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ABSTRACT The exposed residual crust in the Eastern Ghats Province records ultrahigh temperature (UHT) metamorphic conditions involving extensive crustal anatexis and melt loss. However, there is disagreement about the tectonic evolution of this late Mesoproterozoic–early Neoproterozoic orogen due to conflicting petrological, structural and geochronological interpretations. One of the petrological disputes in residual high Mg–Al granulites concerns the origin of fine-grained mineral intergrowths comprising cordierite + K-feldspar ± quartz ± biotite ± sillimanite ± plagioclase. These intergrowths wrap around porphyroblast phases and are interpreted to have formed by the breakdown of primary osumilite in the presence of melt trapped in the equilibration volume by the melt percolation threshold. The pressure ($P$)–temperature ($T$) evolution of four samples from three localities across the central Eastern Ghats Province is constrained using phase equilibria modelling in the chemical system Na₂O–CaO–K₂O–FeO–MgO–Al₂O₃–SiO₂–H₂O–TiO₂–Fe₂O₃ (NCKFMASHTO). Results of the modelling are integrated with published geochronological results for these samples to show that the central Eastern Ghats Province followed a common $P$–$T$–$t$ history. This history is characterized by peak UHT metamorphic conditions of 945–955 °C and 7.8–8.2 kbar followed by a slight increase in pressure and close-to-isobaric cooling to the conditions of the elevated solidus at 940–900 °C and 8.5–8.3 kbar. In common with other localities from the Eastern Ghats Province, the early development of cordierite before osumilite and the peak to immediate post-peak retrograde reaction between osumilite and melt to produce the intergrowth features requires that the prograde evolution was one of contemporaneous increasing pressure with increasing temperature. This counter-clockwise (CCW) evolution is evaluated for one sample using inverse phase equilibria modelling along a schematic $P$–$T$ path of 150 °C kbar⁻¹ starting from the low $P$–$T$ end of the prograde $P$–$T$ path as constrained by the phase equilibria modelling. The inverse modelling is executed by step-wise down temperature reintegration of sufficient melt into the residual bulk chemical composition at the $P$–$T$ point of the 1 mol.-% melt isopleth at each step, representing the melt remaining on grain boundaries after each prograde drainage event, to reach the melt connectivity transition (MCT) of 7 mol.%. The procedure is repeated until a plausible protolith composition is recovered. The result demonstrates that clastic sedimentary rocks that followed a CCW $P$–$T$ evolution could have produced the observed mineral assemblages and microstructures preserved in the central Eastern Ghats Province. This study also highlights the role of melt during UHT metamorphism, particularly its importance to both chemical and physical processes along the prograde and retrograde segments of the $P$–$T$ path. These processes include: (i) an increase in diffusive length scales during the late prograde to peak evolution, creating equilibration volumes larger than a standard thin section; (ii) the development of retrograde mineral assemblages, which is facilitated if some melt is retained post-peak; (iii) the presence of melt as a weakening mechanism and the advection of heat by melt, allowing the crust to thicken; and (iv) the effect of melt loss, which makes the deep crust both denser and stronger, and reduces heat production at depth, limiting crustal thickening and facilitating the transition to close-to-isobaric cooling.

Key words: counter-clockwise $P$–$T$ paths; Eastern Ghats Province; melt reintegration; osumilite; phase equilibria modelling; UHT metamorphism.

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INTRODUCTION

Increasingly, ultrahigh temperature (UHT) metamorphism is recognized from the hinterlands of collisional orogenic belts (Harley, 1998; Brown, 2006, 2007; Kelsey, 2008). Under UHT conditions, clastic sedimentary rocks generate a significant volume of melt, but most of the melt produced along the prograde $P$–$T$ path is thought to have been drained from these UHT rocks to explain their residual chemical compositions and to allow preservation of the largely anhydrous close-to-peak mineral assemblages (e.g. Fyfe, 1973; Powell & Downes, 1990; Barboza & Bergantz, 2000; Brown, 2002; White & Powell, 2002, 2010; Diener et al., 2008; Brown & Korhonen, 2009; Johnson et al., 2010, 2012; Korhonen et al., 2010). The strongly depleted nature of UHT metamorphic rocks leads to uncertainty over the original protolith composition in many cases. This uncertainty limits the application of forward phase equilibria modelling to UHT rocks. As a result, the prograde $P$–$T$ evolution for many UHT metamorphic rocks is largely unconstrained and limited to inference.

Nonetheless, variable retrogression is apparent in some suites of UHT rocks. This retrogression indicates that melt generated around the metamorphic peak may be trapped immediately post-peak by the percolation threshold – the porosity at which a crystallizing rock becomes impermeable – at 8–11 vol.% melt for non-texturally equilibrated rocks (Cheadle et al., 2004). This trapped melt allows retrograde reaction to occur down temperature to the elevated solidus (Brown, 2002; White & Powell, 2002, 2011). In these suites of UHT rocks, retrograde mineral assemblages provide information critical to constraining the overall form of the peak to post-peak $P$–$T$ path (e.g. Brown & Raith, 1996; Raith et al., 1997; Kelsey et al., 2003; Baldwin et al., 2005; Harley, 2008; Brown & Korhonen, 2009; Korhonen et al., 2013). This raises a question about whether peak metamorphic conditions might be underestimated if high-temperature retrograde reaction between peak minerals and melt trapped by the percolation threshold was cryptic.

These issues are addressed in this study using examples from the central Eastern Ghats Province, a subdivision of the Eastern Ghats orogenic belt in India (Dobmeier & Raith, 2003; Dasgupta et al., 2013). The Eastern Ghats Province is characterized by the widespread occurrence of UHT metamorphism. However, conflicting petrological and structural interpretations relating to the $P$–$T$–time ($t$) path (counter-clockwise (CCW) v. clockwise (CW)) and difficulties in deciphering the geological significance of ages that span a range from the late Mesoproterozoic to the early Neoproterozoic (a single $v$. a poly-phase metamorphic evolution) have led to the development of contrasting tectono-metamorphic models for the evolution of the Province. In addition, the interpretation of complex, sometimes enigmatic, microstructures and reaction textures has led to different retrograde $P$–$T$ trajectories (decompression $v.$ cooling) with some fine-grained mineral intergrowths being interpreted as either replacements of primary minerals, particularly osumilite, or as representing products of melt crystallization.

In this study, microstructural observations and quantitative constraints from pseudosections calculated in the chemical system Na$_2$O–CaO–K$_2$O–FeO–MgO–Al$_2$O$_3$–SiO$_2$–H$_2$O–TiO$_2$–Fe$_3$O$_5$ (NCKFMASHTO) are used to define the $P$–$T$ conditions of peak and retrograde metamorphism for four samples from three different localities in the central Eastern Ghats Province. Several of these samples preserve fine-grained mineral intergrowths that are interpreted to have formed by the breakdown of osumilite in the presence of melt. These microstructures are common in granulites throughout the central Eastern Ghats Province, potentially indicating that osumilite was widespread at the metamorphic peak across the Province, but was not preserved during the retrograde history. Some rocks also preserve evidence for the pre- osumilite metamorphic mineral assemblages, which provide important constraints on the form of the $P$–$T$ path. For one sample, a plausible protolith composition is reconstructed using inverse phase equilibria modelling in which melt is reintegrated into the residual bulk chemical composition in a step-wise fashion down temperature. The success of this exercise suggests that an overall CCW $P$–$T$–$t$ path for the central Eastern Ghats Province is a reasonable interpretation of the available data. Based on the results of this study, the role of melt during UHT metamorphism, particularly its importance to both chemical and physical processes at all scales, is discussed and a possible tectonic model for this extreme type of high-$T$, moderate-$P$ style of CCW metamorphism is proposed. We conclude that this type of UHT metamorphism may be explained by a combination of thinned lithosphere and radiogenic heating during prograde thickening of crust weakened by the presence of melt above the solidus.

GEOLOGICAL SETTING

Regional geology

The Eastern Ghats Belt extends over 1000 km along the eastern coast of Peninsular India (Fig. 1a) and expose a deep crustal section through a composite Proterozoic orogenic belt. Despite broad lithological similarities, based on geological and isotopic data, the Eastern Ghats Belt has been separated into several discrete crustal segments with contrasting histories, as follows: the Late Archean Jeypore and Rengali Provinces, the Late Paleoproterozoic Ongole Domain and the Mesoproterozoic–early Neoproterozoic Eastern Ghats Province (e.g. Rickers
The Eastern Ghats Province, which is the largest of these crustal segments, is located in the central and northern parts of the Belt. It comprises most of the western and eastern khondalite belts, and the charnockite–migmatite zone in Fig. 1a. The rocks exposed here preserve a complex imprint of prolonged high-grade metamorphism and intense deformation. Previous petrological studies in the Province have reported estimates of peak UHT metamorphic conditions for the late Mesoproterozoic–early Neoproterozoic orogenic event of > 950 °C and ~9 kbar, although there are differences in interpretation about whether the \( P-T-t \) paths are CW or CCW, or whether both exist but in different sectors of the Province (e.g. Lal et al., 1987; Kamineni & Rao, 1988; Sengupta et al., 1990; Dasgupta et al., 1995; Sen et al., 1995; Mohan et al., 1997; Mukhopadhyay & Bhattacharya, 1997; Shaw & Arima, 1997; Bose et al., 2000, 2006; Rickers et al., 2001b; Bhattacharya & Kar, 2002; Sarkar et al., 2003; Das et al., 2006, 2011; Bose & Das, 2007; Nasipuri et al., 2008; Korhonen et al., 2011, 2013; Dharma Rao et al., 2012).

In addition to contrasting \( P-T-t \) paths, there are disparities in the number of metamorphic events recognized and in the timing and duration of the UHT metamorphism, leading to conflicting tectono-metamorphic models for the evolution of the Eastern Ghats Province (Bhattacharya & Kar, 2002; Bose et al., 2011; Das et al., 2011; Dasgupta et al., 2013; Dharma Rao et al., 2012; Gupta, 2012; Korhonen et al., 2013).

