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Reaction textures and metamorphic evolution of spinel-bearing metapelites of Kerala Khondalite Belt, Southern Granulite Terrain, India

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ABSTRACT
Kerala Khondalite Belt is the southern part of the Southern Granulite Terrain consisting of khondalites, garnet biotite gneiss and cordierite gneiss. This study briefly describes the petrography and reaction textures of spinel-bearing metapelites of KKB. The metapelites with the assemblage of cordierite + garnet + sillimanite + spinel + biotite + quartz + plagioclase + K -feldspar are very well exposed in Kulappara (KLP), Koliakode (KKD) and Ayiravalli (AYV) quarries and garnet + cordierite + orthopyroxene + spinels + plagioclase + k-feldspar assemblage in Koodal Mavanad (KDM), Koodal Dharshan (KDD), Koodal Palakkattu (KDP) and Koodal Ambadiyil (KDA) quarries. This study was carried out to understand the reaction textures of spinel and associated minerals in KKB. Several reaction textures described in this study help to unravel the polyphase metamorphism and evolution of spinel-bearing granulites. The KKB has a clockwise P–T path is indicated by the presence of prograde mineral relics and later retrograde textural reactions. The spinel-forming reactions from biotite-sillimanite assemblages correspond to biotite “dehydration” or “dehydration-melting” reactions. The reaction texture related to spinel-cordierite mineral phase, involving the subsequent decompression reaction in which spinel reacted to produce cordierite, such textures observed in the study area thus mark a series of decompression reactions following peak metamorphism. After the isothermal decompression in the KKB experience, an isobaric cooling path was observed from the growth of biotite. Thus, our present results show three types of reaction textures on spinel-bearing metapelites of KKB, which have already been proposed by different authors based on P-T estimation and petrography as high temperature–moderate pressure peak metamorphism followed by decompression and cooling.

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1. Introduction

The spinel-bearing mineral assemblage is a characteristic phase in high-temperature metamorphic rocks of dominantly sedimentary origin, having garnet, biotite, and sillimanite (Harley, 2008; Kelsey, 2008; Kelsey and Hand, 2015; Cenki et al., 2002;

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Harley and Nandakumar, 2016; Nandakumar et al., 1991; Santosh et al., 2004) and the spinel exhibits a wide range of chemical composition in terms of Al, Cr, Fe, Zn, and Mg elements. In KKB, spinel is hercynite variety with X_{Mg} $\{Mg/(Mg + Fe^{2+})\}$, ranging from 0.15 to 0.41. The ZnO content is 1.35–7.78 wt.%, providing a gahnite component, i.e., X_{Zn} $\{Zn/(Mg+Fe^{2+}+Zn)\}$ of 0.03–0.12. This KKB spinel is characterized by a low content of Cr_2O_3 (less than 1.94 wt.%), and the Al_2O_3 content varies from 57 to 60 wt.%. XMg of spinel shows the higher value towards the northern part of KKB, where X_{Zn} shows the lower value. The ionic substitution of these elements commonly corresponds to the available temperature-pressure conditions and source of materials (Baharifar et al., 2019; Bose et al., 2020; Shimura et al., 2023). The garnet-spinel-cordierite-feldspar-quartz-biotite-sillimanite mineral assemblages in typical metapelite systems indicate high-temperature and medium-pressure metamorphism (Bose et al., 2020; Harley and Nandakumar, 2016; Montel et al., 1986; Sajeev and Osanai, 2002; Shimura et al., 2023).

The Kerala Khondalite Belt (KKB), south of the Achankovil Shear Zone in the Southern Granulite Terrane (SGT), is characterized by the presence of spinel in the migmatized metapelites (Santosh et al., 2004). Chacko et al. (1996) proposed the Ultra-high temperature metamorphism in this terrain. Studies by Nandakumar and Harley (2000) and Santosh et al. (2004) suggested the UHT metamorphism of KKB. The different types of reaction textures and mineral assemblages in this metapelite exhibit a complete picture of the P-T pathway of metamorphism (Cenki et al., 2002, 2004; Harley, 2016; Harley and Nandakumar, 2016; Nandakumar and Harley, 2000; Santosh et al., 2004). Remarkable textural relations reveal multiphase reactions responsible for the formation of diverse mineral paragenesis during the prolonged metamorphic history of the area. The development of reaction texture and symplectitic intergrowth in Al-silicates in these granulites has preserved a record of their evolutionary stages. This work describes the important textures encountered in the spinel-bearing Al-rich metapelites of KKB, giving an excellent opportunity to investigate the metamorphic evolution of the spinel-bearing metapelites of KKB, where spinel is associated with cordierite, biotite, sillimanite, garnet, and orthopyroxene.

2. Geological setting

The SGT is an amalgam of several crustal blocks of granulite-facies rock. Most of them have been metamorphosed during late Neoproterozoic or Ediacaran to Cambrian orogenesis associated with the amalgamation of continental fragments to form Gondwana (Braun and Bröcker, 2004; Braun and Raith, 1994; Cenki et al., 2004; Rajesh and Santosh, 2004; Rajesh and Santosh, 1997, Harley and Nandakumar, 2016; Nandakumar and Harley, 2019). The Kerala Khondalite Belt (KKB) (Fig. 1) constitutes vast supracrustal rocks of granulite grade, south of the Achankovil Shear Zone (Chacko et al., 1992; Nandakumar and Harley, 2000, 2019; Santosh et al., 2004; Satish Kumar et al., 1996; Srikantappa and Ravindra Kumar, 1987), also referred to as the Trivandrum Block (Satish Kumar et al., 1996). Evidence for multiple metamorphic events culminating in granulite facies metamorphism and extensive crustal reworking during the late Pan-African event of ca. 540 Ma has been documented from this area (Cenki et al., 2004; Harley and Nandakumar, 2014; Tomson and Dev, 2024).

The Trivandrum Block (KKB) is composed dominantly of granulite-facies supracrustal rocks, including migmatitic garnet-biotite-quartz-feldspar gneisses and garnet-cordierite-sillimanite gneisses (khondalites), as well as charnockites and localized mafic granulites (Braun et al., 1996; Nandakumar et al., 1991; Rajesh and Santosh, 2004; Satish Kumar et al., 1996), which preserve Paleoproterozoic igneous and metamorphic ages (Braun and Bröcker, 2004; Cenki et al., 2004; Harley, 2016; Harley and Nandakumar, 2014, 2016; Nandakumar and Harley, 2019). Charnockites dominate towards the northern and southern margins, while the central part of KKB mostly comprises spinel-bearing khondalites and leptynites (Nandakumar et al., 1991; Santosh et al., 2004; Shabeer et al., 2002). From north to south, the KKB encloses the Achankovil Unit, the Ponmudi Unit (PU), and the Nagercoil Unit (Srikantappa and Ravindra Kumar, 1987). The Ponmudi Unit and the Achankovil Unit consist of garnet-biotite gneisses and garnet ± biotite ± cordierite ± sillimanite ± graphite gneisses representing a supracrustal sequence of pelitic and psammitic origin (Chacko et al., 1992). Based on conventional Fe–Mg exchange between coexisting minerals, the pressure-temperature estimation of the KKB is reported by moderate

