Crystallization and melt extraction of a garnet-bearing charnockite from South China: Constraints from petrography, geochemistry, mineral thermometry, and rhyolite-MELTS modeling

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Abstract

Since granitic rocks in high-grade terranes commonly undergo amphibolite-granulite facies metamorphic overprint, recovering magmatic records from the metamorphic modification remains a major challenge. Here, we report an early Paleozoic, garnet-bearing Yunlu charnockite that outcropped in the Yunkai terrane of the Cathaysia block from South China and underwent amphibole-grade metamorphic overprint in the late Devonian. Field observation, micro-texture, and mineral geochemistry combined with diffusion modeling constrain that the metamorphic overprint with an extremely short duration of $\sim 0.2-0.5$ Ma only influences a narrow rim of $< 100 \,\mu m$ for most minerals. The magmatic information can be retrieved by combining rhyolite-MELTS modeling with mineral thermobarometry using mineral core compositions to quantitatively estimate magmatic pressure, temperature, and melt H₂O contents. Rhyolite-MELTS modeling results are evaluated by comparison with experimentally determined phase relations for a peraluminous granite with ~69.83 wt% SiO₂ at a pressure of ~500 MPa. The comparison suggests that the modeling reproduces phase relationships of feldspars and quartz within 20-60 °C when the melt H₂O contents are below 7.0 wt%, but fails to account properly for all the phases when the melt H_2O contents are higher than 7.0 wt%. The modeling results using reconstructed primary magma composition of the Yunlu charnockite combined with the orthopyroxene-garnet-plagioclasequartz thermobarometry and fluid inclusion analyses suggest that the magma was emplaced at a pressure of ~600 MPa, a temperature of >900 °C, and an initial H₂O content of ~4.0 wt% with rare CO₂ components. The orthopyroxene-garnet, biotite-garnet, and biotite-orthopyroxene thermometers yield a consistent temperature range of 770–820 \pm 60 °C, which is significantly higher than the H₂Osaturated solidus temperature of ~630 °C estimated from experimental results and two-feldspar thermometry. These results indicate that the early crystallized minerals (e.g., garnet, orthopyroxene, and some euhedral biotite) of the Yunlu charnockite equilibrate at higher temperatures with crystallinities of \sim 30–45%, rather than the H₂O-saturated solidus conditions. We thus propose a hypothesis of melt extraction at 780-820 °C in a deep-seated, slowly cooling, partially crystalline magma reservoir. The melt extraction physically segregates the early crystallized minerals from residual interstitial melts, which inhibits element diffusion equilibration between these minerals and interstitial melts. Granite thermometry commonly yields a large range of temperature estimations, which may be related to melt extraction events. Our study shows that melt extraction recorded in granites can be identified by combining micro-texture, mineral thermometry and rhyolite-MELTS modeling, which further provides quantitative insights into the fractionation process of silicic magmas.

Keywords: Garnet-bearing charnockite, rhyolite-MELTS modeling, mineral thermometer, melt extraction, metamorphic overprint

INTRODUCTION

Orthopyroxene-bearing granitoid (charnockite), though rarely outcropped, represents an important constituent of the middle-lower continental crust, which provides critical information on formation and differentiation of the continental crust (Frost and Frost 2008; Le Maitre 2002; Rajesh and Santosh 2012). Charnockite by definition can be an igneous rock, i.e., solidified magma at low H_2O activity and elevated solidus temperature within the stability field of orthopyroxene (Frost et al. 2000; Harlov et al. 2013), or metamorphic rock, which experienced dehydration reaction to form orthopyroxene due to influx of low H₂O-activity fluids (Harlov et al. 2014; Newton and Tsunogae 2014; Yang et al. 2014). It remains a challenge to distinguish whether the orthopyroxene in the charnockite crystallized from magmas or formed during a later high-grade metamorphic overprint (e.g., Rajesh et al. 2011). This issue is even more prominent for Precambrian igneous charnockites, which are commonly subjected to later high-grade metamorphic overprint (Wang et al. 2018; Ma et al. 2013; Zhao et al. 2014; Mikhalsky and Kamenev 2013). It is thus essential to distinguish the blending information of magmatism and metamorphism to understand the formation of charnockite, yet few attempts have been made to evaluate to what extent the metamorphic overprint has influenced the textures and compositions

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of the original igneous charnockites.

Melt extraction in silicic magma chambers has been considered to be responsible for the generation of crystal-poor rhyolites and high-SiO₂ granites (Bachmann and Bergantz 2004; Lee et al. 2015; Cashman et al. 2017; Bachmann and Huber 2016). Compared to volcanic rocks, intrusive rocks retain a more integrated record of the magma chamber dynamics (Fiedrich et al. 2017). Thus, seeking the evidence related to crystal accumulation and melt extraction in silicic intrusive rocks has received considerable attention (e.g., Fiedrich et al. 2017; Hartung et al. 2017; Schaen et al. 2018; Zhao et al. 2018). Recent studies have claimed that peraluminous charnockite may crystallize without involvement of low H2O-activity fluids and represent granitic cumulate after extraction of evolved interstitial melt through compaction of the crystal framework in a mush reservoir (Zhao et al. 2017, 2018). Such petrogenetic model is different from that for the metaluminous charnockite for which melt extraction is not necessary to be invoked if low H2O-activity fluids have significantly elevated the solidus temperature within the stability field of orthopyroxene (Frost et al. 1999, 2000; Harlov et al. 2013). Peraluminous charnockite is seldom reported so far, except for the Triassic, cordierite-bearing charnockite from Jiuzhou, South China (Zhao et al. 2017, 2018) and the Cenozoic, garnet-orthopyroxene tonalite in the Niikappu River area from Hidaka Metamorphic Belt, northern Japan (Shimura et al. 1992, 2004). Hence, the rare outcropping of the peraluminous charnockite severely restricts our understanding of not only the magmatic fluid conditions and crystallization processes of the igneous charnockite but also the silicic magma differentiation mechanism in the continental crust (Annen et al. 2006).

Constraining the intensive parameters (e.g., pressure, temperature, and oxygen fugacity) that characterize the emplacement and crystallization of granitic rocks remains challenging (Anderson 1996; Anderson et al. 2008; Bartoli et al. 2014; Zhao et al. 2017). Experimentally and empirically calibrated thermobarometers afford the most convenient approach for estimating magmatic crystallization temperatures (Anderson et al. 2008; Putirka 2008). In theory, major element-based mineral-pair thermometers in intrusive rocks should yield consistent near-solidus temperatures only if: (1) the magma crystallizes under conditions of low undercooling or low cooling rate, and (2) various mineral crystals and co-existed melt maintain at continuously chemical equilibrium. This is true for some cases (Frost et al. 2000; Harlov et al. 2013; Zhang et al. 2006), but not for cases where a large range of temperatures are retrieved from the various mineral thermometers (Elliott et al. 1998; Moazzen and Droop 2005; Shimura et al. 1992; Wang et al. 2018). The latter may indicate that the mineral compositions do not represent the equilibrium compositions at near-solidus temperatures due to one or more of: (1) various degrees of crystal-melt disequilibrium for the crystallized mineral assemblages (Best 2003); (2) resetting of mineral compositions by later thermal events [metamorphic overprint (Saha et al. 2008; Bhowmik et al. 2009)]; (3) hightemperature magma recharge (Pietranik et al. 2006; Wiebe et al. 2007); and/or (4) other processes [e.g., crystal entrainment during ascent (Anderson 2008)]. These factors are fundamental issues in granite thermometry but have not been fully assessed so far.

As one of the few peraluminous, igneous charnockites around

the world, the Yunlu garnet-bearing charnockite contains diverse mineral assemblages and textures associated with crystal-melt reactions and abundant symplectite/corona textures related to sub-solidus reactions, providing a rare opportunity to retrieve the micro-texture and pressure-temperature information at the magmatic and metamorphic stages of formation, respectively. We thus study here the whole-rock and mineral geochemistry, petrography, fluid inclusions, mineral thermobarometry, and rhyolite-MELTS modeling of the Yunlu charnockite. Our aim is to distinguish the micro-textures and mineral assemblages associated with the magmatic and metamorphic stages of formation and to quantitatively constrain pressure and temperature conditions, reconstruct the detailed crystallization processes, and decipher the enigmatic connections between mineral thermometry and magmatic crystallization processes.

GEOLOGICAL SETTING AND FIELD INVESTIGATION

The early Paleozoic orogen in the South China Block (SCB) represents the first important crustal reworking event in the Phanerozoic (Li et al. 2010). It resulted in the remobilization of crystalline basement in the entire Cathaysia Block and the eastern Yangtze Block, and formed an orogenic belt stretching for ca. 2000 km in a northeasterly direction (Li et al. 2010; Wang et al. 2007). The orogeny caused an angular unconformity between pre-Devonian deformed strata and undeformed Devonian strata (Grabau 1924). Simultaneously, the early Paleozoic orogeny yielded voluminous syn-orogenic and post-orogenic granitoids and rare mafic rocks (Wang et al. 2013a, 2013b; Yao et al. 2012; Zhang et al. 2015). The high-grade metamorphic rocks, which reach amphibolite- to granulite-facies grades, mainly occur in the northeastern Wuyi terrane and in the southwestern Yunkai terrane (Li et al. 2011; Wang and Wu 2012; Yu et al. 2003, 2005, 2007, 2014).

