Are granites and granulites consanguineous?

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ABSTRACT

An important question in petrology is whether the production of granite magma in orogens is a closed-system process with respect to mass input from the mantle. This is commonly addressed by inversion of geochemical data from upper crustal granites, but a complementary approach is to assess the kinship of residual granulites and associated granites in exhumed orogenic crust. Here we report geochemical data for a suite of contemporaneous metasedimentary granulites and granites from the Eastern Ghats Province, India, part of a Grenville-age orogen. The prograde metamorphic evolution increased involving temperature (T) and pressure (P) to a metamorphic peak at >1000 °C at ~0.7 GPa, followed by slow close-to-isobaric cooling. Variations in the composition of granites are interpreted to be due to local processes, including fractionation during melting or crystallization, and/or peritectic mineral entrainment. The Nd and Sr isotope compositions of the granites can be matched by mixing between different granulites, suggesting that they may have been derived solely from sedimentary protoliths leaving behind granulite facies residues. However, including geochemical data from an adjacent area to the north, it becomes clear that an increasingly important mass input from the mantle was involved in granite genesis from southwest to northeast in the Eastern Ghats Province, as confirmed by modeling assimilation–fractional crystallization between an exemplar mantle-derived melt at 1000 Ma and the residual granulites. The extreme peak metamorphic temperature and P–T evolution suggest extended lithosphere that relaxed thermally to its former thickness during slow cooling. We postulate that the spatial variation in mantle input to the granites was related to changing feedback between the rates of extension and flux of mantle melt.

INTRODUCTION

In active orogens, melt is generated in the middle to lower crust and imaged as sills and magma bodies in the middle to upper crust (Gaillard et al., 2004; del Potro et al., 2013). By contrast, exhumed granulites in ancient orogens represent residues from crustal anatexis after melt has drained away, so they provide insight into granite generation and the process of melt extraction complementary to studies of active orogens (Brown, 2013).

In one school of thought, the kinship between residual granulites and granites has been argued to be consanguineous—i.e., derived from common crustal protoliths (Vielzeuf et al., 1990; Korhonen et al., 2010). In an alternative view, it is posited that although residual granulites and granites have some features in common, the mantle has contributed mass to the crustal magmas (Smithies et al., 2011). The heat necessary to achieve granulite facies temperatures and drive extensive melting may be generated either by high concentrations of heat-producing elements and low erosion rates (Clark et al., 2011), via mantle-derived magmas emplaced at depth (Bohlen, 1991), or by a combination of these processes.

Because granite magmatism plays an important role in crustal reworking and differentiation (Michaut et al., 2009), it is important to determine whether any incursion of mantle heat to promote crustal melting also had an input of mass to the magmas. To assess whether granite generation was a closed- or open-system process with respect to the mantle, we undertook a geochemical study of granulites and spatially associated granites in exhumed lower crust from the Eastern Ghats Province, India. In addition to providing new data along a 130 km traverse, we include in the study data from an area to the north (Shaw et al., 1997) to ensure that any spatial variation in these processes is fully evaluated.

EASTERN GHATS, INDIA

The Eastern Ghats Province lies between the Godavari Rift in the south and the Nagavalli shear zone in the north within the Proterozoic Eastern Ghats belt (Fig. 1). The Eastern Ghats Province is dominated by aluminous granulite, inferred to be derived from pelite protoliths, and migmatitic granulite, inferred to be derived from a greywacke protolith (Fig. 1). The granulites preserve peak mineral assemblages without significant retrogression and have refractory chemical compositions (discussed below), consistent with them being residues after loss of granite melt. The prograde metamorphic evolution of increasing temperature (T) before pressure (P), reaching a peak at >1000 °C at ~0.7 GPa, was followed by slow close-to-isobaric cooling across an elevated solidus appropriate to these residual rocks (Korhonen et al., 2013b, 2014).

Samples

First, we briefly summarize relationships between samples of granulite and granite collected along a 130 km traverse from Bobbili in the northeast to Chintapalle in the southwest (Fig. 1, Fig. DR1 and Table DR1 in the GSA Data Repository1). In the northeast, near Bobbili, a foliated plagioclase-phylitic biotite-garnet trondhjemitic granulite (sample 10-66) is associated with quartz-rich sillimanite-garnet granulite (samples 10-65, 10-67). To the east-southeast of Bobbili, the outcrops are dominated by migmatite composed of an orthopyroxene-garnet granulite (sample 09-52) that hosts both cordierite (sample 10-61) and garnet-bearing and discordant (sample 10-60) garnet±orthopyroxene±biotite–bearing leucosomes (Fig. DR2A). Close to Sunkarametta, K-feldspar-phylitic orthopyroxene granite (sample 09-35) is associated with orthopyroxene-garnet granulite (sample 09-34). To the west of Paderu, biotite-garnet granite (sample 09-19) occurs in association with dominant orthopyroxene-garnet granulite (sample 09-01) and subordinate Mg-rich garnet granulite characterized by pseudomorphs after osmium (samples 09-02, 09-04; Korhonen et al., 2013a). In the

