



# Magma mixing in granite petrogenesis: Insights from biotite inclusions in quartz and feldspar of Mesozoic granites from South China



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## ABSTRACT

Magma mixing is a common process in granite petrogenesis. The major element composition of biotites in granites is primarily controlled by the composition of magmas from which they crystallized. Biotite grains enclosed in quartz and feldspars of granites are naturally protected by their host minerals, so that their compositions are likely original and can potentially be used to track the magma mixing. This is illustrated by a combined study of matrix and inclusion biotites from Mesozoic granites in the Nanling Range, South China. Three granite samples have been used in this study: one two-mica granite and two biotite granites. The biotites of different occurrences in the two-mica granite have no compositional distinctions. Biotites in the two-mica granite have higher  $Al_2O_3$  and lower MgO than those in the biotite granites. The former is consistent with biotites from typical S-type granites of metasedimentary origin. In contrast, biotites from the biotite granites can be categorized into different groups based on their paragenetic minerals and geochemical compositions. They have relatively low aluminous saturation indices but higher Mg numbers, falling in the transitional field between typical S- and I-type granites. In addition, there are two contrasting zircon populations with nearly identical U–Pb ages in the biotite granites. One shows clearly oscillatory zonings in CL images, whereas the other is totally dark and often overgrew on the former one. The zircons with oscillatory zonings have higher  $\delta^{18}O$  values than the dark ones, indicating their growth from two compositionally different magmas, respectively, with different sources. An integrated interpretation of all these data indicates that mixing of two different magmas was responsible for the petrogenesis of biotite granites. Therefore, the study of biotite inclusions provides insights into the magma mixing in granite petrogenesis.

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## 1. Introduction

Magma mixing plays an important role in granite petrogenesis. Mixing between mafic and felsic magmas has been commonly observed and well documented (e.g., Collins, 1996; Barbarin, 2005; Kemp et al., 2007; Slaby and Martin, 2008). Felsic magmas derived from partial melting of various crustal rocks such as metasedimentary and metaigneous rocks may have physical and chemical properties in common, but are obviously different from mantle-derived mafic magmas. Therefore, the mixing of different felsic magmas is more feasible than the mixing between mafic and felsic magmas. The former process has been suggested to play an important role in granite petrogenesis, from subduction zones to collisional orogens (e.g., Waight et al., 2000; Fiannacca et al., 2008; Appleby et al., 2010; Sola et al., 2009; Bolhar et al., 2012). Due to the physical and chemical similarities of various felsic

magmas, mixing of them may be so thorough that it leaves no significant records of either macroscopic petrography such as mafic microgranular enclave (MME) or microscopic disequilibrium structures such as reverse zoning.

Geochemical data obtained from whole-rock analyses represent bulk values, petrogenetic interpretations of which are often non-unique. Thus, identification of magma mixing between different crust-derived magmas calls for the study of individual minerals, in which mixed end-members with distinct compositions may be recorded. For example, magma mixing has been well documented by the geochemical systematics of various minerals from both plutonic and volcanic rocks, such as Ti in quartz (e.g., Wark et al., 2007), Sr isotope in feldspar (e.g., Waight et al., 2000; Ginibre et al., 2007) and apatite (e.g., Tsuboi, 2005), and Hf–O isotopes in zircon (e.g., Kemp et al., 2007; Appleby et al., 2010). Thus, more approaches are needed to identify magma mixing in granite petrogenesis in addition to recognition of magmatic processes such as partial melting, fractional crystallization, magma degassing and crustal contamination.

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As an essential mineral in granites, biotite is a major host of iron and magnesium. Because of its enrichment in titanium, biotite is also an important host of niobium and tantalum in granites. However, the composition of biotite in a granite is primarily dictated by the composition of the granitic magma from which the biotite grew. In general, biotite is rich in Al in peraluminous granites, Mg in calc-alkaline granites and Fe in most alkaline granites (e.g., Abdel-Rahman, 1994). Therefore, its compositional characteristics are an important index to reveal the compositional diversity of granites (e.g., Lavaure and Sawyer, 2011) and the behaviors of metallogenic elements such as Nb and Ta (e.g., Stepanov et al., 2014). In this regard, its major element compositions can provide the key information on magmatic processes in granite petrogenesis; so do other records of trace elements and isotopes in accessory minerals such as zircon and apatite.

In order to explore whether biotite in granites can record magma mixing between different crust-derived magmas, this study focuses on biotites that are enclosed in such rock-forming minerals as quartz and feldspar. These biotite inclusions were prevented from interaction with surrounding melts after their formation. The target granites were sampled from the Longyuanba complex of Mesozoic age in the Nanling Range of South China. They are peraluminous in lithochemistry, leading to previous classification into S-type granite (He et al., 2010) or highly evolved I-type granite (Tao et al., 2013a). In view of their zircon oxygen isotope compositions (Tao et al., 2013a), however, their sources appear to contain both metaigneous and metasedimentary components, similar to many peraluminous granites elsewhere in the world (e.g., Appleby et al., 2010; Sola et al., 2009; Bolhar et al., 2012). This provides us an excellent opportunity to test magma mixing by the study of biotite inclusions from the granites. Mineralogical data for biotite inclusions, in combination with whole-rock geochemistry and zircon oxygen isotope and trace element compositions, demonstrate that magma mixing is responsible for the petrogenesis of the Longyuanba biotite granites.