Specifically, the early Paleozoic gneisses and gneissic migmatites underwent amphibolite- to granulite-facies metamorphism and local crustal anatexis and are regarded as part of the basement rocks in the Yunkai terrane (Wang et al, 2007, 2011). These basement rocks are mainly exposed in the Gaozhou area and are thus referred to as the Gaozhou Complex (Fig. 1a), which mainly consists of paragneiss, orthogneiss, gneissic migmatite/granite and charnockite (Wan et al. 2010). The charnockite is located near Yunlu village and named as the Yunlu garnet-bearing charnockite. It intrudes the gneissic migmatite/granite, as a lenticular body with an area of ~11 km² (Fig. 1b; Wang et al. 2013c). U-Pb dating of zircon and mineral thermometry constrain an early Paleozoic (~440 Ma), amphibole- to granulite-facies metamorphic event for the surrounding gneissic migmatite/granite (Wang et al. 2013c). Geochronological studies of this garnet-bearing charnockite have vielded an early Paleozoic emplacement age of ~440 Ma (Chen et al. 2012; Wang et al. 2013c). Because of thick vegetation and poor outcrops, it is not easy to define the contact relationships between the garnet-bearing charnockite and its surrounding gneissic migmatite/granite. Different kinds of xenolith are distinguished in the Yunlu garnet-bearing charnockite, notably of gneissic granite and garnet-biotite gneiss (Figs. 2a-2b). The gneissic granite xenolith indicates that the Yunlu charnockite postdates the gneissic migmatite/granite.



FIGURE 1. (a) Tectonic schematic map of the South China Block; (b) geologic map of the Gaozhou Complex in Yunkai terrane [modified after Chen et al. (2012), Wang et al. (2013c)] and the sampling locations of the Yunlu garnet-bearing charnockite. (Color online.)

Petrography, mineral chemistry, and fluid inclusions

Petrography and mineral chemistry

The Yunlu garnet-bearing charnockite has an unfoliated, massive structure (Fig. 2a). It contains orthopyroxene, garnet, biotite, ilmenite, K-feldspar, plagioclase, quartz, and minor accessory minerals (apatite, monazite, pyrrhotite, and zircon). Details about the mineral shape, size, inclusion, occurrence, and composition are listed in Table 1. Major element compositions of the rockforming minerals are listed in Online Material¹ Table OM1. The trace element compositions of garnet and orthopyroxene measured by LA-ICP-MS are listed in Online Material¹ Table OM2. Details of the analytical methods are described in the Online Material¹.

Garnet. The garnet crystals are present as three groups:

group 1 garnet (Grt₁) consists of large (1-6 mm), euhedral crystals with a few mineral inclusions (Qz, Ilm) and regular grain boundaries, while group 2 garnet (Grt₂) consists of subhedral to anhedral crystals (1–3 mm) with irregular grain boundary outlines against partial or complete rim of biotite and quartz intergrowths (Fig. 2e). The group 3 garnet (Grt₃) consists of small (10–100 µm), globular, anhedral crystals distributed along plagioclase-ilmenite/orthopyroxene/biotite grain boundaries (Fig. 3). Regarding major element compositions, all groups of garnet crystals (Grt₁, Grt₂, Grt₃) have similar FeO contents, showing these garnets are almandites (Alm = 64-69; Table 1). Both Grt₁ and Grt₂ crystals exhibit Ca-rich and Mg-poor rims (Grt₁ and Grt₂ rim, ~50 µm) (Figs. 4c, 4e, and 4f). Grt₃ crystals exhibit lower MgO and higher CaO contents than Grt1 and Grt2 crystals, comparable to the Grt₁ and Grt₂ rim. Regarding trace element compositions, all groups of garnets have high contents of compatible elements such as Cr (104-174 ppm), V (141-161 ppm), Sc (139-201 ppm), and Y (555-666 ppm). Flat to HREEenriched patterns with clear negative Eu anomalies characterize Grt₁ crystals (Fig. 4d). The Grt₁ crystals have HREE and Y concentrations that decrease from core to rim (Fig. 4b). The Grt₃ crystals exhibit varying degrees of LREE-enrichment and HREE-depletion depending on the reactive minerals involved (Fig. 4d). Note also that the garnet crystals in Bt-Grt gneiss have high contents of MnO (6.03-6.56 wt%) and low contents of CaO (0.56-0.62 wt%), which are apparently different from Grt₁ and Grt₂ crystals in host garnet-bearing charnockite (Fig. 4e).

Orthopyroxene. The orthopyroxene crystals are 0.5-6 mm across (Figs. 2c–2d) and can be divided into two groups based on their grain shapes and occurrences (Table 1). Group 1 orthopyroxenes (Opx₁) have euhedral shapes with regular grain boundaries. Group 2 orthopyroxenes (Opx₂) have subhedral to anhedral shapes with irregular grain boundaries against the partial or complete rims of biotite and quartz intergrowths (Fig. 2c). Both groups rarely contain mineral inclusions of plagioclase, ilmenite, biotite, and quartz. Opx₁ and Opx₂ exhibit indistinguishable compositional characteristics (Fig. 5a) except few grain rims (Opx₁ and Opx₂ rim) adjacent to the Grt₃, which show higher FeO and lower MgO contents. Both Opx₁ and Opx₂ have high FeO

TABLE 1. Mineral shape, size, inclusion, occurrence, and compositions from Yunlu garnet-bearing charnockite

Mineral	Туре	Shape	Size (mm)	Mineral inclusion	Occurrence/ distribution	Average composition	Reference figure
Orthopyroxene	Opx ₁	euhedral	0.5–6	quartz, plagioclase, biotite	#	$X_{\rm Fs} = 53.6; X_{\rm En} = 45.9$	Fig. 2d
	Opx ₂	subhedral to anhedral			enclosed by Bt ₂ +Qz ₂		Fig. 2c
Garnet	Grt ₁	euhedral	1–6	quartz, ilmenite	#	$X_{Alm} = 67; X_{Prp} = 25;$ $X_{Grs} = 4.7; X_{Sps} = 3.1$	Fig. 2e
	Grt ₂	subhedral to anhedral	1–3		enclosed by Bt ₂ +Qz ₂		
	Grt₃	anhedral	0.01-0.1	none	coexistence with Qz_3	$X_{Alm} = 70; X_{Pyp} = 20;$ $X_{Grs} = 6.1; X_{Sps} = 4.1$	Fig. 3
Biotite	Bt ₁	euhedral	0.4–5	none	#	$X_{\text{Fe}} = 0.46; X_{\text{Mg}} = 0.40; X_{\text{Ti}} = 0.10; X_{\text{Al}} = 0.04$	Fig. 2d
	Bt ₂	subhedral to anhedral	0.5-2	quartz	coexistence with Qz ₂		Fig. 2c
Plagioclase	PI	euhedral to subhedral	0.5–3	none	#	$X_{\rm An} = 0.44; X_{\rm Ab} = 0.53$	Fig. 2f
	PI_2					$X_{\rm An} = 0.35; X_{\rm Ab} = 0.61$	Fig. 3
K-feldspar	Kfs₁	subhedral to anhedral	0.5-30	none	#	$X_{\rm Or} = 0.85; X_{\rm Ab} = 0.14$	Fig. 2f
	Kfs₂	anhedral	0.01-0.03	none	coexistence with Qz₃,	$X_{\rm Or} = 0.92; X_{\rm Ab} = 0.07$	Fig. 3b
Quartz	Qz ₁	euhedral to subhedral	0.5-4	none	#	-	Fig. 2d
	Qz ₂	anhedral	0.2-0.5	none	coexistence with Bt ₂		Fig. 2c
	Qz ₃	anhedral	0.02-0.05	none	coexistence with Grt₃		Fig. 3
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Notes: The "#" means that the Opx_{1,2}, Grt_{1,2}, Bt₁, Pl₁, Kfs₁, and Qz₁ are coexistent mineral assemblages. The Pl₁ represents the continuous core-rim composition with normal An zoning in plagioclase crystal. The Pl₂ represents the plagioclase composition that is adjacent to the Grt₃ crystal, which has the lowest An content.



FIGURE 2. Representative outcrops and photomicrographs of the Yunlu charnockite. (a) Garnet-bearing charnockite and Grt-Bt gneiss xenolith. (b) Xenolith is mainly composed of Bt, Grt, Pl, and Qz. (c-f) Micro-textures of the charnockite. (c) Euhedral orthopyroxene crystals are replaced by biotite + quartz intergrowth. (d) Symplectite texture composed of quartz + garnet along boundaries between orthopyroxene and plagioclase. (e) Garnet crystals forming a cluster, or glomerocryst, in charnockite, while part of garnet grain is replaced by biotite + quartz intergrowth. (f) Euhedral to subhedral, tabular plagioclase crystals are impinged to form a skeleton texture, which is filled by anhedral, interstitial quartz crystals. (Color online.)

(29.63–35.10 wt%), low MgO (14.23–16.97 wt%), and extremely low CaO (0.04–0.46 wt%) contents, and are thus classified as ferro-hypersthene or ferrosilite (Fs = 49.4–56.0). In particular, no compositional zoning is observed within individual crystals.

Both groups are enriched in compatible trace elements, e.g., Zn (616–655 ppm), Cr (147–285 ppm), V (260–515 ppm), and Sc (101–133 ppm). The chondrite-normalized REE patterns of orthopyroxenes are characterized by enrichment in MREE with strong negative Eu anomalies (Fig. 5b).

