Sapphirine and corundum bearing ultrahigh temperature rocks from the Palghat-Cauvery Shear System, southern India

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We report a new occurrence of sapphirine- and corundum-bearing silica-deficient Mg-Al rocks from Paramati at the northern margin of the Palghat-Cauvery Shear System which define the Archaean-Proterozoic collisional boundary in southern India. Sapphirine here occurs as medium-grained euhedral to subhedral crystals enclosed within plagioclase and contains inclusions of spinel and sillimanite, and is locally intergrown with corundum, suggesting the reaction $\text{Spl} + \text{Sil} \rightarrow \text{Spr} + \text{Crn}$. Temperatures estimated from sapphirine-spinel equilibria lie around 930–950°C, suggesting ultrahigh-temperature peak metamorphic conditions. Gedrite is also a common rock forming mineral in these rocks, and coexists with cordierite, corundum, and sillimanite. As gedrite is totally surrounded by cordierite, we infer a prograde reaction $\text{Ged} + \text{Sil} \rightarrow \text{Crn} + \text{Crd} + \text{V}$. Lack of orthopyroxene in our samples suggests a decompressional P - T history following the prograde event. Our results suggest that the whole of northern Madurai Block as well as parts of the Palghat-Cauvery Shear System experienced ultrahigh temperature metamorphism followed by exhumation along a clockwise P - T path.

Introduction

Sapphirine-bearing aluminous rocks have been the focus of interest among petrologists for over the last two decades because of their petrogenetic importance in understanding extreme crustal metamorphism and exhumation history. Mineral assemblages and reaction textures in sapphirine-bearing rocks have been used to infer the pressure-temperature conditions of deep crustal metamorphism and the nature of uplift. Rarely, sapphirine, spinel, and corundum coexisting with quartz have also been reported from some pelitic and quartz-feldspathic rocks (e.g. Dallwitz, 1968; Friedman, 1953; Motoyoshi et al., 1990) which provide robust evidence for ultrahigh-temperature (UHT) crustal metamorphism with $T > 900^\circ\text{C}$ (Harley, 1998).

The geological framework of southern India is broadly defined by an Archean granite-greenstone terrain in the north and a granulite facies terrain the south (Fig. 1, inset), dissected by a number of transcrustal shear zones of late Proterozoic age (Drury et al., 1984). The southern granulite terrain comprises a collage of blocks which represent variously exhumed middle and lower continental

crust. Recent petrological studies reported orthopyroxene + sillimanite $\pm$ garnet assemblages from Madurai Block, indicating that at least some parts of the terrane experienced UHT metamorphism (Brown and Raith, 1996; Raith et al., 1997; Sajeew et al., 2001). The Madurai Block, which is perhaps the largest single crustal block among the collage of terrains in the southern high grade terrain, is dominantly composed of biotite-hornblende gneiss and massive charnockite with minor supracrustal rocks such as pelitic granulites, calc-silicate rocks and quartzite. Intercalated sapphirine-bearing lithologies have been previously reported from a number of localities in the central and northern parts of this block including Panrimalai (Grew, 1984), Ganguvarpatti (Mohan, 1985; Mohan et al., 1985a, 1985b; Mohan and Windley, 1993; Sajeew et al., 2001), Perumalmalai (Raith et al., 1997; Prakash and Arima, 2003), Usilampatti (Prakash and Arima, 2003), Kiranur (Ackermann et al., 1981; Lal et al., 1984), Kodaikanal (Mohan et al., 1996; Prakash and Shastry, 1999), Lachmanapatti (Tsunogae and Santosh, 2003), and Malappatty (Tsunogae and Santosh, 2003). Brown and Raith (1996) reported peak P - T conditions of 12 kbar and 900–1000°C from mineral phase equilibria and garnet-orthopyroxene geothermobarometry on samples from Perumalmalai. They inferred a multistage metamorphic evolution history along a clockwise P - T path for the rocks based on several decompression reactions in-

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Figure 1. Geological map of the Madurai Block (based on 1 : 500000 map of Tamil Nadu, GSI, 1995) with the sample locality of sapphirine-bearing aluminous rock discussed in this paper. DC, Dharwar Craton; MRB, Madurai Block; MSB, Madras Block; NNB, Northern Block; NGB, Nilgiri Block; TB, Trivandrum Block; NCB, Nagarcoil Block; ACSZ, Achankovil Shear Zones; PCSZ, Palghat-Cauvery Shear Zone; P, Phanerozoic cover. Sample locality of the examined gneisses is also shown in the figure.

cluding sapphirine. Sajeew et al. (2001) also reported $T > 1000^{\circ}\text{C}$ UHT peak metamorphism and clockwise P - T path for sapphirine- and kornerupine-bearing aluminous granulites from Ganguvarpatti locality. Thus, sapphirine-bearing rocks have provided the first robust evidence for ultrahigh temperature metamorphism in southern India and have aided in understanding the tectonic framework and exhumation history of this continental deep crust.

