

Geology of high- to ultrahigh-temperature granulites from central Madurai block, southern India; with emphasis on the evolution of Grt-Opx-Crd granulite

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The geology of Ganguvarpatti area situated at the central Madurai block of southern India consisting of various high-grade metamorphic rock types. This contribution briefly describes the geology, field occurrences and petrography of metamorphic rocks from Ganguvarpatti area. Ganguvarpatti is known for its occurrence of sapphirine-bearing UHT granulites while the surrounding granulites are less studied. So in this contribution we have discussed the pressure-temperature stability and evolution of granulites surrounding UHT granulites. The pressure-temperature estimation of garnet-orthopyroxene-cordierite granulite resulted a near peak temperature condition of $>950^{\circ}\text{C}$ at a pressure between 9-10 kbar. These results are in good agreement with the stability field in the KFMASH petrogenetic grid.

Keywords: Madurai block, southern India, UHT-granulites, P-T estimation, multi-stage evolution

I. Introduction

Southern India comprises of several granulite facies terranes separated by various deep crustal shear zones (Fig. 1) (Drury and Holt, 1980). Towards the south of Palghat-Cauvery shear zone, the Madurai block is the largest as well as least studied granulite terrane. Recent reports from this terrane record extreme temperature crustal metamorphism (ultrahigh-temperatures (UHT)) (e.g. Brown and Raith, 1996; Raith et al., 1997; Satish-Kumar, 2000; Sajeev et al., 2001). The occurrences of sapphirine-bearing granulites are only reported from the central part of the Madurai block. This rock type has significant importance because of their nature of preserving a wide range of reaction textures, which trace their multi-stage metamorphic evolution. Sapphirine-bearing granulites have been reported only from a few localities in southern India: at Ganguvarpatti (Grew, 1982; Mohan et al., 1986; Hensen, 1988; Sajeev et al., 2001), Panrimalai (Grew, 1984) and Perumalmalai of Palni hills (Sivasubramanian et al., 1991; Brown and Raith, 1996; Raith et al., 1997) (See, Fig. 1 for location distribution). Among these, ultrahigh-temperature metamorphic conditions have been reported only from Palni hills by Brown and Raith (1996) and Raith et al. (1997) and from Ganguvarpatti by Sajeev et al. (2001) with P-T conditions ranging up to ca. 1000°C and ca. 10 kbar. Satish-Kumar (2000) reported ultrahigh-temperature metamorphism of marbles from Kannisseri in the Madurai block using calcite-graphite isotope thermometry.

In this contribution we will deal with the geology and petrographical significance of the area surrounding the sapphirine occurrence of Ganguvarpatti and we will also made an attempt to calibrate the pressure-temperature

stability of Grt-Crd-Opx granulites from the adjacent areas of UHT granulites

II. Geology and petrographical characteristics of Ganguvarpatti area

The present study area is about ca. 20 km² around Ganguvarpatti, within $10^{\circ}5'$ - $10^{\circ}15'$ N longitudes and $77^{\circ}35'$ - $77^{\circ}47'$ E latitudes (Fig. 2). The protolith-based classification is not easy in high-grade metamorphic rocks so that we adopted assemblage-based classification even though the pelitic-semipelitic gneisses, mafic granulites, calc-silicate gneisses and igneous rocks are considered as different categories. The pelitic gneisses inter-layered with mafic granulites and minor amount of calc-silicates are seen parallel to the charnockites (opx-, Hbl-bearing granitic rock). Layered gneisses are mainly garnet-biotite gneiss inter-layered with boudins and disrupted bands of mafic granulites. Thin layers and patches of garnet-sillimanite-cordierite gneisses are also present within the layered gneisses. Sillimanite-bearing rocks are relatively fine grained while the grain size of garnet porphyroblast increases compared to other garnet-bearing granulites. Partial rim of cordierite and biotite around garnet porphyroblasts can be identified from many fresh exposures from the mapped area. Sillimanite-rich garnet-sillimanite gneiss is exposed as patches within the garnet-sillimanite-cordierite-spinel gneiss. The layered quartz-poor, orthopyroxene-bearing granulites are exposed only in one location. Calc-silicates are seen as lenses and disrupted intercalation present within the gneisses. Based on the mineral assemblages pelitic to semipelitic gneisses are classified into seven types while mafic granulites into three and calc-silicates into two types.