Biotite. The biotites can be separated into two groups based on crystal shapes and occurrences (Table 1). Group 1 biotite (Bt₁) comprises euhedral, inclusion-free crystals, with a size range of 0.4-5 mm (Fig. 2d). Group 2 biotite (Bt₂) crystals (0.5-2 mm) are subhedral to anhedral and form intergrowths with quartz that replace garnet/orthopyroxene crystals (Fig. 2c). In addition, the biotite crystals from the gneissic granite xenolith and the Grt-Bt gneiss xenolith were analyzed by EMP for comparison. On major element compositions, the biotite from the Yunlu charnockite shows higher TiO₂ contents (4.10-5.78 wt%) than Grt-Bt gneiss xenolith (0.07-0.21 wt%) and higher FeO contents (18.74-22.79 wt%) than gneissic granite xenolith (15.94-16.69 wt%) (Table 1). For the garnet-bearing charnockite, both groups of biotites (Bt₁ and Bt₂) have similar TiO₂ contents and X_{Mg} values irrespective of occurrence (Fig. 5d). They also have high contents of FeO (18.74-22.79 wt%) and thus can be classified as Fe-rich biotite.

Plagioclase. Plagioclase crystals are euhedral to subhedral with a size range of 0.5–3 mm (Fig. 2f). Some plagioclase

crystals occur as mineral inclusions within orthopyroxene, with sizes of 0.1–0.3 mm (Fig. 2d). Based on their occurrences and compositions, the plagioclase crystals may be divided into two types (Table 1). Group 1 plagioclase (Pl₁) represents the large grain size with normal An zoning (36 mol% \leq An \leq 47 mol%; Fig. 5e). Group 2 plagioclase (Pl₂) represents plagioclase rim adjacent to Grt₃ crystals, which have the lowest An contents (An \leq 36 mol%). The histogram of An contents in Pl₁ shows a unimodal distribution with a peak at ca. An₄₀–An₄₇, with decreasing An contents toward the rims (Fig. 5f).

K-feldspar. The K-feldspar crystals show two groups (Table 1): group 1 K-feldspar (Kfs₁) exhibits euhedral shape with a size of 0.5–30 mm (Figs. 2a and 2f), while group 2 K-feldspar (Kfs₂) exhibits small globular grains (10–30 μ m) distributed along the boundaries between biotite and plagioclase crystals (Fig. 3b). The large Kfs₁ crystals with grain sizes >10 mm have orthoclase contents of 82.9–86.9 mol% in their cores. In comparison, the Kfs₂ crystals have higher orthoclase contents, varying from 91.3–93.5 mol%.



FIGURE 3. Backscattered electron images of the symplectite textures of Yunlu charnockite. (a) Symplectite of quartz (Qz_3) + garnet (Grt_3) along boundaries between orthopyroxene and plagioclase. (b) Symplectite of quartz (Qz_3) + K-feldspar (Kfs_2) + garnet (Grt_3) along boundaries between biotite and plagioclase. (c-d) Symplectite of quartz (Qz_3) + garnet (Grt_3) along boundaries between ilmenite and plagioclase. (Color online.)



FIGURE 4. (a) Backscattered electron image of group1 (Grt₁) euhedral garnet. (b) Y element compositional profile across the garnet crystal in **a**. (c) Compositional profiles of almandine, pyrope, grossular, and spessartine contents of the garnet crystal from **a**. (d) REE compositions of group 1, group 2 (Grt₂), and group 3 (Grt₃) garnets. The gray pattern represents the garnet REE contents from peraluminous granites [data from Rong et al. (2018), see Online Material¹ Table OM8]. (e) Plots of CaO vs. MnO for group 1 and group 2 garnets (modified from Narduzzi et al. 2017). Garnets from Bt-Grt gneiss xenolith are compared. (f) Plots of CaO vs. MgO for group 1, group 2 garnets, and group 3 garnets. (Color online.)



FIGURE 5. (a) X_{Mg} vs. X_{Al} diagram for orthopyroxene compositions. The data of magmatic Opx from igneous charnockite are from Clemens and Birch (2012), Clemens and Phillips (2014), Shimura et al. (1992), and Wyborn et al. (1981). The data of metamorphic Opx from incipient charnockite are from Rajesh et al. (2011), Hansen et al. (1987), and Santosh et al. (1990). The data of peritectic Opx from melting experiments and granulites are from Montel and Vielzeuf (1997), Patiño Douce and Beard (1996), Nair and Chacko (2002), Berman and Bostock (1997), Dempster et al. (1991), Harley et al. (1990), Baba (1999), and Harley (1989). (b) REE compositions of Opx₁ from Yunlu charnockite, together with those from peritectic orthopyroxenes in psammitic granulites (Lavaure and Sawyer 2011) for comparison. (c) Diagrams of Mg# of Opx₁, Opx₂ and Grt₁, Grt₂ crystals. The gray dot represents the garnet and orthopyroxene compositions from melting experiments results where the starting materials are felsic metapelites, gneisses, and granites [SiO₂ = 65–75 wt%, data from Carrington and Harley (1995); Conrad et al. (1988); Montel and Vielzeuf (1997); Skjerlie and Johnston (1993)]. (d) Biotite compositions for the Yunlu charnockite with temperature contours from Henry et al. (2005) and Henry and Guidotti (2002). The uncertainty of the temperature estimate is ~60 °C. (e) Compositional profile of individual plagioclase crystal from Yunlu charnockite. (f) Histogram showing the anorthite contents of plagioclase. (Color online.)

Ilmenite and quartz. The euhedral to subhedral ilmenite crystals are associated either with orthopyroxene and garnet or with mineral inclusions (0.1–0.2 mm) in orthopyroxene and garnet crystals (Figs. 2c and 2e). The quartz crystals can be separated into three groups based on their sizes and occurrences (Table 1). Group 1 quartz (Qz_1) displays euhedral to anhedral crystal shape and poikilitic texture with maximum diameters of 0.5–4 mm (Fig. 2d). Group 2 quartz (0.2–0.5 mm) (Qz_2) forms intergrowths with biotite replaced by orthopyroxene/garnet crystals (Fig. 2c). Group 3 quartz (~20–50 µm) (Qz_3) comprises symplectites on mineral grain boundaries (Figs. 3a–3d).

Fluid inclusions

Fluid inclusions are not abundant in the Yunlu charnockite and are mostly found in quartz and only rarely in orthopyroxene, garnet, biotite, and feldspar. The fluid inclusions have emerged as single isolated individuals without cracks (Figs. 6a–6b). They thus represent the most suitable candidates for primary fluid inclusions, i.e., inclusions that have formed during magmatic crystallization. Thirteen fluid inclusions were found in different groups of quartz crystals (six inclusions in Qz_1 and seven inclusions in Qz_2) and were analyzed at room temperature. The fluid inclusions are mainly present as H₂O-rich compositions irrespective of their occurrence (Qz_1 or Qz_2), apart from one inclusion from Qz_1 , which is CO₂-H₂O-rich.

P-T ESTIMATIONS BY THERMO-BAROMETERS

The orthopyroxene-garnet-plagioclase-quartz barometer and the garnet-orthopyroxene thermometer are used here. The compositions of garnet in Yunlu charnockite are within the required garnet compositions (Online Material¹ Table OM1) with grossular contents of <30 mol% and spessartine contents of <5 mol% (Bhattacharya et al. 1991). The uncertainties of the barometer and thermometer are ${\sim}100$ MPa and ${\sim}50$ °C (Bhattacharya et al. 1991). Several researchers have calibrated the biotiteorthopyroxene thermometer (Aranovich et al. 1988; Sengupta et al. 1990; Wu et al. 1999). Here, we choose the thermometer from Wu et al. (1999), which provides the smallest uncertainty (±60 °C). This thermometer is calibrated under amphibolite- to granulite-facies (590-860 °C) conditions and has been applied successfully in magmatic rocks (Zhao et al. 2017). The garnetbiotite thermometer with an uncertainty of ~25 °C is used to constrain crystallization temperatures (Holdaway 2000, 2001) as in other granite bodies (Anderson et al. 2008). The two-feldspar thermometer was calculated using the Solvcal 2.0 program of Wen and Nekvasil (1994), employing the activity models of Elkins and Grove (1990), Ghiorso (1984), and Fuhrman and Lindsley (1988). It is expected to yield reliable temperature estimations with an uncertainty of ~50 °C (Anderson 1996).

Detailed petrological and geochemical studies on ferromagnesian minerals in granitoids can provide insights into the physicochemical conditions of crystallization, such as pressure, temperature, and melt-H₂O contents (Anderson 1996; Anderson et al. 2008; Clemens and Wall 1988). The presence of almandine-rich garnet without cordierite in Yunlu charnockite indicates a relatively high emplacement pressure (Green 1976). For the Yunlu charnockite, the Grt₁ and Grt₂ (with an average core grossular proportion of 4.7 mol%) coexist with Opx₁, Opx₂, with X_{Mg} values of 0.46,



FIGURE 6. Raman spectra of fluid inclusions in quartz crystals from the Yunlu charnockite with CO_2 -H₂O-rich (**a**) and H₂O-rich (**b**) compositions. Among all the 13 analyzed fluid inclusions, only one inclusion is CO_2 -H₂O-rich, whereas the other 12 fluid inclusions are H₂O-rich. (Color online.)

plagioclase (Pl1 with an average core An value of 46.2), and quartz (Oz_1) crystals, yielding an equilibrium pressure of 610 ± 100 MPa and a temperature of 820 ± 50 °C (Table 2). The euhedral biotite (Bt₁) with an X_{Mg} value of 0.40 coexists with Opx₁, Opx₂ and Grt₁, Grt₂ crystals, which yield temperatures of 780 ± 60 °C and 770 ± 25 °C, respectively (Table 2). K-feldspar generally is the latest phase in peraluminous magma systems (Clemens and Birch 2012; Scaillet et al. 2016), thus it is inferred to co-crystallize with the rim of plagioclase. The two-feldspar thermometry using compositions of plagioclase rim (Pl₁ rim) and K-feldspar core (Kfs₁ core) yields a crystallization temperature of $\sim 630 \pm 50$ °C. The small (10–100 μ m), globular Grt₃ (with an average grossular value of 6.1 mol%) distributes along the grain boundaries between orthopyroxene/biotite/ilmenite and plagioclase (Pl2 with an average An value of 35.4). The compositions of Opx1, Opx2 rim combined with compositions of Grt₃, Pl₂, and Qz₃ yield a pressure of 710 ± 100 MPa and a temperature of 750 ± 50 °C (Table 2). The compositions of Bt₁, Bt₂, and the compositions of Grt₃ yield a temperature of 720 ± 25 °C. The detailed temperatures and pressures obtained from various thermobarometers are listed in Table 2.