In this study, we report a new locality of sapphirine- and corundum-bearing rocks from Paramati in the northern domain of the Palghat-Cauvery Shear System, north of the Madurai Block. We investigate some of the unique mineral assemblages and reaction textures in this rock and evaluate the significance in understanding ultrahigh temperature metamorphism in the Archean-Proterozoic boundary along the Palghat-Cauvery Shear System in southern India.

Petrography and metamorphic reactions

Paramati is located about 15 km north of Karur town (Fig. 1) in the Namakkal district of Tamil Nadu state. The lithologic units in this region comprise hornblende, and hornblende-biotite bearing orthogneisses associated with

charnockite. Deformed mafic lenses and boudins of various dimensions occur within the gneisses. At Paramati, excellent surface outcrops, as well as extensive quarries and pits dug below the surface level expose gneissic rocks with corundum, sapphirine and spinel. The sub-surface quarries and some of the pits extending to several meters in depth are dug by local miners for recovering gem-quality corundum. The corundum from Paramati is cut and polished and sold as star ruby or as rubies of various hues. The dominant part of the exposures at Paramati comprises medium grained melanocratic (mafic) gneisses, extending in width for over 50 meters and exposed over a strike length of exposure for over 150 meters along NE-SW direction. The rocks exhibit strong gneissic fabric and comprise dominantly of amphiboles, dark brownish spinel and small grains of plagioclase. Amphibole + spinel and plagioclase-rich domains alternate within millimeter scale. Small corundum crystals visible in hand specimen occur within the matrix. Large euhedral crystals of corundum up to 5 cm diameter occur embedded in isolated zones, surrounded by plagioclase. The mafic gneisses are intercalated with leucocratic layers ranging in width from a few mm up to several cm. These leucocratic layers are high Mg-Al streaks characterized by sapphirine + corun-

Figure 2. Photomicrographs of examined sapphirine-bearing gneisses from Paramati. (a) Sapphirine and corundum bearing gneiss (sample KRR/P/1/2). (b) Corundum + gedrite + cordierite + plagioclase assemblage in sample KRR/P/1/2. (c) Subhedral sapphirine and spinel in plagioclase aggregates in sample KRR/P/1/2. (d) Cordierite around irregular-shaped gedrite in aluminum-rich domain of sample KRR/P/1/2. (e) Fine-grained spinel inclusions in isolated cordierite in sample KRR/P/1/2. (f) Sapphirine + corundum + plagioclase layer in sample KRR/P/1/1b. (g) Euhedral gedrite in gedrite-rich layer of sample KRR/P/1/1b. (h) Coarse-grained (~ 12 mm) gedrite with plagioclase inclusions in gedrite-rich layer of sample KRR/P/1/1b.

dum + plagioclase assemblage. Aggregates of pale red crystals of corundum and blue sapphirine distributed parallel to the rock foliation can be easily identified in hand specimen all along these domains.

In this study, we collected sapphirine and corundum bearing rocks (e.g. samples KRR/P/1/1b and KRR/P/1/2) from fresh outcrops as well as quarries and pits in the study area and carried out systematic petrographic studies to identify assemblages, textures and mineral reactions. Generally, such aluminous rocks occur along lithological boundaries between mafic gneiss and leucocratic biotite gneiss. Mineral abbreviations used in this paper are after Kretz (1983).