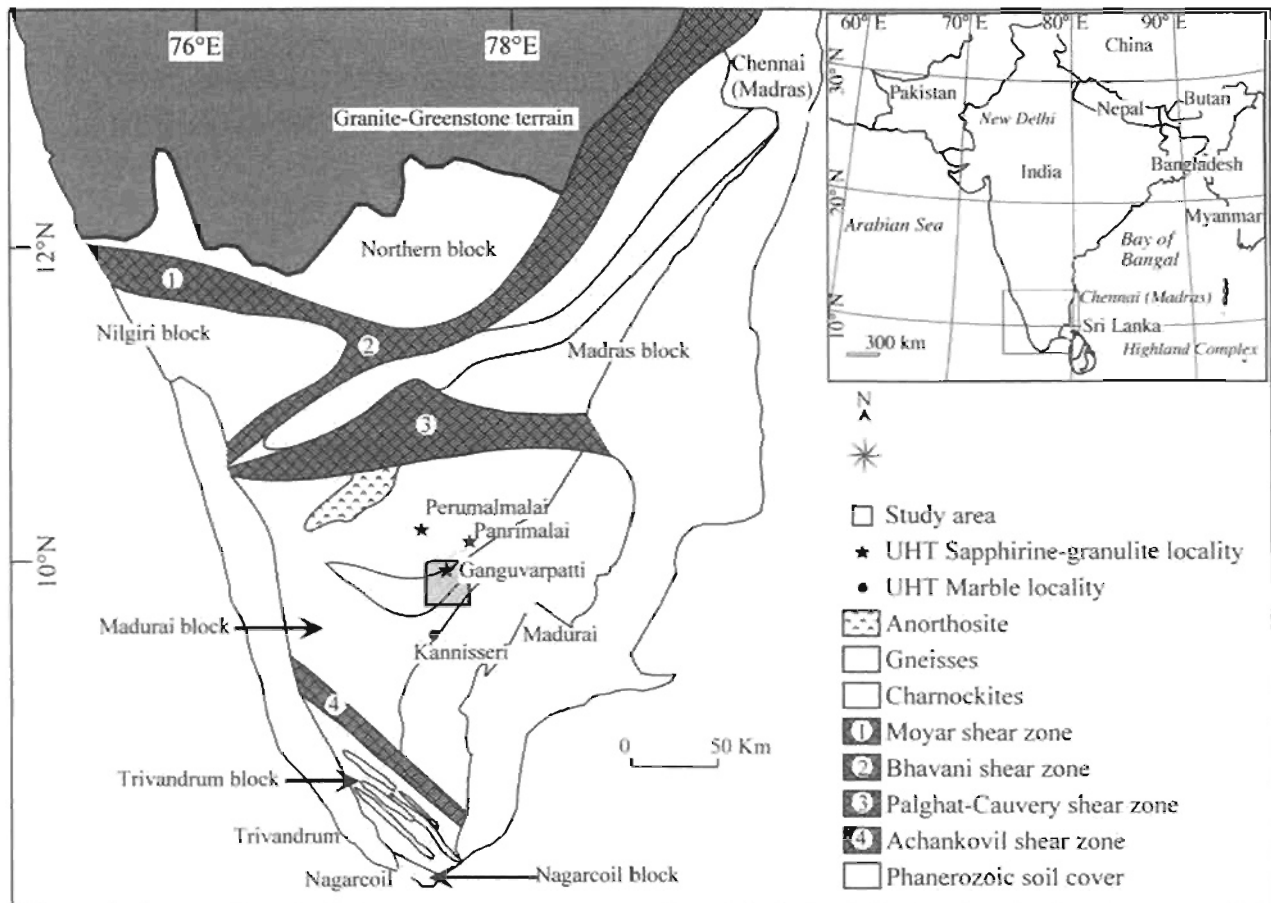


Fig. 1. Tectonic classification of southern India after Drury and Holt (1980). Inset shows the geographic position of India.

The foliation trends almost parallel to all gneisses of the study area. The general foliation varies from N 75° E – S 75° W to E-W with a southward dip of 58° to 75° in the major part of the field

A. Orthopyroxene-sillimanite-quartz granulite

Thin layers of sapphirine-bearing orthopyroxene-sillimanite-quartz granulite, orthopyroxene-spinel granulite and two pyroxene granulites are identified from a small exposure in a pit at Ganguvarpatti village (Fig. 3a). The field exposure of orthopyroxene-sillimanite-quartz granulite is relatively weathered so that direct contact is not well exposed. Garnets in sapphirine-bearing orthopyroxene-sillimanite-quartz granulites are large porphyroblasts, which is rimmed by various symplectites, can be identified from the hand specimen. On the northern border of the exposure it is of a quartzite ridge followed by a thin layer of biotite gneiss.

Petrography and evolution of these granulites are explained in Sajeew et al. (2001) and Sajeew et al. (submitted). The Mg- and Al-rich silica under-saturated granulites from Ganguvarpatti, preserves an assemblage of orthopyroxene-sillimanite-garnet ± quartz ± K-feldspar, is considered to be formed at near peak condition of ultrahigh-temperature metamorphism (1050° C and 11 kbar). Porphyroblasts of cordierite and sapphirine are present in few samples, which is also considered to be a near peak assemblage. These assemblages were strongly overprinted by symplectite, coronas and later aggregates of sapphirine, spinel, cordierite and orthopyroxene during the metamorphic evolution (Fig. 4a). Coarse and scattered

arrangements of biotite in the matrix are interpreted to be formed during the retrograde during later stage. Rare occurrence of kornepine is identified in a garnet-, quartz-, sillimanite-absent and spinel-, sapphirine-, cordierite present domains locally.