RHYOLITE-MELTS MODELING

Rhyolite-MELTS, a modified calibration of the original MELTS modeling, is designed to better capture the quartz and K-feldspar saturation surfaces for high-accuracy modeling of silicic magmas (Ghiorso and Sack 1995; Gualda et al. 2012). It was mainly developed for metaluminous, silicic magma systems with crystallinities of <50% (Gualda et al. 2012), and has been widely applied to volcanic rocks at ≤200 MPa pressures (Bachmann et al. 2012; Gualda and Ghiorso 2013; Pamukcu et al. 2013). Although the uncertainties of this modeling have been evaluated by comparison with experimentally determined phase relationships (Gardner et al. 2014), these evaluations involved metaluminous compositions at ≤200 MPa pressures. The uncertainties remain unknown when applied to peraluminous, silicic magma systems at higher pressures (>200 MPa). In this section, the rhyolite-MELTS modeling results (Gualda et al. 2012; Ghiorso and Gualda 2015) are first rigorously evaluated by comparison with the experimental data of a peraluminous system (Clemens and Birch 2012), then applied to the case of the Yunlu charnockite to simulate its geochemical variation and phase relationship.

Evaluation of uncertainties

A peraluminous, garnet-bearing ignimbrite (LMI 9399, Table 3), the starting material in experiments of Clemens and Birch (2012), was chosen as the initial composition for modeling and the pressure was set at 500 MPa to facilitate the comparison. As shown in Figure 7, the plagioclase and quartz saturated curves in the modeling are consistent with the experimentally determined curves with differences of <60 °C irrespective of H₂O contents. For the K-feldspar, the modeling of the saturated curve matches the experimentally determined boundary within ~20 °C at low H₂O (<6.0 wt%) contents, while the differences increase to 80 °C at high H2O (~8.0 wt%) contents. The modeled garnet curve is consistent with the experimentally determined curve with a difference of <50 °C at >5.5 wt% H₂O but is predicted at ~100 °C below the experimentally determined curve at ~5.0 wt% H₂O. The modeling of the saturated curve of biotite is lower than the experimentally determined curve with a difference of >100 °C at both low and high H₂O contents. Similarly, the modeled saturated curve of orthopyroxene-in is higher than



FIGURE 7. T-H₂O in melt diagram of comparison phase relations determined by rhyolite-MELTS modeling and those determined in crystallization experiments reported by Clemens and Birch (2012). The sub-vertical, stippled lines are the calculated isopleths for the concentration of H2O dissolved in the melt (Newman and Lowenstern 2002). The thickened, dotted curves are the phase boundaries determined by Clemens and Birch (2012), while the thickened, solid curves are the modeled phase boundaries for various initial H₂O contents (2.0-7.0 wt%) constrained by rhyolite-MELTS modeling. The modeled phase boundaries of various minerals are made by the following procedure. We first constrain the equilibrium crystallization processes of initial composition under various initial H2O contents, while the pressure and oxygen fugacity remain constant. We then plot the crystallization path (fitted by saturated points of various minerals) according to the temperatures and H₂O contents in melts for each crystallizing mineral. Finally, the phase-saturated points of same minerals for various initial H₂O contents are fitted to yield a curve, which is the mineral saturated boundary shown by thickened, solid curves. The phase-saturated boundaries of other minerals are also made by this method. (Color online.)

TABLE 2. Temperature and pressure results of the Yunlu garnet-bearing charnockite

Stage	Method		Pressure (MPa)					
		Grt-Opx	Grt-Bt	Bt-Opx	1	Two-feldspar therm	Grt-Opx-PI-Qz	
		thermometry	thermometry	thermometry	Ghiorso (1984)	Fuhrman and Lindsley (1988)	Elkins and Grove (1990)	barometry
Magmatic	Mineral pairs	Grt _{1,2} -Opx _{1,2}	Grt _{1,2} -Bt ₁	Bt ₁ -Opx _{1,2}	Pl₁ rim-Kfs₁ core			Grt _{1,2} -Opx _{1,2} -
crystallization	Results	820	770	780	642	623	630	PI ₁ -Qz ₁ 610
Metamorphic	Mineral pairs	Grt ₃ -Opx _{1.2}	Grt ₃ -Bt _{1.2}	-	_			Grt ₃ -Opx _{1.2}
overprint		rim	rim					rim-Pl ₂ -Qz ₃
	Results	750	720					710

Notes: Grt-Opx thermometry and Grt-Opx-PI-Qz barometry (Bhattacharya et al. 1991); Grt-Bt thermometry (Holdaway 2000); Opx-Bt thermometry (Wu et al. 1999; Fuhrman and Lindsley 1988; Elkins and Grove 1990). Note that in order to avoid the diffusion re-equilibrium result from cooling and later metamorphic overprint, only the core and mantle compositions of the $Grt_{1,2}$, $Opx_{1,2}$, and Bt_1 crystals with grain size ≥ 4 mm are chosen for thermometric calculations in magmatic crystallization. In addition, considering the K-Na inter-diffusion in K-feldspar, only the big Kfs₁ core compositions with grain size ≥ 10 mm are used for thermometric calculation.

TABLE 3. Starting materials used for thermodynamic modeling

					5						
Sample	SiO ₂	TiO ₂	AI_2O_3	FeO*	MnO	MgO	CaO	Na₂O	K ₂ O	ASI	Mg#
LMI 9399	69.83	0.65	14.75	4.21	0.05	1.50	2.76	2.45	3.79	1.11	38.9
D19-4	68.65	0.76	14.36	4.88	0.10	1.86	3.92	2.43	1.63	1.12	40.7
MC01	68.16	0.85	14.14	4.94	0.07	1.59	2.67	2.74	3.20	1.10	36.7
		(a)	1.0.1.1.4.0.0		1						1 6 4 4 4 4

Notes: Sample LMI 9399 is from Clemens and Birch (2012), while sample D19-4 is from Wang et al. (2013c). The hypothetical sample MC01 is composed of 60% most mafic charnockite 15GZ19 and 40% minimum melt composition. See text for detailed description.

the experimentally determined saturated curve with a difference of >100 °C. However, the orthopyroxene-out saturated curve is predicted at ~50 °C below the experimentally constrained curve irrespective of H_2O contents.

In summary, the rhyolite-MELTS modeling can predict phase relationships for quartz and two feldspars within the acceptable differences of ~20–60 °C irrespective of H₂O contents, except for the slightly larger difference of ~80 °C for K-feldspar at 8.0 wt% H₂O contents. Meanwhile, the orthopyroxene-out saturated curve is well predicted by rhyolite-MELTS with the temperature differences <50 °C. The modeling results do, however, poorly constrain the phase relationships for the garnet, biotite, and orthopyroxene-in. The modeling results are consistent with the evaluation of Gardner et al. (2014), who concluded that the rhyolite-MELTS could not always predict the saturated curves of ferromagnesian minerals exactly. This may result from the deficiencies of thermodynamic data of H₂O-rich silicate liquids and activity-composition models for ferromagnesian mineral phases (i.e., pyroxene, garnet, and biotite).

Modeling the geochemical variation of the Yunlu charnockite

Whole-rock compositions of the studied samples are generally used as input parameters of the system's initial composition to constrain the phase relationship utilizing thermodynamic modeling. This appears to be an over-simplification because the wholerock composition may be modified by various processes (e.g., Zhao et al. 2018). For the Yunlu charnockite, the major element compositions are more mafic compared with the metasedimentderived experimental melts (Fig. 8), suggesting that whole-rock compositions of charnockite samples have deviated from primary melt compositions. The more mafic compositions of the Yunlu charnockite are likely caused by involvement of significant cumulate components (see below discussion), although mixing with more mafic magmas or entrainment of restitic materials may also have played minor roles as reflected by the homogeneous, enriched Nd-Hf isotopic compositions and the absence of restitic components (Wang et al. 2013c; Qiu et al. 2018).

Here, we model the continuous compositional variation trend for the Yunlu charnockite based on an in situ (incremental) fractional crystallization process (Nishimura and Yanagi 2000; Hertogen and Mareels 2016; Zhao et al. 2018). In the modeling, the incremental fractionation with cumulate formation and melt extraction in a solidification front is considered by mass-balance calculation (see details in Online Material¹). Mass-balance equations were solved in a step-wise fashion to model such incremental fractionation. The interstitial melt composition in the solidification front at each step is acquired by rhyolite-MELTS modeling, i.e., by determining the melt composition at the critical crystallinity of 40%. The geochemical modeling requires initial composition and H₂O contents as input parameters, while the former remains unknown and the latter are likely at a range of 2.0-5.0 wt% for typical peraluminous charnockites (Shimura et al. 1992; Zhao et al. 2017). We thus vary the initial compositions and H2O contents to best fit the variation of the whole-rock data. The initial H2O contents of 2.0 and 4.0 wt% are selected as representatives. The most felsic charnockite sample D19-4 (with a SiO₂ content of 68.65 wt%; Table 3) is selected as a candidate because it has the most approximate composition with the metasediment-derived experimental melts (Fig. 8). The most mafic charnockite sample 15GZ19 with a SiO₂ content of ~63.12 wt% may have experienced a significant amount of melt loss, e.g., as high as 40% (Zhao et al. 2018; Online Material¹ Table OM3). The primary composition may be approximated through adding ~40% interstitial minimum melt into the wholerock composition of sample 15GZ19. The interstitial minimum melt is the average chemical composition of Tilmunda granite in the New England batholith, whose compositions are plotted very close to the minimum melting point in the Q-An-Or ternary system (White and Chappell 1977; Online Material¹ Table OM5). We note that such a method cannot precisely reconstruct the primary magma composition but can at least provide a feasible way. Details of the model descriptions are provided in Online Material¹, while the results are given in Online Material¹ Table OM5 and summarized in Figure 8.

