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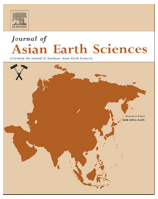

Fluid inclusion studies on the Koraput Alkaline Complex, Eastern Ghats Province, India: Implications for mid-Neoproterozoic granulite facies metamorphism and exhumation

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ABSTRACT

Following ultrahigh temperature granulite metamorphism at ~1 Ga, the Eastern Ghats Province of India was intruded by the Koraput Alkaline Complex, and was subsequently re-metamorphosed in the granulite facies in the mid-Neoproterozoic time. Fluid inclusion studies were conducted on silica undersaturated alkali gabbro and syenites in the complex, and a pre-metamorphic pegmatitic granite dyke that intrudes it. High density (1.02–1.05 g/cc), pseudo-secondary pure CO_2 inclusions are restricted to metamorphic garnets within the gabbro and quartz within the granite, whereas moderate (~0.92–0.95 g/cc) and low density (~0.75 g/cc) secondary inclusions occur in garnet, magmatic clinopyroxene, plagioclase, hornblende and quartz. The isochores calculated for high density pseudo-secondary inclusions pass very close to the peak metamorphic window (~8 kbar, 750 °C), and are interpreted to represent the fluid present during peak metamorphism that was entrapped by the growing garnet. Microscopic round inclusions of undigested, relict calcite in garnet suggest that the CO_2 present during metamorphism of the complex was internally derived through carbonate breakdown. Pure to low salinity (0.00–10.1 wt% NaCl equivalent) aqueous intra-/intergranular inclusions showing unimodal normal distribution of final ice-melting temperature (T_m) and temperature of homogenization (T_h) are present only in quartz within the granite. These represent re-equilibrated inclusions within the quartz host that were entrapped at the metamorphic peak. Rare, chemically precipitated graphite along the walls of carbonic inclusions is interpreted as a post-entrapment reaction product formed during decompression. The fluid inclusion evidence is consistent with rapid exhumation of a thickened lower crust following the mid-Neoproterozoic granulite facies metamorphic event. The study suggests that mantle CO_2, transported by alkaline magma into the crust, was locked up within carbonates and released during granulite metamorphism.

1. Introduction

Granulite facies metamorphism is characterized by low water activity (Harley, 1989) leading to the stabilization of anhydrous mineral assemblages. Various theories (see Rajesh and Santosh, 2012, and references therein) have been proposed to explain the lowering of water activity during metamorphism, among which the influx of CO_2 rich fluids (Janardhan et al., 1982; Newton et al., 1980; Stahle et al., 1987) has been a popular early model. Some recent studies (e.g. Touret and Huizenga, 2012a, and references therein) have also suggested that ultra-high temperature granulite assemblages could have been stabilized in the presence of high density CO_2 fluid and brines (Ohyama et al., 2008; Santosh et al., 2008; Tsunogae et al., 2008; Touret and Huizenga, 2012a). While the mechanism is plausible in itself, there have been problems with identifying a source that can supply and transport the CO_2 on a scale substantial enough to cause terrane-scale granulite metamorphism, with only few examples (e.g. Rajesh et al., 2011, 2013; Santosh and Omori, 2008). Based on modeling approach, Banerjee et al. (2013) concluded that batholith scale dehydration to form charnockite massifs requires 'multiple high-temperature CO_2' pulses. One of the most effective sources of supplying such large quantities of CO_2 to the crust is the earth's mantle (e.g. Ohyama et al., 2008; Santosh et al., 2010; Touret and Huizenga, 2012a); theoretical studies have suggested that CO_2 degassing from the mantle, combined with crustal thickening, can be very efficient in generating granulites (Ganguly et al., 1995). In granulite terranes, however, the problem has generally been to find field evidence for a suitable carrier that could transport carbonic fluid from the mantle into the crust.