## 2. Geological setting and samples

The Longyuanba complex is located in the southwestern edge of Jiangxi Province, South China (Fig. 1A). It has an outcrop area of ~450 km<sup>2</sup>, and mainly consists of Triassic granites that were intruded by minor granites and syenites of Jurassic age (Fig. 1B). It is one of Mesozoic granitic plutons/batholiths in the Nanling Range, South China (e.g., Zhou et al., 2006; Wang et al., 2013; P. Gao et al., 2014; Zhao et al., 2015).

Both Triassic and Jurassic granites are composed of biotite granite and two-mica granite. Zircon U–Pb dating reveals that the Longyuanba complex was formed by several magma pulses at ~240 Ma, ~176 Ma, ~166 Ma and ~156 Ma (He et al., 2010; Tao et al., 2013a). The Triassic granites have limited variations in SiO<sub>2</sub> from 71.4 to 72.8 wt.% and aluminous saturation index, A/CNK = Al<sub>2</sub>O<sub>3</sub>/(CaO + Na<sub>2</sub>O + K<sub>2</sub>O) in mol, from 0.96 to 1.02 (Zhang et al., 2006; He et al., 2010), whereas the Jurassic granites exhibit large variations in SiO<sub>2</sub> from 70.5 to 78.9 wt.% and A/CNK from 1.05 to 1.33 (He et al., 2010; Tao et al., 2013a). SIMS zircon δ<sup>18</sup>O values for the Jurassic granites are in the range of 7.91–10.08‰ (Tao et al., 2013a). High zircon δ<sup>18</sup>O values indicate that these granites were mainly produced by partial melting of metasedimentary rocks, whereas metaluminous (A/CNK < 1.0) granites imply contributions from metaigneous components.

This study focuses on three samples selected from the Longyuanba complex: one Triassic two-mica granite (10SC74A), one Triassic biotite granite (10SC71) and one Jurassic biotite granite (10SC77). They were chosen because of the following considerations.

Firstly, the two-mica granite is strongly peraluminous (A/CNK = 1.18), whereas the biotite granites are weakly peraluminous (A/CNK < 1.1). Secondly, whole-rock Nd and zircon O isotopes in the two-mica granite are lower and higher than the biotite granites, respectively (see below). Such compositional differences are substantial to decipher the possible involvement of different crust-derived magmas in their petrogenesis. All mineralogical and geochemical features of the two-mica granite are consistent with previously reported S-type granites in the adjacent regions of South China (e.g., P. Gao et al., 2014; Zhao et al., 2015). Nevertheless, the biotite granites are characterized by lower zircon δ<sup>18</sup>O values but higher whole-rock ε<sub>Nd</sub>(t) values than those of the two-mica granite. In addition, they contain accessory minerals such as allanite and titanite, which are more common in I-type granites. These mineralogical and geochemical differences indicate that more than one source components might be involved in the petrogenesis of biotite granites.

The three samples used in this study are medium-grained, porphyritic with K-feldspar as phenocrysts. Sample 10SC74A (two-mica granite) is relatively fresh with little alteration. It is composed of plagioclase, K-feldspar and quartz with subordinate biotite and primary muscovite. Apatite, zircon, monazite and ilmenite are common accessory minerals. Sample 10SC71 (biotite granite) is composed of plagioclase, K-feldspar, quartz and biotite. Biotite rims were partly altered to chlorites. This sample contains various accessory minerals, including apatite, zircon, titanite, allanite, ilmenite and magnetite. Sample 10SC77 (biotite granite) is composed of altered feldspars, quartz and chlorite. Apart from some fresh biotites that are enclosed in quartz, the rest biotites have almost been chloritized. Several primary muscovites were also observed in quartz, which either coexist with ilmenite and/or biotite or are independent. Apatite and zircon are common accessory minerals in this sample. Ilmenite is paragenetic with muscovite and/or biotite, and they are enclosed together in quartz. There are rare magnetite and titanite enclosed in quartz.

There are different occurrences of biotite in the target granites (Figs. 2 and 3). Biotite in two-mica granite 10SC74A occurs not only as one of rock-forming minerals in matrix but also as inclusions in quartz and K-feldspar (Fig. 2A and B). Both the matrix and inclusion biotites have the same paragenetic minerals of muscovite and ilmenite. Similarly, there are three occurrences of biotite in biotite granite 10SC71: in feldspar, in quartz and in matrix (Fig. 3). The biotite inclusions in feldspars are generally euhedral plates and have widths of 30–200 μm with aspect ratios of about 3:1 (Fig. 3A and B), whereas biotites in quartz and matrix are usually subhedral flakes (Fig. 3C–F). In biotite granite 10SC77, except for chloritized biotites, fresh biotite inclusions in quartz can be categorized into two groups. Group A is euhedral, platy and about 50 μm in size, and coexists with primary muscovite and ilmenite (Fig. 2C). Group B is subhedral to anhedral, about 30–40 μm in width and 60–80 μm in length, and is included independently (Fig. 2E and F). Table 1 presents a summary of the basic information on the samples, with categorization of the biotites into different types in terms of their occurrences and compositions.

Two contrasting zircon populations are distinguished in biotite granite 10SC77 (Fig. 4). One is bright and shows oscillatory zonings in CL (cathodoluminescence) images, whereas the other is very dark and has no discernible zonings. The two zircon populations are either as individual grains or present together with the later overgrowing the former (Fig. 4), which indicates that the dark zircons crystallized later than the bright ones. Most of zircons are either enclosed in biotites or present interstitially. Few zircons coexist with muscovite and ilmenite and are enclosed in quartz (Fig. 2D).

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