Our geochemical modeling results show that initial compositions and H₂O contents control the modeled compositional trend. For instance, sample D19-4 has distinct higher CaO and lower Na₂O contents compared to sample MC01, which results in the obviously different modeled CaO and K2O content variations (Fig. 8). In addition, the modeled SiO₂ and MgO contents of sample D19-4 with a 2.0 wt% initial H2O content are significantly higher than sample D19-4 with 4.0 wt% H2O. In other words, sample D19-4 with a high-H2O content (4.0 wt%) defines a better fit to the Yunlu charnockites compared to the same sample with a low-H₂O content (2.0 wt%). This comparison suggests that the Yunlu charnockite should contain higher H₂O contents. Compared with sample D19-4, the virtual sample MC01 could better match the compositional variation of the Yunlu charnockite, although it shows slightly higher (by <0.5 wt%) modeled TiO2 and slightly lower (by <1.0 wt%) CaO contents than natural whole-rock contents (Fig. 8). The modeling result of MC01 predicts that the cumulate pile composition (cumulus solid plus unextracted melt) has ~63.30 to 68.97 wt% SiO2, which matches the range of the Yunlu whole-rock SiO2 contents. Meanwhile, it also best fits the compositional variation of FeO, MgO, Na2O, and Al₂O₃ contents of the Yunlu charnockite (Fig. 8).

Modeling the phase relationship of the Yunlu charnockite

The thermodynamic modeling requires a series of input parameters, e.g., initial whole-rock composition, fluid composition, pressure, and temperature. Fractional crystallization modeling in "Modeling the geochemical variation of the Yunlu charnockite" section has shown that the virtual composition MC01 is a suitable initial whole-rock composition used for thermodynamic modeling. For the initial H₂O content, we use a range of H₂O contents from 2.0 to 5.0 wt% with an interval of 1.0 wt% in the modeling. The effect of CO₂ is also considered to determine its effects on mineral phase relationships and evolutional paths of mixed CO2-H2O fluids. Five different initial CO2 contents (100, 500, 1000, 2000, and 3000 ppm) are employed in the modeling. The pressure is set at 600 MPa based on our barometric estimates. The crystallization temperature started at 1100 °C and ended at 630 °C, with an interval of 10 °C. Given that the Yunlu charnockite contains accessory ilmenite and pyrrhotite without magnetite, the oxygen fugacity is restricted



FIGURE 8. (a–f) Harker diagrams showing the major element compositions of the Yunlu charnockite (blue circle) and the modeled compositional evolution for incremental fractionation (lines with different colors). D19-4 is the most felsic charnockite in Yunlu pluton, while MC01 is the synthetic composition that consists of 60% charnockite 15GZ19 and 40% interstitial melt (Table 3; Online Material¹ Table OM5). See the Online Material¹ for detailed descriptions. The green area represents the compositions of experimental melt derived from meta-sedimentary rocks (Online Material¹ Table OM4). (Color online.)

to FMQ-1 (the fayalite-magnetite-quartz buffer assemblage) (Clemens and Birch 2012).

The modeling results are shown in Figures 9 and 10 and listed in Online Material¹ Tables OM6 and OM7. Results of the mixed H_2O-CO_2 fluid simulations show that the different initial CO_2 contents with fixed H_2O contents (4.0 wt%) have a substantial effect on the solidus temperature of the magma, e.g., ~820 °C with 0.3 wt% CO₂, ~720 °C with 0.2 wt% CO₂, and ~630 °C with 0.1 wt% CO₂. The exsolved fluid composition is CO₂-rich at 0.3 wt% $CO_2 + 4.0$ wt% H_2O conditions and contains 55 mol% CO_2 at near-solidus conditions. Under 0.2 wt% $CO_2 + 4.0$ wt% H_2O conditions, the fluids exsolved from the magma are gradually CO_2 -poor and H_2O -rich, which contain 20 mol% CO_2 at nearsolidus conditions. Under 0.1 wt% $CO_2 + 4.0$ wt% H_2O conditions, the fluid evolves to become more H_2O -rich as the system crystalizes, and the fluid eventually contains ~90 mol% H_2O at near H_2O -saturated solidus temperatures. The modeling results indicate that the granitic systems commonly evolve toward a



FIGURE 9. (a) Rhyolite-MELTS modeling results of H_2O-CO_2 evolution paths during magma crystallization at different initial H_2O+CO_2 contents. The filled- and open-symbols on lines with different colors represent the CO_2 and H_2O evolutional curves, respectively. All the modeling results are presented in Online Material¹ Table OM6. The solidus temperature is calculated by the methods from Papale et al. (2006) and Newman and Lowenstern (2002). (Color online.)

CO₂-rich, H₂O-rich fluid composition at near-solidus temperatures when the magma contains ≤ 0.1 wt% initial CO₂ content.

At different initial melt H₂O contents without CO₂, orthopyroxene is always a liquidus phase, while the liquidus temperature is variable, i.e., it decreases from 1117 °C at 2.0 wt% initial H2O, over 1097 and 1077 °C at 3.0 and 4.0 wt% initial H₂O, respectively, to 1067 °C at 5.0 wt% initial H₂O (Fig. 10). Orthopyroxene disappears at ~777 °C at 2.0-5.0 wt% initial H₂O. The modeling predicts that garnet starts to crystallize at 857-887 °C at 2.0-5.0 wt% initial H2O and down to H₂O-saturated solidus conditions at ~630 °C. It also predicts that biotite starts to saturate at 777 °C at 2.0-5.0 wt% initial H₂O (Fig. 10). Initial H₂O contents significantly influence the liqudus curves of quartz and plagioclase. Quartz and plagioclase saturation temperatures decrease from 927 and 977 °C at 2.0 wt% initial H2O, over 877-837 and 927-877 °C at 3.0-4.0 wt% initial H2O, to 817 °C at 5.0 wt% initial H2O (Fig. 10). K-feldspar is predicted to crystallize at 807–737 °C at 2.0–5.0 wt% initial H2O, and thus it is the last phase to crystallize. Melt H₂O exhibits obviously incompatible characteristics during crystallization, and it reaches saturation at ~717 °C irrespective of H₂O content (Fig. 10). The H₂O-saturated solidus is fixed at 630 °C using the experimental data of Clemens and Birch (2012) and Clemens and Phillips (2014).



FIGURE 10. (a–d) Rhyolite-MELTS modeling results of mineral crystallization sequences and water concentration in the residual melts of the sample MC01 (Gualda et al. 2012; Gualda and Ghiorso 2015) assuming initial H_2O contents of 2.0–5.0 wt%. The H_2O -saturated content is restricted to 10.0 wt% according to Tamic et al. (2001) and Holtz et al. (2001). (Color online.)

DISCUSSION

The Yunlu garnet-bearing charnockite: Genetic type and metamorphic overprint

Igneous or metamorphic origin? The charnockite could have either an igneous or a metamorphic origin depending on whether orthopyroxene crystallized directly from melt or formed by solid-state dehydration reaction during granulite-facies metamorphism (Frost and Frost 2008). The Yunlu charnockite lacks oriented structures such as foliation and lineation. No small (tens to hundreds of centimeters) irregular patches or veins of charnockite, which are the diagnostic characteristics of metamorphic charnockite, are found on the field outcrops (Newton and Tsunogae 2014). In addition, the xenoliths in the Yunlu charnockite were most likely captured when the host magma (charnockite) ascended and solidified (Fig. 2a). The reaction textures that group 2 biotite and quartz crystals ($Bt_2 + Qz_2$) surround, or the orthopyroxene (Opx1 and Opx2) and garnet (Grt1+Grt2) crystals that they replace, indicate hydrous crystallization reaction during the magmatic stage (Figs. 2c-2e) (Beard et al. 2004, 2005). The euhedral to subhedral, tabular plagioclase crystals form a skeleton texture, which is filled by anhedral, interstitial quartz crystals (Fig. 2f; Online Material¹ Fig. OM1b, OM1d, and OM1f). The plagioclase crystals are characterized by normal anorthite zoning (Fig. 5e;). The plagioclase inclusions hosted in large plagioclase crystals (Online Material¹ Fig. OM1a, OM1c, and OM1e) are typically euhedral in the Yunlu charnockite, retaining shapes that indicate growth in a melt-rich environment. Furthermore, the Grt_{1and2}, Opx_{1and2}, and Bt_{1and2} porphyroblasts in granulites are euhedral to anhedral rather than rounded or anhedral (Figs. 2d and 2e), and they share similar chemical compositions to those of igneous origin (see below). All of the above favor an igneous origin for the Yunlu charnockite.

