LETTER

Carbonic fluid inclusions in ultrahigh-temperature granulite from Kumiloothu in the northern Madurai Block, southern India

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We report fluid inclusion data on ultrahigh–temperature (UHT) granulites from Kumiloothu in the northern Madurai Block situated along the Palghat–Cauvery Shear Zone system in southern India. Three categories of fluid inclusions have been observed: primary inclusions in garnet comprising the dominant category, secondary inclusions in garnet, and rare primary inclusions in rutile and apatite enclosed within garnet. The melting temperatures of all the categories of inclusions lie in the narrow range of –57.0 to –56.6 °C, close to the triple point of pure CO_2. Most of the fluid inclusions homogenize into the liquid phase between a temperature range of +11.3 to +30.3 °C, corresponding to low-CO_2 densities of 0.59–0.85 g/cm^3. Slightly higher density of 0.95 g/cm^3 was obtained from a primary inclusion in rutile that homogenized at –3.6 °C. The fluid densities, when computed into isochores, indicate lower pressures (~ 6.6 kbar at 1000 °C) than the peak P–T conditions (T >1000 °C at ~ 8 kbar) estimated for this region. The results of this study, together with the primary nature of the inclusions trapped in high–grade minerals, indicates density reversal of peak metamorphic fluid, a common feature for many UHT granulites along the Gondwana suture zone as well as other UHT terranes showing clockwise P–T history.

Keywords: Carbonic fluid inclusion, Ultrahigh–temperature granulite, Madurai Block, Palghat–Cauvery Shear Zone System, Gondwana suture, Southern India

INTRODUCTION

The Palghat–Cauvery Shear Zone System (PCSZ) at the northern margin of the Madurai Granulite Block (MGB) in southern India is regarded as the boundary between the Archean terrane to the north and Proterozoic granulite blocks to the south (Fig. 1). This is also regarded as the trace of the collisional suture of the Gondwana supercontinent during its final assembly in the Late Neoproterozoic to Early Cambrian (e.g., Santosh et al., 2006; Chetty and Bhaskar Rao, 2006; Collins et al., 2007a). Recently, ultrahigh–temperature (UHT; T > 1000 °C at ~ 8 kbar) granulites have been reported from several localities in the northern MGB and PCSZ probably formed by deep subduction and subsequent continent–continent collision along this suture zone (Tsunogae and Santosh, 2003; Koshimoto et al. 2004; Shimpo et al., 2006; Santosh and Sajeev, 2006: Collins et al., 2007b; Tsunogae and Santosh, 2006a, 2007; Tsunogae et al., 2008a). However, only few studies on the role of fluids related to the UHT metamorphism have been carried out in this region. A recent study by Ohyama et al. (2008) reported rare high–density (1.00–1.06 g/cm^3) carbonic fluids trapped at the peak metamorphic stage in matrix plagioclase and porphyroblastic staurolite within Mg–Al–rich rocks from Sevitturangampatti in the PCSZ. However, it is still not known whether the occurrence of such synmetamorphic carbonic fluid is a regional character of the PCSZ or related to a local event. In this study, we present new results of petrographic and microthermometric investigations on fluid inclusions trapped in high–grade minerals in granulites from

