Occurrence of sapphirine-bearing granulites from Kothuru, Eastern Ghats Mobile Belt: implications on ultra-high temperature metamorphism

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In this study, we present evidence for the stable coexistence of sapphirine + quartz and the compositional characteristics of the sapphirine-bearing granulites from Kothuru in the Eastern Ghats Mobile Belt (EGMB), India. The study area is an integral part of the Precambrian terrane in the western part of EGMB and is characterized by the granulite facies rocks comprising mainly of pelitic granulites such as charnockites, enderbites, leptynites, khondalites and gneisses, and sapphirine-spinel-quartz-bearing rocks. The chemistry of the minerals present in the assemblage has been examined using the electron probe micro analyser to infer their occurrence and distribution in various reaction textures observed during the petrographic study. The peak and post-peak history of the sapphirine-bearing granulites of Kothuru section have been constrained in the NCKFMASHTO system showing decompressional P–T path of high-grade metamorphic rocks through the intersection of the isopleth contours of various mineral phases present. The proposed P–T path with a steep isothermal decompression retrograde trajectory may be attributed to the over-thrust processes. The results obtained from the petrographic study of the mineral assemblages along with their textural relationship, mineral chemistry, especially Fe³⁺/FeTotal ratio and pseudosection modelling reveal that the studied segment has arrested promising ultra-high temperature metamorphic signatures and is tectonically distinct from those reported in the adjacent areas.

Keywords: Granulites, mineral chemistry, pseudosection modelling, reaction textures, sapphirine-bearing, ultra-high temperature metamorphism.

The Eastern Ghats Mobile Belt (EGMB), India, is a polycyclic granulite terrane, which due to its ultra-high temperature (UHT) has elicited great interest among researchers. It serves as a window to study the lower continental crustal processes and offers a potential tool for obtaining an integrated geodynamic picture of the region. Sapphirine is a complex silicate mineral found in high-temperature metamorphic rocks or xenoliths with abundant aluminium and magnesium content. When it occurs in stable coexistence with quartz (i.e. sapphirine + quartz), this is one of the diagnostic features of UHT metamorphism. The evidence of these diagnostic features of UHT metamorphism has localized occurrences in the granulite facies of rocks. They represent an extreme tectonothermal event that took place in the lower crust, which may).
which swings slightly to N–S and NNW–SSE near the southern part. Conspicuously, at the northern end, near the Mahanadi valley, the trend sharply changes to ESE–WNW and E–W.

The study area falls in the WCZ and WKZ, lithologically characterized by granulite facies rocks. These rocks have undergone various phases of deformation along with simultaneous and subsequent metamorphism. The localized occurrence of sapphire–spinel–quartz-bearing rocks trending N 30°E can be observed in relatively thin bands associated with charnockite, enderbite, khondalites, and at few places with the migmatized granulites (Figure 1 b). Garnet-free sapphire–spinel–quartz granulites are also extensively present. The marker bands of the sapphireine granulites in the study area are characterized by greyish-coloured granulites having a bluish tint of the cordierite-rich matrix, along with elongated grains of spinel, ilmenite/magnetite and garnet.

Textural relations and interpretation of metamorphic reactions

The excellent textural relations preserved in the form of symplectites, coronas and other reaction textures in the sapphire–bearing granulites are described in this section. Minerals present in the sapphire–bearing granulites include sapphireine, spinel, garnet, orthopyroxene, sillimanite, quartz, K-feldspar, cordierite and biotite. At the thermal peak of metamorphism, temperature and pressure were so high that most of the earlier history has been lost. Staurolite and muscovite are completely absent. However, the relics of biotite, sillimanite, orthopyroxene in garnet, sapphireine and spinel minerals are useful tools for inferring the pre-history of the thermal peak of metamorphism. Coarse porphyroblasts of garnets, (Grt), are formed during the early episodes of granulite facies metamorphism. The presence of inclusions of biotite, quartz and sillimanite within megacrystic garnet and K-feldspar may be ascribed to the following prograde reaction (Figure 2 a):

\[
\text{Biotite} + \text{sillimanite} + \text{quartz} = \text{garnet}_1 + \text{K-feldspar} + \text{H}_2\text{O}. \tag{1}
\]

Unusual grain contact of spinel/sapphireine with quartz was present in a number of samples (Figure 2 b and c), which suggests that spinel/sapphireine and quartz were in equilibrium during the thermal peak of metamorphism. In the later stages, sapphireine formed a rim around spinel and spinel was isolated from quartz. This early corona texture may be related to the following reactions:

\[
\text{Spinel} + \text{quartz} = \text{sapphireine}_2 : 2 : 1. \tag{2}
\]

\[
\text{Spinel} + \text{sillimanite} + \text{quartz} = \text{sapphireine}_7 : 9 : 3. \tag{3}
\]

The textural evidences indicate that spinel was associated with quartz, and later reacted with quartz to form different reaction coronas due to change in metamorphic conditions. On the basis of textural evidences, it can be inferred that spinel is first retrograded to sapphireine, followed by spinel + sillimanite, orthopyroxene + sillimanite and spinel + cordierite + orthopyroxene + sillimanite. Spinel with exsolution textures occurs in the matrix of cordierite and quartz. The exsolved spinel was mantled by sillimanite.