The Grt₁ and Grt₂ crystals have identical major element compositions and are classified as almandite. They have low CaO and MnO contents, similar to those of the garnets from S-type granitoids (Fig. 4e). Several pieces of petrographic and geochemical evidence indicate that the Grt1 and Grt2 crystals are of magmatic origin. (1) They exhibit euhedral shapes with few mineral inclusions rather than the anhedral shapes (porphyroblast) or inclusion-rich peritectic or metamorphic garnets from granulite and migmatite (Fig. 2e) (Acosta-Vigil et al. 2014; Dorais et al. 2009; Dorais and Tubrett 2012; Dorais and Spencer 2014). (2) The compositional profiles of individual garnet grains reveal the near-flat major element features from core to mantle, apart from a thin Ca-rich rim (~30 µm) (Figs. 4a and 4c). These flat patterns are usually considered to indicate a high temperature, magmatic origin, unlike the metamorphic garnet that shows bell-shaped Mn compositional zoning (Dahlquist et al. 2007; Xia and Zhou 2017). (3) The REE patterns of the Grt₁ and Grt₂ crystals are comparable to those of the magmatic garnet from typical S-type granites (Rong et al. 2018; Fig. 4d). (4) The absence of sillimanite in the Yunlu charnockite also supports a magmatic origin of the garnet as the peritectic garnet commonly coexists with various prograde metamorphic minerals such as sillimanite (Dorais and Tubrett 2012). Furthermore, the Grt₂ crystals were partly replaced, or surrounded by, anhedral $Bt_2 + Qz_2$ intergrowths around the grain boundaries, indicating a hydration crystallization reaction between magmatic garnet and residual H_2O - and K_2O -rich melt (Beard et al. 2004, 2005) (Fig. 2e). In addition, the different MnO contents of garnets from charnockite (Grt₁ and Grt₂) and the Bt-Grt gneiss xenolith also exclude the possibility that Grt₁ and Grt₂ are xenocrysts (Fig. 4e). The slightly humped REE patterns toward the rims of Grt₁ crystals may have resulted from preferential depletion of HREEs from the rock-magma matrix during progressive garnet growth (Yu and Lee 2016).

The orthopyroxene crystals (Opx1 and Opx2; Figs. 2c and 2d) in Yunlu garnet-bearing charnockite are euhedral-anhedral with size of 0.5-6 mm. The Opx1 crystals are mainly euhedral, which is different from the orthopyroxenes in granulites with their subhedral to anhedral shapes and restricted grain sizes (Harley 1985; Tang et al. 2017). They are classified as ferro-hypersthene (Fs = 49-56) according to classification scheme of Morimoto (1988), and resemble orthopyroxenes that crystallized from crust-derived felsic rocks (Clemens and Birch 2012; Shimura et al. 1992). The orthopyroxene crystals have low Al₂O₃ contents with X_{Al} values of 0.012–0.086 and X_{Mg} values of 0.44–0.50, matching the magmatic orthopyroxenes from igneous charnockite (Fig. 5a). The mineral paragenesis between orthopyroxene and biotite (orthopyroxene is commonly replaced/surrounded by biotite) also precludes a metamorphic origin (Figs. 2c-2e). Although Chen and Zhuang (1994) identified both restitic and magmatic orthopyroxene based on their crystal shapes and mineral inclusions, they have indistinguishable compositions (Fig. 5a). In addition, the minerals that form inclusions (biotite and plagioclase) in the orthopyroxene crystals are the same, both in terms of assemblage and composition, as those forming crystals in the charnockite (Online Material¹ Table OM1; Fig. 5d). This strongly supports a magmatic origin for both groups. The analyzed orthopyroxenes display MREE-enriched patterns, which are different from the peritectic orthopyroxenes in granulite (Fig. 5b). The unusually low HREE contents of Opx1 may be caused by the coexistence of Grt1 that consumed a significant proportion of HREEs from the magma.

The biotites of garnet-bearing charnockite have different geochemical characteristics from those of Grt-Bt gneiss and gneissic granite xenoliths, ruling out the possibility that Bt1 and Bt₂ are xenocrysts (Online Material¹ Table OM1). Bt₁ and Bt₂ have identical compositions irrespective of their occurrences (Fig. 5d). The Bt₁ crystals have euhedral shape and seldom contain mineral inclusions, which indicates a magmatic origin. The Bt₂ crystals exhibit anhedral shapes and replace euhedral Opx₁/Grt₁ crystals with Qz₂, forming an intergrowth texture (Figs. 2c and 2e). The presence of orthopyroxene/garnet and ilmenite relicts in Bt₂ and the titaniferous nature of biotite also favor a hydration crystallization reaction, i.e., orthopyroxene/garnet + ilmenite + melt \rightarrow biotite + quartz (Clemens and Wall 1988; Shimura et al. 1992; Bhowmik et al. 2009). To summarize, we believe that the Yunlu garnet-bearing charnockite is of igneous origin based on evidence from field outcrops, petrography, and mineral chemistry.

Metamorphic overprint. The metamorphic overprint on Yunlu igneous charnockite is documented by the occurrences of garnet (Grt₃) + quartz (Qz₃) \pm K-feldspar (Kfs₂) corona/ symplectite textures at boundaries between plagioclase and ferromagnesian minerals (orthopyroxene, biotite, and ilmenite). The reactions are as follows:

 $\begin{array}{l} Orthopyroxene \ (Opx_{1and2}) + plagioclase \ (Pl_2) \rightarrow \\ quartz \ (Qz_3) + garnet \ (Grt_3) \quad (1) \\ Biotite \ (Bt_{1and2}) + plagioclase \ (Pl_2) \rightarrow \end{array}$

 $\begin{array}{l} \mbox{quartz} \ (Qz_3) + \mbox{garnet} \ (Grt_3) + \mbox{K-feldspar} \ (Kfs_2) \ (2) \\ \mbox{Ilmenite} \ (Ilm) + \mbox{plagioclase} \ (Pl_2) \rightarrow \mbox{quartz} \ (Qz_3) + \mbox{garnet} \ (Grt_3) \ (3) \end{array}$

All of the Grt₃ crystals in reactions 1–3 have lower MgO but higher CaO contents compared to Grt1 and Grt2 crystals (Fig. 4f). Meanwhile, although the Grt3 crystals exhibit a range of REE patterns following reactions 1-3, they generally exhibit higher LREE and lower HREE contents than Grt1 and Grt2 (Fig. 4d). This may be related to the different REE contents of the reactive minerals (e.g., ilmenite, biotite, and orthopyroxene). The geochemical characteristics, mineral distributions/occurrences and paragenesis clearly support a sub-solidus (metamorphic) origin for the Grt₃ (Harley 1989). The Kfs₂ is anhedral (10-30 µm), associated with Grt₂ and Qz₃ and with Or contents of 91-94, and the Qz₃ coexists with Grt₃ and Kfs₂, with a size range of 20-50 µm. In view of grain size, shape, distribution, and chemical composition, we consider Qz₃ and Kfs₂ are both metamorphic origins (Figs. 3a-3d). The Grt3 has higher grossular but lower pyrope contents than Grt₁ and Grt₂, revealing an increase in pressure and decrease in temperature (Green 1976, 1977, 1992). The estimated P-T conditions of 710 ± 100 MPa and $720-750 \pm 50$ °C (Table 2) indicate a biotite dehydration reaction 2 during amphibolite-facies prograde metamorphism (Bhowmik et al. 2009). Despite the estimated P-T conditions for metamorphic overprint are indistinguishable within uncertainties of thermobarometry from the estimated magmatic crystallization conditions at 610 ± 100 MPa and $780-820 \pm 60$ °C, it does not mean that the Yunlu charnockite has been totally reset or re-equilibrated by the metamorphic overprint. This is verified by the mineral zoning, e.g., oscillatory An zoning of magmatic Pl1 and Ca-rich zoning of Grt1 (Figs. 4c and 4e), and different mineral compositions of magmatic from metamorphic minerals, e.g., higher MgO, but lower CaO content for magmatic garnet (Grt₁ and Grt₂), and higher anorthite contents of the magmatic plagioclase (Pl₁).

Several lines of micro-textural evidence also suggest that the influence of the amphibolite-facies metamorphic overprint is very limited, only forming the corona/symplectite texture at mineral boundaries (Fig. 3), but the igneous micro-textural and mineral chemical characteristics related to magmatic processes are largely preserved. Under the optical microscope, no pervasive granoblastic or re-equilibrium (sub-solidus grain-shape adjustment) textures have been observed in Yunlu charnockite. The polygonal crystal aggregate composed of quartz and plagioclase is minor in thin sections. Instead, the rock exhibits micro-textures typical of granitic rocks [Figs. 2c-2f; Online Material¹ Fig. OM1; Vernon and Paterson (2008), Vernon (2010)]. No inclusions of quartz and plagioclase with rounded shapes were identified. The rounded inclusions provide evidence for adjustment of their boundaries toward low energy configurations through the minimization of the interfacial area in granulites (Vernon 1968, 1999). No dehydration or melting reaction micro-textures that resemble those of metamorphic charnockite or granulite are observed in thin sections (Tang et al. 2017). This observation precludes the strong metamorphic overprint of the Yunlu charnockite, in which the biotite is replaced by orthopyroxene as a result of dehydration reactions during granulite-facies metamorphism (Vernon 2004). The general preservation of An normal and oscillatory zoning in plagioclase excludes extensive recrystallization or grainboundary migration, as it would then be truncated or obliterated in granulite-facies metamorphism (Holness et al. 2018). Finally, the monazite crystals enclosed by Grt₃ record a late Devonian age (~370 Ma; Chen et al. 2012), while the zircons in garnetbearing charnockite do not have overgrowths and yield an early Paleozoic age [~430 Ma; Wang et al. (2013c); Online Material¹ Fig. OM2]. This suggests that the temperature of metamorphic overprint is enough to reset the monazite U-Pb systematics with a closure temperature of 600-700 °C, but not enough to reset the zircon U-Pb systematics with a higher closure temperature of 750-850 °C (Corfu 1988; Cherniak and Watson 2003; Smith and Giletti 1997). The metamorphic overprint likely has a temperature range of 700-750 °C, consistent with our estimation for metamorphic overprint at $720-750 \pm 50$ °C (see Table 2).