Evidence for granulite facies metamorphism and felsic magmatism between \( c. 1000 \) and \( c. 950 \) Ma has been well documented (Grew & Manton, 1986; Shaw et al., 1997; Mezger & Cosca, 1999; Bhattacharya et al., 2003; Simmat & Raith, 2008; Das et al., 2011; Korhonen et al., 2011, 2013; Bose et al., 2011). However, older ages ranging from \( c. 1400 \) Ma (U–Pb in zircon, Pb–Pb in feldspar – reviewed in Simmat & Raith, 2008) to \( c. 1250–1100 \) Ma (Th–U–Pb chemical ages retrieved from monazite – Simmat & Raith, 2008) have been interpreted to date an early UHT metamorphic event. As a result of these studies, a common interpretation is that there was an early UHT event (\( M_1 \)) in which the metamorphic peak was followed by close-to-isobaric cooling to ~750–800 °C. Furthermore, the ages of \( c. 1000–950 \) Ma are argued to record a later pervasive granulite facies event (\( M_2 \)) that reached peak conditions of ~850 °C and ~8 kbar before near-isothermal decompression to ~5 kbar (Dasgupta & Sengupta, 2003; Simmat & Raith, 2008; Bose et al., 2011). Alternatively, the UHT metamorphism has been interpreted as a single long-lived event in the late Mesoproterozoic to early Neoproterozoic (e.g. Korhonen et al., 2011, 2013; Dharma Rao et al., 2012; Gupta, 2012). In a recent review, Korhonen et al. (2013) proposed that the late prograde to peak UHT metamorphism and initial close-to-isobaric cooling occurred between \( c. 1130 \) and \( c. 970 \) Ma. During close-to-isobaric cooling to the solidus, crystallization of melt trapped by the percolation threshold (Cheadle et al., 2004) resulted in populations of zircon and monazite that yield weighted mean ages between \( c. 970 \) and \( c. 930 \) Ma. These ages are interpreted to reflect differences in solidus temperature from rock to rock across the Province, consistent with a slow cooling rate of ~1 °C Ma\(^{-1}\) during the retrograde stage of a single long-lived UHT metamorphic event (Korhonen et al., 2013).

This study is located in the central part of the Eastern Ghats Province (Fig. 1a), in Domain II of
Rickers et al. (2001a). The dominant rocks include migmatitic sillimanite–garnet-bearing gneiss (referred to locally as khondalite), orthopyroxene-free garnetiferous quartzo-feldspathic gneiss (referred to locally as leptynite), orthopyroxene-bearing charnockitic and enderbitic quartzo-feldspathic gneiss, and two-pyroxene mafic granulite. Small lenses of calcisilicate and high Mg–Al granulites are present in the gneisses.

The local geology and outcrop setting for each of the samples studied in detail are described below, including a sample described previously from the Sunki locality (sample SK2-6-05; Korhonen et al., 2011), which is reinterpreted as part of this study. For each of the samples, geochronological results from Korhonen et al. (2013) are summarized. Brief discussion of the P–T–t histories proposed in previous studies of similar rocks from nearby localities is included for completeness. Unless otherwise indicated, these earlier interpretations have relied on petrogenetic grids in simplified chemical systems and conventional thermobarometry to determine P–T conditions.

**Paderu locality**

Southwest of Paderu, in the area around Gangaraja Madugula, pelitic migmatite, mafic granulite, charnockite–enderbite, and intrusive granites are all well exposed. Rare high Mg–Al granulites (Fig. 2a), some with sapphirine, are present as small blocks and folded layers within massif-type charnockite–enderbite bodies and as small blocks in granites.

In a study of sapphirine-bearing granulites near Gangaraja Madugula, Mohan et al. (1997) interpreted the metamorphic peak to have been at >900 °C and 8.4 kbar, which, they argued, was followed by a retrograde evolution that involved a decrease in pressure of up to 3 kbar and cooling of 150–200 °C. In the area to the southwest of Gangaraja Madugula, Bhattacharya & Kar (2002) proposed that peak metamorphism was followed by high-temperature decompression from ~10 to ~8 kbar at 1000 °C and subsequent cooling to a ~600 °C. These authors inferred a CW P–T path and proposed a tectonic model in which crustal thickening and granulite metamorphism was the result of homogeneous shortening in a compressional setting. By contrast, Sengupta et al. (2004) reinterpreted the data of Bhattacharya & Kar (2002) to argue that the decompression segment of the P–T path only began at a pressure of ~7–8 kbar at a temperature of ~850 °C and that it postdated cooling from peak UHT conditions. These authors inferred a general CCW P–T–t path for the UHT metamorphism, broadly consistent with the conclusions of Pal & Bose (1997; see also Lal et al., 1987), who, 15 years earlier, had proposed a CCW path reaching peak conditions of ~1000 °C and 9.5 kbar, followed by near-isobaric cooling to 900 °C and 9 kbar.

For samples collected ~2 km northeast of Paderu at Panasapattu, Dharma Rao et al. (2012) proposed a minimum temperature of 1030–1050 °C at
> 10 kbar for the peak of metamorphism, based on univariant reactions in FMAS, results from phase equilibria modelling in NCKFMASH and conventional thermobarometry. They suggested that peak conditions were followed by decompression to <10 kbar with subsequent near-isobaric cooling to below 900 °C. Based on a record of UHT decompression preceding isobaric cooling, these authors proposed a CW P–T path, with the sapphire granulites produced during high temperature melting along the prograde segment. Twenty-five years earlier, Lal et al. (1987) had proposed a CCW path passing through 900 °C at 6.5 kbar and 760 °C at 5 kbar for samples collected ~1.5 km southwest of Paderu at Gundurum.

For this study, sample EGB-09-01 was collected about 4 km northwest of Gangaraja Madugula, approximately 12 km southwest of Paderu (Fig. 1b), and sample EGB-09-04 was collected about 2 km north–northwest of sample EGB-09-01. Zircon from sample EGB-09-01 yielded a weighted mean 207Pb/206Pb age of 929 ± 17 Ma, and monazite from sample EGB-09-04 yielded a weighted mean 207Pb/206Pb age of 968 ± 20 Ma (Korhonen et al., 2013). These ages have been interpreted to record the timing of final melt crystallization, with the variability in the weighted mean ages reflecting differences in the temperature of the elevated solidus between the two samples.

Sunkarametta locality

Sample EGB-10-82 was collected approximately 7 km northwest of Anantagiri and 1.5 km west of Sunkarametta (Fig. 1b). This area exposes migmatic gneiss, mafic granulite and charnockite–enderbite. High Mg–Al granulite with either sapphire or spinel (Fig. 2b) is present as small elongate bodies within the dominant migmatic gneiss (Fig. 2c) near the margins with mafic and enderbitic granulites. Bose et al. (2000; see also Bose et al., 2006) have interpreted massive coarse-grained orthopyroxene–cordierite–sapphire–migmatite and orthopyroxene–spinel granulites from this locality to be associated with prograde melting of biotite–plagioclase–quartz-bearing protoliths at pressures of ~6–8 kbar and temperatures in excess of 850 °C, with peak metamorphic conditions reaching ~9 kbar and ~950 °C, followed by slight decompression and cooling to ~750–700 °C.

Monazite from sample EGB-10-82 yielded a weighted mean 207Pb/206Pb age of 953 ± 7 Ma (Korhonen et al., 2013) and monazite from a similar sample collected from the same outcrop yielded a weighted mean 207Pb/206Pb age of 948 ± 5 Ma (sample EGB-10-84; Korhonen et al., 2013). These ages have been interpreted to record the timing of final crystallization of residual melt at the solidus. Additional age information for the Sunkarametta locality is provided by sample EG-San3A from the study of Bose et al. (2011). This orthopyroxene-bearing quartz-feldspathic orthogneiss has a reported location about 120 m southwest of sample EGB-10-82. It yielded a range of discordant 207Pb/206Pb spot ages from recrystallized domains in moderate-CL oscillatory-zoned zircon from c. 1600 to c. 1100 Ma, defining a lower intercept age of 1008 ± 49 Ma. Four near concordant spot ages from bright-CL oscillatory-zoned grains range from c. 1025 to c. 950 Ma. A single spot age from an overgrowth domain has an age of c. 980 Ma.

Sunki locality

This locality is approximately 10 km south of Sunki (Fig. 1b) and exposes dominantly enderbites with subordinate metasedimentary granulites. High Mg–Al granulate with or without sapphire is present as small bodies within metapelitic granulite (khondalite).

Sample SK2-6-05 is a migmatitic high Mg–Al granulate with discrete melanosome s and leucosomes ranging in thickness from a few millimetres to several centimetres. Using phase equilibria modelling, Korhonen et al. (2011) estimated peak P–T conditions for this sample to have been in excess of 950 °C and 9.5 kbar, although pressure was not well constrained. The retrograde evolution was interpreted to involve decompression and minor cooling to the elevated solidus at ~900 °C and 7.5 kbar.

Although osmumite was included in the phase equilibria modelling of this sample in Korhonen et al. (2011), it was not stable in any of the phase assemblage fields in the pseudosections calculated in that study. This appears to have been a consequence of the a–x model used for osmumite at that time. Because this study uses an updated osmumite a–x model in the phase equilibria modelling (see below), the phase equilibria modelling for sample SK2-6-05 has been redone and the revised P–T pseudosection is discussed below. The results from an additional sample from that study (sample D1.3-S3; Korhonen et al., 2011) are also discussed. Based on this re-evaluation, the peak pressure estimated in Korhonen et al. (2011) may have been too high.

