Mixing of cogenetic magmas in the Cretaceous Zhangzhou calc-alkaline granite from southeast China recorded by in-situ apatite geochemistry

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**ABSTRACT**

Mixing of cogenetic magmas represents an important process in granite petrogenesis but is difficult to identify and is consequently often overlooked due to the absence of obvious isotopic distinctions between the mixed melts. We have conducted situ elemental and O isotope analyses on apatite from Cretaceous Zhangzhou calc-alkaline granite in southeast China. We integrated these data with micro-analyses on other minerals (plagioclase, zircon, and titanite) as well as whole-rock geochemistry to decipher the mixing history of this granitic complex. The apatite occurs as an early crystallizing phase forming inclusions in biotite, plagioclase, and titanite, and is characterized by core-rim zonation textures with a dark core and bright rims in backscattered images. The core domains have remarkably higher SO$_3$ and Li concentrations but much lower SiO$_2$, REE, and Y concentrations than the rim domains. However, both the cores and rims show geochemical compositions similar to that from typical I-type granite and also have mantle-like O isotope compositions (the core has $\delta^{18}$O = 5.3–6.8‰ and the rim has $\delta^{18}$O = 5.2–6.4‰, respectively), indicating crystallization from magmatic melts derived from newly accreted crust. The combined major and trace element and O isotope compositions of apatite and whole-rock geochemistry suggest that compositional evolution of the Zhangzhou granite involved mixing between two cogenetic magma batches, with variable degrees of subsequent differentiation. Batch I magma was a low-SiO$_2$ and high-SO$_3$ melt, whereas Batch II magma was a high-SiO$_2$ and low-SO$_3$ melt that experienced devolatilization. The high-S content in apatite cores further suggests the parental magma of the Zhangzhou granite likely originated from a sulfur-rich source comprising mainly newly accreted arc crust in response to subduction of the paleo-Pacific Ocean. The geochemical records of these magmatic processes are rarely observed in coeval zircon, titanite, and plagioclase. Our study, therefore, demonstrates that apatite geochemistry is potentially a more suitable monitor of complex magmatic evolution, including devolatilization and mixing of isotopically indistinguishable magmas.

**Keywords:** Apatite geochemistry, mixing, devolatilization, cogenetic magmas, Cretaceous, SE China

**INTRODUCTION**

Granitic rock (hereafter simply referred to as granite) is a major constituent of the upper continental crust and contains abundant mineral resources essential for sustained economic development. The compositions of granite vary extensively and can be broadly divided into I-, S-, M-, and A-type based on geochemical features and melting sources (Chappell and White 1974; Whalen et al. 1987). Many petrogenetic hypotheses, e.g., fractional crystallization, assimilation via fractional crystallization (AFC) (DePaolo 1981), and magma mixing (Griffin et al. 2002), have been proposed to interpret the geochemical diversity of granite. Nevertheless, it remains difficult to fully understand the magmatic evolution of granite since clear geochemical evidence for many hypothesized petrogenetic processes is lacking.

Recent techniques in studying chemistry and isotopic composition of minerals such as plagioclase, titanite, zircon, and apatite have become widely used petrogenetic tools in supplementing or even replacing conventional bulk-rock analyses (e.g., Streck 2008; Lisowiec et al. 2015; Nathwani et al. 2020). However, the sensitivity or applicability of these minerals in tracking magmatic processes is extremely variable because they each partition (or exclude) elements (or isotopes) of specific geochemical behavior and are typically relevant to only parts of a given crystallization sequence. Minerals that indelibly record geochemical proxies of changing magma compositions over a wide crystallization interval are rare.

Apatite is one such mineral, containing measurable concentrations of a range of elements of various geochemical behavior, including halogens, S, rare earth elements (REEs), Sr, and Y (Ayers and Watson 1993; Pan and Fleet 2002; Marks et al. 2012; Harlov 2015; Webster and Piccoli 2015; Bruand et al. 2017), that are sensitive to specific magmatic/petrogenetic processes. For example, the textural and compositional variations in apatite from the Pingtan complex in southeast (SE) China records both magmatic evolution and post-crystallization fluid activity regardless of a narrow range in Nd isotopic composition (Zhang et al. 2020). As a near-liquidus phase, apatite crystallizes early in metaluminous felsic magma (Piccoli and Candela 2002; Webster