Alkaline, silica undersaturated magmas are commonly generated by mantle melting in the presence of CO_2-rich fluids

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(Philpotts, 1990), and can be efficient transporters of the associated fluids from the mantle into the crust. These fluids are subsequently released into the crust as the magma crystallizes or may be preserved within the pluton in the form of various carbonate phases. The Eastern Ghats Province of India (Dobmeier and Raith, 2003) is a granulite terrane that is bordered along its western margin by a linear array of alkaline complexes. Among these complexes, the Koraput Alkaline Complex is known to have undergone granulite facies metamorphism (Nanda et al., 2008). The role of the alkaline magma as a carrier of carbonic fluids that may have played a role during subsequent granulite facies metamorphism has never been explored. In this study, a detailed fluid inclusion study was carried out on selected silica under-saturated lithounits within the complex, and on an 'alkali granite' (Bose, 1970) dyke that intruded the complex following its emplacement, to document the nature of the fluid phase, if any, that was present during subsequent granulite metamorphism of these units (Nanda et al., 2008, 2009).

The Eastern Ghats Province experienced a "long-lived ultra high temperature" metamorphic event at ~1130–930 Ma (Korhonen et al., 2013 and references therein) prior to intrusion of the Koraput Alkaline Complex with its constituent lithologic units at ~917 Ma (Bhattacharya and Basei, 2010). Subsequently, the western part of the province, along with the newly intruded complex, underwent a second phase of granulite facies metamorphism in the mid-Neoproterozoic time (~745 Ma; Bhattacharya and Basei, 2010; Hippe et al., 2008). Systematic documentation and interpretation of structures, microstructures and metamorphic *P*–*T* data (Gupta et al., 2005a; Nanda and Gupta, 2012; Nanda et al., 2008, 2009) has established that after intrusion, the Koraput Alkaline Complex initially experienced hydrous fluid infiltration concomitant with shearing. Thereafter, anhydrous granulite facies assemblages stabilized and overgrew the shear fabrics (peak *P*–*T* conditions at 8 kbar, 750 °C; Nanda et al., 2008) either through partial melting or dehydration reactions, as suggested for different granulite terranes (e.g., Harlov, 2012 and references therein), or by lowering of water activity in the fluid phase by the presence of alternative components (e.g. CO_2) in the fluid phase (Janardhan et al., 1982). However, none of the earlier studies focused on the fluid regime during the second granulite facies metamorphic event in the western part of the Eastern Ghats Province. The present study is an attempt to independently assess the fluid composition during this metamorphic event from a detailed fluid inclusion study of the Koraput Alkaline Complex. The scope of this study is limited to the rocks of complex, which intruded following the UHT event, and consequently, was only metamorphosed during the second granulite facies event; the country rocks, that have also experienced the earlier granulite event (Nanda et al., 2008), have been deliberately not considered for this reason. We argue that apart from the role played by fluids in stabilizing granulite facies assemblages, they also throw light on the exhumation of the lower crustal rocks of the western part of the Eastern Ghats Province.

2. Brief geology of the rocks in the Koraput Alkaline Complex

The Koraput Alkaline Complex (Fig. 1a and b) has a gabbroic core ("alkali gabbro" of Bose, 1970), the most voluminous of the silica undersaturated lithologies, fringed by a band of nepheline syenite in the east and syenodiorite in the west (Fig. 1b). Syenite dykes cut across the gabbro or form a network of veins within the gabbro, but are in turn truncated by mafic dykes (now amphibolites) and a 'pegmatitic alkali granite', the only silica oversaturated unit within the complex (Bose, 1970). Bose (1965, 1970) interpreted this "per-alkaline hypersolvus granite" as a differentiated product of silica under-saturated alkali basaltic magma that intruded pelites/semipelites intercalated with calc-silicate rocks of the Eastern Ghats Province (Fig. 1b). The pegmatitic alkali granite occurs as a band along the syenodiorite – gabbro contact or as band/dyke that cuts across the gabbro. It is now established that the complex also underwent solid state deformation during the two successive shearing events, designated as D_{2AC} (characterized by NE–SW trending east dipping shears), and D_{3AC} (E–W trending steeply south dipping shears) respectively, followed by metamorphism in the granulite facies (Gupta et al., 2005a; Nanda et al., 2008). Fluid inclusions are found to be hosted in primary (magmatic) minerals of the gabbro/syenite dyke/syenodiorite, and also within minerals that grew at the time of the second granulite facies metamorphic event (like Grt in gabbro). These fluid inclusions, therefore, preserve invaluable evidence of the nature of fluids that were present before, during and after granulite facies metamorphism.