Monazite analysed in situ from each of these two samples yielded weighted mean 207Pb/235U ages of c. 980 Ma, with a spread of 207Pb/235U spot ages from c. 1043 to c. 922 Ma (Korhonen et al., 2011, 2013). A monazite inclusion in an orthopyroxene porphyroblast was interpreted to date the late prograde growth of the peak minerals at c. 1042 Ma, and the weighted mean ages of c. 980 Ma were interpreted to date crystallization of residual melt trapped by the percolation threshold during cooling to the solidus. The spread of ages reflects protracted monazite growth and implies very slow cooling from peak conditions at a rate of ~1 °C Ma⁻¹.
PETROGRAPHY AND PETROGENESIS

Petrographic observations are separated into those relating to the inferred prograde to peak UHT metamorphic phase assemblages and those relating to mineral assemblages developed during the post-peak retrograde stage. Minerals that comprise the peak assemblage generally occur as coarse embayed grains that are commonly isolated from each other by coronae or intergrowths of finer grained minerals that represent post-peak reaction products. Mineral chemistry data have not been used in this study because in a slowly cooled, melt-present UHT terrane, mineral compositions do not generally provide information about peak conditions but tend to record conditions close to the solidus, as seen, for example, for the Al contents of orthopyroxene in the study of Korhonen et al. (2011) and discussed below.

Sample descriptions

Sample EGB-09-01 (Paderu locality)

In sample EGB-09-01, coarse-grained garnet porphyroblasts (up to 10 mm in diameter), smaller orthopyroxene porphyroblasts (up to 2 mm in diameter), quartz, plagioclase, K-feldspar, ilmenite and magnetite comprise the inferred peak metamorphic mineral assemblage. Garnet has minor inclusions of biotite, ilmenite and magnetite (Fig. 3a). The orthopyroxene is less abundant than garnet and may be in direct contact with it (Fig. 3a). Biotite is also present as minor inclusions in orthopyroxene and as coarse laths in the matrix, where it is inferred to be a post-peak phase. A second generation of garnet is characterized by having numerous fine-grained inclusions of quartz, resulting in a distinct ‘spongy’ appearance. This secondary garnet typically forms rims around the coarse-grained garnet porphyroblasts (Fig. 3b,c) and less commonly as rims around orthopyroxene, ilmenite and biotite (Fig. 3a–c).

Sample EGB-09-04 (Paderu locality)

In sample EGB-09-04, large embayed orthopyroxene porphyroblasts (up to 8 mm in diameter), sillimanite, quartz and rutile form part of an inferred peak metamorphic mineral assemblage (Fig. 4a), and define the foliation on a centimetre scale. Sillimanite occurs as sparse resorbed grains, which may contain fine vermicular quartz inclusions. This type of sillimanite (Fig. 4a) is commonly separated from coarse-grained orthopyroxene (Fig. 4b) by a fine-grained intergrowth of orthopyroxene + sillimanite + quartz ± biotite. Coarse-grained quartz has fine rutile needles in core domains (Fig. 4a), and displays undulose extinction and elongate subgrains. A fine-grained intergrowth composed of cordierite + K-feldspar ± quartz ± biotite ± sillimanite ± plagioclase makes up a signifi-

Fig. 3. Photomicrographs from sample EGB-09-01 (Paderu locality). (a) Orthopyroxene adjacent to a garnet porphyroblast (bottom right). Both phases are rimmed by a second generation of garnet (‘g2’), characterized by abundant fine-grained inclusions of quartz. (b) Rims of ‘g2’ garnet around garnet, orthopyroxene and ilmenite. (c) Detail of microstructure in (b). Mineral abbreviations: bi, biotite; cd, cordierite; g, garnet; ilm, ilmenite; ksp, K-feldspar; mt, magnetite; opx, orthopyroxene; pl, plagioclase; q, quartz; sa, sapphire; sill, sillimanite; ru, rutile.

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Fig. 4. Photomicrographs from sample EGB-09-04 (Paderu locality). (a) Orthopyroxene and sillimanite separated by a fine-grained intergrowth of sillimanite + quartz (±biotite) replacing orthopyroxene. Coarse-grained quartz has fine rutile needles in the core domains creating the 'dirty' appearance. (b) Garnet with abundant vermicular inclusions forming rims on orthopyroxene. Patches of the fine-grained orthopyroxene + sillimanite + quartz intergrowth are also present. (c,d) Folia of intergrown cordierite + K-feldspar + quartz (±biotite ± sillimanite ± plagioclase) aligned in the foliation enclose resorbed orthopyroxene porphyroblasts; plane polarized (c) and cross-polarized (d) light respectively. (e,f) Intergrowths of cordierite + K-feldspar + quartz partially pseudomorphing early cordierite and some patches of fine-grained intergrown orthopyroxene + sillimanite + quartz (±biotite) that appear to be a pseudomorph after an earlier phase; plane polarized (e) and cross-polarized (f) light respectively.
The cordierite + coarse quartz in the matrix, the garnet has abundant interpreted to be a post-peak phase. Where adjacent to orthopyroxene porphyroblasts (Fig. 4b), and is interpreted to be a post-peak phase. Where adjacent to coarse quartz in the matrix, the garnet has abundant vermicular inclusions of quartz, whereas adjacent to the cordierite + K-feldspar ± quartz ± biotite ± sillimanite ± plagioclase intergrowths, the garnet has abundant inclusions of K-feldspar, biotite and quartz. Biotite occurs as rare inclusions in orthopyroxene, in the post-peak intergrowths, as inclusions in garnet, and as coarse laths in the matrix.

Sample EGB-10-82 (Sunkarametta locality)

Sample EGB-10-82 comprises coarse-grained orthopyroxene, garnet, cordierite and quartz with lesser amounts of sapphire, sillimanite, rutile, biotite, ilmenite, K-feldspar and plagioclase. Monazite and apatite are ubiquitous accessory phases. Orthopyroxene-rich and cordierite-quartz-rich layers ~2–5 mm in thickness define the foliation on a centimetre scale. There are sporadic garnet-rich layers throughout the outcrop and garnet is present in some thin sections. Orthopyroxene porphyroblasts (up to 5 mm) occur throughout the sample as embayed grains with abundant exsolved Fe–Ti oxide lamellae (Fig. 5a,b). Sillimanite occurs as rare isolated and embayed grains (Fig. 5c,d) commonly surrounded by sillimanite + quartz (± biotite) intergrowths near orthopyroxene (Fig. 5c) or biotite near cordierite (Fig. 5d). Garnet porphyroblasts (up to 5 mm) are concentrated in discrete layers with minor orthopyroxene and rutile (Fig. 5e). A second generation of garnet with numerous fine-grained inclusions of quartz forms rims on the garnet porphyroblasts (‘g2’ on Fig. 5e). Cordierite porphyroblasts (up to 3 mm) are abundant and are commonly surrounded by a fine-grained intergrowth of cordierite + K-feldspar ± quartz ± plagioclase (Fig. 5a–g). Typically, orthopyroxene and cordierite are separated by fine-grained intergrowths of sillimanite + quartz ± biotite with rounded relics of orthopyroxene that may be optically continuous with coarse-grained porphyroblasts (Fig. 5a,b), whereas orthopyroxene and quartz may be in direct contact (Fig. 5b). Plagioclase is distributed within the cordierite-K-feldspar domains as rounded grains, surrounded by moats of K-feldspar with rounded cordierite ± quartz. Rare elongate grains of sapphire are present in some cordierite-rich layers (Fig. 5h), separated from orthopyroxene-rich layers by ~3–5 mm. The sapphire grains primarily occur along grain boundaries of coarse-grained cordierite, but a few grains occur as inclusions. The cordierite-rich layers associated with sapphire are not altered to the fine-grained cordierite + K-feldspar intergrowths. Sapphirine is intergrown with and rimmed by sillimanite (Fig. 5h), and may also be present as small rounded inclusions in sillimanite. Small grains of orthopyroxene may form rims on the sillimanite + sapphire associations.

Based on these observations, the peak metamorphic mineral assemblage in this sample is interpreted to include orthopyroxene, cordierite, quartz, plagioclase, ilmenite and rutile. Garnet is a peak phase in some layers and sapphire in others, and sillimanite also could be a peak phase. These interpretations will be discussed in more detail below.

Sample SK2-6-05 (Sunki locality)

The peak metamorphic mineral assemblage in the melanosome of this sample is characterized by polygonal cordierite with orthopyroxene (up to 8 mm) and garnet (up to 5 mm) porphyroblasts (fig. 3 in Korhonen et al., 2011). Sillimanite is sparse, occurring as small rounded or ragged grains within cordierite and as rare inclusions rimmed by cordierite hosted in garnet. Modally minor quartz is present as small rounded grains throughout the melanosome and as inclusions in garnet. Ilmenite grains with exsolved

Fig. 5. Photomicrographs from sample EGB-10-82 (Sunkarametta locality). (a) Coarse-grained orthopyroxene porphyroblasts with exsolution lamellae of oxide. Orthopyroxene and cordierite or cordierite + K-feldspar intergrowths are commonly separated by intergrown sillimanite + quartz (±biotite) that include rounded relics of orthopyroxene in optically continuity with the orthopyroxene porphyroblasts. (b) Orthopyroxene porphyroblasts adjacent to cordierite with rounded and optically continuous relics and fine-grained intergrowths of sillimanite–quartz (±biotite). Orthopyroxene in direct contact with quartz lacks this microstructure. (c) Orthopyroxene porphyroblast and sillimanite are surrounded by a fine-grained intergrowth of sillimanite + quartz (±biotite) along grain boundaries between cordierite grains. (d) Coarser grained sillimanite separated from cordierite or cordierite + K-feldspar intergrowth by sillimanite hosting vermicular quartz (in boxes) and biotite, and fine-grained rounded orthopyroxene aggregates. (e) Secondary garnet rims (‘g2’) with fine vermicular quartz inclusions located on a garnet porphyroblast overgrows the adjacent to cordierite + K-feldspar intergrowths. (f,g) Orthopyroxene and cordierite porphyroblasts are separated by folia of intergrown cordierite + K-feldspar; plane polarized (f) and cross-polarized (g) light, respectively. (h) Elongate grains of sapphire as inclusions and along grain boundaries of coarse-grained cordierite. The sapphire is intergrown with and rimmed by sillimanite. © 2013 John Wiley & Sons Ltd
hematite lamellae are present in garnet-rich domains, either as inclusions in garnet porphyroblasts or as grains in cordierite near garnet.