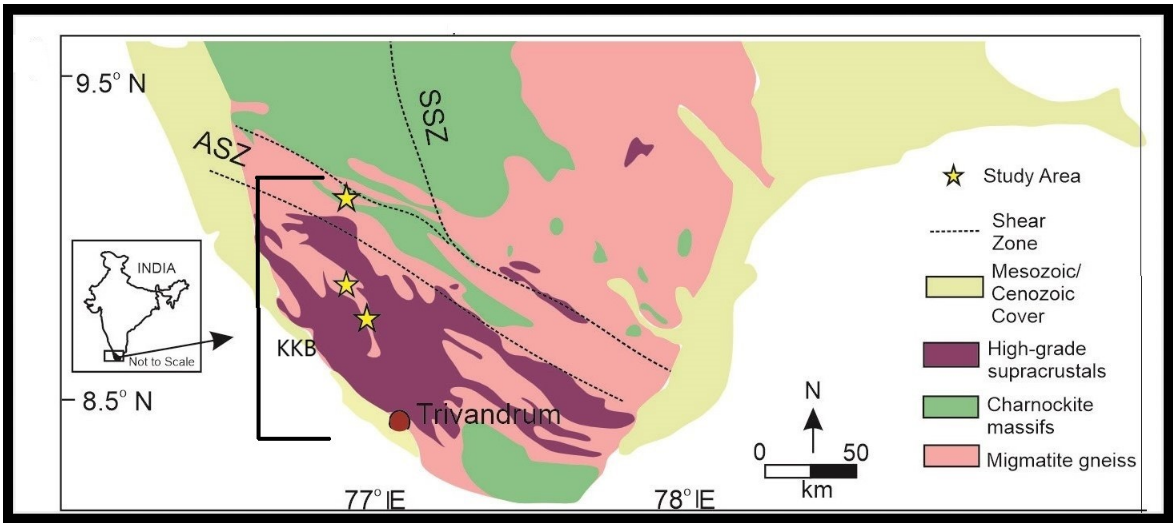

Fig. 1. A simplified geological sketch of southern India showing the charnockite massifs of Madurai block, Suruli Shear Zone (SSZ), Achankovil Shear Zone (ASZ) and Kerala Khondalite Belt (KKB), modified from Kumar et al. (2017). Sample locations are marked.

P-T conditions of 600–750°C and 4–5 Kbar (Hansen et al., 1987; Cenki et al., 2004), studies by Chacko et al. (1996), Nandakumar and Harley (2000), Santosh et al. (2004), Braun and Bröcker (2004) and Sorcar et al. (2020), revealed temperatures more than 900°C, based on different thermobarometric studies and mineral phase equilibria in the pelitic rocks.

3. Field relationships

Detailed field studies were undertaken in the following localities (working quarries) in the KKB: Kulappara (KLP) and Koliakode (KKD) in the Southern part of KKB, Ayiravalli (AYV) in the central part and Koodal Mavanad quarry (KDM), Koodal Dharshan quarry (KDD), Koodal Palakkattu granites (KDP) and Koodal Ambadiyil granites (KDA) in the Northern part of KKB. Cordierite-bearing gneisses and khondalites are the dominant rock types of these locations, having spinel in garnet-bearing cordierite gneisses and orthopyroxene-bearing migmatites towards the northern part of KKB. The metapelites with the assemblage of cordierite + garnet + sillimanite + spinel + biotite + quartz + plagioclase + K-feldspar are very well exposed in this area. Layers of cordierite-garnet-biotite-sillimanite-spinel assemblage, alternating with quartzo-feldspathic layers, define the compositional layering of this rock. These gneisses show the effects of multiple deformations and migmatisation.

Migmatisation resulting in the formation of partially discordant leucosomes is commonly seen in all areas. The melanosome is a relatively silica-poor assemblage comprised of cordierite, spinel, garnet, sillimanite, biotite, and oxide phases. Cordierite occurs both in the layers and as large, discrete grains in some domains. Megascopically, the rock consists of coarse-grained quartz, feldspar, garnet, cordierite, biotite, and sillimanite. Spinel, ilmenite and magnetite are the accessory minerals in the rock. The rock has gneissosity with the compositional layering of cordierite/biotite-mafic bands within the quartz-rich felsic matrix. Garnet + biotite + cordierite forms melanocratic zones in the Kulappara (KLP), Koliakode (KKD) and Ayiravalli (AYV). Pyroxene is associated with garnet, cordierite and biotite in the Koodal Mavanad quarry (KDM), Koodal Dharshan quarry (KDD), Koodal Palakkattu granites (KDP) and Koodal Ambadiyil granites (KDA). Representative field photographs from these localities are shown in Fig. 2. A Summary of the sample locations, coordinates, rock types, and general mineralogy is presented in Table 1.

4. Locations

4.1. Location 1. Spinel-bearing metapelites in the Southern part of KKB – Kulappara (KLP), Koliakode (KKD)

Spinel-bearing cordierite gneisses and associated leucosomes are the major lithology of the Kulappara and Koliakode quarries (Harley and Nandakumar, 2014). The major mineral assemblage of this

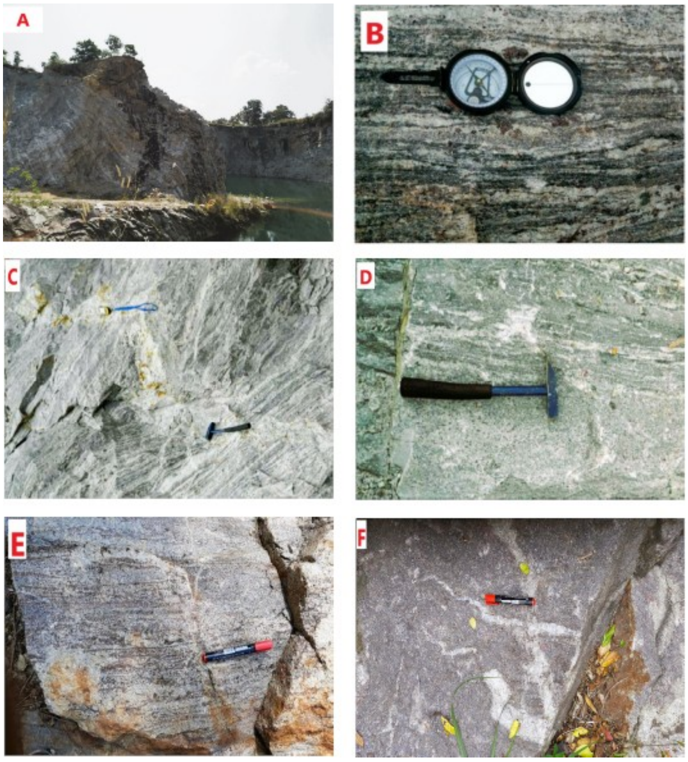

Fig. 2. **(A, B & E)** Field photographs of garnet-cordierite gneiss from the Kulappara, Koliakode and Ayiravalli quarries, gneissic layering comprising Grt, Bt, and Crd mesosomes and quartzo-feldspathic leucosome. **(C and D)** warping of migmatitic layering along foliation planes in gneiss, indicating partial melting during HT metamorphism. **(F)** Quartzo-feldspathic leucosomes in cordierite gneisses at Ayiravalli.

Table 1. Location, rock type, and mineralogy of samples.