1GSA Data Repository item 2015334, Figures DR1–DR6 and Tables DR1–DR4, is available online at www.geosociety.org/pubs/ft2015.htm, or on request from editing@geosociety.org or Documents Secretary, GSA, P.O. Box 9140, Boulder, CO 80301, USA.
GEOCHRONOLOGY AND GEOCHEMISTRY

Geochronology

We determined zircon and monazite U-Pb data for a migmatitic orthopyroxene-garnet granulite (sample 09-02) and an associated leucosome (10-61), and zircon U-Pb data for two sillimanite-garnet granulites (10-67 and 10-94) and associated granites (10-66 and 10-93) to assess contemporaneity with Grenville-age orogenesis. The analytical protocol and data are provided in the Data Repository (Tables DR2 and DR3) together with a discussion of the concordia plots, normalized rare earth element plots, and DR3) together with a discussion of the concordia plots, normalized rare earth element plots, cordierite plots, and backscattered-electron images of zircon and backscattered-electron images of monazite (Figs. DR3–DR5). These new data confirm that granulite facies metamorphism and crustal anatexis occurred during the interval 1000–900 Ma, consistent with the regional interpretation of zircon and backscattered-electron images of monazite (Figs. DR3–DR5). These new data confirm that granulite facies metamorphism and crustal anatexis occurred during the interval 1000–900 Ma, consistent with the regional study of Korhonen et al. (2013b), who interpreted zircon and monazite ages of 980–930 Ma to record post-peak cooling to an elevated solidus at a rate of ~1 °C/m.y. For granites associated with the sillimanite-garnet granulites (Fig. 2), Al2O3 and (MgO + FeO + Fe2O3 + TiO2) are lower and (Na2O + CaO) is higher than in the local host granulite. K2O and Rb/Sr are higher in the granites than in the granulite and generally increase with increasing SiO2, except in one sample that is dominated by plagioclase rather than K-feldspar (sample 10-66), as reflected in the highest (Na2O + CaO). Trace element concentrations are variable. The two granites with the highest SiO2 and lowest (MgO + FeO + Fe2O3 + TiO2) also have low La, Zr, Y, U, and Th (Fig. DR6). By contrast, granite 10-93, which has higher modal garnet than spatially related granites (10-90 and 10-92), has higher (MgO + FeO + Fe2O3 + TiO2), K2O, and Rb/Sr variations compared to the local host granulite. Trace element concentrations are variable. For the two granites, one (sample 10-19) has high La, Zr, Y, U, and Th, whereas the other (09-35) has lower La, Zr, and Y, suggesting no control by, or systematic variations in, modal apatite, monazite, or zircon contents.

For granites and leucosomes associated with the orthopyroxene-garnet granulites (Fig. 2), SiO2 varies from ~64 to ~76 wt%, while Al2O3 and (Na2O + CaO) are lower and (MgO + FeO + Fe2O3 + TiO2), K2O, and Rb/Sr vary compared to the local host granulite. Trace element concentrations are variable. For the two granites, one (sample 10-19) has high La, Zr, Y, U, and Th, whereas the other (09-35) has moderate La and Y and increasing U. The granites do not have correlated La and P2O5, La and Y, or Zr and Y, suggesting no control by, or systematic variations in, modal apatite, monazite, or zircon contents.