The immediate post-peak mineral assemblage is represented by recrystallized grains of garnet, orthopyroxene and quartz that are commonly developed along the former grain boundaries between garnet and orthopyroxene porphyroblasts (fig. 3a in Korhonen et al., 2011). Garnet relics are common in second-generation cordierite. Biotite occurs as coarse laths and aggregates around garnet, orthopyroxene and cordierite. These observations suggest that the post-peak metamorphic mineral assemblage was garnet, orthopyroxene, sillimanite, cordierite and biotite.

Fine-grained mineral intergrowths

Intergrowths composed of cordierite + K-feldspar ± quartz ± orthopyroxene ± biotite ± sillimanite ± plagioclase are abundant in the samples from this study (Fig. 6) and in many samples from other studies in the central Eastern Ghats Province (e.g. Bose et al., 2000, 2006; Bhattacharya & Kar, 2002; Bose & Das, 2009; Das et al., 2011; Korhonen et al., 2011). The intergrowths are present as discrete patches (e.g. Figs 4e & 6a,b), but may also form interstitial and cuspate films and folia around matrix grains (e.g. Figs 4c,d & 5f,g). Fine-grained vermicular cordierite ± quartz occurs in a groundmass generally made up of K-feldspar, which may continue as a thin film along grain boundaries of adjacent grains (Fig. 6a). Minor coarser grains of quartz and biotite are present within the intergrowths (Fig. 6a,b). Some intergrowths are zoned, with patches of cordierite + K-feldspar ± quartz (± biotite ± sillimanite) adjacent to cordierite + quartz (± biotite ± sillimanite) (Fig. 6b,c). Some intergrowths also contain small rounded grains of orthopyroxene (Fig. 6d,e). The intergrowths are aligned within the foliation and are among the youngest microstructures observed in the samples from this study; they wrap around primary porphyroblasts and most other retrograde microstructures. However, in some samples (e.g. EGB-09-04), late garnet overgrows the cordierite + K-feldspar intergrowths, with quartz inclusions in the garnet concentrated near coarse quartz in the matrix, and K-feldspar, biotite and quartz inclusions concentrated near the cordierite + K-feldspar ± quartz ± biotite ± sillimanite ± plagioclase intergrowths (Fig. 6f).

Phase relations that relate to the formation of this intergrowth (cordierite + K-feldspar ± quartz ± orthopyroxene ± biotite ± sillimanite ± plagioclase) are investigated in the silica-saturated ternary system KAl2O3-(Fe,Mg)O-Al2O3. Integrated chemical compositions of these intergrowths (from Bose & Das, 2009) are projected through SiO2 and plotted in the ternary system in Fig. 7. These integrated compositions were either calculated from proportions estimated by image analysis and mineral compositions or based on broad area quantitative electron microprobe scans (filled and open squares, respectively, in Fig. 7). The results from the broad area scans show a wide scatter of chemical compositions (Fig. 7), which may reflect inaccuracies associated with broad area scanning, since the use of image analysis and mineral compositions has been shown to produce more reliable results in other studies (e.g. Korhonen & Stout, 2005).

Representative phase compositions are also shown in Fig. 7. Natural osmilibite compositions from the literature (n = 34; Berg & Wheeler, 1976; Ellis et al., 1980; Grew, 1982; Armaruster & Oberhansli, 1988; Arima & Gower, 1991; Audibert et al., 1995; Adjerid et al., 2013) and a predicted osmilibite composition from the phase equilibria modelling for sample EGB-09-04 (discussed below) are very similar (Fig. 7; yellow and grey circles respectively). A predicted melt composition at peak conditions (calculated at 945 °C and 8.3 kbar) for sample EGB-09-04 is also plotted in Fig. 7 (grey triangle). The integrated chemical compositions of the cordierite + K-feldspar intergrowths plot across the tielines joining the range of osmilibite compositions and the predicted melt composition, suggesting that the intergrowths could have been formed by the breakdown of osmilibite in the presence of melt. Nonetheless, some of the integrated chemical compositions are slightly displaced off the cordierite–K-feldspar tieline in the direction of sillimanite, consistent with the minor amount of sillimanite (+ quartz) observed in the intergrowths (e.g. Fig. 6c,e). Projecting the appropriate compositions through sillimanite onto the cordierite–K-feldspar tieline (grey diamonds, Fig. 7) shows that the intergrowths are typically composed of 28–52% K-feldspar and 72–48% cordierite, similar to the range of observed proportions in Fig. 6. Two of the integrated chemical compositions determined by broad area scanning by Bose & Das (2009) plot close to the sillimanite–K-feldspar edge of the ternary diagram suggesting these areas may have been intergrowths of mostly sillimanite + K-feldspar with minor cordierite and a third composition plots with the natural osmilibites in Fig. 7.

Based on the lack of crystal form, the common absence of orthopyroxene and their occurrence as folia wrapping other minerals, Bose et al. (2000, 2008) and Bose & Das (2009) argued that this type of intergrowth could not represent replacement after osmilibite. Instead, these authors proposed that the intergrowths were the last assemblage formed from the late crystallization of trapped melt at ~800 °C and 6.5–5.5 kbar, although they left open the possibility of interaction between melt and residual minerals (Bose et al., 2008; Bose & Das, 2009). However, there is no obvious mechanism by which a late-stage melt could achieve the necessary conditions to make symplectic intergrowths of this kind. Such intergrowths in siliceous melts generally owe their origin to a state...
Fig. 6. Backscatter electron images of cordierite + K-feldspar + quartz (± biotite) intergrowth microstructures. Within the intergrowth, lighter grey areas are K-feldspar and darker grey lamellae are cordierite. (a) Intergrowth forming a cuspatel film between matrix quartz grains. (b) Intergrowths showing compositional zoning, with cordierite + K-feldspar + quartz + biotite on the right side of the intergrowth, and cordierite + quartz (with minor sillimanite and biotite) on the left side. (c) Higher magnification image of the cordierite + quartz (with minor sillimanite and biotite) portion. (d) K-feldspar groundmass with vermicular cordierite, quartz and minor sillimanite, orthopyroxene and plagioclase. Intergrowth surrounds a cordierite porphyroblast. (e) Higher magnification image of the cordierite + quartz (+ minor sillimanite, orthopyroxene) portion. (f) Garnet ('g2') with abundant vermicular inclusions to show quartz inclusions concentrated near the coarser quartz grains in the matrix, and K-feldspar, biotite and quartz inclusions concentrated near the cordierite + K-feldspar ± quartz ± biotite ± sillimanite ± plagioclase intergrowths.

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of high supersaturation of the melt in the crystallizing mineral components (in this case, cordierite + K-feldspar ± quartz ± orthopyroxene ± biotite ± sillimanite ± plagioclase), a high rate of crystal growth (once nucleation and/or growth commences) and the high viscosity of the melt. These conditions are normally achieved through liquidus undercooling, which results in local saturation and essentially one-dimensional (towards melt) crystal growth (London, 2009). Such a mechanism seems unlikely to apply at UHT conditions. Finally, the postulated origin by late crystallization of trapped melt at ~800 °C and 6.5–5.5 kbar is not consistent with the results of the phase equilibria modelling presented below, which yields both higher temperature and pressure for the formation of these intergrowths.

In contrast, Bhattacharya & Kar (2002) interpreted the cordierite + K-feldspar intergrowths to be pseudomorphs after osmumite, based on reconstructed chemical compositions and the presence of relict osmumite in one of the intergrowths. Similarly, the preferred interpretation here is that the intergrowths formed from the decomposition of osumilite in the presence of melt trapped in the rock during cooling from peak conditions. The involvement of the melt serves two purposes. First, it explains the variable composition of the intergrowths (Fig. 7), which represent different amounts of interaction between osmumite and melt during replacement. Second, the osmumite + melt reaction is inferred to be a weakening mechanism at the reaction sites allowing the development of the distinctive wrapping microstructure (Figs 4c,d & 5a,f,g), including the folia of Bose et al. (2000).

PHASE EQUILIBRIA MODELLING

The conditions of metamorphism and the microstructural evolution of two granulite samples (EGB-09-01 and -04) from the Paderu locality and one sample (EGB-10-82) from the Sunkarametta locality are investigated using pseudosections based on bulk rock chemical compositions. These are residual compositions as a consequence of melt loss; thus, they are suitable to determine the peak P–T conditions and the immediate post-peak retrograde evolution. In addition, sample SK2-6-05 from the Sunki locality is remodelled using the melanosome composition reported in Korhonen et al. (2011). Finally, a plausible protolith composition was reconstructed for sample EGB-10-82 using an inversion technique that reintegrates melt into the residual composition in a stepwise fashion down temperature along a schematic pregrade P–T path of 150 °C kbar⁻¹, as explained below.

The bulk chemical compositions were determined by X-ray fluorescence spectroscopy (Table 1) using a Phillips 2404 XRF vacuum spectrometer at Franklin & Marshall College, USA, together with loss on ignition (LOI). FeO contents were analysed by Fe²⁺ titration also at Franklin & Marshall College, USA, and Fe₂O₃ contents were calculated by difference. The samples contain negligible MnO (<0.2 wt%, Table 1), which was not considered in the modelling.