Sl. No.	Latitude (N)	Longitude (E)	Location	Rock Type	Mineral Assemblage
1	8.603	76.9005	Kulappara quarry	Cordierite Gneiss	Qtz -Bt-Grt- Sill-Spl-Crd- Pl
2	8.6394	76.891	Koliakkode quarry	Cordierite Gneiss	Qtz-Bt-Grt- Sill-Spl-Crd- Pl
3	8.7938	76.8667	Ayiravalli quarry	GBG	Qtz-Bt-Grt-Sill-Spl-Crd-Plg
4	9.148	76.8991	Koodal Mavanal quarry	Cordierite Gneiss	Qtz-Bt-Grt-Spl-Crd-Opx- Pl
5	9.1514	76.9071	Koodal Dharsan Quarry	Cordierite Gneiss	Qtz-Bt-Grt-Spl-Crd-Opx- Pl
6	9.2529	76.8645	Koodal Plakkattu quarry	Cordierite Gneiss	Qtz-Bt-Grt-Spl-Crd-Opx- Pl
7	9.2116	76.8127	Koodal Ambadiyil quarry	Cordierite Gneiss	Qtz-Bt-Grt-Spl-Crd-Opx- Pl

location is quartz, plagioclase, K-feldspar, cordierite, biotite, sillimanite and accessories like illmenite, spinel, magnetite, monazite and zircon. Leucosome contains quartz + feldspar with minor amounts of garnet and/or cordierite, biotite, and ilmenite. Petrographical studies reveal the prograde and decompression metamorphic reactions in this section, such as cordierite coronas and sillimanite intergrowth in garnet, biotite, and plagioclase.

4.2. Location 2. Spinel-bearing metapelites of the Ayiravalli quarry – Central part of KKB

Ayiravalli quarry is located in the central part of KKB, near Kilimanur, about 40 km north of Trivandrum city. The metapelites with the assemblage of cordierite, garnet, sillimanite, spinel, biotite, quartz, plagioclase, and K-feldspar are very well exposed in this area. These gneisses exhibit the effects of migmatization and multiple deformations. Cordierite-garnet-biotite-sillimanite-spinel assemblage alternating with quartzo-feldspathic layers defines the compositional layering in the rock (Fig. 2E & F). The melanosome is a relatively silica-poor assemblage comprised of cordierite, spinel, garnet, sillimanite, biotite, and oxide phases.

4.3. Location 3. Spinel-bearing metapelites of Koodal – Northern part of KKB

There are several active quarries in Koodal and samples were collected from fresh exposure. The rock consists of alternating leucocratic layers and melanosomes (Fig. 3). Cordierite gneiss with garnet-orthopyroxene association is observed in the field.

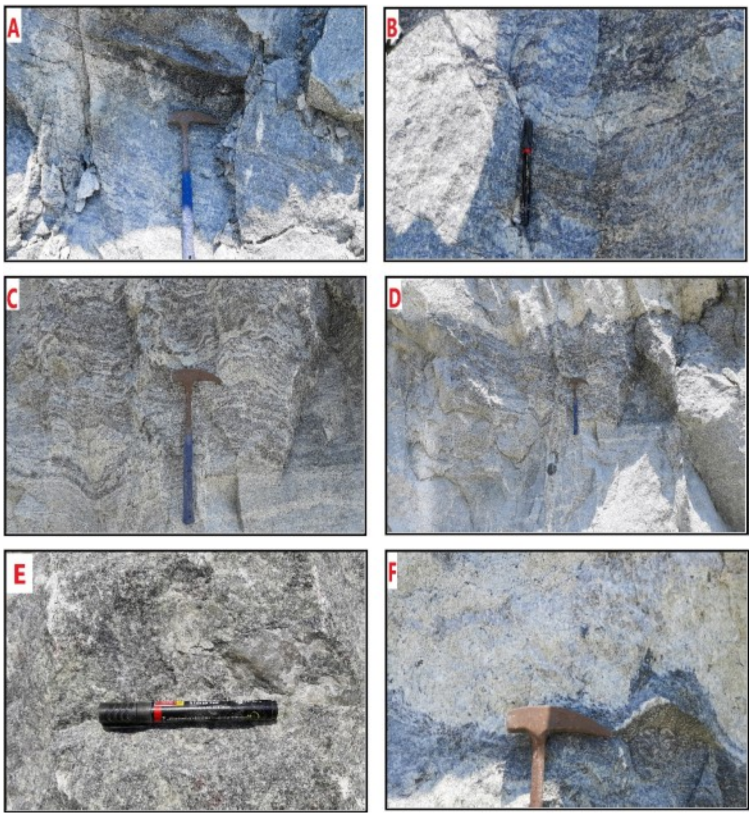

Fig. 3. **(A)** Gneissic layering of Koodal comprising Grt+Opx+Crd+Grt mesosomes and garnet-bearing leucosomes. **(B)** Migmatitic cordierite-bearing pelitic rocks show the discordant quartz-feldspathic part in the leucosomes as pockets and patches. **(C)** Leucosome occurs as irregular patchwork, melt-rich domains, and restitic domains melanosome (rich in cordierite and orthopyroxene). **(D)** Typical quarry face showing intensely intercalated dark grey to blue-grey migmatitic pelitic and semi-pelitic gneisses with leucosomes. **(E)** Opx+Bt+Grt+Crd mineral assemblage is noticed in the mesosome. **(F)** Patchy cordierite-rich melanosomes within the sheet of leucosome.

The leucocratic part is composed of quartz and feldspars with a minor amount of garnet and biotite. The melanocratic part comprises biotite-garnet-orthopyroxene-cordierite-spinel and ilmenite (Fig. 3E). The dominant lithology is characterized by combining garnet–cordierite–orthopyroxene–spinels–plagioclase–K-feldspar–quartz–ilmenite.

5. Petrography

A detailed petrographical study was conducted on the rock samples collected from these locations. The majority of the samples investigated from Kulappara (KLP), Koliakode (KKD) and Ayiravalli (AYV) quarries comprise migmatitic cordierite gneisses with major minerals as quartz, plagioclase, K-feldspar, garnet, cordierite, biotite, hornblende, sillimanite, ilmenite, spinel and magnetite and accessories like monazite, and zircon. In Koodal Mavanad quarry (KDM), Koodal Dharshan quarry (KDD), Koodal Palakkattu granites (KDP), Koodal Ambadiyil granites (KDA) the important mineral assemblages include quartz, plagioclase, K-feldspar, cordierite, orthopyroxene, biotite, spinel, magnetite and accessories.

