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On oriented ilmenite needles in garnet porphyroblasts from deep crustal granulites: Implications for fluid evolution and cooling history

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ABSTRACT

Garnet porphyroblasts from a litho-assemblage containing aluminous granulite and quartzofeldspathic gneisses of the Eastern Ghats granulite belt, India contain nanometer- to micrometer-thick ilmenite needles oriented crystallographically. Petrographic and chemical analyses reveal that garnet was formed by dehydration melting reaction(s) of titaniferous biotite in an oxidized condition. Elevated oxygen fugacity might have promoted enrichment of Ti-bearing andradite component of garnet porphyroblasts formed during pre- to peak metamorphic condition in appropriate bulk chemistry. During the post-peak cooling history, Ti-bearing components in garnet decomposed to rhombohedral oxide solid solution (ilmenite–hematite). Detailed transmission electron microscopic study of the host garnet and ilmenite solid solution indicates that though there is an overall parallelism of (011) plane of host garnet and (011) plane of ilmenite, structural coherence between the two phases was progressively lost during growth from thin to thick needles. Appropriate cooling rate from high-temperature peak metamorphic condition arguably promoted growth of ilmenite solid solution through reaction–exsolution process within garnet porphyroblasts.

1. Introduction

High-temperature mineral assemblages often preserve complex textures that serve as unique sensors to document anomalous *P–T–X-fluid* regimes prevailing in the deep interior of the crust. Many of these textures are subsequently modified by high-temperature recrystallization and/or fluid-induced alteration processes (*cf.* White and Powell, 2011). However, few intra-grain textures and microstructures may survive to act as fossil evidence (*cf.* Frost and Chako, 1989). Ti-bearing mineral inclusions (particularly rutile) in clinopyroxene, garnet and biotite have been reported to be formed from ultra-high pressure (UHP) conditions where these host minerals can accommodate TiO_2 in their structure to be subsequently unmixed during retrogression producing oriented intergrowth textures (Hwang et al., 2007; Zhang et al., 2003). On the other hand, exsolution textures in pyroxene, feldspar and spinel grains have provided important clues on high-temperature to ultrahigh-temperature (UHT) metamorphic processes (Harley, 1987; Hokada, 2001; Sengupta et al., 1999; Waters, 1991). The above-mentioned examples represent exsolution from complex solid solution, resulting in oriented intergrowth of one end-member within the host end-member. The high-temperature complex solid solution phases sometimes decompose at lower temperatures to form an array of different minerals. Tschermak-enriched orthopyroxene thus decomposes to sapphirine, spinel and cordierite during cooling at low- to mid-crustal depths (Bose et al., 2006; Das et al., 2006; Gasparik, 1994). Sometimes, these textures are a product of redox reactions (Harlov and Hansen, 2005; Harlov et al., 1997; Sengupta et al., 1999) and hence become important to assess the role of fluids. The choice of proper petrogenetic grid in appropriate bulk rock compositions to characterize the evolutionary path (s) depends heavily on the proper assessment of fluid, particularly oxygen fugacity (Carrington and Harley, 1995; Das et al., 2001, 2003; Hensen, 1986). Careful textural characterization is important in such complex intergrowths since similar intra-grain textures could also form due to multi-phase mineral inclusion within a porphyroblastic mineral (Wang et al., 1999). Although it is really problematic to decide which one of these two processes is responsible for a particular case, it is noted from textural standpoint that exsolution textures normally follow crystallographic planes (Dymek and Gromet, 1984; Jaffe and Schumacher, 1985).

Different reaction textures and intergrowth textures in granulite-grade rocks over the last decade have revealed several cases of anomalous *P–T* conditions in the lower continental crust. Characterization of UHT metamorphism is one such extremity (*e.g.*, Clark et al., 2011; Harley, 2008; Kelsey, 2008). It has been argued that many regional granulite terrains preserve evidence of UHT metamorphism, putting important constraints on the thermal structure and related tectonic setting of ancient orogens (Clark et al., 2011; Harley, 2008; Johnson and Harley, 2012; Kelsey, 2008). Apart from the conventional textures revealing diagnostic UHT assemblages (*e.g.* sapphirine–quartz–aluminous

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orthopyroxene in aluminous granulites), other textures and chemical signatures also provide important clues for UHT metamorphism and subsequent retrograde evolutionary processes (Bose et al., 2006; Das et al., 2006; Harley, 2008). Such criteria are particularly relevant for rocks where diagnostic assemblages are absent and UHT metamorphism cannot otherwise be proved. It has been demonstrated that careful textural and chemical analyses in microdomain-scale can be used to unravel UHT peak conditions even after significant retrogressive change occurs in such rocks (Harley, 2008). It is therefore important to evaluate such unusual textures from rocks where UHT metamorphism has already been characterized. The detailed textural analysis not only helps in understanding extreme conditions of crustal metamorphism, but also reveals the histories of complex fluid-rock interactions whose direct evidences are often not preserved in the rocks.