The calculations were performed using THERMOCALC version tc333 (Powell & Holland, 1988; updated June 2009) and the internally consistent thermodynamic data set, tc-ds55s, a sapphire-specific update of Holland & Powell (1998), as used in Kelsey et al. (2004). The calculations were undertaken in the chemical system Na₂O-CaO-K₂O-FeO-MgO-Al₂O₃-SiO₂-H₂O-TiO₂-Fe₂O₃ (NCKFMASHTO), which is currently the most realistic system in which

The phases considered in the modelling and the corresponding $a$–$x$ models include biotite and melt (White et al., 2007), orthopyroxene and spinel–magnetite (White et al., 2002), garnet (Diener et al., 2008), hydrous cordierite (Holland & Powell, 1998), sapphire (Taylor-Jones & Powell, 2010), osumilite (modified from Holland et al., 1996 by T.J.B. Holland; pers. comm. via R.W. White, April 2012), K-feldspar and plagioclase (Holland & Powell, 2003) and ilmenite–hematite (White et al., 2000). The aluminosilicates, quartz and rutile are treated as pure end-member phases. The mineral abbreviations are as follows: bi – biotite; cd – cordierite; g – garnet; ilm – ilmenite, sensu lato; ksp – K-feldspar; ky – kyanite; liq – silicate liquid/melt; mt – magnetite; pl – plagioclase; opx – orthopyroxene; osm – osumilite; q – quartz; ru – rutile; sa – sapphireine; sill – sillimanite; sp – spinel.

The H$_2$O content used in the modelling was adjusted, so that the final phase assemblage is stable just above the solids, assumed to reflect the conditions at which this assemblage would have been in equilibrium with the last remnants of melt (e.g. White et al., 2004; Diener et al., 2008). The effects of H$_2$O on the phase equilibria can also be evaluated using $T$/$P$–$M_{H2O}$ diagrams (e.g. Fig. 8a), as outlined in Korhonen et al. (2011, 2012b). Similarly, the appropriate O (for Fe$^{3+}$) content was evaluated using $T$–$M_O$ diagrams, which allow the effect of Fe$_2$O$_3$ on the phase equilibria to be assessed over the range between all Fe as Fe$^{2+}$ to all Fe as Fe$^{3+}$ (e.g. Diener & Powell, 2010; Korhonen et al., 2012b). In all samples considered in this study, the FeO:Fe$_2$O$_3$ proportion determined by Fe$^{2+}$ titration was appropriate to reproduce the observed assemblage on the $T$–$M_O$ diagrams, suggesting that sample powders were not substantially oxidized during or after sample preparation (cf. Fitton & Gill, 1970; Whipple et al., 1984).

### Peak and retrograde evolution

**Sample EGB-09-01**

The subsolidus mineral assemblage preserved in this sample comprises garnet–orthopyroxene–magnetite–K-feldspar–biotite–quartz–plagioclase-ilmenite. A $T$–$M_{H2O}$ diagram was constructed at 9 kbar, which is within the range of previous estimates of peak pressure (Dasgupta et al., 1995; Rickers et al., 2001b; Sarkar et al., 2003; Bhattacharya et al., 2003; Korhonen et al., 2011), to determine an appropriate H$_2$O content (Fig. 8a). The H$_2$O contents investigated range from a near-anhydrous composition ($M_{H2O} = 0$; Table 1) to a composition with a solidus temperature below 850 °C ($M_{H2O} = 1$; Table 1). At 9 kbar, the subsolidus mineral assemblage is stable at $M_{H2O}$ contents <0.2. At higher H$_2$O contents, orthopyroxene is not predicted to be part of the peak assemblage, and the temperature of the solidus is much lower than is appropriate for such a residual granulite facies assemblage (~850 °C; dashed line on Fig. 8a). Based on these constraints, a $M_{H2O}$ value of 0.10 (~0.4 mol.% H$_2$O, Table 1; grey bar on Fig. 8a) was selected for subsequent modelling of this bulk composition.

### Table 1. Bulk compositions.

<table>
<thead>
<tr>
<th>Sample</th>
<th>XRF whole rock compositions (wt%)</th>
<th>Normalized molar proportion used for phase equilibria modelling</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>SiO$_2$</td>
<td>TiO$_2$</td>
</tr>
<tr>
<td>EGB-09-01</td>
<td>62.62</td>
<td>1.41</td>
</tr>
<tr>
<td>EGB-09-04</td>
<td>67.56</td>
<td>0.93</td>
</tr>
<tr>
<td>EGB-10-82</td>
<td>68.03</td>
<td>0.68</td>
</tr>
<tr>
<td>SK2-6-05*</td>
<td>53.74</td>
<td>2.35</td>
</tr>
</tbody>
</table>

FeO analysed by Fe$^{2+}$ titration; Fe$_2$O$_3$ contents calculated by difference; *from Korhonen et al., 2011; - not analysed; (0), x-axis = f; (1), x-axis = 1.
A $T$–$M_O$ diagram was constructed at 9 kbar using the adjusted H$_2$O content (Fig. 8b). The changes in $M_O$ shown in Fig. 8b correspond to a range of possible O contents from all Fe as Fe$^{2+}$ to 67% Fe as Fe$^{3+}$ (Table 1). The observed mineral assemblage is stable at temperatures below the solidus for $M_O$ contents >0.4 (Fig. 8b), which calculates to at least ~27% Fe as Fe$^{3+}$. Magnetite is not stable at lower $M_O$ values. Based on the predicted phase assemblages across the range of Fe$^{3+}$ contents, a $M_O$ value of
0.50 (~35% Fe as Fe$^{3+}$; grey bar on Fig. 8b) was selected to construct the $P$–$T$ pseudosection (Fig. 8c). This estimate is equivalent to the FeO:Fe$_2$O$_3$ proportion determined by Fe$^{2+}$ titration (Table 1).

The $P$–$T$ pseudosection for sample EGB-09-01 is shown in Fig. 8c. In this pseudosection, the solidus is predicted at temperatures between 830 and 900 °C over the range of modelled pressures (4–12 kbar; dashed line on Fig. 8c), although the solidus temperature will vary slightly with any change in H$_2$O content. The elevated solidus reflects the residual bulk chemical composition of this sample, inferred to be due to loss of melt at some point during the metamorphic evolution. Biotite-out occurs at temperatures just above the solidus.

The peak phase assemblage in this sample is inferred to have been garnet–orthopyroxene–magnetite–quartz–K-feldspar–plagioclase–ilmenite–melt, which is represented by the broad g–opx–mt–liq (+q, ksp, pl, ilm) field on Fig. 8c, stable at conditions above 860 °C between ~6 and ~11 kbar. Garnet and orthopyroxene ± magnetite define the lower and upper pressure limits, respectively; cordierite is stable at pressures less than ~6 kbar.

Changes in predicted mineral abundance can be used to model mineral growth and consumption as a consequence of multivariant reactions during the post-peak (retrograde) evolution (e.g. White et al., 2002; Kelsey et al., 2003; Diener et al., 2008; Korhonen et al., 2011). The $P$–$T$ pseudosection for sample EGB-09-01 is contoured for mol.% garnet (solid lines; Fig. 8d) and orthopyroxene (dotted lines; Fig. 8d). The isopleths for mol.% garnet have similar slopes to those for orthopyroxene, but the change in mol.% garnet with a decrease in pressure or temperature is the opposite of that for orthopyroxene (increase and decrease in mol.%, respectively). Garnet with vermicular inclusions of quartz (±biotite, plagioclase, K-feldspar) rimming orthopyroxene and garnet porphyroblasts (Fig. 3b) is interpreted to be a second generation of garnet that grew close to the conditions of final melt crystallization. These reaction relationships indicate an increase in the mol.% of garnet (±biotite) at the expense of orthopyroxene, which may occur along a near-isobaric cooling path as temperature decreases across the peak phase assemblage field g–opx–mt–liq (+q–ksp–pl–ilm) and then across the narrow g–opx–mt–bi–liq (+q–ksp–pl–ilm) field, crystallizing a small amount of biotite (<4 mol.%), and into the subsolidus g–opx–mt–bi (+q–ksp–pl–ilm) field, where no further reaction is expected (Fig. 8d).

**Sample EGB-09-04**

The metamorphic mineral assemblage preserved in this sample comprises biotite, garnet, cordierite, orthopyroxene, sillimanite, K-feldspar, plagioclase, quartz, ilmenite and rutile, which most likely reflects conditions following final melt crystallization at the solidus. A similar approach to that described above for sample EGB-09-01 was used to constrain appropriate H$_2$O and O contents for the $P$–$T$ pseudosection, which produces low H$_2$O contents and confirms that the FeO:Fe$_2$O$_3$ proportion determined by Fe$^{2+}$ titration (~24% Fe as Fe$^{3+}$; Table 1) is a suitable estimate of O content.

The $P$–$T$ pseudosection for sample EGB-09-04 is shown in Fig. 9a. In this pseudosection, the observed mineral assemblage (without rutile) is predicted to be stable at conditions just below the solidus (Fig. 9b), represented by the very narrow bi–g–cd–opx–sill–ksp–pl (+q–ilm) field extending up to ~905 °C and 8.3 kbar (inset in Fig. 9b). Osumilite is predicted to be stable at temperatures above ~940 °C below ~8.4 kbar. Sapphirine is predicted at slightly higher temperatures above ~7.5 kbar. Cordierite + K-feldspar (+quartz ± sillimanite, biotite, plagioclase) intergrowths commonly form thin films along grain boundaries and wrap around primary phases, including orthopyroxene and cordierite (Fig. 4c–f). These intergrowths are interpreted to have formed by the breakdown of osumilite in the presence of melt; thus osumilite (+cordierite + orthopyroxene) is inferred to have been part of the peak assemblage, represented by the cd–opx–osm–sill–ksp–ru–liq (+q–ilm) field in Fig. 9b. Cooling from the peak phase assemblage field into the cd–opx–sill–ksp–ru–liq (+q–ilm) field accounts for the decomposition of osumilite and the growth of the cordierite–K-feldspar (+quartz ± sillimanite, biotite, plagioclase) intergrowths (Fig. 9b). Further cooling extends into biotite-bearing fields, consistent with the occurrence of sparse biotite in the post-peak intergrowths and in the matrix. The growth of garnet during cooling is predicted at temperatures just above the solidus (Fig. 9b, insert), which can explain the symplectic garnet in this sample, typically closely associated with the cordierite + K-feldspar + quartz intergrowths (Fig. 4b).