The common mineral assemblage in Paramati samples comprises plagioclase, sapphirine, cordierite, corundum, and gedrite (Fig. 2a–e). Sillimanite, rutile, and spi-

nel occur as accessory minerals. There is a marked compositional layering defined by plagioclase-dominant layer and corundum-sapphirine-gedrite-rich layer. Calcite and sericite occur as secondary phases. Mineral assemblages in Paramati are shown in triangular diagrams (Fig. 3). Compositions of the minerals will be discussed later. Plagioclase is the most dominant mineral in the sample (40–50 vol.% in mafic layer and 30–40 vol.% in aluminous layer). It occurs as medium- to coarse-grained (0.2–1.2 mm) and partly granoblastic aggregates. Sapphirine, corundum, spinel, and cordierite occur along grain boundaries of plagioclase. Rarely, tiny sapphirine and spinel are completely included within single plagioclase crystal. Some fine-grained plagioclase grains (<0.1 mm) are in turn included in sapphirine, corundum, and cordierite.

Sapphirine is pale bluish and occurs as medium-grained (0.1–0.6 mm) euhedral to subhedral aggregate enclosed in plagioclase aggregates (Fig. 2a, c). It commonly contains rounded plagioclase as inclusions (Fig. 4a). Rarely, the sapphirine includes fine-grained (<0.03 mm) sillimanite and spinel (dark brownish) (Fig. 4a, b). Although spinel is present also as inclusions in matrix plagioclase, sillimanite occur as inclusions in sapphirine and corundum. Although there are several possible quartz-deficient MAS reactions to explain the presence of spinel and sillimanite in sapphirine in Paramati as follows, we prefer the reaction involving corundum (reaction (1)) because corundum locally occurs together with sapphirine as an equilibrium pair in some cases as described in a later section.

Domains composed of cordierite, gedrite, and corundum are scattered in aggregates of plagioclase (Figs. 2c and 4c). Sapphirine is absent in these patches. Corundum in the assemblage is poikiloblastic and contains numerous

inclusions of plagioclase and rare sillimanite (Fig. 4c). Occurrence of gedrite is markedly unique in this sample. Gedrite shows irregular shape, lacks inclusions, and is completely surrounded by megacrystic cordierite. The texture clearly suggests that the gedrite was a reactant in the cordierite forming reaction (Fig. 4c). Some of the previous reports from the northern margin of Madurai Block also identified gedrite in association with cordierite within sapphirine-bearing rocks (e.g. Lal et al., 1984; Tsunogae and Santosh, 2003). Lal et al. (1984) found reaction zones of sapphirine + cordierite + spinel between gedrite and sillimanite, and inferred that the following reaction took place.

Tsunogae and Santosh (2003) identified fine-grained sapphirine in plagioclase, which is in turn surrounded by gedrite. However, the appropriate reaction was not constrained due to the lack of adequate assemblages. The mode of occurrence of gedrite in Paramati is different from the association reported by Tsunogae and Santosh

(2003). In the present case, gedrite shows irregular grain contours, surrounded by cordierite, and rare sillimanite inclusion occurs in corundum (Fig. 4c). We therefore suggest the following MASH reaction to explain the texture (Goscombe, 1992).

We consider that this dehydration reaction took place during the prograde metamorphic stage in the Paramati rocks.

Locally, isolated medium-grained (~ 0.5 mm) cordierite occurs in plagioclase aggregates (Figs. 2e and 4d). There is no marked compositional difference between this cordierite and that associated with corundum and gedrite. The cordierite usually contains fine-grained (< 0.05 mm) spinel inclusions. We use such cordierite + spinel association for temperature computations, as discussed in a later section.

Mineral assemblages vary slightly among various samples. Domains in some samples are composed mainly of plagioclase, sapphirine, corundum, and gedrite (Fig. 2f–h). Spinel occurs as an accessory mineral. The characteristic assemblages in such cases are shown in triangular diagrams (Fig. 3). Pale bluish sapphirine (0.1–0.5 mm in length) is mostly prismatic and defines weak foliation together with gedrite and spinel aggregate (Fig. 2f). It occasionally contains tiny (< 0.2 mm) inclusions of plagioclase and corundum, although corundum locally intergrows with sapphirine (Fig. 4e). The corundum is sub- to anhedral, and occurs mostly with sapphirine. Such a sapphirine–corundum association has not been reported from the northern Madurai Block so far, except for sapphirine–cordierite–corundum symplectite from Lachmanapatti (Tsunogae and Santosh, 2003). The texture support the progress of reaction (1) to from sapphirine + corundum. Spinel (< 0.1 mm) is dark brownish and occurs as fine-grained aggregates along grain boundary of or inclusion in plagioclase. In this case, spinel inclusion in sapphirine, as observed in some samples, is absent (Fig. 4f).