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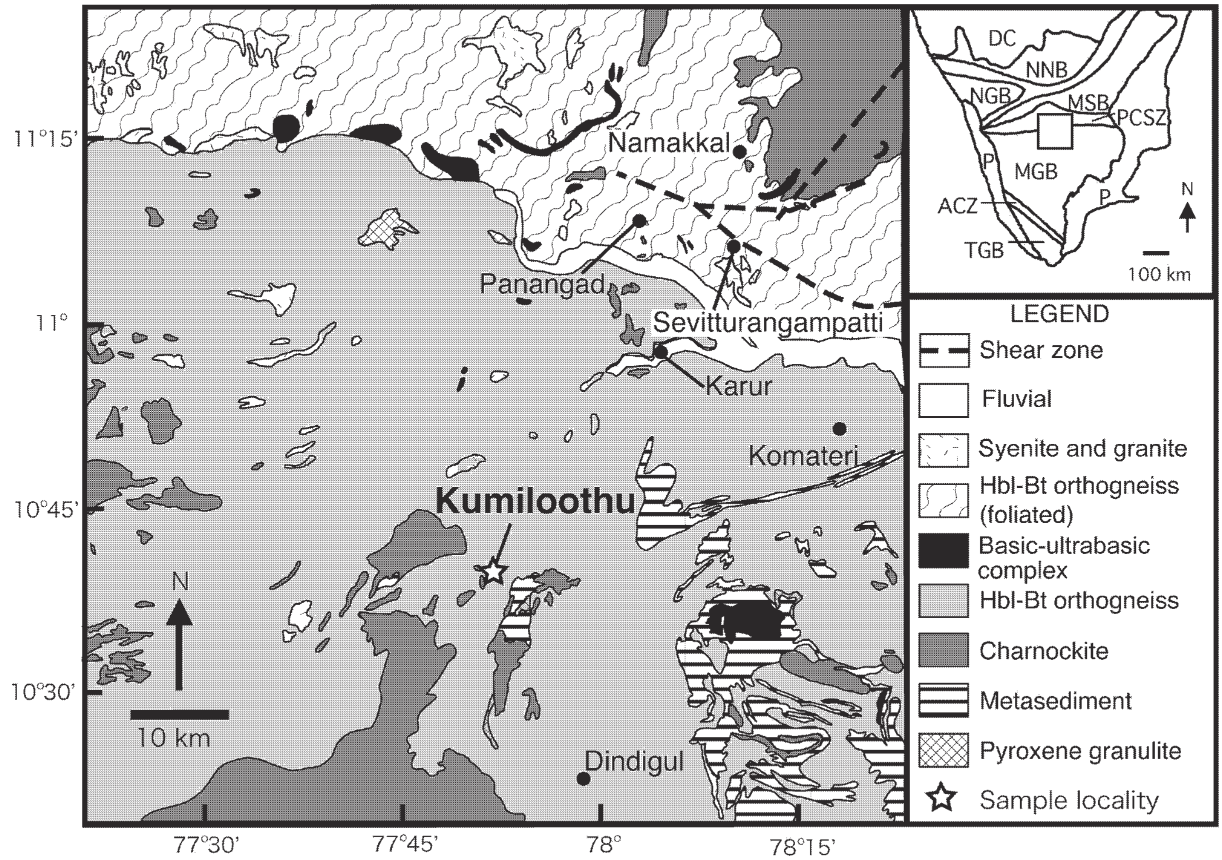

Figure 1. Geological map of the northern Madurai Block and the Palghat-Cauvery Shear Zone System (based on 1 : 500000 map of Tamil Nadu, GSI, 1995) with the sample locality of garnet-orthopyroxene granulite discussed in this paper. DC, Dharwar Craton; MGB, Madurai Block; MSB, Madras Block; NNB, Northern Block; NGB, Nilgiri Block; TGB, Trivandrum Block; ACZ, Achankovil Zone; PCSZ, Palghat-Cauvery Shear Zone System; P, Phanerozoic cover.

Kumiloothu, a newly discovered UHT locality near Karur in the northern MGB. Tsunogae et al. (2008a) inferred prograde high-pressure ($P > 12$ kbar) metamorphism and subsequent peak UHT conditions of $T \sim 1000$ °C along a clockwise P-T trajectory from this region. The results of the present study provide important information of the nature and role of deep crustal fluids in collisional orogenic belt.

PETROLOGY

The sample of garnet-orthopyroxene granulite from Kumiloothu examined in detail in this study (MD21-1L) is composed of poikiloblastic garnet (Alm_{49-52} Pyr_{40-43} Grs_{7-8} Sps_{0-1}) in the matrix of orthopyroxene (X_{Mg} = Mg/(Fe + Mg) = 0.65-0.69, Al = 0.25-0.27 pfu), quartz, plagioclase (An_{32-37}), and retrograde biotite (X_{Mg} = 0.68-0.76, Ti = 0.11-0.40 pfu). Garnet is coarse-grained (up to 2 cm in length) and poikiloblastic, and contains numerous inclusions of sapphirine (X_{Mg} = 0.70-0.74), spinel (X_{Mg} = 0.37-0.49, Zn < 0.01 pfu), staurolite (X_{Mg} = 0.33-0.42), orthopyroxene, plagioclase, quartz, sillimanite, and rutile. Preliminary P-T estimates using garnet + orthopyroxene geothermobarometry of Lee and Gangly (1988) and Harley and Green (1982) for the sample yielded metamorphic conditions of 890-920 °C and 7.5-9.0 kbar, which is consistent with the UHT condition inferred by Sato et al. (2008). Cordierite around garnet is often intergrown with vermicular orthopyroxene probably formed by the following reaction (1).