The dominant lithology of Kulappara (KLP), Koliakode (KKD) and Ayiravalli (AYV) is migmatitic garnet cordierite gneiss. Rocks generally show inequigranular and medium to coarse-grained with a well-developed interlocking texture. Petrographic studies of the samples from locations one and two reveal the major mineral assemblages as Grt-Bt-Sill-Spl-Crd-Qtz (Fig. 4). Garnet has a subhedral shape and is formed from a biotite-dehydration melting reaction. Garnet-Sillimanite-Spinel assemblage is considered to be the near-peak assemblage and is present in these sections. Textural features of these associated minerals show the prograde metamorphism (Fig. 5B–F), where spinel, sillimanite and biotite are seen as inclusions in garnet (Fig. 6A & 7F). The textural relationship (Fig. 4) indicates that the prograde condition leads to the breakdown of unstable biotite

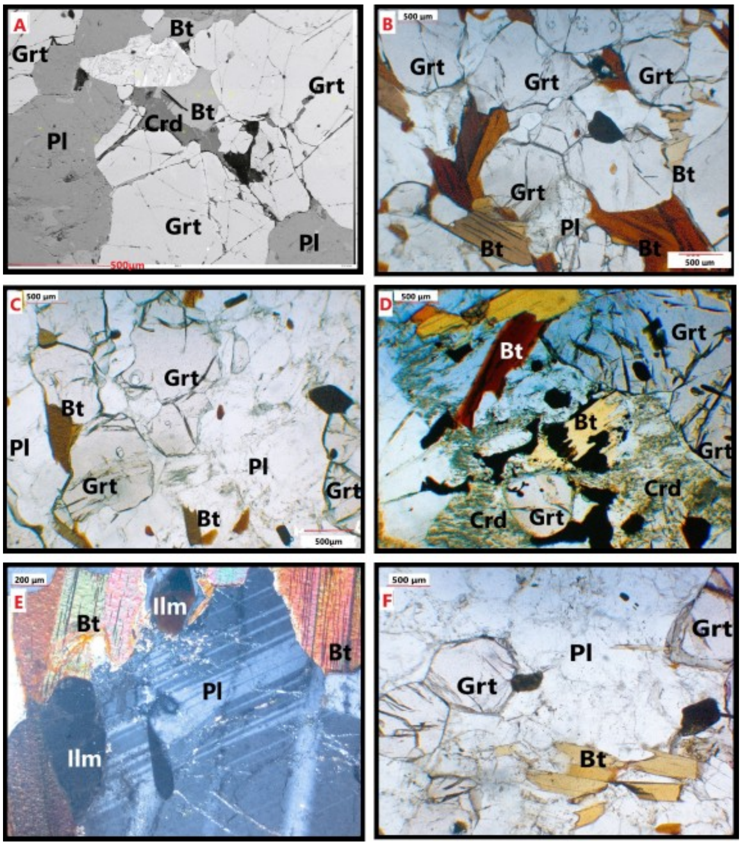

Fig. 4. Photomicrographs illustrating textural relations in spinel-bearing granulites of KKB. (**A, B & C**) show the important mineral assemblages in the prograde phase of metamorphism. Sharp faces of garnets in association with biotite and plagioclase indicate the dehydration reaction of biotite in prograde metamorphism. **(D)** Symplectite of cordierite suggests the growth of this mineral and the reaction (1). **(E & F)** The growth of ilmenite and garnet by the consumption of biotite and plagioclase during prograde metamorphism.

to more stable cordierite (porphyroblast) and garnet at high PT conditions. This suggests the following reaction might have occurred during the peak metamorphic phases (Spear et al., 1999).

$$\mathrm{Bt + Sil + Pl + Qtz = Grt + Crd + Melt + Kfs + Ilm} \quad (1)$$

The reaction textures with the sharp faces of garnets in associated with biotite and plagioclase, which shows the growth of garnet during the prograde reaction path. The symplectitic texture of garnet and cordierite (Fig. 4D) indicates the simultaneous growth of these minerals as per the reaction (1).

The major mineralogy of the migmatitic garnet cordierite gneiss of the Koodal region is quartzo-feldspathic leucosomes and garnet-cordierite-orthopyroxene mesosomes (Fig. 3). These assemblages were strongly overprinted by symplectite, coronas, and later aggregates of spinel, cordierite, and orthopyroxenes. Garnet mostly has a granoblastic texture, which shows intergrowth with cordierite and orthopyroxene. Garnets and cordierite in these granulites show a large porphyroblastic texture with spinel, biotite, zircon, and monazite as inclusions (Fig. 7D & F). Spinels are generally present as large anhedral grains as well as inclusions in garnet and cordierites (Fig. 8D). Cordierite porphyroblasts also contain small inclusions of rounded plagioclase, alkali feldspar, opaques, and spinel-ilmenite aggregates (Fig. 7D & 8A). Plagioclase and cordierite rims are typically observed around garnet crystals (Fig. 8), though plagioclase corona structures may also be seen around orthopyroxene (Fig. 7C). Garnet breaks down to fine-grained intergrowths of biotite, spinel, plagioclase and K-feldspar (Fig. 9A–F), the biotite and cordierite are well-known for the breakdown products of garnet. Greenish spinel is a common accessory in this area and occurs as composite grains of magnetite+hercynite association. In many cases, the spinel grains are rimmed by cordierite coronas and are associated with hypersthene.

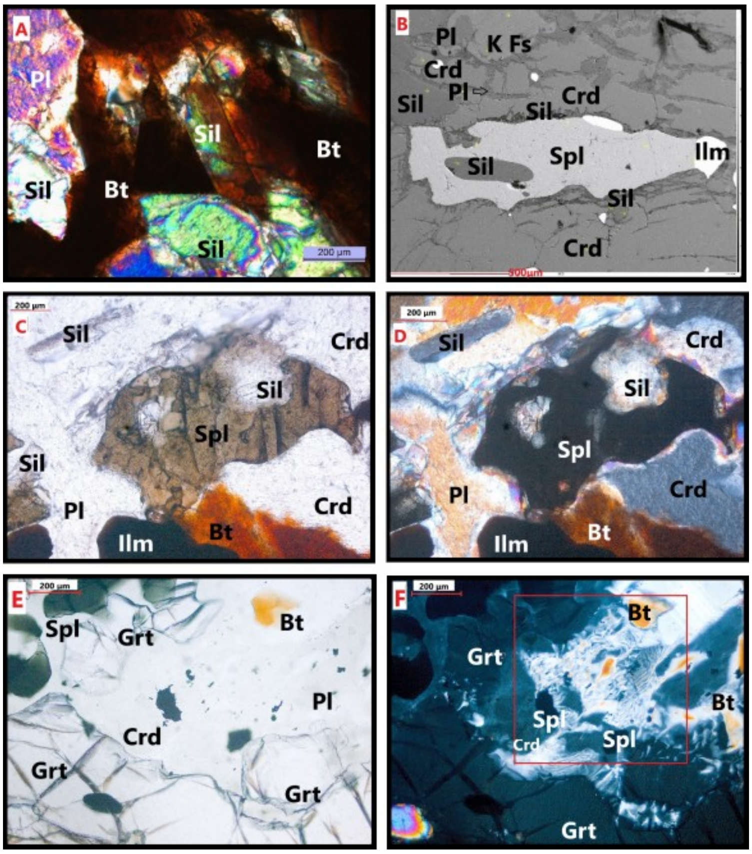

Fig. 5. Photomicrographs illustrating the textural relations in the growth of spinel from biotite in KKB. **(A)** Growth of sillimanite from biotite during prograde metamorphism. **(B–D)** Sillimanite inclusion in spinel, spinel is rimmed by sillimanite, suggesting the following mineral reaction Bt + Sil = Hc + Crd + liquid. **(E & F)** Symplectitic growth of cordierite and spinel with garnet in the presence of some relict biotite minerals, suggesting the equilibrium growth of Crd and Spl.