Medium-grained, typically xenoblastic garnet, (Grt), occurs usually as granular aggregates around coarser grains of garnet, or orthopyroxene (Figure 2 d). These garnets contain inclusions of sapphireine and spinel. Sometimes garnet is separated from the inclusions of spinel by sillimanite or sapphireine (Figure 2 d), which suggests the following reactions:

\[
\text{Spinel} + \text{quartz} = \text{garnet}_2 + \text{sillimanite}. \tag{4}
\]

\[
\text{Spinel} + \text{quartz} = \text{sapphireine} + \text{garnet}_2. \tag{5}
\]
The first generation of orthopyroxene1 (Opx1) is medium-to coarse-grained, xenoblastic to subidioblastic, highly fractured, isolated from any type of symplectite and coronas and contains inclusions of quartz, sillimanite, spinel, sapphirine, biotite and K-feldspar (Figure 2 e). The retrograde biotite occurs either along the crack or on the outer margin of orthopyroxene1. The second generation of orthopyroxene2 (Opx2) is feeble to strongly pleochroic, medium to fine-grained and occurs in the different coronas and granular aggregates in the symplectites (Figure 2 f). Medium-grained orthopyroxene2 is associated with sapphire and spinel separated by sillimanite, suggesting the following reactions:

\[
\text{Spinel} + \text{quartz} = \text{orthopyroxene}_2 + \text{sillimanite}. \quad (6)
\]

\[
\text{Sapphirine} + \text{quartz} = \text{orthopyroxene}_2 + \text{sillimanite}. \quad (7)
\]

As the temperature decreases due to cooling and pressure being released during exhumation, the sapphirine–spinel–quartz assemblage becomes incompatible. The sapphirine is now rimmed by cordierite in spite of orthopyroxene, sillimanite and quartz (Figure 2 g). Thus, cordierite is formed and sapphirine–spinel–cordierite becomes the compatible assemblage. The reactions involved in the formation of cordierite are

\[
\text{Spinel} + \text{quartz} = \text{cordierite}. \quad (8)
\]

\[
\text{Sapphirine}_{2:2:1} + \text{quartz} = \text{cordierite}. \quad (9)
\]

At the end of the last phase of uplifting, sapphirine and spinel became incompatible with quartz and cordierite. Water activity (fluid) dominates over the CO2 fluid because hydrous minerals like biotite and cordierite begin to react to produce different types of symplectites (Figure 2 h). The coronas do not form due to non-refractory behaviour of the minerals. Garnet which is in the early stage of retrogression, ultimately became unstable due to the following reaction:

\[
\text{Garnet}_1 + \text{K-feldspar} + \text{H}_2\text{O} = \text{cordierite} + \text{biotite} + \text{quartz}. \quad (10)
\]

**Mineral chemistry**

The chemical analyses of minerals were carried out using an electron probe micro analyzer (EPMA; CAMECA SX-Five instrument) at the DST-SERB National Facility, Department of Geology, Banaras Hindu University, Varanasi, India. Table 1 lists the representative microprobe analyses of various minerals from Kothuru.

**Sapphirine**

This is highly aluminous with Al2O3 content ranging from 60.98 to 62.36 wt%. Sapphirine is also fairly rich in iron with FeO content up to 10.38 wt%, substantial amounts of ferrous (up to 0.452 wt%) and ferric content (up to 0.076 wt%), characterizing the sapphirine-bearing pelitic granulites. The $X_{\text{Mg}}$ values calculated on 10-oxygen basis for sapphirine range from 0.749 to 0.788, with negligible variations between core and rim data. The sapphirine occurs as rims around porphyroblasts of spinel in the stoichiometric (Mg, Fe) O : Al2O3 : SiO2 relation 2 : 2 : 1. The $X_{\text{Mg}}$ values for sapphire rims within garnet are found to be slightly higher than those within cordierite.