The interpretation that the cordierite–K-feldspar intergrowths represent peak to immediate post-peak retrograde reaction between osumilite and melt together with the early development of cordierite implies that the prograde evolution was one of coeval increasing temperature and increasing pressure (Fig. 9b). The peak and retrograde conditions constrained by sample EGB-09-04 are consistent with the close-to-isobaric cooling path determined from sample EGB-09-01 (Fig. 9c). However, the $P$–$T$ pseudosections for these samples are based on the residual bulk chemical composition; therefore, they are not appropriate to investigate the prograde history. A method to investigate the prograde evolution by inverse modelling of melt loss is described below for sample EGB-10-82.
Sample EGB-10-82

The minerals present in this sample are orthopyroxene, garnet, sapphirine (along grain boundaries between cordierite and as inclusions in cordierite in cordierite-rich layers), cordierite, sillimanite, K-feldspar, biotite (sparse), plagioclase, quartz, ilmenite and rutile, which, with the possible exception of sapphirine, is interpreted to represent the solidus mineral assemblage. There is some compositional heterogeneity in the sample larger than the scale of a thin section, with interspersed cm-scale garnet-rich layers and mm-scale saphirine + cordierite layers. Orthopyroxene, sillimanite and cordierite are ubiquitous
throughout the sample. The H$_2$O and O contents used for the $P$–$T$ pseudosection (Fig. 10a) were assessed using $T$–$M_{H_2O}$ and $T$–$M_O$ diagrams, as described above.

The $P$–$T$ pseudosection for sample EGB-10-82 is shown in Fig. 10a. Based on the observations above, the metamorphic mineral assemblage present at conditions just below the solidus is best approximated by
the bi–g–cd–opx–sill–ksp (+ q–pl–ilm–ru) field, which is stable up to ~8.25 kbar at 910–915 °C (Figs 10b & 11a). Biotite is not stable at temperatures >920 °C. Os-umilite is stable at temperatures >940 °C and sapphire is stable at temperatures >950 °C above 7 kbar. The inferred peak phase assemblage in this sample includes cordierite, orthopyroxene, osumilite and melt (purple-shaded fields in Fig. 11). Garnet and sapphire are also interpreted to be peak minerals, despite some compositional control on their distribution from layer to layer, implying that the equilibrium volume at >900 °C is larger than the scale of a thin section. The P–T pseudosection predicts several small fields within the stability of cd–opx–osm-bearing assemblages (Figs 10b & 11a), including the occurrence of garnet between 945 and 965 °C from 7.4 to 7.9 kbar (stippled fields in Fig. 11a) and sapphire (blue-shaded fields in Fig. 11a). These small phase assemblage fields are generally consistent with the petrographic observations and the inferred peak phases, and likely have geological significance in a slowly cooled UHT terrane where cooling rates of ~1 °C Ma⁻¹ mean that it could take up to 10 Ma for a sample to traverse these fields. However, in addition to the uncertainties intrinsic to any calculated pseudosection (Powell & Holland, 2008), slight changes in the chemical composition affect the existence of small phase assemblage fields in pseudosections, so it is not sensible to deduce an exact P–T trajectory through such fields. The arrow shown in Fig. 11a visualizes the uncertainty in the P–T path. This relatively wide swath shows that the P–T evolution may pass through a number of small phase assemblage fields, but given the uncertainties involved, this does not have a significant effect on the overall interpretation.

With these caveats, the peak P–T conditions are estimated at ~955 °C and ~7.8 kbar. Cooling with thickening from these conditions into the cd–opx–sill–ksp–liq (+q–pl–ilm–ru) field (from field F to field G on Fig. 11a) accounts for the final elimination of osumilite in the presence of melt, which produced the intergrowths of the cordierite-K-feldspar (+ sillimanite). Further cooling with continued thickening crosses the narrow g–cd–opx–sill–ksp–liq (+q–pl–ilm–ru) field (field L on Fig. 11a) at conditions just above the solidus, consistent with the growth of the second generation of garnet that forms rims on the coarse-grained garnet porphyroblasts (Fig. 5e), into the bi–g–cd–opx–sill–ksp (+q–pl–ilm–ru) field by cooling across the solidus, which is represented by a univariant reaction (labelled U on Fig. 11a) at ~8.25 kbar between 915 and 910 °C, permitting the minor growth of biotite during final crystallization of the last dregs of melt.

Prograde evolution
The cordierite–K-feldspar intergrowths, which represent the breakdown of osumilite in the presence of melt, wrap around cordierite porphyroblasts in several samples and may indicate that the growth of cordierite predated osumilite. This interpretation requires a CCW P–T path. The relationship between cordierite and the intergrowths is particularly well preserved in sample EGB-10-82. Therefore, this sample was selected for inverse phase equilibria modelling.

Reconstruction of a plausible bulk chemical composition for the protolith requires that melt that drained from the system during the prograde evolution be reintegrated into the residual bulk chemical composition via a series of down temperature steps along an inferred prograde P–T path. This inverse modelling involves the addition of melt of a composition in equilibrium with the residue at a given pressure and temperature, progressing step by step to lower P–T conditions along the inferred P–T path (cf. White et al., 2004; Diener et al., 2008). There are several important unknowns in this process, including: the number of melt drainage events along the original prograde P–T path and, therefore, the number of reintegration steps required for the inversion; the amount of melt that drained from the system in each of these events and, therefore, the amount of melt to reintegrate at each step in the inversion; and the P–T conditions for each melt drainage event along the original prograde P–T path and, therefore, the P–T conditions along the inferred P–T path where this melt should be reintegrated. These issues are addressed next.

In general, natural anatexic systems are neither ideally open nor ideally closed on all length and time-scales of deformation, particularly at outcrop scale where they typically behave as conditionally open systems in which periods of melt buildup and melt loss alternate (Handy et al., 2001; Brown, 2013; Yakymchuk et al., 2013). The melt volume at which this melt loss occurs is not well known and, in any case, it will vary with temperature and strain rate. Notwithstanding, a value of 7 mol.% melt, which is approximately equivalent to 7 vol.% on a one-oxygen basis, corresponding to the MCT of Rosenberg & Handy (2005), is commonly taken as an upper bound (Brown, 2010). Accordingly, this value is taken to be the point at which melt may have drained from a melt-bearing source during the prograde evolution and, therefore, it is used as the step size for the inverse reintegration of melt. However, the melt does not drain completely and a small volume (~1 vol.%) is likely to have been retained on grain boundaries after each drainage event (Sawyer, 2001). Based on this information, the procedure used for the inversion involves backtracking down temperature along a schematic prograde P–T path to a P–T point where the amount of melt remaining in the phase assemblage field is 1 mol.%. At this point, 6 mol.% melt of the composition in equilibrium with the phase assemblage at these P–T conditions is rein-
Fig. 11. (a) Calculated $P$–$T$ pseudosection for sample EGB-10-82 (derived from the upper part of Fig. 10b) with proposed $P$–$T$ path. (b) Composite summary of pseudosection panels derived from the inverse modelling and melt reintegration. Phase fields are simplified according to the colour-coding shown on the legend. In (b) the successive $P$–$T$ pseudosection panels from right to left shows the effect of changing bulk composition as melt is reintegrated on the phase assemblages. Melt is reintegrated at the 1 mol.% melt isopleth down temperature along a schematic $P$–$T$ path of 150 °C kbar$^{-1}$. See text for further detail of the methodology. The final pseudosection panel (<750 °C) is derived from a plausible protolith composition. Dashed blue lines are calculated contours for melt proportion (in mol.%). Compositions used for modelling are listed in Table 1.
tegrated into the bulk chemical composition, resulting in 7 mol.% total melt at this \( P-T \) condition. This reproduces an amount of melt equivalent to the MCT at which melt is assumed to have drained on the real prograde path. This procedure is the inverse of that adopted by Korhonen et al. (2012a) and Yakymchuck & Brown (2013) in their investigations of the effects of prograde melt loss. The reintegrated bulk chemical composition is then used to construct a new pseudosection and this pseudosection is used for the next melt reintegration step.

Whether the amount of melt used in the reintegration affects the outcome significantly was assessed by a larger but arbitrary value of 10 mol.% and repeating the reintegration. This procedure showed that the size of the melt increment is not critical to the final outcome. Nevertheless, the size of the melt increment determines the number of melt drainage events that have to be inverted to reach a plausible protolith composition. Similarly, equilibrium melt compositions within the same phase assemblage field do not change significantly with small changes in \( P-T \); therefore, the exact \( P-T \) point of the melt reintegration step is also not critical to the final outcome.

Starting from the \( P-T \) pseudosection for the residual bulk rock chemical composition and the point where the low \( P-T \) end of the high-temperature prograde segment of the \( P-T \) path constrained by the phase equilibria modelling intersects the 1 mol.% melt isopleth, the melt composition at this \( P-T \) point was used for the first melt reintegration step (Fig. 11b; step 1). From this \( P-T \) point, a schematic prograde \( P-T \) path of 150 °C kbar\(^{-1} \) was used for the reintegration. Subsequent melt reintegration steps were modelled by backtracking down temperature along this \( P-T \) path to the 1 mol.% isopleth and repeating the procedure described above. The change in topology of the phase assemblage fields on the \( P-T \) pseudosection for each of the new bulk chemical compositions after each melt reintegration step is shown by successive pseudosection panels in Fig. 11b (the left-hand six panels down temperature from the right-hand panel, which is the pseudosection for the bulk rock chemical composition shown in Fig. 10a).