6. Metamorphic pathways: spinel and associated prograde mineral reactions

Spinel is associated with sillimanite, biotite, and cordierite in Kulappara, Koliakode, and Ayiravalli quarries are noticed with the breakdown of biotite. Vielzeuf and Montel (1994) suggested that the biotite breakdown reaction releases water, which may induce partial melting of the adjacent quartzo-feldspathic phases and these reactions may occur together with other melting reactions from biotite and sillimanite. Growth of cordierite porphyroblast from the assemblage biotite + sillimanite + quartz is noticed in the sections, where sillimanite occurs both as porphyroblasts and as inclusions in spinel and cordierite cores (Fig. 5B & C). Intergrowth of cordierite + spinel developed from biotite and sillimanite with abundant plagioclase and K-feldspar in the leucocratic layers representing the in-situ crystallization of a melt phase.

The growth of sillimanite from biotite (Fig. 5A) suggests the high-temperature metamorphism with the peak PT conditions in KKB. Sillimanite-spinel-porphyroblastic cordierite association and sillimanite inclusion in spinel (Fig. 5B–D) suggest the mineral reactions (2) and (3); both these prograde reactions are dehydration and melt-producing. Fig. 5B and 5C suggest the growth of spinel and associated minerals as per the following reactions.

$$\text{Bt} + \text{Sil} = \text{Hc} + \text{Qtz} + \text{Kfs} + \text{vapor} \quad \text{(Vielzeuf and Montel, 1994)} \tag{2}$$

$$\text{Bt} + \text{Sil} = \text{Hc} + \text{Crd} + \text{liquid} \quad \text{(Montel et al., 1986; Jones and Brown, 1990)} \tag{3}$$

Garnet-spinel symplectitic texture with relict grains of biotite suggests the equilibrium growth of spinel and garnet. Symplectite texture between cordierite, and spinel (Fig. 5E & 5F) in the presence of some relict biotite minerals, suggesting the breakdown of biotite and the generation of garnet, spinel, and cordierite during the prograde metamorphism.

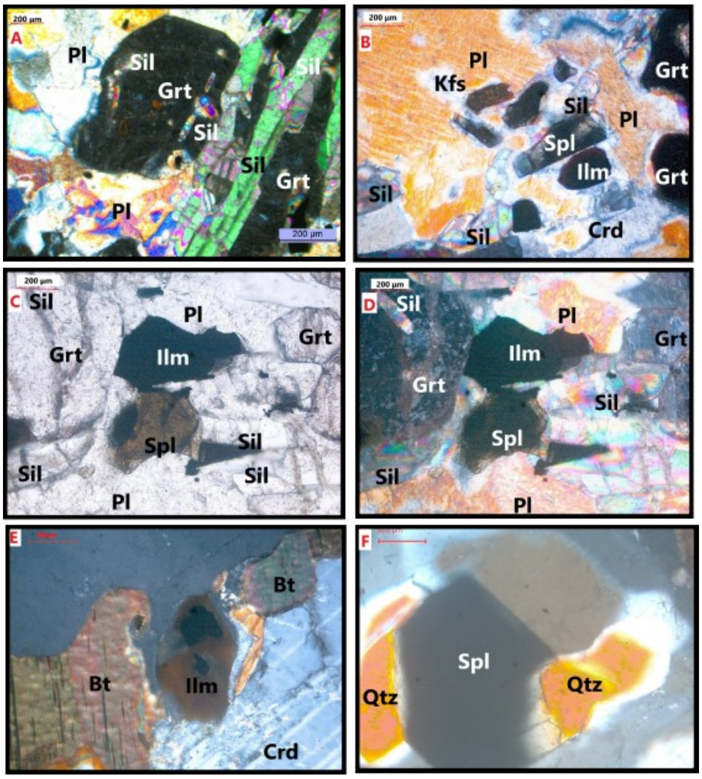

Fig. 6. Spinel association in peak metamorphic reaction textures. **(A)** Sharp-edged garnet with slight bending and inclusions of sillimanite in garnet suggest the later stage of garnet growth. **(B)** The coexistence of spinel, sillimanite, garnet, plagioclase, cordierite, and K feldspar suggests the mineral reaction associated with peak temperature. **(C and D)** PPL and XL images show the growth of spinel from garnet in association with sillimanite and plagioclase with the following reaction: Grt +Sil = Spl + Pl. **(E)** Growth of titanium-bearing ilmenite from biotite. **(F)** Spl–Qtz direct contact is noticed from Koliakode, suggesting ultra-high temperature metamorphism.

This spinel probably originated from the breakdown of Ti-rich biotite with cordierite porphyroblasts leaving small relics of garnet, biotite, and quartz in the matrix.

$$\mathrm{Bt + Sil} \quad = \quad \mathrm{Grt + Spl + Mag + L\ (melt)} \quad \text{(Vielzeuf and Holloway, 1988)} \qquad (4)$$

Fig. 7E suggests the growth of spinel from garnet and biotite, in the presence of relict grains of garnet and biotite near the spinel porphyroblast, indicating reaction (5) may generate spinel-cordierite assemblage. Fig. 6A–D indicates that spinel and plagioclase replace the garnet and sillimanite, suggesting the reaction texture (6).

$$\mathrm{Grt + Bt + Sil + Pl} \quad = \quad \mathrm{Spl + Crd + (Kfs) + Melt} \quad \text{(Cenki et al., 2002)} \qquad (5)$$

$$\mathrm{Grt + Sil} \quad = \quad \mathrm{Spl + Pl} \quad \text{(Shimura et al., 2023)} \qquad (6)$$

Elongate aggregates of orthopyroxene with cordierite and plagioclase form in the foliation, also it mimics a former garnet shape, suggesting that they are pseudomorphs after garnet (Fig. 7A–D). A slightly Fe-rich bulk composition generates a mineral assemblage- orthopyroxene + spinel + quartz. (Cenki et al., 2002) and the reaction texture is given below.

$$\mathrm{Bt + Pl + Qtz} \quad = \quad \mathrm{Opx + Spl + (Kfs) + Melt} \quad \text{(Vielzeuf and Montel, 1994)} \qquad (7)$$

Spinel associated with ilmenite (Fig. 6A–E) suggests the breakdown of Ti-rich biotite. In the Koliakode quarry, spinel, garnet, cordierite, and quartz coexistence is observed and spinel-quartz direct contact is noted (Fig. 6F). Spinel-quartz direct contact is considered as an ultra-high-temperature assemblage (Hensen and Harley, 1990; Satish-Kumar and Harley, 1998). Vielzeuf and Holloway (1988) experimentally determined melting relations in pelitic systems, placing quartz-spinel growth at around 1000°C at 8 kbar. Santosh et al. (2004) reported this type of quartz spinel direct contact from Chittikara in KKB and estimated the PT condition of 950 °C and 8 kbar