B. Garnet-biotite-sillimanite-spinel-cordierite gneisses

This rock type exposed in the central part of the study area. These exposures are partly migmatized and in many exposures initial foliation was disbursed by the partial melting processes. Distinct melanosomes as well as leucosomes can be identified even in meter scale from the small quarry near Ghat road junction (Fig. 3b, c). Petrographic studies on this rock type reveals the major mineral assemblages are Grt-Bt-Sil-Spl-Crd-Qtz-Kfs±Pl. Sillimanite, quartz, biotite and minor opaque minerals are present as major inclusion phases in garnet porphyroblasts. Cordierite-sillimanite-spinel assemblage is present as partial rim around garnet porphyroblasts (Fig. 4b). The direct coexistence of spinel and quartz is not present in any of our studied samples. In some samples very thin rim of cordierite separates the grain boundary of spinel and quartz. From the textural relations spinel-cordierite-quartz assemblage is considered to be the near-peak assemblage present in this rock type.

C. Garnet-orthopyroxene-cordierite-biotite gneiss

At the central part of the studied area garnet-orthopyroxene-cordierite-biotite gneiss is exposed as thin layers and is associated with garnet-biotite-sillimanite-

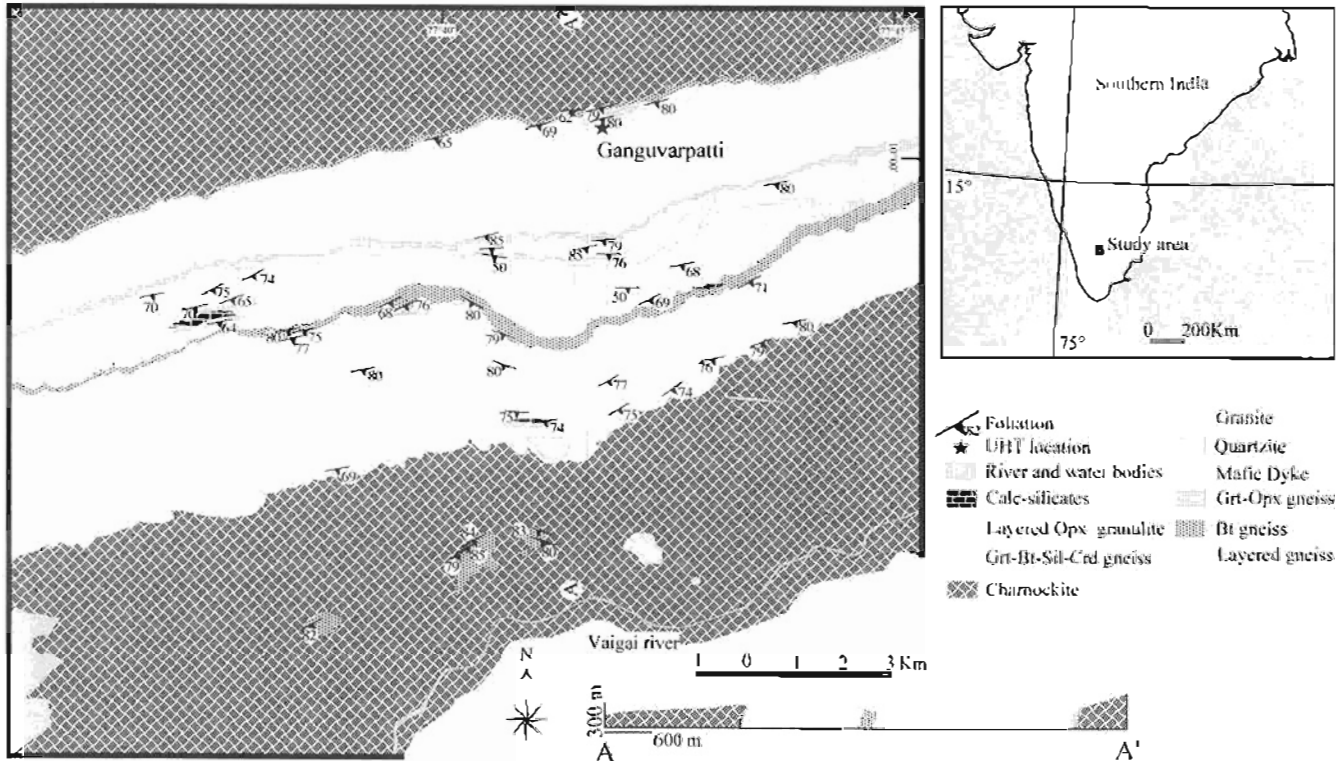


Fig. 2. Geological map of the study area. The inset shows the location within the southern India. A-A' in the figure represents the position of cross section as shown below. The layered gneiss as well as layered Opx granulite represents very fine layered granulites/gneiss, which is described in the text.

spinel-cordierite gneisses (Fig. 3b, c). Garnet is rarely present in this orthopyroxene-rich rock type. Other than garnet, biotite, quartz and feldspars can be well identified under the naked eye. This rock type are also migmatized along with the associated gneisses in many of the exposure. From the petrographic observations cordierite is also identified which forms partial rim around resorbed garnets and orthopyroxene porphyroblasts (Fig. 4c). This association could be used as one of the most reliable pair of the thermobarometric analysis.

