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Thermodynamic modeling for an incrementally fractionated granite magma system: Implications for the origin of igneous charnockite

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ABSTRACT

Understanding fractionation of silicic magma is crucial to advance our knowledge of differentiation of continental crust, enrichment of elements of economic interest, and plutonic–volcanic connection. Microstructural records afford critical appraisals for silicic magma fractionation, yet are rarely reported in granite plutons. Here we combine detailed microstructural observations and thermodynamic modeling to quantify the components and the conditions of silicic magma fractionation using the peraluminous Jiuzhou pluton (South China) as an example. The pluton shows compositional gradients from primitive orthopyroxene-bearing granite (charnockite) at stratigraphically low levels to relatively evolved orthopyroxene-free granite at stratigraphically high levels. Deviation of whole-rock compositions from metasediment-sourced experimental melts, and step-zoned plagioclase and alkali feldspar crystals in the exposed rocks suggest open-system fractionation by melt extraction, partial dissolution, and subsequent crystallization from trapped minimum melt. Crystal cluster and chain fabrics and viscous deformation are more abundant in the charnockites than in the overlying orthopyroxene-free granites, suggesting that gravitational, compaction-driven fractionation increased towards the bottom of the pluton. Field observations, thermodynamic modeling and petrographic studies further demonstrate that gravitational compaction reduces the trapped melt fraction of a crystal mush with thickness of ≥100 m from ∼30 wt% at the upper level to ∼10 wt% at the lower level of the pluton. Significant melt extraction restricted back-reaction with high-temperature phases during progressive crystallization, which preserved orthopyroxene during the solidification of granitic magma. The compositional, mineralogical and textural zoning of the Jiuzhou pluton suggests that incremental fractionation of granite systems may be an important process that produces compositionally zoned cumulate. Incremental fractionation may occur in many zoned granite plutons worldwide, causing their whole-rock composition to deviate from their primary melt composition. Detailed microstructural examination for these granite plutons may provide insights into the mechanism(s) for melt extraction and crystal accumulation of silicic magma, providing key insights towards quantifying fractionation of magma systems.

1. Introduction

Magma fractionation plays an important role in the formation and differentiation of the continental crust (e.g. Keller et al., 2015), and in the enrichment of elements of economic interest (e.g. Mustard et al., 2006). Many studies on low-viscosity, mafic layered magma series have suggested that cumulate formation by gravitational settling is a key process of magma fractionation (e.g. Wager et al., 1960). Other studies have advocated that cumulates form by in situ crystallization in solidification fronts and subsequent removal of evolved melt (e.g. Latypov and Egorova, 2012; Holness et al., 2017). Silicic magmas have been considered to be largely stagnant during much of their lifetime in crustal reservoirs, given their high viscosities (e.g. Huber et al., 2009; Glazner, 2014), but vigorous magma-flow-driven crystal–liquid segregation of crystal-rich magma is at least locally recorded (Paterson et al., 1998; Zak et al., 2007). The formation of crystal-poor rhyolites or other evolved melts (e.g. aplites) requires efficient segregation of melts from crystal mush through hindered settling, compaction and/or filter pressing (Bachmann and Bergantz, 2004; Gelman et al., 2014). Direct microstructural evidence for melt extraction and crystal accumulation, however, is rarely examined in intrusive magma bodies (Fiedrich et al., 2017), and mechanisms

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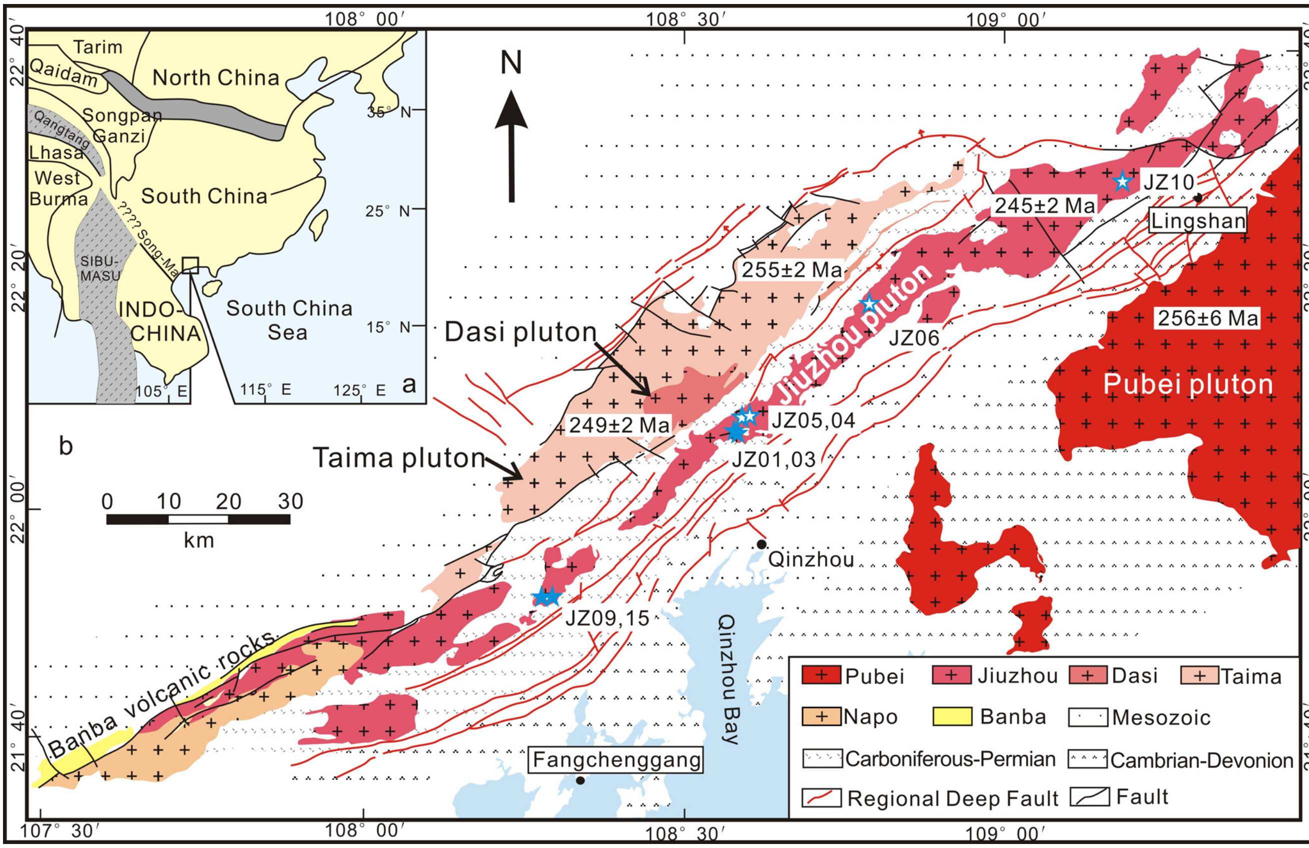