**Orthopyroxene**

Orthopyroxene grains show noticeable variations in Al2O3 content. They are characterized by a decrease in Al2O3...
### Table 1. Electron microprobe analyses of the minerals

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Content from core (9.43 wt%) to rim (8.70 wt%), and increase in MgO content from core (Xₑ₀ₓ = 0.658) to rim (Xₑ₀ₓ = 0.652), irrespective of their association with garnet or sapphire in the pelitic granulite. The high Al₂O₃ values in the core suggest the development of the mineral during the peak-P-T condition of metamorphism, while lower Al₂O₃ values towards the rim indicate the later cooling stage of metamorphism. Orthopyroxene, (9.43–8.70) is...

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observed to be more aluminous than orthopyroxene (6.87–6.89).

**Cordierites**

These are mostly dry and the most magnesian phase among all the minerals present in the rock sample, with $X_{Mg}$ values ranging between 0.87 and 0.97. The occurrence of cordierite is in accordance with the substitution proposed by Schreyer et al., i.e. $\text{Si}^+ \leftrightarrow \text{Al}^+$ (Na, K). However, the alkalies are almost negligible to absent. The cordierites are unzoned, occurring as inclusions and intergrowth with quartz and feldspar.

**Spinel**

This is generally Mg spinel – hercynite and magnetite solid solutions with $X_{Mg}$ values ranging from 0.363 to 0.502, which are less than the coexisting $X_{Mg}$ values of orthopyroxene, sapphirine, biotite, cordierite and garnet.

**Garnets**

These are mainly solid solutions of almandine (46.93–64.78 mol%) and pyrope (30.62–62.64 mol%) with minor amounts of grossularite (up to 4.2 mol%) and spessartine (up to 1.7 mol%). The coexistence of garnet with orthopyroxene is sporadic on rare occasions, indicating that the assemblage garnet–orthopyroxene–cordierite could have coexisted in the same phase at some stage during the metamorphic evolution of these granulites. Garnet1 (0.530–0.523) has higher $X_{Mg}$ values than garnet2 (0.509–0.489). The $X_{Mg}$ values of sapphirine-bearing garnet range from 0.53 to 0.49. The contrast in the $X_{Mg}$ values of garnet is due to the higher MgO content in the sapphirine-bearing garnets.

**Biotites**

Biotites with high TiO$_2$ content (4.27–5.35 wt%) characterize the sapphirine-bearing mineral assemblage of the pelitic granulite. Biotites are fairly rich in fluorine (up to 5.30 wt%) and occur in close association with aluminous orthopyroxene and cordierite, suggesting high temperatures of melting of the prograde mineral assemblage. The biotites present are highly magnesian with $X_{Mg}$ values ranging from 0.76 to 0.88.

**K-feldspars**

These are generally present as grains associated with orthopyroxene, sapphirine and quartz. They also occur as inclusions as well as intergrowth textures with cordierite and quartz in the matrix. Perithitic intergrowth textures occur commonly in the metapelites. The presence of high sanidine/anorthoclase in some metapelites is likely to be the result of high-temperature melting. The $X_K$ values of K-feldspar range from 0.72 to 0.89.

**Plagioclases**

These are found in less abundance compared to K-feldspars in the metapelites. The $X_{An}$ values for plagioclase have a narrow range from 0.36 to 0.37 and are mainly albite in nature.

**Ilmenite**

This is found mainly in the matrix. The TiO$_2$ content (48.63 wt%) is slightly higher than the FeO content (45.52 wt%).

**P–T pseudosection modelling**

Isochemical pseudosection modelling from the average bulk composition (XRF data in wt%: Na$_2$O – 1.39, MgO – 10.44, Al$_2$O$_3$ – 15.7, SiO$_2$ – 56.3, K$_2$O – 2.07, CaO – 0.85, TiO$_2$ – 1.47, MnO – 0.09, FeO – 10.42; loss of ignition (LOI) – 0.86), to estimate the peak and post-peak (retrograde) $P$–$T$ condition of the sapphirine-bearing granulites from the Kothuru section have been used. The XRF analysis was carried at the Birbal Sahni Institute of Palaeosciences (BSIP), Lucknow (WD-XRF; power – 3 KW, 60 kV–160 mA) to detect the elements.

The peak and post-peak history of the sapphirine-bearing granulites was constrained using the Perple_X software (version 6.8.7) from the internally consistent thermodynamic dataset and the equation of state for H$_2$O of Holland and Powell, which is based on the Gibbs free energy minimizations. The $P$–$T$ evolution of the sapphirine-bearing granulate was estimated within the pressure–temperature range 6–10 kbar and 900–1050°C respectively, based on the NCKFMASHTO (Na$_2$O–CaO–K$_2$O–FeO–MgO–Al$_2$O$_3$–SiO$_2$–H$_2$O–TiO$_2$–Fe$_2$O$_3$) model system. The amount of H$_2$O (wt%) used in the computation of the $P$–$T$ pseudosection was approximated from the LOI value obtained in the bulk composition analysis.
and fs), sapphirine (Spr4, Spr7 and fspr), spinel (sp, herc and usp), cordierite (crd, hcrd and fcrd), biotite (phl, ann and east), plagioclase (ab and an), K-feldspar (san and mic), silicate melt phase (fo8L, fa8L, sill8L and q8L), sillimanite (sill, ky & and) and quartz (q, trd, coe and stv).