To quantitively evaluate the influence of metamorphic event superimposed on the mineral compositions in the Yunlu charnockite, we carry out a series of calculations to estimate the duration of the metamorphic event and diffusion lengths of key elements (used in thermobarometers) in various minerals. Details of the modeling method and results are described in the Online Material¹. The results suggest that Ca-diffusion modeling of Grt1 compositional profile constrains the timescale of the late Devonian metamorphic event on an order of 0.2-0.5 Ma (Fig. 11a), which is consistent with the timescale for an extremely short-duration metamorphism [<1.0 Ma; Viete and Lister (2017)]. Under given metamorphic P-T condition (750 °C, 710 MPa) and maximum duration of ~0.5 Ma, we quantitatively evaluate the Fe-Mg inter-diffusion lengths in mafic minerals (garnet, orthopyroxene, and biotite), CaAl-NaSi interdiffusion length in plagioclase and Na-K inter-diffusion length in K-feldspar. The calculation parameters and results are shown in Figure 11b and Online Material¹. The calculated results show that only rim (<100 µm) of the mafic minerals are influenced and reset by this thermal disturbance. The calculated diffusion distance in K-feldspar is ~4.0 mm because of the fast Na-K inter-diffusion, while that in plagioclase is <1.0 µm because of the extremely slow CaAl-NaSi inter-diffusion. Therefore, it is believed that the magmatic crystallized compositions of the mafic minerals, plagioclase, and core of big K-feldspar crystals (grain size >10 mm) are well preserved and have not reset by metamorphic overprint.

The identification of a \sim 370 Ma amphibolite-facies metamorphic overprint in the Yunlu igneous charnockite supports a regional thermal event in late Devonian. It has been also recognized in the rare metamorphic rocks (e.g., schist, gneiss, migmatite, amphibolite) exposed in northeastern region of the Cathaysia Block (Chen et al. 2018). However, the \sim 370 Ma thermal activity was mostly recorded by secondary monazites of rare metamorphic rocks and detrital zircons from Permian sedimentary rocks (Chen et al. 2018; Li et al. 2012). There are no reports of \sim 370 Ma felsic magmatism, and the coeval mafic magmatism was only found in the southern Zhejiang (an amphibolite with a Late Devonian crystallization age of \sim 370 Ma; Chen et al. 2018). The extremely short-duration of the late Devonian metamorphic event is generally interpreted as a result of local thermal turbulence with rapid tectonic burial and exhumation of relatively thin tectonic slices (Spear 2014). Nevertheless, more attention is needed to decipher the details of tectonic activity and thermal evolution in late Paleozoic.

Reconstruction of the crystallization processes

Magmatic fluids play an important role in magmatic crystallization (Scaillet et al. 2016; Scaillet and Macdonald 2001; Dall'Agnol et al. 1999; Costa et al. 2004). If granitic magma contains fluids with low H2O activity, it solidifies under "hot" and "dry" conditions (Anderson et al. 2003; Harlov et al. 2013), e.g., at an elevated solidus temperature of 800-850 °C and low water activities of 0.3-0.5 at a pressure of ~400 MPa for the Thor Range intrusive complex from Antarctica (Bucher and Frost 2006). Conversely, if the granitic magma evolves under H2O-rich fluid conditions, it will solidify at relatively "cold" and "wet" conditions (Shimura et al. 1992; Clemens and Birch 2012), e.g., under H2O-saturated solidus conditions of ~670 °C and ~200 MPa for the peraluminous Jiuzhou charnockite from South China (Zhao et al. 2017). For the Yunlu garnet-bearing charnockite, fluid inclusions are not ubiquitous. Thirteen inclusions have been observed in both Qz1 and Qz2, and they are mostly H2O-rich monophase inclusions (Fig. 6b). Only one inclusion in Qz₁ is characterized by a CO₂-H₂O mixture (Fig. 6a), implying that the CO₂ is a minor component in the fluid compositions of the Yunlu charnockite. This observation is consistent with the modeling results shown in Figure 9, which suggests that the exsolved fluids are CO2-poor $(\sim 10 \text{ mol}\% \text{ CO}_2 + \sim 90 \text{ mol}\% \text{ H}_2\text{O})$ at near-solidus temperatures under 0.1 wt% CO2 + 4.0 wt% H2O conditions. Therefore, the scarcity of CO2-rich fluid and enrichment of H2O-rich fluid suggest the Yunlu magma may contain ≤0.1 wt% CO₂. According to the experimentally determined isobaric curve of mixed H₂O-CO₂ in the rhyolitic melt at 600 MPa, the CO₂ contents with ≤0.1 wt% have little influence on the H₂O solubility in rhyolitic melts (Papale et al. 2006; Duan 2014). We thus posit that H₂O was the dominant fluid that controlled the phase relationships and solidus temperature of the Yunlu charnockite.

Quartz and plagioclase stability fields shrink with increasing initial melt H₂O content (Fig. 10; Clemens and Birch 2012; Clemens and Phillips 2014). According to the experimental data, quartz and plagioclase crystallize earlier than garnet at melt H2O of <3.0 wt%, while they crystallize later than garnet at ≥ 3.0 wt% melt H₂O at 500 MPa (T-X^{Fl}H₂O diagram Fig. 14 of Clemens and Birch 2012). Our rhyolite-MELTS modeling also requires that the quartz and plagioclase crystallize later than garnet at ≥ 4.0 wt% melt H₂O at ~600 MPa (Fig. 10). In the Yunlu charnockite, magmatic garnet is euhedral and seldom contains euhedral quartz and plagioclase inclusions, indicating that garnet crystallizes earlier than, or at the same time as, quartz and plagioclase. The initial melt H₂O thus should be ~4.0 wt% according to the phase relationship modeling (Fig. 10). Furthermore, the geochemical modeling results in "Modeling the geochemical variation of the Yunlu charnockite" above also suggest a relatively high-H₂O content (4.0 wt%). Therefore, we infer that the initial H₂O content of Yunlu charnockite is ~4.0 wt%.

As discussed in "Evaluation of uncertainties" above, the rhyolite-MELTS modeling cannot be used to predict accurately the saturation temperatures of ferromagnesian minerals, given the errors of ≥ 100 °C. The chosen sample MC01 in our modeling has a similar composition to that of the starting material LMI 9399 in experiments of Clemens and Birch (2012) (Table 3). They have similar SiO₂ contents (69.83 vs. 68.15 wt%), ASI (1.11 vs. 1.10), and Mg# values (38.9 vs. 36.7), and the pressures are also similar (600 vs. 500 MPa). Moreover, the oxygen fugacity in both our rhyolite-MELTS modeling and crystallization experiments of Clemens and Birch (2012) is QFM-1. Given their similarities, the phase relationships of ferromagnesian minerals in experiments of Clemens and Birch (2012) are used to calibrate the rhyolite-MELTS modeling results in the following discussions.

At 4.0 wt% initial H_2O (Fig.10c), the orthopyroxene-in temperature is ~1077 °C according to rhyolite-MELTS modeling,



FIGURE 11. (a) Model diffusion profiles of a grossular content in Grt_1 at various timescales at given diffusion coefficients compared with measured profile in garnet rim. (b) Diffusion length (m) as a function of time (year). Blue solid lines indicate the diffusion coefficients. The given inter-diffusion coefficients of various elements in minerals are shown in Online Material¹ Table OM1. (Color online.)

which, however, is an unrealistic result for the granitic systems. Accordingly, the orthopyroxene-in temperature is adjusted to 950 °C based on the experimental data from Clemens and Birch (2012). The rhyolite-MELTS modeling predicts that orthopyroxene is stable until the temperature decreases to ~777 °C, which is similar to ~800 °C at 500 MPa for LMI 9399 in Clemens and Birch's experiments. Garnet starts to crystallize at ~887 °C and is stable down to the solidus temperature as predicted by the rhyolite-MELTS modeling (Fig. 10c). This estimate is close to the saturation temperature at ~920 °C of LMI 9399 in the experimental study of Clemens and Birch (2012). Biotite is predicted to crystallize at ~777 °C. This value is constrained by the rhyolite-MELTS modeling at 4.0 wt% initial H₂O (Fig. 10c), which is a significant underestimate (>100 °C) compared to the experimental value. As with the orthopyroxene, the biotite saturated temperature is calibrated to 870 °C on the basis of experimental results from Clemens and Birch (2012). The garnetorthopyroxene ($Grt_{1,2}$ -Opx_{1,2}), orthopyroxene-biotite ($Opx_{1,2}$ -Bt₁), and garnet-biotite (Grt1.2-Bt1) thermometers nevertheless yield approximate temperatures of ~770-820 °C, implying that orthopyroxene, garnet, and biotite did not equilibrate at solidus temperatures (Fig. 12). Plagioclase and quartz are predicted to saturate at ~877 and ~837 °C, based on the rhyolite-MELTS modeling at 4.0 wt% initial H2O. This is simultaneous or slightly later than garnet. K-feldspar is the last phase to crystallize, and it saturates at ~757 °C in the modeling. Two-feldspar (Pl₁ rim-Kfs₁ core) thermometry constrains the temperature to ~ 630 °C, which is consistent with the solidus temperature determined by the experiments of Clemens and Birch (2012). The two-feldspar thermometry outlined above, combined with fluid inclusion compositions, indicate that the Yunlu magma solidified at the H₂O-saturated solidus (630 °C) at 600 MPa (Fig. 12). It is believed that the igneous charnockite usually represents a hightemperature ("hot"), H2O-unsaturated ("dry") magma because of the presence of orthopyroxene. However, the above temperature and melt H₂O content estimates demonstrate that the Yunlu garnet-bearing charnockite finally solidified under "cold" and "wet" conditions. In addition, the Yunlu charnockite contained high initial H₂O contents (~4.0 wt%). We propose that, at intermediate H₂O contents, the granitic magma could crystallize orthopyroxene as well, even if it may be consumed by residual melt to produce biotite + quartz ($Bt_2 + Qz_2$).