GEOCHEMISTRY

We report new mineral-chemistry data for a migmatitic orthopyroxene-garnet granulite (sample 10-61) and an associated leucosome (10-66), and zircon U-Pb data for two sillimanite-garnet granulites (10-67 and 10-94) and associated granites (10-66 and 10-93) to assess contemporaneity with Grenville-age orogenesis. The analytical protocol and data are provided in the Data Repository (Tables DR2 and DR3) together with a discussion of the concordia plots, normalized rare earth element plots, cordierite plots, and backscattered-electron images of zircon and backscattered-electron images of monazite (Figs. DR3–DR5). These new data confirm that granulite facies metamorphism and crustal anatexis occurred during the interval 1000–900 Ma, consistent with the regional study of Korhonen et al. (2013b), who interpreted zircon and monazite ages of 980–930 Ma to record post-peak cooling to an elevated solidus at a rate of ~1 °C/m.y. For granites associated with the sillimanite-garnet granulites (Fig. 2), Al2O3 and (MgO + FeO + Fe2O3 + TiO2) are lower and (Na2O + CaO) is higher than in the local host granulite. K2O and Rb/Sr are higher in the granites than in the granulite and generally increase with increasing SiO2, except in one sample that is dominated by plagioclase rather than K-feldspar (sample 10-66), as reflected in the highest (Na2O + CaO). Trace element concentrations are variable. The two granites with the highest SiO2 and lowest (MgO + FeO + Fe2O3 + TiO2) also have low La, Zr, Y, U, and Th (Fig. DR6). By contrast, granite 10-93, which has higher modal garnet than spatially related granites (10-90 and 10-92), has higher (MgO + FeO + Fe2O3 + TiO2), K2O, and Rb/Sr variations compared to the local host granulite. Trace element concentrations are variable. For the two granites, one (sample 10-19) has high La, Zr, Y, U, and Th, whereas the other (09-35) has moderate La and Y and increasing U. The granites do not have correlated La and P2O5, La and Y, or Zr and Y, suggesting no control by, or systematic variations in, modal apatite, monazite, or zircon contents.

For granites and leucosomes associated with the orthopyroxene-garnet granulites (Fig. 2), SiO2 varies from ~64 to ~76 wt%, while Al2O3 and (Na2O + CaO) are lower and (MgO + FeO + Fe2O3 + TiO2), K2O, and Rb/Sr vary compared to the local host granulite. Trace element concentrations are variable. For the two granites, one (sample 10-19) has high La, Zr, Y, U, and Th, whereas the other (09-35) has moderate La and Y and high Zr, but low U and Th (Fig. DR6). With increasing SiO2, the two leucosomes show decreasing La, Zr, and Y and increasing U. The granites do not have correlated La and P2O5, La and Y, or Zr and Y, suggesting no control by, or systematic variations in, modal apatite, monazite, or zircon contents.
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Compositional variations in the granites are best explained as a consequence of processes such as fractionation during melting or crystallization and peritectic mineral entrainment acting locally, consistent with the granites being crystallized vestiges of draping melt. The discordant leucosome (sample 10-61) and the two leucogranites from the southwestern area of the study area (10-90 and 10-92) have compositions similar to those of experimental melts derived from the two typical pelite compositions, such as high SiO₂, low (MgO + FeO + Fe₂O₃ + TiO₂), high Rb/Sr, and low La, Zr, Y, U, and Th, but modified by plagioclase fractionation and K-feldspar accumulation (lower Na₂O + CaO and higher K₂O, respectively). By contrast, the discordant leucosome (10-60) and two of the granites (09-35 and 10-66) from the northeastern area of the study area have compositions consistent with accumulation of feldspar, such as high Na₂O + CaO, and for sample 09-35, high K₂O, high Sr, and moderate La and Y. Finally, several granites (09-19, 10-66, and 10-93) and the discordant leucosome (10-60) record evidence of peritectic mineral entrainment, particularly garnet ± orthopyroxene, as seen in the field and in thin section and as expressed by high (MgO + FeO + Fe₂O₃ + TiO₂) and, for samples 09-19 and 10-93, high Zr and Y.

**Isotope Geochemistry**

The Nd and Sr isotope compositions of the granulites and granites at 1000 Ma are variable (Fig. 3A), but most are relatively unradiogenic. However, four of the granites have higher ⁸⁷Sr/⁸⁶Sr and trend toward the two highly radiogenic high-Mg granulites which have ⁸⁷Sr/⁸⁶Sr of 1.058304 and 1.365787 respectively, consistent with the highest values from augen gneisses of the Indian basement under southern Tibet (Zeng et al., 2011). The depleted-mantle model age (TDM) values range from 1.8 to 2.3 Ga (Table DR4), with one sillimanite-garnet granulite at 2.8 Ga, similar to the range of 1.8–2.9 Ga determined by Rickers et al. (2001) for the Eastern Ghats Province.