The obtained pseudosection was then contoured with the compositional modal proportion isopleths of various mineral phases, i.e. $X_{\text{Mg}}$ sapphirine, $X_{\text{Mg}}$ spinel, $X_{\text{Mg}}$ cordierite, $X_{\text{Mg}}$ biotite, $X_{\text{Mg}}$ garnet and $X_{\text{Mg}}$ orthopyroxene ($X_{\text{Mg}} = \text{Mg}/(\text{Mg} + \text{Fe})$).

The $P$–$T$ path derived from the intersection of the isopleth contours ($X_{\text{Mg}}$ compositional values), suggests the peak mineral assemblage to be spinel–garnet–orthopyroxene–cordierite–biotite–plagioclase–sapphirine–melt–quartz–rutile at a pressure of about 9.5 kbar and temperature in excess of 980°C (Figure 3). The decompression path projected shows an abrupt release in pressure from 9.5 to 6.8 kbar, which corresponds to the exhumation of these granulites.

Discussion and conclusion

The stable coexistence of sapphirine and spinel with quartz in contact, and their incompatibility at later stages represented by polymineral reaction coronas provide robust evidence that the studied granulite terrane has undergone extreme crustal metamorphism at UHT (>950°C at ~10 kbar). Several UHT localities have been reported from different parts of the EGMB by earlier workers (Figure 1a) and their extent of metamorphism lies in close proximity with results obtained in terms of $P$–$T$ condition in the present study. However, it differs in textual relations and the mechanism through which such extreme temperature and pressure have resulted. The highly aluminous orthopyroxene (with Al$_2$O$_3$ content up to 9.43 wt%) characterizes the granulites of the locality and this is found to be in accordance with other UHT belts like the Enderby Land, Antarctica (Al$_2$O$_3$ content of 8–9.5 wt%) with similar $P$–$T$ conditions of 10 ± 1.5 kbar and 950 ± 50°C respectively. The observed aluminous assemblage and $P$–$T$ conditions of the study area are also in close correlation with the UHT models documented from the Southern Granulite Terrane of India and in the adjacent areas of the EGMB. The calculated ratio of Fe$^{3+}$/Fe$^{total}$ in sapphirine from the data obtained from the microprobe studies is significantly low (<0.3), which in turn fulfils a major criterion as the indicator of UHT metamorphism.

The derived $P$–$T$ trajectory of metamorphism from pseudosection modelling for the high-grade metamorphic rocks shows the peak $P$–$T$ condition and post-peak isothermal decompression retrograde trajectory followed by isobaric cooling (second stage of retrograde trajectory). The proposed clockwise $P$–$T$ path with steep isothermal decompression retrograde trajectory is considered to be in favour of collision tectonics and over-thrust processes, which is also evident from the abrupt occurrence of transition zone to the west of the presented segment. In such metamorphic belts, the peak $P$–$T$ condition (mainly pressure ranges) is often underestimated due to the dominance of widely occurring retrograde overprints in mineral assemblages and arrested reaction textures. Santosh and Kusky proposed a model for the estimation of extreme $P$–$T$ conditions associated with collision/thrust tectonics which may also be applicable in the present study, in which the heat required to balance the anhydrous mineral assemblages of various UHT occurrences from collisional belts may be derived from the asthenospheric upwelling developed due to subduction of the ridges. The present study provides evidences (petrographic, geochemical and pseudosection modelling) for the occurrence of a UHT locality which is tectonically different from those reported in the adjacent localities, suggesting an anti-clockwise $P$–$T$...
path with primary retrograde stage of isobaric cooling. Further studies of the mineral inclusions and isotopic geochemistry may help unravel the mechanism and precise timing involved in the evolution of the tectonometamorphic framework related to the UHT metamorphic belts of collisional suture.


ACKNOWLEDGEMENTS. S.S. and D.P. thank the Department of Science and Technology, New Delhi for DST-INSPIRE Fellowship (IF 180879) and DST (SERB) Research Project (P-07-704) respectively. We thank the Head, Department of Geology, Banaras Hindu University (BHU), Varanasi and the CAS programme of University Grants Commission, New Delhi at BHU for providing necessary infrastructural facilities. We also thank the anonymous reviewer for valuable suggestions that helped improve the manuscript.

Received 1 September 2021; revised accepted 19 March 2022

doi: 10.18520/cs/v122/i11/1298-1304