D. Biotite gneiss

Biotite gneiss is exposed as thin layers at the northern boundary, in the central part of the mapped area. Biotite gneiss is granitic in composition, which exposed as thin layers. The contact of biotite gneiss with layered gneisses in the north and biotite gneisses in the south are well exposed. Most of the exposures are well-foliated (Fig. 3d) but in some locations the foliation is completely disturbed by the migmatitic processes (Fig. 3e). The major mineral assemblage is garnet-biotite-plagioclase-K-feldspar-quartz (Fig. 4d)

E. Garnet-sillimanite ± cordierite gneiss

Thin layers and patches of garnet-sillimanite gneiss with minor cordierite are exposed at some locations in the eastern part of the study area. The foliation of garnet-sillimanite gneiss is always seen parallel to the associated garnet-biotite gneiss. In some locations, large amount of sillimanite with minor cordierite forms partial rim around

garnet porphyroblasts. The felsic portion is dominated by K-feldspar, quartz and minor plagioclase.

F. Garnet-biotite gneiss

Garnet-biotite gneiss is dominated in the layered gneiss (fig. 3f). Normally garnet-biotite gneiss is seen in association with two pyroxene granulite and garnet-sillimanite ± cordierite gneiss. In almost all cases exposures of garnet-biotite gneiss is seen as fine grained rocks but an exposure near Ghat road, garnet-biotite gneiss is seen as very coarse grained. In this exposure large porphyroblasts of garnet is rimmed by aggregates of biotite. Felsic minerals are almost absent in this layer. In some samples from the south of Valliyur have similar assemblages to that of other areas but have minor inclusions of spinel within the garnet (fig 4e). In this rock type there is no quartz is present in association with spinel as inclusions in garnet.

G. Quartzite

The quartzites are normally pure and always forming ridges due to its high resistance to weathering (Fig. 3g). Quartzite is mainly exposed in the central part associated with biotite gneiss or with layered gneisses.

H. Garnet two pyroxene granulite

Garnet-bearing two pyroxene granulite is exposed in only one location at the eastern part of the study area. In this exposure, they form boudins within the garnet-biotite