Binary mixing lines were calculated using the Nd and Sr concentrations and isotope values of more and less radiogenic end members of the granulite suite (Fig. 3A). These binary mixing lines enclose the Sr and Nd isotope values for all of the granulites, granites, and leucosomes of this study. The Sr and Nd isotope compositions of both leucosomes (samples 10-60 and 10-61) and granite 09-35 are consistent with derivation by partial melting from orthopyroxene-garnet granulite. However, the Sr and Nd isotope compositions of four of the five granites (09-19, 10-90, 10-92, and 10-93) require a mixed source comprising orthopyroxene-garnet granulite and/or sillimanite-garnet granulite with high-Mg granulite in variable proportions (Fig. 3A). The trondhjemite (10-66) has the highest ɛNd and appears to require an additional source component with more radiogenic Nd and relatively unradiogenic Sr.

In a wider context, in Figure 3B we include data from the study of Shaw et al. (1997) from an area near Rayagada, to the north of Bobbili (Fig. 1), where up to kilometer-scale bodies of leucogranite intrude sillimanite-garnet granulites, orthopyroxene granulites, and mafic granulites. In particular, the Nd and Sr isotope data for the mafic granulites, orthopyroxene granulites, and granites have significantly more radiogenic Nd but similarly non-radiogenic Sr isotope compositions compared to the new data from granulites and granites further southwest reported here (Fig. 3B). The extended data set defines a coupled trend of increasingly primi-
tive (mantle-like) isotope compositions with decreasing whole-rock SiO₂ and increasing MgO (Fig. 4). These relationships, particularly the large changes in major element compositions, are typical of assimilation–fractional crystallization (AFC) between crust-like and mantle-like end-member components.

**AFC Modeling**

Figure 3B shows modeled AFC trends produced by interaction between an exemplar mantle-derived melt (average mid-oceanic ridge basalt, assuming an asthenospheric source appropriate to extended lithosphere, using trace element concentrations from Jenner and O’Neill [2012] and present-day ¹⁴Nδ¹⁴N = 0.513108 and ⁸⁷Sr/⁸⁶Sr = 0.702900, corrected back to 1000 Ma) and the range of crustal lithologies repre-
sented by orthopyroxene-garnet and sillimanite-garnet granulites (higher Sr) and Mg-rich granulites (lower Sr). In such models, the Nd/Sr of the radiogenic crustal end member controls the curvature of the mixing line (DePaolo, 1981). An AFC process could simultaneously explain the entire array of granulite and granite compositions, which range from dominantly crustal melts around Chintapalle and Paderu in the southwest (Fig. 3, samples 10-93, 10-92, 10-19, and 10-90) to those with an increasing mantle component to the northeast (Fig. 3, samples 09-35 and 10-66 and the Rayagada granites). Granulites that plot to higher values of \(^{87}Sr/^{86}Sr\) than the more radiogenic of the two modeled AFC trends may be explained if their original Rb/Sr has been modified by alteration, which affects the age-corrected \(^{87}Sr/^{86}Sr\), or if the Nd/Sr value chosen for the radiogenic crustal end member was not appropriate along the extended traverse from Chintapalle to Rayagada (185 km).

**DISCUSSION**

When viewed in isolation, the new data presented herein permit derivation of the granites in the southern Eastern Ghats Province by mixing among anatectic melts derived from the regionally distributed granulites. However, when viewed in a wider context by including data from an area to the north, it becomes clear that mass input from the mantle is required to explain the expanded range of Nd isotope compositions. We envisage this suite of granulites and granites to have formed as a consequence of increasing open-system interaction from southwest to northeast between mantle-derived melts and suprasolidus metasedimentary rocks in the lower crust of an ultrahot orogen, similar to the process described for the genesis of S-type granites by Jenner et al. (2001). The ultrahigh temperatures recorded regionally likely require an incursion of heat from the mantle, and the metamorphic evolution of thickening after heating suggests an extended lithosphere that relaxed thermally to its former thickness during slow cooling.

In this tectonic context, we postulate that the southwest-to-northeast spatial variation in mantle contribution to the granites was related to the changing feedback between rates of extension and mantle melt flux from southwest to northeast (cf. Karakas and Dufek, 2015). This process allowed the preservation of refractory granulite with remnants of crustal-sourced granite in the southwest, but to the northeast produced granites that require the involvement of an increasingly higher proportion of mantle melt in their genesis. This outcome is consistent with earlier speculation that crustal growth in the Eastern Ghats during Grenvillian orogenesis might have occurred in a northeast direction (Rickers et al., 2001).

In conclusion, we have used a combination of data to show that granites in the southwest of the Eastern Ghats Province are consanguineous with their regional granulite-facies residues, whereas those to the northeast require a significant mass input from the mantle. Thus, in the Eastern Ghats Province the granulites in the southwest represent one end of a continuum in which there is a gradient in mantle contribution to granite magmas to the northeast as the granite–granulite kinship evolves from consanguineous to affinial.

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