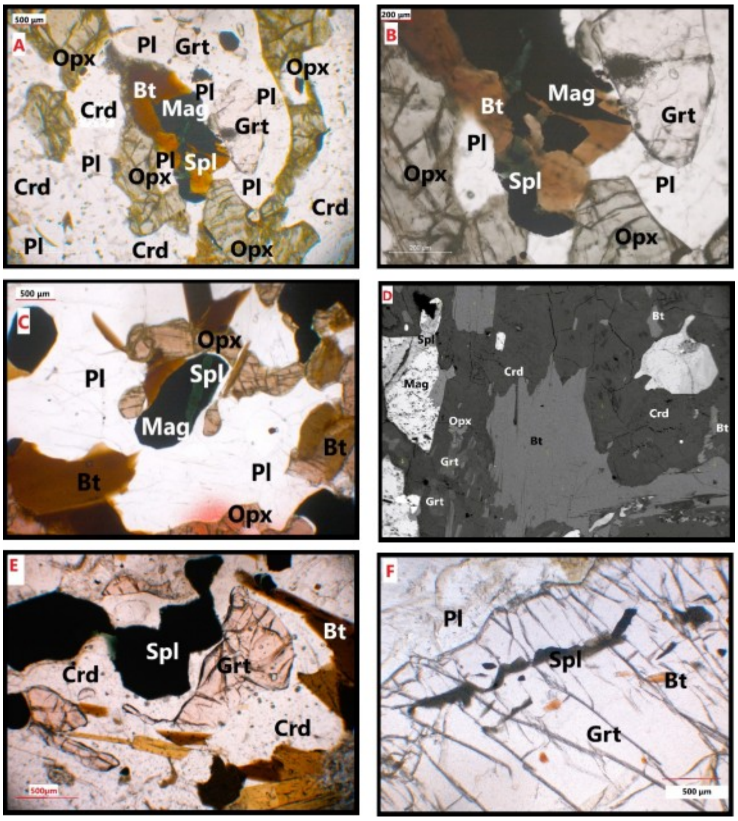

Fig. 7. **(A–D)**: Dehydration reactions lead to the growth of orthopyroxene, cordierite, and spinel with the consumption of biotite, garnet, and plagioclase noted; the mineral reaction might be Bt + Pl + Qtz = Opx + Spl + (Kfs) + Melt. **(E)** Suggest the growth of spinel and cordierite from garnet and biotite- reaction texture Grt + Bt + Sil + Pl = Spl + Crd + (Kfs) + Melt. **(F)** Biotite and spinel inclusion in porphyroblastic garnet.

pressure. This suggests the following reaction:

Grt+Crd+Sil = Spl+Qtz (Santosh et al., 2004) (8)

7. Spinel associated with isothermal decompression reactions

Spinel is mostly associated with garnet in KKB, greenish isotropic spinel as magnetite + hercynite (Hc) composite occurs adjacent to garnet porphyroblasts, developing symplectites intergrowth with cordierite. Symplectitic textures of spinel and cordierite can explain the formation of spinel and cordierite from the biotite, garnet, sillimanite, and plagioclase (Cenki et al., 2002). The photomicrograph shows that cordierite occurs as coronal rims around garnet and spinel (Fig. 8A–C). Spinel is mostly associated with ilmenite and magnetite and occurs as an inclusion in garnet porphyroblasts. Petrographical studies reveal that most of the garnet grains partially break down and are rimmed by coronas that consist of either anhedral cordierite or fine-grained cordierite + quartz ± plagioclase symplectites and have some biotite inclusions in cordierite. Cordierite formation from the breakdown of garnet, sillimanite, and quartz from cordierite-bearing migmatite is reported by Santosh (1987), and Nandakumar and Harley (2000) reported rims of cordierite formed on and replacing garnet adjacent to sillimanite from TGB. The reaction (10) proceeds from left to right through decompression was reported by Dasgupta et al. (1995) and Brandt et al. (2003) from ultrahigh-temperature granulites. Some cordierite porphyroblast includes biotites and garnet, textural evidence suggests that the reactants are garnet and sillimanite, and the products are spinel and either cordierite or plagioclase (Fig. 8A–D and F) and the following reactions have been suggested.

Grt + Sil = Crd + Spl (Bendaoud et al., 2008) (9)

Grt + Sil + Qtz = Crd + Hc (Hercynite) + Ilm (Jones and Brown, 1990) (10)

Grt + Sil = Spl + Pl (Shimura et al., 2023) (11)

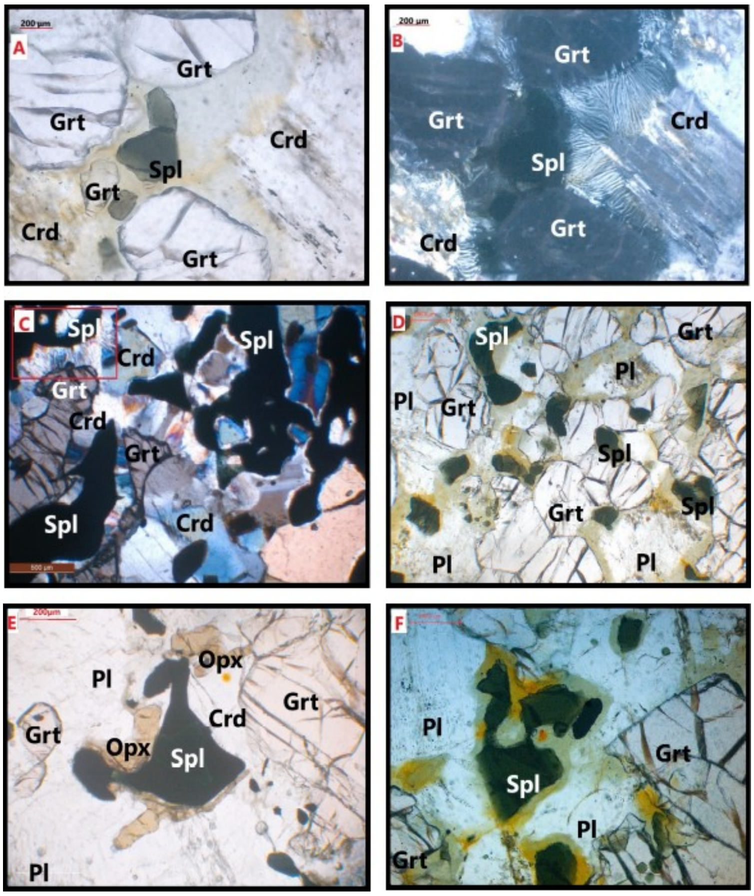

Fig. 8. **Fig. 8 (A–C)**: Spinel, garnet, and cordierite mineral assemblage with symplectite texture of cordierite with spinel with some relict garnet, suggesting the growth of cordierite and spinel from garnet as the reaction Grt + Sil = Crd + Spl. **(D & F)** Occurrences of spinel + plagioclase in symplectite. Photomicrograph illustrates the reaction texture suggesting the breakdown of garnet to spinel and plagioclase Grt +Sil = Spl + Pl. **(E)** Spinel, orthopyroxene and plagioclase mineral assemblage with some relict and broken garnet suggests the reaction Grt = Opx + Spl + Crd + Pl.