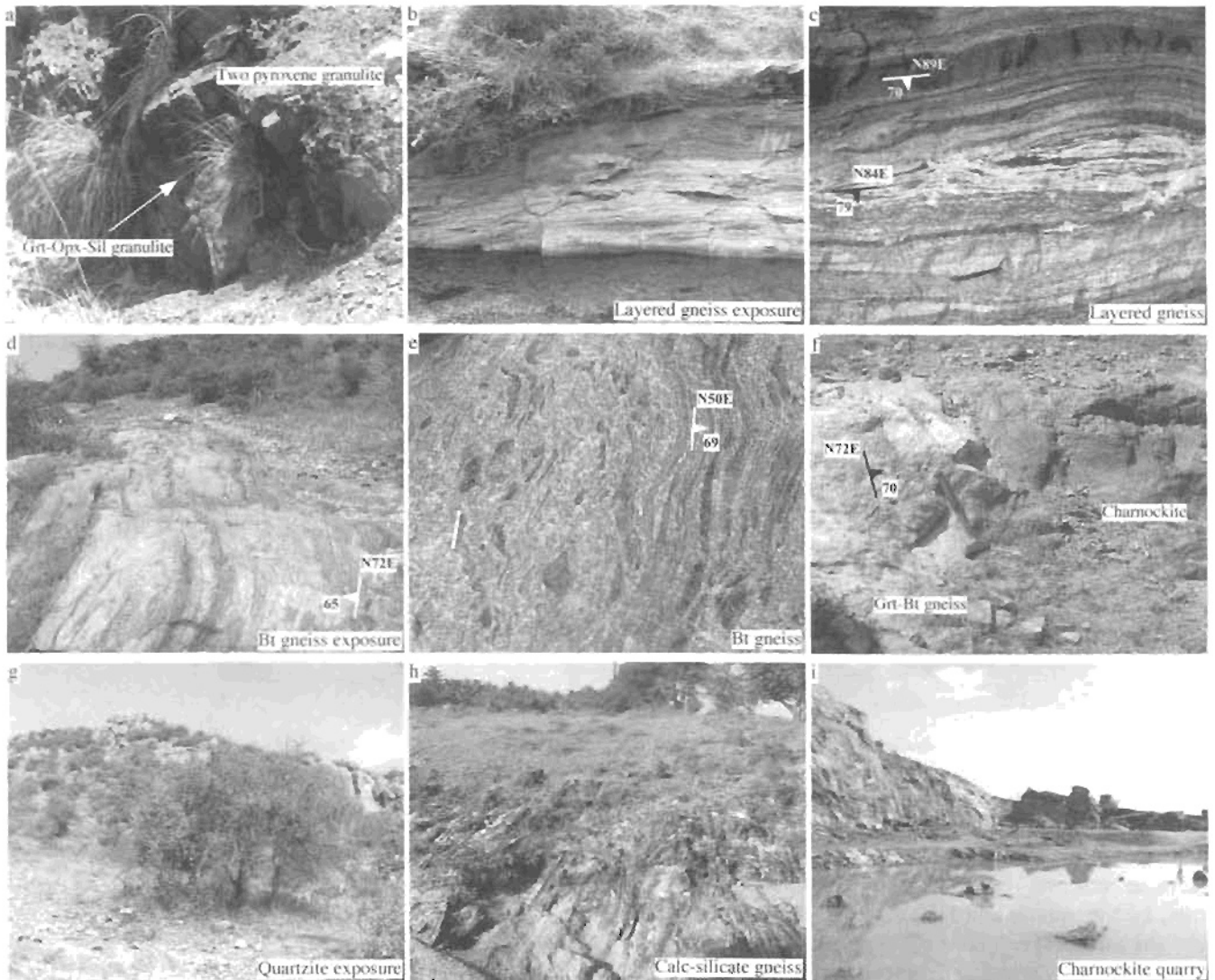


Fig. 3. Field occurrences of Ganguvarpatti area. a) Exposure of Spr-bearing Opx-Sil-Qtz granulite associated with two pyroxene granulite. b) An outcrop of layered gneisses exposed at the central part of the study area. c) A close view of layered gneiss where Grt-Opx-Crd granulite samples were collected. d) Well foliated Bt gneiss exposure. e) Bt gneiss exposure in which foliation is disturbed by migmatic processes. f) Exposure of a contact between Grt-Bt gneiss and charnockite. g) Field exposure of quartzite h) Field occurrences of calc-silicate gneiss in which both Grt-bearing and -absent types intercalated. i) A charnockite quarry at the northern part of the study area.

gneiss. Fine grains of garnet can be identified from the hand specimen.

I. Two pyroxene granulite

Two pyroxene granulites are exposed in the northern part of the study area, which are associated with sapphirine-bearing orthopyroxene-sillimanite-quartz granulite and orthopyroxene-spinel granulite. No garnet can be identified from any of the thin sections of this rock type. Minor amount of opaque minerals is also present in this rock type apart from orthopyroxene, clinopyroxene, quartz, plagioclase and minor biotite (Fig. 4f)

J. Orthopyroxene-spinel granulite

Orthopyroxene-spinel granulite is exposed only at Ganguvarpatti, in association with two pyroxene granulite and sapphirine-bearing orthopyroxene-sillimanite-quartz granulite. It is very difficult to identify the mineral

assemblages through hand specimen because the rock seems to be homogenous. In thin sections only spinel and orthopyroxene is present and shows perfect granular texture (Fig. 4g). Inclusion of orthopyroxene in spinel as well as spinel in orthopyroxene is the only inclusion texture preserved in this granulite.

K. Garnet-bearing calc-silicates

Garnet-bearing calc-silicate exposed at the west-central part of the mapped area (Fig. 3h). The mineral assemblages consist of garnet (grossular), diopside, scapolite, titanite, wollastonite, calcite, plagioclase and quartz. Major notable textural features are the formation of garnet rims, scapolite-quartz symplectite and garnet-quartz symplectite (Fig. 4h). The textural evolution is not well determined from these localities till now as the garnet-bearing symplectite have not been identified from any other calc-silicate localities from southern India.