The gabbro is dominantly composed of amphibole, clinopyroxene, orthopyroxene, plagioclase, biotite, garnet and ilmenite, with calcite as a minor phase. Olivine and green spinel are present in pockets of ultramafic cumulates in. Amphibole, clinopyroxene, orthopyroxene, and biotite are of both magmatic (Fig. 2a) and metamorphic (Fig. 2b and c) origin, as interpreted from detailed petrographic study (Gupta et al., 2005a; Nanda et al., 2008). Biotite is more abundant along shear bands and defines the foliation. Garnets ($\sim X_{Alm}$ 0.49–0.60, X_{Py} 0.31–0.12, X_{Grs} 0.19–0.26) are coronal (Fig. 2d) on plagioclase/amphibole ($X_{Mg} \sim 0.40$–0.60)/biotite ($X_{Mg} \sim 0.37$–0.43; Fig. 2b and c)/ilmenite, though the large sizes of some garnets (containing amphibole inclusions) makes their original coronal nature indistinct. Calcite occurs as a matrix component or included phase in garnet and sometimes as fracture fillings.

The gneissic syenodiorite consists of alternate bands of mafic (amphibole + biotite + ilmenite ± clinopyroxene) and felsic (plagioclase + K-feldspar + perthite) minerals (Fig. 2e). Garnet occur as coronae or growing along margins of plagioclase and amphibole (X_{Alm} = 0.56–0.65, X_{Py} = 0.10–0.06, X_{Grs} = 0.29–0.25), and clinopyroxene (forming after amphibole) are anhydrous metamorphic products that overgrow the foliation; the new assemblage forms a granoblastic mosaic. Biotite broke down marginally into symplectitic intergrowth of ilmenite and K-feldspar, indicating low fo_2 conditions during the dehydration reaction

$$\mathrm{Bt + Rt = Ilm + Kfs + H_2O} \quad \text{(Fig. 2f)}. \tag{1}$$

This reaction pre-dates the growth of coronal garnet (Nanda et al., 2008).

The syenite dykes or veins hosted in gabbro are almost equigranular with a dominantly granoblastic texture that overgrows the earlier shear related biotite – amphibole defined foliation (Nanda et al., 2008). The mineralogy includes varying proportions of perthite, K-feldspar, plagioclase, biotite, amphibole, ilmenite, garnet, and green spinel. Nepheline is rarely present. Garnets ($\sim X_{Alm}$ 0.65–0.62, X_{Py} 0.12–0.14, X_{Grs} 0.12–0.21, see Nanda et al., 2008) are mostly coronal on amphibole/biotite, with no compositional difference between the garnets overgrowing different minerals. No compositional variations are observed in K-feldspar or plagioclase occurring in different textural modes.

The pegmatitic alkali granite is composed of alkali feldspar (mostly perthite), plagioclase, biotite, amphibole and quartz. It is also mylonitised in sheared domains (Nanda et al., 2009) and in such sheared samples, the quartz ribbons show grain boundary migration recrystallisation (Fig. 2g) that overprints the foliation. In unstrained domains, frequent wedges of quartz within alkali feldspar have abundant fluid inclusions trails (Fig. 2h).

The nepheline syenite is composed of perthite, biotite, amphibole, nepheline, anti-perthite and plagioclase. Calcite, ilmenite, sphene, rutile, apatite, scapolite and zircon are accessories. Calcite