In many cases, the spinel grains are rimmed by cordierite coronas and are associated with hypersthenes and garnets (Fig. 8E). Association of orthopyroxene – cordierite – spinel – plagioclase is noticed in which cordierite corona inhibits the contact of spinel and quartz. Spinel grains also show evidence for breakdown to cordierite and produce some symplectitic textures. Orthopyroxene-cordierite and orthopyroxene-cordierite-spinel assemblage at the expense of garnet is noticed. Prakash and Arima (2003) have also reported a similar textural breakdown of garnet-producing orthopyroxene-cordierite symplectites in pelitic granulites. This reaction makes up the textural evidence for isothermal decompression (Hensen and Green, 1972). The Spl-Opx intergrowths occur adjacent to the relict garnet, implying that the reaction has an overall decompressive history.

$$\text{Grt} = \text{Opx} + \text{Spl} + \text{Crd} + \text{Pl} \quad \text{(Bendaoud et al., 2008)} \tag{12}$$

The metapelites and the microdomains rich in Si and Mg are characterized by an orthopyroxene–cordierite association by the expense of garnet, quartz, and biotite, in the absence of sillimanite. Garnet breakdown to orthopyroxene + plagioclase via reaction (12) occurred at decompression rather than heating (Cenki et al., 2002). The occurrence of cordierite as rims around garnet, symplectite with plagioclase (Fig. 9C & D) and quartz (Fig. 9A & B) indicates that cordierite is a reaction product after garnet. Cordierite also occurs as symplectitic intergrowth with quartz and K-feldspar (Fig. 9E). Mutual contacts of cordierite and orthopyroxene in biotite-poor assemblages (Fig. 9F), with reaction textures indicating partial consumption of garnet and biotite. Reaction textures and symplectites of cordierite, cordierite + quartz, or cordierite + K-feldspar + quartz, as well as cordierite corona surrounding garnet, suggest that a pressure decrease occurred during the thermal peak (Thompson, 1976; Schenk, 1984).

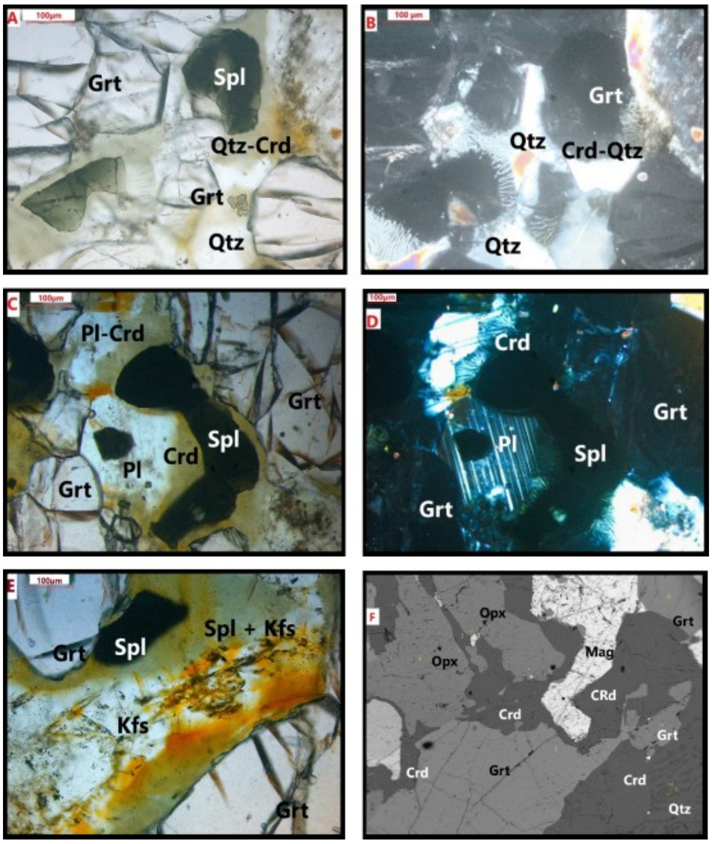

Fig. 9. Photomicrographs show some symplectite textures associated with spinel. **(A & B)** Symplectitic texture of Qtz and Crd in association with garnet and spinel in PPl and XN. **(C & D)** Symplectitic texture of Pl and Crd associated with garnet and spinel. **(E)** Symplectitic texture of Kfs and Crd in association with garnet and spinel. **(F)** Resorbed garnets suggest the growth of orthopyroxene, cordierite, spinel, and plagioclase from garnet; the reaction texture might be: Grt = Opx + Spl + Crd + Pl.

The previous studies in KKB by Chacko et al. (1992), Harley and Nandakumar (2016), and Santosh et al. (2004) reported rapid decompression from different symplectite textures with the breakdown of garnet.

8. Spinel associated with cooling / hydration reactions

In some localities, garnet is partly resorbed and displays embayed grain boundaries filled with intergrowths of anhedral cordierite (Fig. 10A & B), biotite-cordierite (Fig. 10A–C), and biotite-plagioclase-quartz intergrowths (Fig. 10E & F). Spinel grains also show evidence of breakdown to cordierite (Fig. 10B & C), also resorbed garnet by cordierite, spinel, and biotite is observed. Garnet, orthopyroxene, and cordierite deterioration are evidenced by the symplectitic texture of biotite-cordierite and biotite-plagioclase (Fig. 10A–F), which suggests the mineral reaction of 13, 14, and 15. The high modal abundance of incongruent phases in the melanosome suggests retrograde reactions with the in situ crystallizing melt during cooling (Cenki et al., 2002).

$$\text{Grt} + \text{Liq} = \text{Crd} + \text{Bt}(+\text{Pl-rich leucosome}) \quad \text{(Cenki et al., 2002)} \tag{13}$$

$$\text{Spl} + \text{Liq} = \text{Crd} + \text{Bt}(+\text{Pl-rich leucosome}) \quad \text{(Cenki et al., 2002)} \tag{14}$$

$$\text{Spl} + \text{Grt} + \text{Liq} = \text{Crd} + \text{Bt}(+\text{Pl-rich leucosome}) \quad \text{(Cenki et al., 2002)} \tag{15}$$

The growth of biotite from the orthopyroxene and garnet indicates retrogressive hydration reactions (Cenki et al., 2002). Orthopyroxene is observed at the edges of large garnet crystals (Fig. 10F) and shares crystal faces, but is not intergrown. Resorbed garnet near orthopyroxene suggests that it was formed from garnet breakdown. Newly formed orthopyroxenes mimic the shape of garnet, also the encircled biotite around the resorbed garnet suggests the growth of orthopyroxene and biotite from garnet (Fig. 10D). The only leucosome phase closely associated with