$$\text{Grt} + \text{Qtz} \rightarrow \text{Crd} + \text{Opx} \qquad (1)$$

This texture has been reported from many granulite terranes in the world, as an evidence of near-isothermal decompression after the peak metamorphism.

FLUID INCLUSIONS

Three types of fluid inclusions are present. The most dominant category is primary inclusions (group of synchronous inclusions, as per the scheme of Touret, 2001)

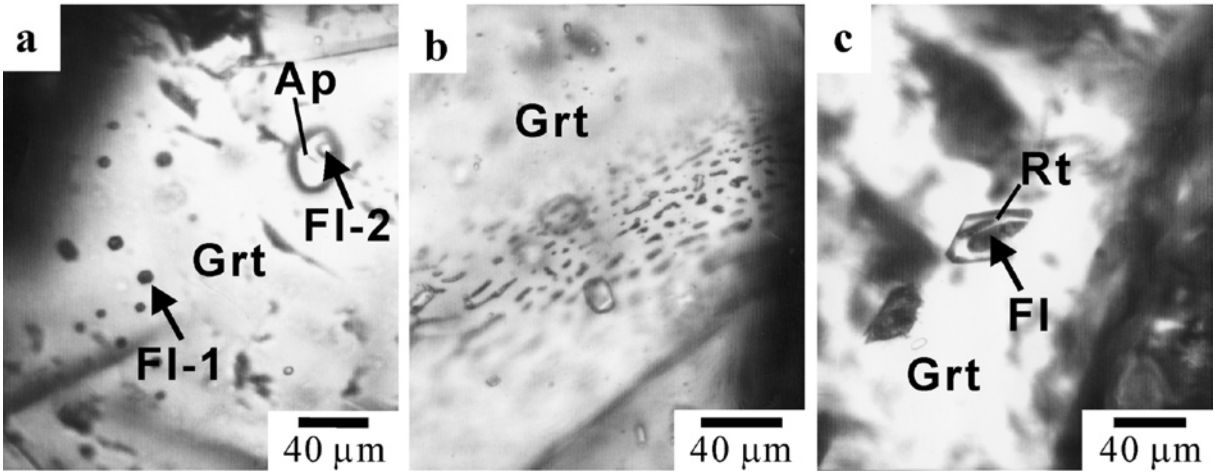

Figure 2. Photomicrographs of representative fluid inclusions discussed in this study. (a) Negative-crystal shaped primary inclusion in garnet (FI-1) and primary inclusion in apatite (FI-2) enclosed in garnet. (b) Array of secondary inclusion in garnet. (c) Primary inclusion (FI) with rectangular cavity in rutile enclosed in garnet.