After reintegration of ~40 mol.% melt, the synthetic chemical composition used for the final pseudosection approximates a plausible protolith composition as demonstrated by the presence of an H2O-saturated solidus between 650 and 690 °C (Fig. 11b, left-hand panel). A possible prograde evolution can be assessed by following an arbitrary \( P-T \) path across the sequence of pseudosections from the fictive protolith chemical composition in the left-hand panel, through six melt drainage events, as represented by the middle five panels (between steps 6 and 1), to the final residual bulk rock chemical composition in the right-hand panel (above the temperature for step 1), to connect with the low \( P-T \) end of the high-temperature prograde segment of the \( P-T \) path constrained by the phase equilibria modelling. An arbitrary \( P-T \) evolution predicts a plausible assemblage of bi–cd–sill–pl-liq (+q, ilm) during initial melting and requires an elevated thermal gradient to reach the peak \( P-T \) conditions. The growth of orthopyroxene is predicted at intermediate temperatures (green-shaded fields in Fig. 11b), with an increase in melt production across each phase assemblage field as temperature increases (dashed lines in Fig. 11b), followed by the disappearance of biotite and the growth of cordierite at higher temperatures (orange-shaded fields in Fig. 11b), again with an increase in melt production across each phase assemblage field (dashed lines in Fig. 11b). Osumilite-bearing assemblages are predicted at high temperature and moderate pressure conditions (purple-shaded fields in Fig. 11b). Although this arbitrary prograde evolution is an outcome predetermined by the inversion methodology, it is nonetheless a plausible progression that leads to the sequence of cordierite growth followed by osumilite along a CCW \( P-T \) path.

\( P-T-t \) evolution of samples from the Sunki locality: a reevaluation

The new results from this study discussed above show that samples from two different localities in the central Eastern Ghats Province shared a similar metamorphic evolution with peak conditions of approximately 950 °C and 8 kbar, and post-peak cooling to the solidus with a slight increase in pressure. The \( P-T \) paths are interpreted to be CCW. In contrast, for the samples from the Sunki locality (SK2-6-05, D1-3-S3), Korhonen et al. (2011) estimated peak \( P-T \) conditions to have been in excess of 950 °C and 9.5 kbar. Furthermore, these authors argued that the metamorphic peak was followed by decompression and cooling to the elevated solidus at ~900 °C and 7.5 kbar. This interpretation implies a CW \( P-T \) evolution that contrasts with the new results herein.

The predominant zircon and monazite age populations at Paderu, Sunkametta and Sunki all yield weighted mean ages in the interval c. 980–930 Ma (Korhonen et al., 2011, 2013). These ages are interpreted to record close-to-isobaric cooling from peak UHT conditions and growth of zircon and/or monazite near the elevated solidus for individual samples. Thus, the UHT metamorphism in the central Eastern Ghats Province is interpreted to be a single event that was essentially coeval at all three localities.

This raises the question of whether the contrasting \( P-T \) paths (CW v. CCW) are correct or whether the implied CW evolution at Sunki was a flawed interpretation. To address these discrepancies, and to incorporate the recently updated \( a-x \) model for osumilite in the interpretation in appropriate samples from the Sunki locality, sample SK2-6-05 is reinvestigated here. The results from sample D1-3-S3 reported in Korhonen et al. (2011) are also discussed.
The $P$–$T$ pseudosection for sample SK2-6-05 is shown in Fig. 12. This rock contains sparse sillimanite as rounded or ragged grains within cordierite. The sillimanite was interpreted by Korhonen et al. (2011) as a post-peak phase that formed during decompression from the inferred peak phase field of g–opx–liq (+q, ilm; Fig. 12). Notwithstanding, an interpretation that the sillimanite is primary is also consistent with the microstructures, which would result in a peak phase assemblage of g–opx–sill–liq (+q, ilm), stable at lower pressures at ~950 °C (Fig. 12). There is no evidence in this sample for the former presence of osumilite, which, therefore, defines a lower pressure limit at ~8.4 kbar. Sparse biotite inclusions in cordierite (fig. 3c in Korhonen et al., 2011) imply minor biotite growth contemporaneous with or just prior to cordierite nucleation and growth. These features suggest that the retrograde $P$–$T$ path passed through the bi–g–opx–sill–liq (+q, ilm) and bi–cd–g–opx–sill–liq (+q, ilm) fields (field B on Fig. 12), consistent with cooling and slight decompression just before final melt crystallization at the elevated solids around 900 °C and 8.3 kbar (Fig. 12). The microstructures described in detail by Korhonen et al. (2011) for this sample are consistent with the revised $P$–$T$ trajectory shown in Fig. 12.

The Al content in orthopyroxene was also used by Korhonen et al. (2011) to estimate peak conditions >950 °C and 9 kbar. Sample SK2-6-05 contains orthopyroxene cores with maximum $y$(opx) ($=\text{VALM1}$) contents of 0.17–0.18 (Korhonen et al., 2011; unpublished data, F.J. Korhonen). Temperatures predicted by these $y$(opx) values and the calculated temperature of the elevated solids shown in Fig. 12 are within 2σ uncertainty, suggesting that the Al contents in orthopyroxene may record the conditions close to crystallization of the last vestiges of melt during the high-temperature retrograde history.

To summarize, the results from sample SK2-6-05 indicate peak temperatures in excess of 950 °C (Fig. 12). Pressure is more poorly constrained, but the inferred peak phase assemblage (g–opx–sill–liq–q–ilm) limits pressure to between ~8.4 and 9.7 kbar (Fig. 12). The retrograde $P$–$T$ path recorded is characterized by cooling and slight decompression to the elevated solidus around 900 °C and 8.3 kbar (Fig. 12). The post-peak $P$–$T$ path retrieved from sample D1-3-S3 in Korhonen et al. (2011) is consistent with the revised trajectory retrieved from sample SK2-6-05 (Fig. 12). However, the spinel-bearing equilibria reported in Korhonen et al. (2011; fig. 8d) are predicted to be metastable with respect to sapphire-bearing equilibria. This discrepancy may be due to either nucleation issues of sapphire in the equilibration volume leading to the metastable growth of spinel, or, more likely, to oversimplifications in the phase equilibria modelling. The presence of 1.2–1.4 wt% ZnO in spinel from sample D1-3-S3 (Korhonen et al., 2011; unpublished data, F.J. Korhonen) shows that ZnO is an important component and that NCKFMASTHO is a smaller chemical system than that controlling the equilibria. Therefore, phase equilibria modelling in the NCKFMASHTO system for sample D1-3-S3 could produce spurious results. Despite the limitations of modelling this sample, the cordierite + K-feldspar intergrowths interpreted to be pseudomorphs after osumilite are well preserved in sample D1-3-S3. These intergrowths surround inferred peak or near-peak orthopyroxene and cordierite porphyroblasts (fig. 4d in Korhonen et al., 2011), similar to observations from samples EGB-09-04 and EGB-10-82.

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Fig. 12. Revised* $P$–$T$ pseudosections for sample SK2-6-05 with proposed $P$–$T$ path from Sunki locality. Solid portion indicates that part of the path is well constrained by equilibria, whereas the dashed path is inferred. Osumilite-bearing equilibria occur within heavy black line; labelled ‘+ osm’, which provide a lower pressure limit for this sample. Dashed blue lines are calculated contours for melt proportion (in mol.%). The heavy dashed line is the solidus. Composition used for modelling is listed in Table 1. * From Korhonen et al. (2011).
The revised interpretation presented above for sample SK2-6-05 shows that the peak and retrograde $P$–$T$ evolution presents a CCW to that retrieved from the Sunkarametta and Paderu localities. In addition, the cordierite + K-feldspar intergrowths in sample D1-3-S3 imply peak to immediate post-peak retrograde reaction between osmumite and melt and the early development of cordierite. In common with many samples from the central Eastern Ghats Province, these microstructures may be consistent with a prograde evolution of increasing temperature with increasing pressure, although the evolution of this sample cannot be evaluated with phase equilibria modelling. The revised interpretation suggests that the peak and retrograde $P$–$T$ evolution at the Sunki locality is similar to that retrieved from the Sunkarametta and Paderu localities, and indicate a common CCW $P$–$T$ path for the central Eastern Ghats Province.

**DISCUSSION**

**$P$–$T$ paths and mineral assemblage evolution**

A similar $P$–$T$–$t$ evolution is retrieved from samples from the Paderu (EGB-09-01, -04), Sunkarametta (EGB-10-82) and Sunki (SK2-6-05) localities in the central Eastern Ghats Province (Fig. 13). Peak conditions are ~945 °C and 8.2 kbar for sample EGB-09-04 from Paderu (Fig. 9c) and ~955 °C and 7.8 kbar for sample EGB-10-82 from Sunkarametta (Figs 10 & 11). Peak conditions for samples EGB-09-01 from Paderu and SK2-6-05 from Sunki are more poorly constrained at >955 °C and ~8.3 kbar and >960 °C and <8.6 kbar, respectively, but are consistent with estimates from the first two samples. There is evidence in the distribution of peak minerals within some samples, for example in the distribution of sapphireine and garnet in sample EGB-10-82 from Sunkarametta, for equilibration volumes exceeding the scale of a standard thin section at UHT conditions, demonstrating the need to study multiple thin sections for UHT samples. The growth of cordierite before osmumite requires a CCW $P$–$T$ path for the central Eastern Ghats Province. Overall, the results from the phase equilibria modelling suggest a slight increase in pressure immediately post-peak temperature. All samples preserve microstructural evidence for final close-to-isobaric cooling to an elevated solidus. The interpretation of a CCW $P$–$T$ path for the central Eastern Ghats Province is supported by inverse modelling involving reintegration of melt in sample EGB-10-82 to generate a plausible protolith composition (Fig. 11b).

The cordierite + K-feldspar (+quartz ± sillimanite, biotite, plagioclase) intergrowths that are common in many samples across the central Eastern Ghats Province are interpreted to have formed by the reaction of primary osmumite with melt trapped in the equilibration volume by the melt percolation threshold immediately after peak temperature as cooling began. The phase equilibria modelling predicts that these intergrowths would be produced at conditions between the metamorphic peak and the solidus according to the individual sample (Figs 9c & 11a). In the absence of such distinctive intergrowths in UHT rocks elsewhere, it is possible that peak metamorphic conditions would be underestimated if the high-temperature retrograde reaction between peak minerals and melt trapped by the percolation threshold was cryptic.