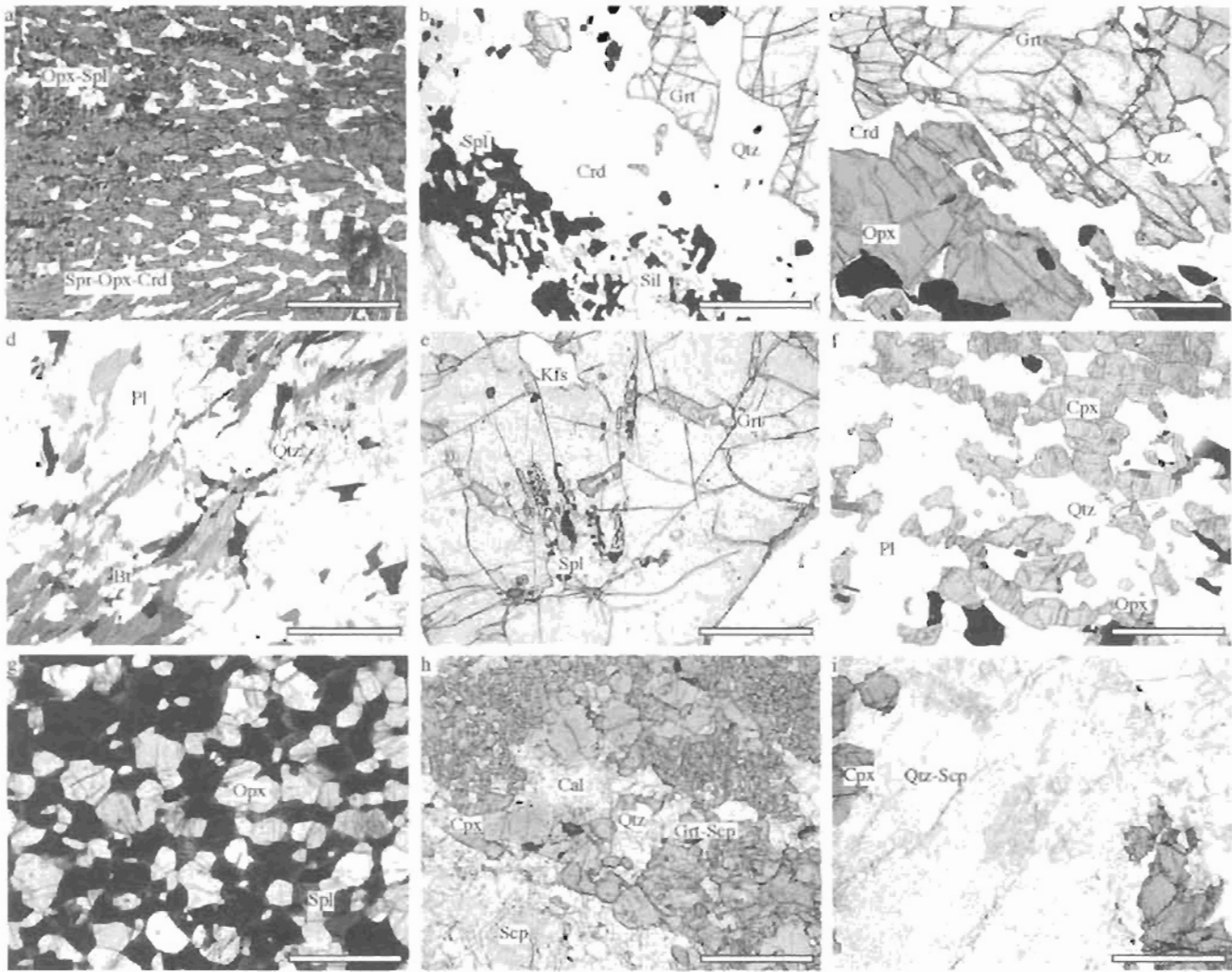


Fig. 4. Photomicrographs of various rock types from Ganguvarpatti area. a) Spr-Opx-Crd \pm Pl symplectite, a very common retrograde texture from Ganguvarpatti. b) Partial rim of Crd-Sil-Spl around resorbed garnet. c) Grt-Opx-Crd granulite. Note the fine rim of cordierite in between Grt and Opx porphyroblast. d) Photomicrograph of Bt gneiss. e) Spl inclusions in Grt porphyroblast in Grt-Bt gneiss. f) Photomicrograph of two pyroxene granulite which associated with sapphirine-bearing Opx-Sil-Qtz granulite from Ganguvarpatti. g) Spl-Opx granulite from Ganguvarpatti. h) Grt-Scp symplectite in garnet-bearing calc-silicate i) Scp-Qtz symplectite in garnet-absent calc-silicate. The scale bar represents 1 mm.

L. Calc-silicate gneiss

Calc-silicates are inter layered with garnet-bearing calc-silicates which are present as lenses and disrupted intercalation within the garnet-biotite-sillimanite-cordierite gneiss. Mineral assemblages are similar to garnet-bearing calc-silicate except the presence of garnet. Scapolite-quartz symplectite is one of the dominant textures in this rock type (Fig. 4i).

M. Charnockite

The study area is dominated by massive charnockite (orthopyroxene \pm hornblende bearing granitic rock) (Fig. 3i) in the northern and southern part block. Some exposures show weak foliation while the textures have not show any metamorphic features.

N. Granite

Hornblend- and biotite-bearing granites are exposed in the southern part of the study area as small hillocks. The association with charnockites are exposed in some part of the exposure.

III. Pressure-Temperature estimation

The different closure temperatures in exchange thermometers and net transfer reactions barometers have limitations on the reliability of conventional thermobarometry to calculate the thermal peak of high- and ultrahigh-temperature rocks (e.g. Raith et al., 1997; Fitzsimons and Harley, 1994; Frost and Chacko, 1989). The pressure-temperature estimation had been carried out by using garnet-orthopyroxene pairs from garnet-orthopyroxene-cordierite biotite gneiss. The X_{Mg} [$Mg/(Mg+Fe)$] composition of garnet core varies from 0.324 - 0.342. The orthopyroxene has a X_{Mg} that varies from 0.510-0.592. Cordierite preserves a X_{Mg} of 0.715-0.794. Plagioclase associated with garnet and

