metamorphic rocks are more common than their Archean counterparts in the SCB. The outcrop of Mesoproterozoic rocks is very limited in the SCB, with only a few outcrops in local areas. Neoproterozoic magmatic rocks are widespread in the Yangtze Block, but they are minor in the Cathaysia Block. Early Paleozoic granitoids are widespread in the Cathaysia Block, but late Paleozoic igneous rocks are very limited (Wang et al., 2013, and references therein). Zircon Hf isotope studies indicated that there are four periods of crustal growth in the SCB, i.e. Archean, middle Paleoproterozoic, late Mesoproterozoic and Neoproterozoic (Zhang and Zheng, 2013, and references therein).

The characteristic feature of the SCB is the voluminous outcrop of Mesozoic magmatic rocks, with an exposed area of ~220,000 km^2 (e.g., Chen and Jahn, 1998; Zhou and Li, 2000; Zhou et al., 2006; Wang et al., 2013). These Mesozoic magmatic rocks are mainly distributed in the Cathaysia terrane and the Jiangnan orogen, and most of them are granitoids or equivalent volcanics with minor basaltic to andesitic rocks. The Mesozoic magmatic rocks are generally subdivided into three age groups: Triassic, Jurassic and Cretaceous, which are named Indosinian, Early Yanshanian and Late Yanshanian, respectively, in the Chinese literature (e.g., Zhou et al., 2006; Li and Li, 2007; Wang et al., 2013).

The Taoshan granitic batholith of Mesozoic age in the Nanling Range is located geographically in Jiangxi province of South China and geologically in the northwestern edge of the Cathaysia Block (Fig. 1a). It can be subdivided into five units based on both petrography and field relationships (Zhao et al., 2011): (1) the Caijiang medium- to coarse-grained porphyritic biotite granite, (2) the Huangpi medium- to coarse-grained biotite granite, (3) the Daguzhai medium-grained two-mica granite, (4) the Luobuli medium-grained granite, and (5) the late fine-grained biotite granite (Fig. 1b). These granitoids were intruded into the Sinian-Cambrian metamorphic rocks, which are composed of phyllites, slates and metasandstones. Field observations show that the Caijiang intrusion was intruded by the Huangpi granite, the Huangpi intrusion was intruded by the Daguzhai granite, and the Daguzhai intrusion was intruded by the Luobuli granite. The late fine-grained granite was emplaced into the above four intrusions in some areas or into the Sinian-Cambrian metamorphic rocks in the other areas (Fig. 1b). Late Cretaceous to Tertiary reddish conglomerates, sandstones, and shales uncomfortably overlie the Sinian-Cambrian metamorphic rocks (Zhao et al., 2011). The exposed oldest basement rock in central Jiangxi province is the Mesoproterozoic Zhoutan Group, which is composed of schists, granulites and amphibolites (Hu, 1998).

Samples used in this study were collected from the Caijiang, Huangpi, Daguzhai and Luobuli intrusions in the Taoshan batholith. The Caijiang granitic samples are gray to pink in color, medium- to coarse-grained with massive structure. Some samples show porphyritic texture with K-feldspar phenocryst grain sizes of 3–4 cm. They are primarily composed of quartz, K-feldspar, plagioclase and minor biotite with accessory minerals of zircon, apatite, monazite, magnetite and ilmenite. The Huangpi granites are medium- to coarse-grained with massive structure. They are composed of quartz, K-feldspar, plagioclase and biotite with accessory minerals of zircon, apatite, monazite and magnetite. The Daguzhai samples are medium-grained two-mica granites, which are composed of quartz, K-feldspar, plagioclase, biotite and muscovite with accessory minerals of zircon, apatite and monazite. The Luobuli granites are fine- to medium-grained with massive structure, and composed of quartz, K-feldspar, plagioclase and biotite with accessory minerals of zircon, apatite and magnetite.

3. Analytical methods

3.1. Whole-rock major-trace elements and Sr–Nd isotopes

The samples used in this study are generally fresh without significant weathering. They were crushed to powders of 200 mesh in agate mortars. Whole-rock major and trace elements were analyzed at ALS Chemex (Guangzhou, China) Co., Ltd. A stoved whole-rock powder (~0.9 g) was added to ~9.0 g Lithium Borate Flux (50%–50% $Li_2B_4O_7$-$LiBO_2$), which was then mixed well and fused in an auto fluxer between 1050 °C and 1100 °C. A flat molten glass disk prepared from the resulting melt was used for major element oxide determination using an X-ray fluorescence spectrometer (XRF), the analytical precision is better than ±1–2%. For trace elements, whole-rock powder (~0.2 g) was added to lithium metaborate flux (~0.9 g), mixed well and fused in a furnace at 1000 °C. The resulting melt was then cooled and dissolved in 100 ml 4% nitric acid. This solution was used to analyze trace elements using a PerkinElmer ICP-MS. The analytical precision is better than ±5% for most trace elements, which is indicated by the measured results for Chinese standards GBW07121 and GBW07122 (Table 1). Whole-rock aluminum saturation indices are calculated by defining $A/CNK = Al_2O_3/(CaO + Na_2O + K_2O)$ in molar. Zircon saturation

Fig. 1. Simplified map of geology showing the distribution of Mesozoic granites and volcanic rocks in South China (a), modified from Wang et al. (2013); schematic geological map of Mesozoic Taoshan granitic intrusions in Jiangxi province, South China (b), modified from Zhao et al. (2011). Inset in (a) shows that the Yangtze Block is separated from the Cathaysian Block by the Jiangshan–Shaoxing fault in the northeast and by the Chenzhou–Linwu fault in the southwest.