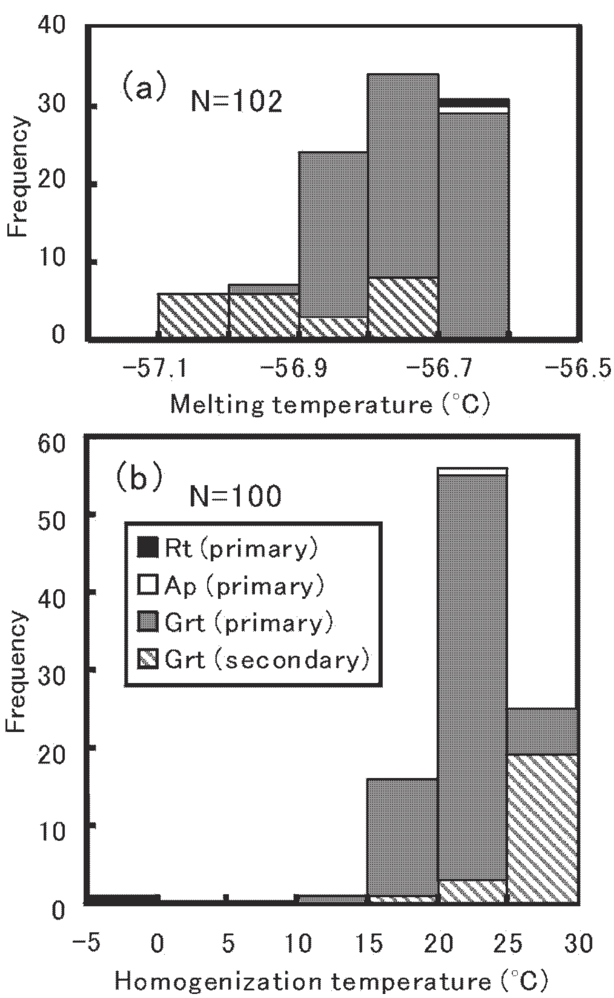

Figure 3. Histograms showing the distributions of (a) melting and (b) homogenization temperatures of fluid inclusions trapped in garnet (Grt), apatite (Ap), and rutile (Rt).

that occur as random clusters in garnet (Fig. 2a). They show negative-crystal shape and often accompany carbonate phases (possibly calcite). The second category is secondary inclusions that are present along later cracks in garnet (Fig. 2b). The inclusions often show irregular shape, which is clearly different from primary inclusions. Such inclusions contain fluids presumably trapped during the exhumation stage. Apatite and rutile enclosed in garnet also contain fluid inclusions of apparently primary nature similar to those in the host garnet, constituting the third category (Figs. 2a and 2c).

Microthermometric measurements of fluid inclusions were performed with a Linkam heating/freezing stage at the University of Tsukuba. The dominant category of inclusion in all the minerals is monophase at room temperature. On supercooling, the inclusions freeze into a solid aggregate and on slow warming, abrupt melting occurs at temperatures (T_m) at –57.0 to –56.6 °C (Fig. 3a), which is close to the triple point of pure CO_2 (–56.6 °C). On continued heating, all the trapped fluids homogenized into the liquid phases at temperatures (T_h) in the range of –3.6 to +30.3 °C (Fig. 3b). T_h of primary fluid inclusions in garnet and apatite indicate a sharp peak at +21.9 ± 2.8 °C, broadly similar to the range of secondary inclusions in garnet (+18.1 to +30.3 °C). In contrast, T_h of fluid inclusions in rutile is significantly low at –3.6 °C.

The composition of fluid, together with temperature and phase of homogenization, provides an estimate of the density. For the fluid inclusions of present study, CO_2 densities of 0.95 g/cm^3 for primary inclusions in rutile, 0.76 g/cm^3 for primary inclusions in apatite, 0.68–0.85 g/cm^3 for primary inclusions in garnet, and 0.58–0.79 g/cm^3 for secondary inclusions in garnet were estimated. Iso-