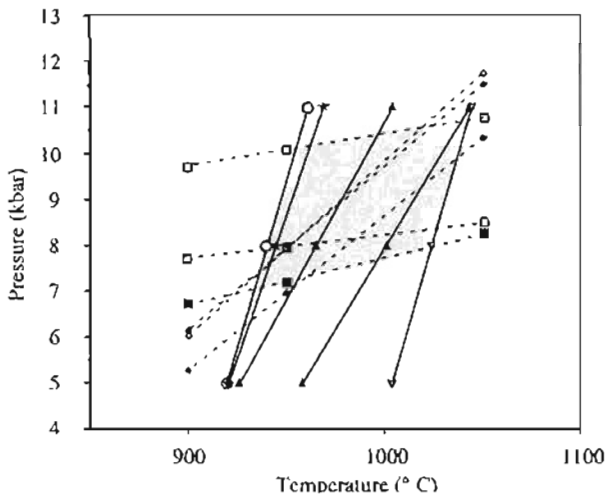


Fig. 5. Pressure-temperature estimation of garnet-orthopyroxene-cordierite granulite using garnet-orthopyroxene-plagioclase pairs. See text for description. Open squire represents barometer of Bhattacharya et al. (1991), filled diamond for Harley and Green (1982), filled squire for Harley (1984b) and open diamond for Wood (1974). For geothermometers open circle represent Harley (1984a) Open triangle pointing down represent thermometer of Lee and Ganguly (1988) while filled triangle for Bhattacharya et al. (1991). Open triangle represents Sen and Bhattacharya (1984) and star for Lal (1993).

orthopyroxene show reverse zoning with a X_{An} content of 0.562-0.600.

On considering the $K_2O-FeO-MgO-Al_2O_3-SiO_2-H_2O$ (KFMASH) petrogenetic grid (discussed below) a reference temperature between 900° C to 1050° C is suitable for the mineral assemblage, where orthopyroxene and garnet is stable. Reference pressure is also determined on the similar basis with a pressure which is below the orthopyroxene-sillimanite-quartz stability field (11 kbar) and above the univariant reaction which produce spinel, cordierite and quartz (about 5 kbar) where the peak assemblage is stable in the petrogenetic grid. The pressure estimation corresponding to the initial mineral assemblages was made using garnet-orthopyroxene barometer (Wood, 1974; Harley and Green, 1982; Harley, 1984b). At a reference temperature of 1050° C, the calibrations by Wood (1974) yield a pressure of 13.7 kbar, while at 950° C, 9.7 kbar and at 900° C resulted 8.0 kbar. The barometer suggested by Harley and Green (1982) results pressure values of 11.1, 7.6 and 6.1 kbar for temperature of 1050, 950 and 900° C, respectively. Method of Harley (1984b) yielded a slightly lower pressure values with respect to other barometers. Barometry following the method of Bhattacharya et al. (1991) yielded pressure values of 9.3, 8.7, 8.2 kbar respectively for the same reference pressures explained above.

Peak temperatures were estimated using garnet-orthopyroxene pairs for the different data sets. The reference pressures 11 kbar, 8 kbar and 5 kbar, which are described in the same order for all calibrations below. The experimental thermometer of Harley (1984a) yield a temperature of 929, 909 and 889° C, while that of Lee and

Ganguly (1988) provides the highest reliable limit of 1056, 1032 and 1011° C. The calibration of Bhattacharya et al. (1991) yields an intermediate value of 1018, 977 and 937° C for each reference pressure respectively.

A reasonable convergence from the above thermobarometers would be around 950-1025° C at 8-10 kbar. The result of pressure temperature calibration is shown in Fig. 5.

IV. Metamorphic evolution

The application of petrogenetic grids in realising the stability field in turn to understand the pressure-temperature conditions and is considered to be a powerful tool in metamorphic geology to understand the evolution. The evolution of UHT granulites from Ganguvarpatti is well explained by Sajeew et al. (2001) and Sajeew et al. (submitted). In the present study we will consider the evolution of garnet-orthopyroxene-cordierite-biotite gneisses and garnet-biotite-sillimanite-spinel-cordierite gneisses. We will also discuss the possible relation of these surrounding granulites with that of UHT granulites.

The metamorphic history of most of the mineral assemblages and their chemical relationships can be graphically represented using $K_2O-FeO-MgO-Al_2O_3-SiO_2-H_2O$ (KFMASH) petrogenetic grid. To avoid the unnecessary complexity in the reaction negligible factors like Ca, Na and Ti are not considered. Minor Ti content may enter into the crystal structure of biotite and the remaining will be accumulated in ilmenite, while Ca and Na in plagioclase are not considered.

The KFMASH petrogenetic grid developed in this study is based on the calculations of Hensen and Harley (1990) and Spear et al. (1999) considering quartz in excess (Fig. 6). The cordierite-absent invariant point (hereafter represented as [Crd] for absent phases at invariant points), [Opx], [Ms] are fixed based on the data sets of Berman (1988). The [Spl] invariant point is fixed which is based on the experiments of Carlington and Harley (1995) with reference to the new work on high-temperature assemblages on KFMASH by Mac Dade and Harley (2000). Carlington and Harley (1995) fix the [Spl] invariant at a temperature of 900° C at 8.8 kbar.

From the textural features garnet-biotite-sillimanite-spinel-cordierite gneisses preserve inclusions of biotite, sillimanite and quartz in garnet and cordierite is the prograde assemblage preserved. In garnet-orthopyroxene-cordierite-biotite gneisses cordierite forms partial rim in between garnet and orthopyroxene is considered to be the near peak assemblage and later decompression results spinel-cordierite assemblage.