Melt extraction of the Yunlu garnet-bearing charnockite: Insight from mineral thermometry

Plutonic rocks commonly crystallize at slow cooling rates with prolonged crystallization histories compared with their volcanic counterparts (Holness et al. 2018), which allows more efficient element exchange and chemical equilibration between minerals and melt. Hence, the major element-based mineral-pair thermometers for intrusive rocks should record solidus or nearsolidus temperatures. However, a wealth of thermometric studies on some granitic batholiths yields a large range of temperature estimations (Shimura et al. 1992; Wang et al. 2018; Elliott et al. 1998; Moazzen and Droop 2005), indicating that equilibrium crystallization near the (H₂O-saturated) solidus may not always happen (Anderson 1996; Anderson et al. 2008). Disequilibrium may be caused by recharge of more primitive, high-temperature magma, which produces high-temperature domains within partial dissolution and/or resorption of minerals [e.g., orthopyroxene, garnet, and plagioclase (Day et al. 1992; Nixon 1988; Pietranik et al. 2006; Shcherbakov et al. 2011)]. Such disequilibrium features may be well preserved in shallow-emplaced granites and small volume intrusions [e.g., granitic dikes (Pietranik et al. 2006)].

For the Yunlu charnockite, the rhyolite-MELTS modeling and the two-feldspar thermometer constrain the solidus temperature of Yunlu charnockite at ~630 °C, which is consistent with the experimentally determined H2O-saturated solidus temperature of granitic rocks of ~600-650 °C at 600 MPa (Johannes and Holtz 1996; Ebadi and Johannes 1991; Huang and Wyllie 1973; Tuttle and Bowen 1958). Nevertheless, garnet-orthopyroxene, garnetbiotite, and orthopyroxene-biotite Fe-Mg exchange thermometers yield temperatures of $\sim 820 \pm 50$, $\sim 770 \pm 50$, and $\sim 780 \pm 60$ °C, respectively, which are significantly above the H2O-saturated solidus. The Mg# values of magmatic garnet and orthopyroxene $(Grt_{1,2} \text{ and } Opx_{1,2})$ lie along experimentally calibrated arrays, supporting equilibrated Fe-Mg partitioning between the early crystallized garnet and orthopyroxene (Fig. 5c). In other words, the early crystallized ferromagnesian minerals equilibrate at a temperature range of 770-820 °C, which instead equilibrate at the H₂O-saturated solidus (Fig. 12). The higher equilibrium temperature for the early crystallized ferromagnesian minerals is not likely caused by metamorphic overprint as suggested by the clear distinct mineral compositions between magmatic (Grt₁₂ and Pl₁) and metamorphic origin (Grt₃ and Pl₂) and compositional zoning of garnet and plagioclase (Figs. 4 and 5).

For the Yunlu charnockite with a depth of emplacement of ~20 km, a very slow cooling rate and prolonged crystallization process should be in favor of magma equilibrium at near-solidus



FIGURE 12. Crystallization sequences of different minerals along with the decrease of temperature (from liquidus to solidus) of sample MC01, given by rhyolite-MELTS modeling (4.0 wt% initial H_2O content). The mineral-saturated temperatures are constrained by modeling results of the rhyolite-MELTS coupled with experimental data from Clemens and Birch (2012). The temperature results yielded by various thermometers are marked in plot and the speculative melt extraction window is shown. See text for further discussion. (Color online.)

temperatures. The absence of partial dissolution and/or resorption texture as well as the Mg- or Ca-rich rims for the early crystallized minerals, e.g., garnet, orthopyroxene, plagioclase, and the normal An zoning of plagioclase further collectively suggest an closed-system, equilibrium crystallization of these early crystallized phases. Generally, the consistency temperatures derived from different Fe-Mg exchange thermometers could result from loss of a pervasive transport medium, such as a melt or fluid, because chemical equilibration is easy to achieve due to the fast diffusion rate in the interstitial melt (Pattison and Begin 1994a, 1994b). One possible hypothesis is that extraction of interstitial melt from a highly crystalline framework (the so-called "crystal mush") took place in the Yunlu magma chamber continuously at 770-820 °C, which physically segregates the crystallized minerals from the interstitial melt. This leads to pervasive contact among the minerals, thus chemical equilibrium is difficult to achieve because of the diffusion barrier at grain boundaries, especially when ferromagnesian minerals are in contact with quartz and feldspar (Pattison and Begin 1994a). Therefore, the compositions of the mafic minerals will be in equilibrium with co-existed interstitial melt at the temperature of melt extraction, which is constrained at ~780-820 °C with corresponding crystallinities of ~30-45% (the orthopyroxene will be consumed below 777 °C) (Figs. 10 and 12) (Bachmann and Bergantz 2004, 2006, 2008). After the majority of the interstitial melt is expulsed, the less amount of residual melt would crystallize K-feldspar and the overgrowths of the quartz and plagioclase (Zhao et al. 2018). Hence, the K-feldspar, being the last mineral to crystallize, would be in equilibrium with plagioclase rim at near solidus temperature. Using the rim composition of plagioclase and core composition of big K-feldspar, the two-feldspar thermometer yields a near solidus temperature of ~630 °C (Fig. 12). The occurrence of melt extraction can be supported by the micro-texture evidence (Fig. 2f), i.e., the significant accumulation of plagioclase, garnet, and orthopyroxene crystals in thin sections (Figs. 2e and 2f). Moreover, locally high concentrations of euhedral to subhedral plagioclase crystals form a framework with interstitial quartz crystals, thereby explaining the cumulate texture of the Yunlu charnockite (Fig. 2f; Vernon and Collins 2011).

IMPLICATIONS

In some granitic plutons, the calculated temperatures by mineral thermometry are higher than experimentally determined H₂O-saturated solidus temperatures. Although various models have been proposed, e.g., non-equilibrium crystallization, high-temperature magma recharge, and post-magmatic metamorphic overprints, this discrepancy remains controversial and restricts the application of granite thermometry. Here, the near consistent temperatures (~780-820 °C) obtained for the Yunlu garnet-bearing charnockite constrained by garnet-orthopyroxene, garnet-biotite, and orthopyroxene-biotite Fe-Mg exchange thermometers significantly deviate from its experimental solidus temperature (~630 °C). This higher temperature recorded by ferromagnesian minerals (i.e., orthopyroxene, garnet, and biotite) may result from melt extraction of the interstitial melt in a crystal mush at 30-45% crystallinity (Fig. 12). This interpretation is also supported by the cumulate textures and the geochemical modeling of the whole-rock compositions of the charnockite.

In addition, the influence of melt extraction on the application of mineral thermometers and the interpretation of thermometry data should be carefully reconsidered in granitic plutons.

The widely applied rhyolite-MELTS modeling has been rigorously compared with experimental petrology studies of metaluminous, silicic volcanic systems under low-pressure (≤300 MPa) conditions (Gardner et al. 2014). However, it had never been evaluated and compared with experimental data for peraluminous magma systems at higher pressures (>300 MPa). Here, we carried out a rigorous comparison between modeling results of rhyolite-MELTS and experimental petrology data on a peraluminous ignimbrite at 500 MPa to estimate its uncertainties. Our study shows that rhyolite-MELTS modeling can predict phase relationships for quartz and two feldspars within reasonable limits (≤ 60 °C) at ≤ 7.0 wt% H₂O, but that it poorly constrains the phase saturation temperatures for the ferromagnesian minerals (≥100 °C). Hence, the rhyolite-MELTS software may need modifications in the future to better constrain the saturation curves of the ferromagnesian minerals.

The high emplacement temperature (900 °C) and pressure (600 MPa) of the Yunlu charnockite require a high geothermal gradient (>45 °C/km) in the Yunkai terrane, in which the melting temperature in the source (lower crust) exceeds 900 °C. Radiogenic heating in the thickened crust is inadequate to supply such a high heat flux (Xu and Xu 2015; Xia et al. 2014). The heat from the deep mantle is necessary, such as via basaltic magma underplating and asthenospheric upwelling followed by post-orogenic collapse and lithospheric thinning of the early Paleozoic intra-continental orogen in the SCB (Huang et al. 2013; Zhong et al. 2016; Yu et al. 2018). Furthermore, an extremely short-duration (~0.5 Ma), amphibolite-facies (750 °C, 710 MPa), late Devonian thermal event is recognized in this region (Chen et al. 2012, 2018; this study). However, its geodynamic mechanism still remains controversial. Spear (2014) proposed that the short-duration metamorphic event requires rapid tectonic burial of relatively thin tectonic slices. Based on the duration of the late Devonian metamorphic event, we speculate that it may result from the local thermal turbulence with rapid tectonic burial and exhumation of thin nappe tectonic complexes. However, further work related to this late Devonian metamorphism needs to be implemented to document its tectonic significance.

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Endnote:

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