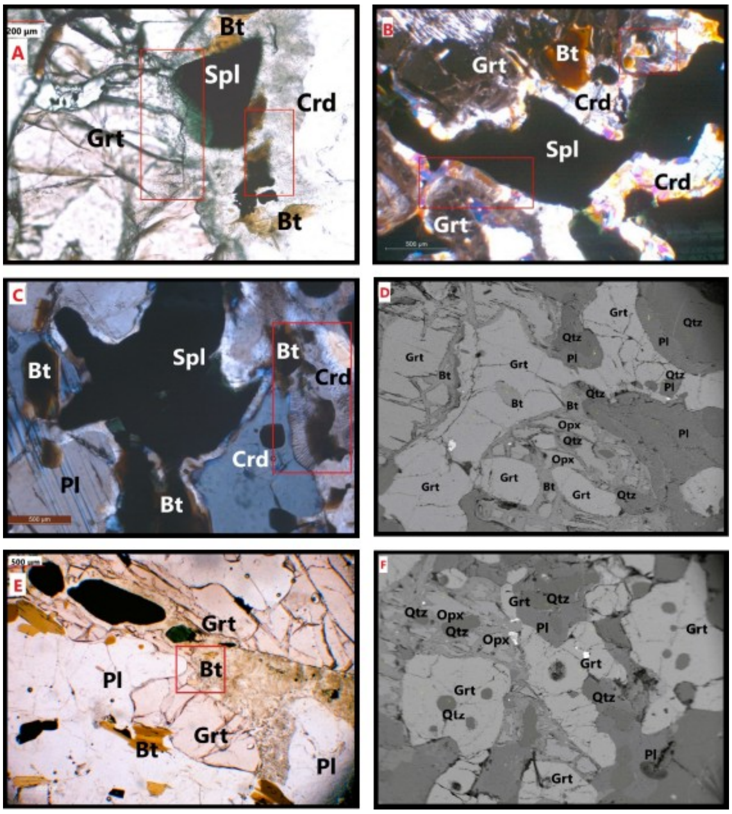

Fig. 10. **(A–C)**: Photomicrographs showing melt-consuming reactions indicate retrograde metamorphism leads to the formation of biotite. Symplectite texture between biotite and cordierite in association with garnet breakdown- reaction texture (13) and (14). **(C)** Biotite cordierite symplectitic texture and the intergrowth of biotite over spinel suggest the growth of biotite from spinel and cordierite-reaction texture (15). **(D)** Biotite around garnet and biotite quartz intergrowth texture indicates resorption of garnet to biotite- reaction texture-(13), the growth of orthopyroxenes in association with plagioclase, quartz, in the presence of relict grains of garnets suggests the reaction texture-(16). **(E)** Bt-Crd symplectites in the resorbed part of garnet porphyroblast in association with plagioclase-reaction texture (13). **(F)** Orthopyroxene is observed at the edges of large garnet crystals and shares crystal faces. Resorbed garnet near orthopyroxene suggests that it formed from garnet breakdown reaction texture (16).

these symplectites and which might have crystallized from the in-situ melt leaving behind an alkali-rich granitic liquid, suggests that it was formed from a garnet breakdown reaction:

$$\mathrm{Grt} + \mathrm{Qtz} = \mathrm{Opx} + \mathrm{Pl} \quad \text{(Cenki et al., 2002)} \tag{16}$$

$$\mathrm{Opx} + \mathrm{Kfs} + \mathrm{V} = \mathrm{Bt} + \mathrm{Qtz} \quad \text{(Mohan et al., 1997)} \tag{17}$$

$$\mathrm{Opx} + \mathrm{Crd} + \mathrm{KfS} = \mathrm{Bt} + \mathrm{Qtz} \quad \text{(Mohan et al., 1997)} \tag{18}$$

$$\mathrm{Opx} + \mathrm{KfS} + \mathrm{L} = \mathrm{Bt} + \mathrm{Crd} \quad \text{(Mohan et al., 1997)} \tag{19}$$

For the calc-silicate samples from KKB, Satish-Kumar and Harley (1998) proposed an isobaric cooling path in the temperature range of 840–750 °C. Nandakumar and Harley (2000) supported and refined their conclusion that the initial part of the post-peak P-T path dominated this P-T path and proposed near-isobaric cooling until temperatures of 775–800°C and pressures of 5.5–6 kbar and subsequent stage of decompression to pressures of 3 kbar at temperatures still above 700°C was inferred from garnet breakdown to cordierite and orthopyroxene + plagioclase. Sorcar et al. (2020) estimated P–T condition of the retrograde stage (based on rim composition) lies in the range of 3.5–5 kbar and 450–480°C.

9. Discussion and conclusion

Several reaction textures described in this study help to unravel the polyphase metamorphism and evolution of spinel-bearing granulites of KKB. The earlier fabric development in the rock was the assemblages of biotite, sillimanite, and quartz, which reacted to produce garnet and cordierite porphyroblast during prograde metamorphism. Migmatization of the gneisses was triggered by several biotite dehydration-melting reactions and which operated at different P-T conditions. As indicated by several reaction textures, the spinel-bearing metapelites of KKB were exhumed along a clockwise path. They recorded a clockwise P-T evolution with different stages during the Pan-African event. The KKB has a clockwise P-T path is indicated by the presence of prograde mineral relics and later retrograde textural reactions. Cordierite gneisses from the KKB attained peak P-T conditions of ~900 °C at 7.5–8 kbar. Biotite dehydration-melting reactions at ~7.5 kbar and above 850°C caused the elimination of biotite in the rocks. The spinel-forming reactions from biotite-sillimanite assemblages correspond to biotite "dehydration" or "dehydration-melting" reactions. In silica-rich domains, sillimanite probably ran out during the first melting reaction, which produced garnet and, more Mg-rich cordierite. The metapelites of the Koodal region are characterized by an orthopyroxene–cordierite association at the expense of garnet, quartz, and biotite. Biotite mantled by the corona of orthopyroxene indicates biotite forms the main reactant phase to produce orthopyroxene, this dehydration reaction has often been taken to represent the highest metamorphic grade reached and the P-T estimation of Nandakumar and Harley (2000), who obtained 6.5–7.0 kbar and 900±20°C from garnet–orthopyroxene thermobarometry on charnockites and cordierite gneisses from the same area suggest the peak metamorphic phases at this location. Coexistence of orthopyroxene and sillimanite is not found in this study, so the pressure did not exceed 8 kbar (Hensen and Green, 1971; Bertrand et al., 1991; Carrington and Harley, 1995).

The spinel-cordierite mineral phase equilibria thermometry involves the subsequent decompression reaction in which cordierite corona forms in association with spinel and garnet. The textures observed in the study area thus mark a series of decompression reactions following peak metamorphic conditions. In all the cases above, it is noted that higher-pressure assemblages have been replaced by lower-pressure assemblages. The occurrence of cordierite + quartz symplectites, as well as continuous coronas of cordierite around garnet grains also indicates decompression after the peak metamorphic phase. During a late stage and decreasing P-T conditions, biotite replaced earlier grown garnet porphyroblasts, orthopyroxene, cordierite and K-feldspar; this garnet-consuming reaction proceeds by a drop in pressure. Similarly, reactions involving garnet, sillimanite and quartz to produce cordierite are pressure-dependent and proceed in the direction of higher to lower pressures. The possibility that spinel is also a product phase in these reactions, which show coarse graphic intergrowth with cordierite, this reaction is an unusually steep decompression path. In some cases, garnet is rimmed by cordierite and sillimanite, suggesting that garnet is probably breaking down to form cordierite. Reaction textures and symplectites of cordierite, cordierite+quartz, or cordierite+K-feldspar+quartz, as well as cordierite corona surrounding garnet, suggest that a pressure decrease occurred during the thermal peak (cf. Thompson, 1976; Schenk, 1984). The similarity of these symplectites of the present study with those of similar garnet breakdown reactions reported by previous studies in KKB (e.g. Santosh, 1987; Chacko et al., 1996) further implies rapid decompression. After the isothermal decompression in KKB, an isobaric cooling path at a temperature range of 840–750°C was suggested by Satish-Kumar and Harley (1998) for calc-silicate samples. Nandakumar and Harley (2000), Sorcar et al. (2020) also proposed this cooling event after the initial post-peak P-T path. All retrogressive reactions are observed, which is possibly a retrograde P-T path explains these cordierites producing symplectites and the cooling stage was established by the growth of biotite at the expense of orthopyroxene. Thus, our present results also have three different types of reaction textures on spinel-bearing metapelites of KKB, which have already been proposed by different authors based on P-T estimation and petrography as high temperature-moderate pressure peak metamorphism followed by decompression and cooling.

Conflict of Interest Statement

Arun J. John and V. Nandakumar declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

CRediT

AJJ: Conceptualization, Investigation, Methodology, Formal analysis, Writing – original draft. **VN:** Conceptualization, Data curation, Formal analysis, Supervision, Writing – review & editing.

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