V. Discussion and Conclusion

From the petrogenetic grid the rock exhibit a normal evolution profile. The peak temperature estimated using geothermobarometer (900-1000° C) is in good agreement with the results from petrogenetic grids (Fig. 6). The divariant assemblages in each field is described using $SiO_2-Al_2O_3-(FeO+MgO)$ diagram in fig. 6. Sajeew et al.

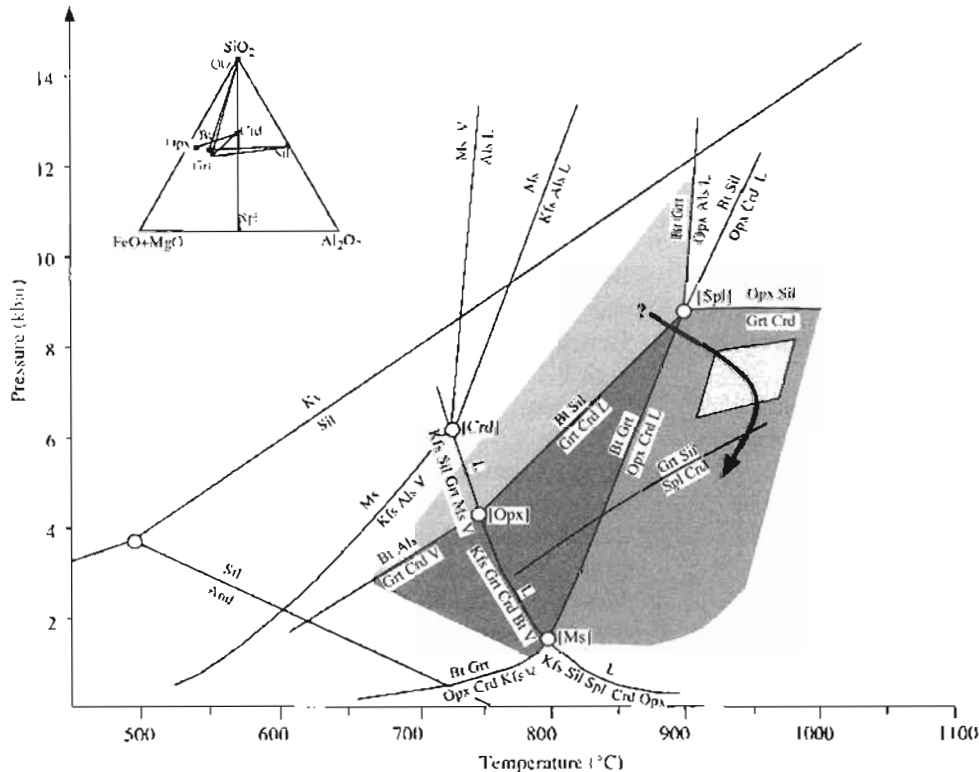


Fig. 6. KFMASH petrogenetic grid modified from Spear et al. (1999). The description of the grid construction is given in the text. Tie-lines in tri-plots indicate the univariant reactions and the grey rectangle represents the calculated P-T field

(2001) and Sajeew et al. (submitted) suggest a multi-stage metamorphic evolution for the sapphirine-bearing granulites of Ganguvarpatti. So it is apparent that the same terrane preserves a different evolution history for the surrounding rock types.

Isotope geochronological data are sparse from Madurai block and any evaluation of the timing of the various events would be arbitrary. Few available isotope ages indicate Paleoproterozoic emplacement of intrusive enderbites (chamockites) in the Kodaikkanal region, adjacent to Ganguvarpatti (Bartlett et al., 1995, Jayananda et al., 1995). Sm-Nd and U-Pb dating of garnet, monazite and metamorphic zircon overgrowths from Kodaikkanal granulites yielded Pan-African cooling ages (Bartlett et al., 1995, Jayananda et al., 1995). It is thus apparent that the terrane evidenced multiple metamorphic episodes. While the recent studies from the adjacent metamorphic terrane of Sri Lanka, Osanai et al. (1996) and Sajeew and Osanai (2002) reported older ages for the UHT granulites from Highland complex. In this view the sapphirine-bearing granulites from the Madurai block could also be older and hence it is acceptable to have a different evolution history. Even though the above possibility exists it is not possible to explain a clear tectonic model for this terranes because of the absence of isotopic data from the sapphirine-bearing granulites and from the surrounding granulites. Apart from geochronology, petrologic work is also insufficient from Madurai block. Many of the work have been concentrated on the sapphirine-granulite (e.g. Grew, 1982; Mohan et al., 1986; Hensen, 1988; Grew, 1984 Sivasubramanian et al., 1991; Brown and Raith, 1996; Raith et al., 1997), while the surrounding granulites have been studied by few workers (e.g. Harris et al., 1994; Sajeew et al., 2000). So the present contribution is not sufficient enough to correlate this large granulite

terrane to other continental fragments while it is a step-ahead in understanding the evolution of high-temperature granulites surrounding the UHT granulites.

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