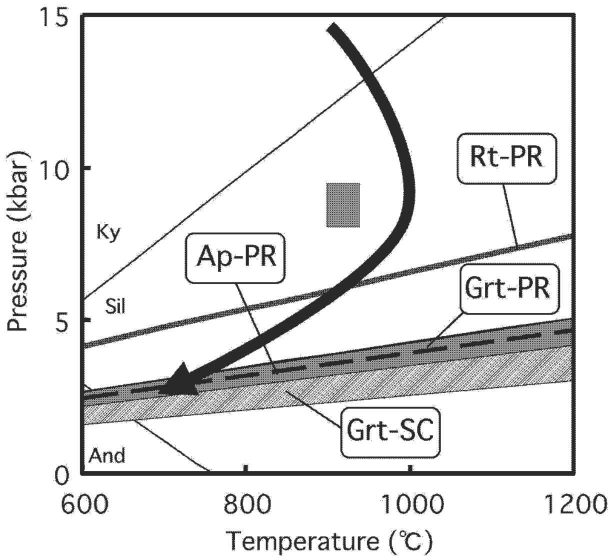

Figure 4. *P–T* diagram showing calculated isochores for the UHT granulite from Kumiloothu, northern Madurai Block. Hatched box indicates the peak *P–T* condition obtained from garnet-orthopyroxene-plagioclase-quartz assemblages in sample MD21-1L. Arrow indicates the *P–T* trajectory of the studied locality (after Sato et al., 2008). Isochores for primary inclusion in rutile (T_h = –3.6 °C, Rt-PR) and primary inclusions in apatite (Ap-PR) are plotted together with those of primary (Grt-PR) and secondary (Grt-SC) inclusions in garnet. The ranges of isochores for primary and secondary inclusions in garnet indicate the error (standard deviation) of T_h data. Phase relations of aluminosilicates are based on the thermodynamic data of Holland and Powell (1998).

chores were calculated for each category of inclusions using the computer program "MacFlinCor" developed by Brown and Hagemann (1995) and the thermodynamic model of Brown and Lamb (1989). The results are shown in Figure 4 together with available *P–T* path for Kumiloothu locality (Sato et al., 2008).

DISCUSSION

Microthermometric measurements of fluid inclusions in the UHT granulite from Kumiloothu, northern MGB, indicate that the trapped fluids are dominantly CO_2-rich. Such occurrences of primary carbonic fluid inclusions have been reported from many UHT terranes in the world (e.g., Tsunogae et al., 2002, 2003, 2008b, 2008c; Santosh et al., 2008). Such CO_2-rich fluids, probably derived from sub-lithospheric sources, have been considered to be instrumental in buffering the water activity and generating granulite facies assemblages at high- and ultrahigh-temperature conditions (e.g., Tsunogae et al., 2002; Santosh et al., 2004; Santosh and Omori, 2008a, 2008b, and references therein). However, the ranges of CO_2 isochores shown in Figure 4 indicate that the fluid densities are not sufficiently high to indicate the entrapment of CO_2 at the peak thermal conditions because the corresponding isochores (~ 6.6 kbar at 1000 °C) do not pass through the peak *P–T* conditions of metamorphism (~ 8 kbar at *T* > 1000 °C), although the inclusions show textually of primary nature. The low-density nature of the fluids can be interpreted to be a result of post-peak fluid entrapment along a retrograde path during exhumation. However, this model is not realistic because of the primary nature of fluid inclusions in garnet, apatite, and rutile which indicates that the fluids were trapped during the prograde to peak metamorphism. Although counterclockwise *P–T* history as proposed by Santosh and Sajeev (2006) and Tsunogae and Santosh (2006b) from the MGB might be consistent with the occurrence of such low-density carbonic fluid, available textures discussed in this study (e.g., relic staurolite inclusions in garnet) support clockwise history of this locality. An alternate explanation is that, as the rock underwent significant pressure decrease during rapid exhumation along a clockwise trajectory, the fluid inclusions experienced density reversal due to sudden volume changes of the inclusion cavities (e.g., Ohyama et al., 2008). Such near isothermal decompression after the peak event is supported by the occurrence of various corona textures such as orthopyroxene + cordierite and gedrite + sapphirine + spinel symplectites around garnet, and sapphirine + spinel + cordierite symplectite between kyanite and garnet (or gedrite) in this region (e.g., Shimpo et al., 2006; Santosh and Sajeev, 2006; Tsunogae and Santosh, 2007; Tsunogae et al., 2008a; Kanazawa et al., 2008). Such density modification of fluid inclusions has been reported earlier from some of the granulites along the PCSZ (Santosh and Tsunogae, 2003; Tsunogae et al., 2008b). Similar primary to pseudosecondary fluid inclusions with extremely low-density CO_2 have also been reported from some other UHT terranes (e.g., Tsunogae et al. 2003; Tsunogae and van Reenen, 2007), that underwent extreme decompression after the peak metamorphism. We therefore conclude that significant density modification of carbonic fluids in primary inclusions is a common feature of granulites that underwent high-grade metamorphism followed by rapid decompression along a clockwise *P–T* trajectory.

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