Fig. 1. (a) Tectonic schematic map of South China and its surrounding plates (Zhao et al., 2017b and references therein). (b) Geological map showing the area in which the orthopyroxene-bearing to orthopyroxene-free Jiuzhou pluton is exposed. Filled and open stars within the Jiuzhou pluton mark our sample locations for charnockite and orthopyroxene-free granite, respectively.

of melt–crystal segregation thus commonly remain hypothetical (Holness, 2018).

Thermodynamic modeling (e.g. the using of the rhyolite-MELTS, Magma Chamber Simulator, or Perple_X program packages) is a powerful tool for constraining phase relationships, intensive crystallization parameters, and the compositional evolution of liquids and solids (e.g. Connolly, 2005; Gualda et al., 2012; Spera and Bohrson, 2001; Zhao et al., 2017a). The basic requirement for the application of most thermodynamic models is that the systems considered have approached total equilibrium (i.e. equilibrium for all chemical components and phases in the system) or at least local equilibrium (i.e. equilibrium for crystal rims and host liquids) in a compositionally closed system. Mass and energy exchange as a result of open-system processes, e.g. magma recharge, assimilation, and fractional crystallization (leading to melt and/or volatile loss), may cause partial disequilibrium on the mineral scale, e.g. crystal zoning (Humphreys, 2009), and deviation of whole-rock compositions from those of primary melts (e.g. Montel and Vielzeuf, 1997). The open-system evolution of magma systems through the addition of material, e.g. magma recharge or country-rock assimilation (Spera and Bohrson, 2001), has been numerically constrained for many systems. Modeling the compositional and the mineralogical effects resulting from the loss of liquids from evolving magma systems is still rare (with few exceptions, such as the studies of Gelman et al., 2014; Lee and Morton, 2015), yet crucial for quantifying parental magma composition and intensive system variables.

This study investigates such open-system evolution, using the peraluminous Jiuzhou pluton, South China, as an example. The pluton comprises orthopyroxene-bearing granite (charnockite) and orthopyroxene-free granite with assemblages that permit the characterization of crystallization pressure, temperature, and melt H_2O content. Previous work has shown that the system likely experienced partial melt extraction, which was crucial for the preservation of orthopyroxene in solidification of granite magma (Zhao et al., 2017a). To further assess possible melt extraction, and to quantify the magmatic system evolution, we have (1) carried out geochemical modeling to evaluate the potential magmatic processes including magma mixing, restite entrainment and fractional crystallization, and (2) characterized the pluton- and mineral-scale processes of magmatic evolution using whole-rock compositions, mineral textures and compositions, crystal size distribution, microstructure, and thermodynamic modeling utilizing the Perple_X program package of Connolly (2005). Our approach can be applied to constrain the role of melt extraction and cumulate formation in H_2O-poor to moderately H_2O-rich granitic magma systems, which may contribute new insights into the processes and the conditions of granite fractionation that lead to compositional zoning and deviation of whole-rock composition from primary melt composition.

2. Geological background

The Qinzhou Bay Granitic Complex (QBGC), South China, comprises several strongly peraluminous (ASI > 1.1) granitic intrusions including the orthopyroxene-bearing to orthopyroxene-free Jiuzhou pluton (Fig. 1). The granitic rocks are classified as S-type granites derived from partial melting of a crustal source with minor or no input of mantle-derived magma (Qi et al., 2007; Zhao et al., 2012; Jiao et al., 2015). Restitic granulite enclaves hosted by the Jiuzhou pluton are inferred to record source partial melting at ∼0.7–0.8 GPa and ∼900–1000 °C and granite emplacement at ∼0.2–0.3 GPa (Zhao et al., 2017b).