**The tectonics of CCW UHT metamorphism**

Samples from different localities across the central Eastern Ghats Province register CCW $P$–$T$ paths that reach peak metamorphic conditions of ~950 °C or higher at ~8 kbar (Fig. 13). Following a slight increase in pressure during the immediate post-peak cooling (Figs 9c & 11a), the crust underwent close-to-isobaric cooling to the elevated solidi. The variability in the calculated weighted mean ages across the region was interpreted by Korhonen et al. (2013) to be due mainly to differences in the temperature of the elevated solidi of these residual granulites from sample to sample, suggesting a slow cooling rate of ~1 °C Ma⁻¹ during the retrograde stage of the CCW evolution.

The combination of a CCW $P$–$T$ evolution with extremely high temperatures at moderate pressures during the late Mesoproterozoic–early Neoproterozoic orogenic event in the central Eastern Ghats Province requires an elevated thermal gradient in the crust. Furthermore, the slight increase in pressure immediately...
post-peak temperature and the close-to-isobaric cooling to the solidus (Fig. 13) imply that the crust was not significantly overthickened and the erosion rate was low. The elevated thermal gradient indicates that additional heat flux from the mantle was most likely involved, possibly via replacement of the lithospheric mantle with melt-bearing asthenospheric mantle during early extension prior to contractional thickening during the prograde heating to the metamorphic peak. In addition, the residual granulites in the central Eastern Ghats Province are characterized by higher than average heat production (Senthil Kumar et al., 2007). Thus, it is likely that the original sedimentary succession would have generated more heat by radioactive decay than average crust during thickening (Clark et al., 2011; Bea, 2012).

The early stage of the tectonic scenario described above for the central Eastern Ghats Province is similar to results of 2D petrological–thermomechanical numerical modelling of orogenesis for an upper mantle temperature of 150 °C above the present day value and radiogenic heat production of 1.5 times the present value (Sizova et al., 2013). Such values are reasonable for the late Mesoproterozoic (Herzberg et al., 2010). In particular, the numerical experiments that develop the truncated hot collision regime of Sizova et al. (2013) may provide an appropriate initial condition for the development of UHT metamorphism via a CCW $P$–$T$ evolution as seen in the central Eastern Ghats Province. In the experiments of Sizova et al. (2013), during the subduction phase, dehydration of the slab weakens the overriding plate, which undergoes extension associated with decompression melting of the mantle wedge and replacement of the subcontinental lithospheric mantle by hot melt-bearing asthenospheric mantle prior to shallow slab breakoff. The extension and lithospheric thinning generates a wide sedimentary basin with higher than average heat flow in $<$10 Ma (figs 7 & 10 in Sizova et al., 2013). Subsequent shortening of this hot thinned lithosphere in response to far-field applied stress would generate a CCW $P$–$T$–$t$ evolution that would return the crust to ‘normal’ thickness. When combined with a high heat-producing sedimentary infill, the thickening could have achieved UHT metamorphic conditions, particularly given the slow evolution implied by the zircon and monazite geochronology of Korhonen et al. (2013), which shows that the crust of the central Eastern Ghats Province sustained UHT conditions for $>>$50 Ma, and perhaps for as long as 200 Ma from c. 1130 to c. 930 Ma.

The role of melting and melt migration in the evolution of CCW orogens

At the local scale, anatectic systems may be open (melt is drained) or closed (melt is retained) or conditionally open (cyclic closed- and open-system behaviour), although at the scale of the crust, anatectic systems must have been open as they represent the source for upper crustal granites (Handy et al., 2001; Brown, 2013). In general, as crust continues to heat and thicken after the prograde $P$–$T$ path crosses the solidus, melt volume increases to a threshold value, at which point the melt nucleates rheological instabilities that lengthen and connect to allow melt drainage from the anatectic system (Handy et al., 2001; Brown, 2010, 2013). However, the amount of melt buildup required to trigger a local melt drainage event and the frequency of these events will be a function of strain rate and/or temperature, and it is plausible that at UHT conditions, strain rates were low enough that parts of the crust would have deformed by granular flow. In these circumstances, if the melt production rate locally exceeded the melt segregation rate, melt could be squeezed out of the system fast enough to pre-empt the formation of rheological instabilities and the system would become unconditionally open (Handy et al., 2001).

Notwithstanding, the behaviour of an anatectic system is likely to vary spatially and temporally according to protolith fertility, rheology and strain rate (Handy et al., 2001; Yakymchuk & Brown, 2013; Yakymchuk et al., 2013). Thus, along the prograde $P$–$T$ path, the orogenic crust could have undergone cycles of melt-induced weakening followed by hardening until UHT conditions, although the threshold for melt extraction may not have been the same from lithology to lithology, and in any case, the MCT of Rosenberg & Handy (2005) likely represents a maximum (Brown, 2010). At UHT conditions, the crust could have become sufficiently weak, at least locally, that melt drainage was effectively continuous from some lithologies. This is consistent with the variability in the amount and style of leucosome preserved in UHT granulites, both in the study area (Fig. 2) and elsewhere (e.g. Guermima & Sawyer, 2003; Zhang et al., 2012). In a complementary effect, during the prograde evolution, heat would have been advected through the orogen, both displacing the growing thermal anomaly to shallower crustal levels and promoting weakening of the orogenic infrastructure (cf. Brown & Solar, 1999; Leitch & Weinberg, 2002).

Prograde thermal weakening was enhanced by melting, melt migration and advection of heat that would have enabled the crust to thicken under granulite facies to UHT metamorphic conditions (Sandiford & Powell, 1991). Close to the metamorphic peak, as the deep crust became progressively more residual and drier due to cumulative melt loss, it also became denser and stronger (Menegon et al., 2011; Yakymchuk & Brown, 2013) limiting then terminating thickening. This effect was associated with a reduction in heat production as high heat-product-
ing elements, particularly K and Th, were lost with fugitive melt to shallow levels in the crust. Assuming uniform melt loss across the UHT domains, this process could result in long-term cooling of the residual crust by several tens of degrees (Sandiford et al., 2002). Such a postulate is consistent with the time-scale for the CCW P–T evolution in the central Eastern Ghats Province, which recent geochronological data suggest occurred over a prolonged period on the order of >>50 to 200 Ma (Korhonen et al., 2013). Concomitantly, thickening of the underlying subcontinental lithospheric mantle displaced the asthenosphere to greater depth reducing the heat flux from the mantle.

The interpretation that the fine-grained mineral intergrowths, which may form more than 20 vol.% of the rock, were formed by the breakdown of osumilite in the presence of melt has implications for the amount of melt retained at the metamorphic peak. The amount of melt at the metamorphic peak may be estimated from the melt contents predicted by the phase equilibria modelling. Predicted melt amounts at peak conditions are typically 5–20 mol.% based on the residual bulk compositions (Figs 8d, 9b & 11b; Table 1). The slight increase in pressure following peak temperature in the central Eastern Ghats Province could reflect final thickening due to the presence of this melt, which is terminated once melt is trapped by the percolation threshold and begins to crystallize during cooling. By this stage, both heating and crustal thickening had ceased, enabling the transition to close-to-isobaric cooling in crust that was not overthickened to the extent of becoming gravitationally unstable.

CONCLUSIONS

The similarity in the P–T paths retrieved from multiple samples from several localities in the central Eastern Ghats Province using a combination of microstructural interpretation and phase equilibria modelling reduces the ambiguity associated with interpreting single samples. Therefore, the results of this study provide confidence in the interpretation that the central Eastern Ghats Province achieved UHT metamorphic conditions and experienced a common CCW evolution. This confidence is supported by the results of inverse phase equilibria modelling, which demonstrate that CCW P–T evolution could have produced the observed mineral assemblages and microstructures in one particular sample. A possible tectonic evolution for the central Eastern Ghats Province is proposed involving extension of the continental lithosphere during hot collision prior to slab breakoff followed by renewed convergence and thickening in response to far-field applied stress.

This study shows that the equilibration volumes at UHT conditions may be larger than the scale of a standard thin section, which makes deciphering the history of such rocks challenging and requires study of multiple thin sections. Furthermore, the P–T pseudosections constructed for the high Mg–Al granulites used in this study predict the stability of multiple small phase assemblage fields at close-to-peak metamorphic conditions. This confirms that these bulk compositions are highly reactive and susceptible to significant mineralogical change over small P, T intervals, and demonstrates the usefulness of these rocks as recorders of mineral assemblage evolution during UHT metamorphism, especially for slowly cooling terranes. It also suggests that the presence or absence of such small phase assemblage fields in pseudosections is likely to be sensitive to the bulk (or domainal) composition used. These features demand that great care be taken when applying phase equilibria modelling to UHT rocks.

The results from this study highlight the role of melting during UHT metamorphism and its importance to both chemical and physical processes from the thin section scale to the crustal scale. At the thin section scale, the development of retrograde mineral reaction assemblages is facilitated by the presence of melt trapped by the percolation threshold as cooling begins. As a result of this study, we speculate that peak metamorphic conditions may sometimes be underestimated where high-temperature retrograde reaction between peak minerals and melt trapped by the percolation threshold was cryptic.

At the crustal scale, the extensive melting predicted to occur along the prograde evolution for UHT metamorphism initially weakens the deep crust, but melt loss redistributes melt and heat causing weakening in the overlying orogenic suprastructure and densification and strengthening of the orogenic infrastructure. For CCW orogens, these processes enable thickening to occur during the high-temperature part of the prograde evolution to the metamorphic peak. Conversely, because drainage of melt leads to densification and strengthening of the deeper crust, overall thickening is limited. Redistribution of the high heat-producing elements, particularly K and Th, leads to long-term cooling in the source and allows orogens of this type to evolve isobarically to an elevated solidus.

ACKNOWLEDGEMENTS

We thank R.W. White and D. Kelsey for useful discussions about osumilite stability, and S. Mertzman for XRF analyses at Franklin & Marshall College. D. Kelsey and J. Baldwin provided constructive reviews that enabled us to significantly improve the study during revision. We also thank R.W. White for careful editorial comments. This project was funded through the DIISR Australia–India Strategic Fund project ST030046. C. Clark acknowledges salary and research support from DECRA (DE120103067).
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