The Eastern Ghats Belt (EGB) occurs along the eastern coast of India (Fig. 1) and represents a regional granulite terrain having different crustal domains with separate metamorphic, structural and isotopic characteristics (Dasgupta and Sengupta, 2003; Dasgupta et al., 2012; Dobmeier and Raith, 2003; Rickers et al., 2001). Petrological data reveal that the rocks of central part of the EGB (*i.e.* Domain II of Rickers et al., 2001) evolved through anticlockwise *P*–*T* trajectory and reached UHT condition during peak metamorphic stage at ca. 1030–990 Ma (Bose et al., 2011, Das et al., 2011; Korhonen et al., 2011). Subsequently, these rocks cooled isobarically before being transported to mid-crustal level by a decompressive tectonics (Dasgupta and Sengupta, 2003) during a second granulite-facies metamorphism at ca. 950–900 Ma (Bose et al., 2011, Das et al., 2011). The rocks, thus witnessed multiple phases of granulite-facies metamorphism displaying complex textures and microstructures. However, discrete temporal relationship of orogenic events among different domains of the EGB makes it difficult to offer a unified tectonic model for the entire belt (Dasgupta et al., 2012). Furthermore, the exact nature and cause of sustained heat flow beneath the EGB crust is still a matter of speculation in absence of unique model of tectonic development (Gupta, 2012).

In this work, we study intergrowth textures within garnet porphyroblasts from a lithological assemblage containing aluminous granulite and quartzofeldspathic gneisses from the central part of the EGB. The submicroscopic intergrowths have been investigated under scanning electron microscope and analytical transmission electron microscope to identify their relationship with the host garnet. The possible formation mechanism of such intergrowths has been discussed in terms of fluid-rock interaction during peak metamorphism and subsequent retrograde processes suffered by the rocks of this terrain.

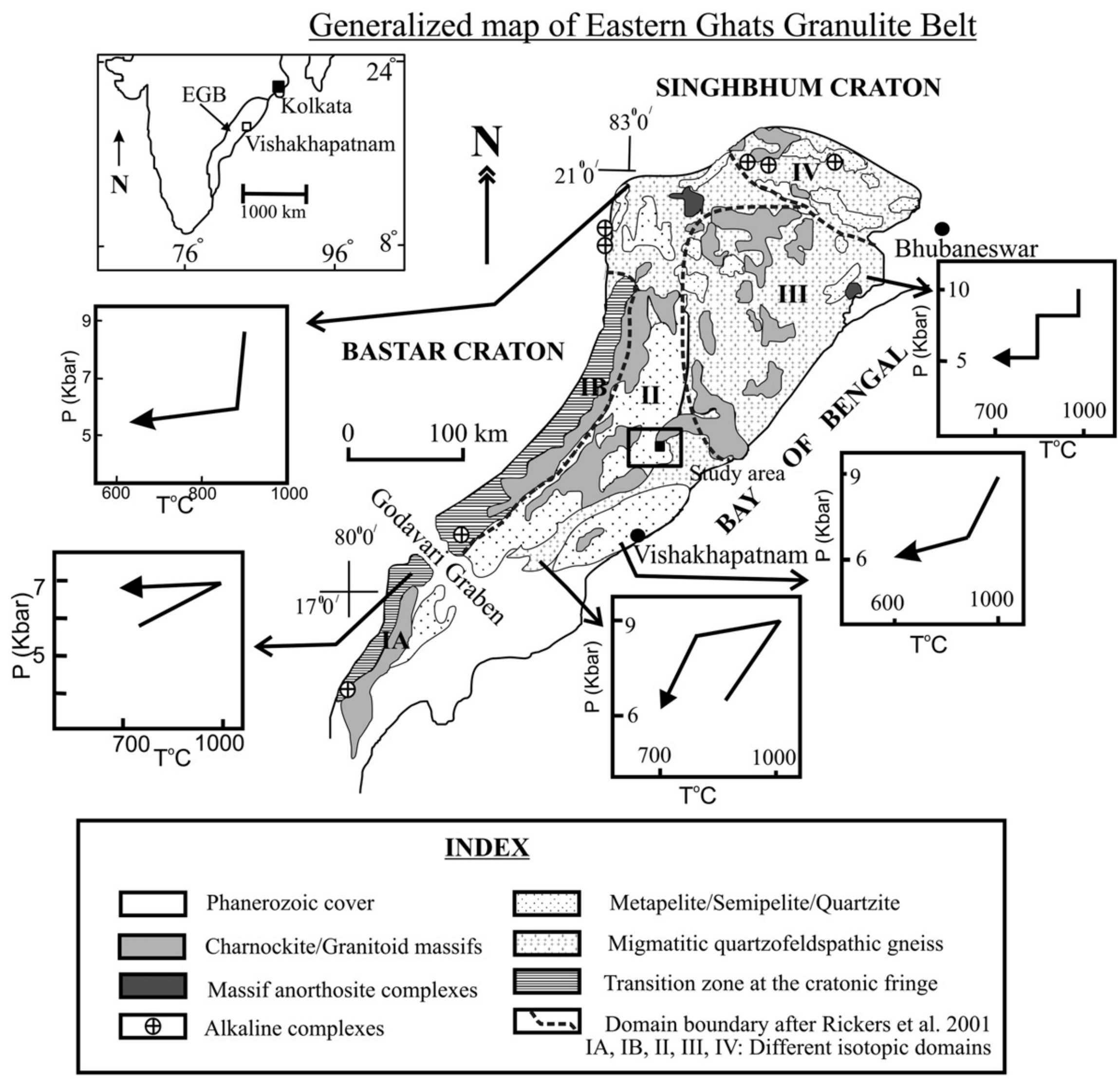

Fig. 1. Geological map of Eastern Ghats Belt, India showing the location of the study area (in the rectangular box). General map of India, showing the position of the Eastern Ghats Belt, is given in the inset at upper left hand corner. Dotted lines indicate the isotopic domain (IA, IB, II, III, and IV) boundaries after Rickers et al. (2001). Disposition of different major rock types is plotted and indexed. Representative *P*–*T* evolutionary paths are plotted for each of these domains (after Dasgupta and Sengupta, 2003).