Gedrite in these domains is pale brownish and shows weak pleochroism. It occurs as medium grained (~ 0.4 mm) and sub- to euhedral mineral in sapphirine + corundum + plagioclase layer, but never in contact with sapphirine and corundum. In contrast, coarse-grained (up to 12 mm) euhedral gedrite defines gedrite-rich layer (with minor plagioclase) elongated parallel to the rock foliation (Fig. 2g, h). The alternation of sapphirine + corundum + plagioclase and gedrite-rich layers probably indicate compositional layering or primary chemical variation in the protolith. Secondary calcite vein cuts across minerals in the sample.

Mineral chemistry

Chemical analyses of minerals were performed by electron microprobe analyzer at the Chemical Analysis Center of the University of Tsukuba (JEOL JXA8621) for all minerals. The analyses were performed under conditions of 15 kV accelerating voltage and 20 nA sample current, and the data were regressed using an oxide–ZAF correction program supplied by JEOL. Representative compositions of minerals in analyzed samples are given in Table 1. Fe^{3+} of sapphirine given in the table has been calculated after Higgins et al. (1979). Mineral compositions are shown in Figures 5 to 7.

Sapphirine

X_{Mg} of sapphirine in sample KRR/P/1/2 shows only slight variation from 0.84–0.87 and is less magnesian than some of the sapphirines reported from some other gedrite-bearing rocks (up to 0.98, Raith et al., 1997). The $(\text{Mg,Fe})\text{O}:\text{Al}_2\text{O}_3:\text{SiO}_2$ ratio of the sapphirine is close to 7:9:3, and the average structural formula of the mineral can be written as $(\text{Mg,Fe})_{3.5}\text{Al}_9\text{Si}_{1.5}\text{O}_{20}$ (Fig. 5). Other components total less than 1 wt.% except for Cr (0.01–0.07 pfu, 20 oxygen base). Si and Cr increase from core to toward rim (from 1.37 to 1.43 and from 0.01 to 0.05, respectively), although X_{Mg} is almost constant as 0.86. Sapphirine in sample KRR/P/1/1b is slightly magnesian ($X_{\text{Mg}}=0.87\text{--}0.89$) and Cr-poor (< 0.01 pfu) than that in sample KRR/P/1/2.

Spinel

Spinel in sample KRR/P/1/2 occurs as inclusions in sapphirine, plagioclase, and cordierite. It is a solid solution of Mg–spinel and hercynite ($X_{\text{Mg}}=0.55\text{--}0.56$), occasionally with small amounts of Cr, Mn, and Zn (Fig. 6). The Cr content varies from 0.02 to 0.06 pfu among analyzed spots, but the Mn and Zn contents are less than 0.01 pfu. Cordierite-hosted spinel is compositionally slightly Mg-poor ($X_{\text{Mg}}=0.48\text{--}0.51$) and markedly Cr-rich ($\text{Cr}=0.11\text{--}0.12$ pfu) compared to sapphirine- and plagioclase-hosted ones. Spinel in sample KRR/P/1/1b is also Mg-rich as $X_{\text{Mg}}=0.59\text{--}0.60$. Its Cr content is higher than that of sample KRR/P/1/2 as 0.14–0.16 pfu. In this study, such high-Cr spinel was not adopted for temperature calculations.

Cordierite

Coarse-grained cordierite surrounding gedrite in sample KRR/P/1/2 is Mg-rich with $X_{\text{Mg}}=0.91\text{--}0.92$. Medium-grained cordierite with spinel inclusion in the same thin

Figure 3. SiO_2 - $\text{MgO}+\text{FeO}$ - Al_2O_3 (a and c) and ACF (b and d) diagrams showing mineral assemblages and compositions in the examined samples.

section shows a similar X_{Mg} value. The analytical totals of cordierite are less than 100% by 1–2 wt.%, suggesting the presence of channel-filling volatiles such as CO_2 and/or H_2O .

Plagioclase

The plagioclase in examined samples is anorthite-rich, and has a compositional range of $\text{Ab}_{4-7}\text{An}_{93-96}\text{Or}_{0-1}$. There is no obvious compositional variation among coarse-grained, sapphirine-hosted, and corundum-hosted plagioclases. Compositional zoning within single grain is not observed.

Gedrite

Compositional variations of gedrite are illustrated in Figure 7. They are compositionally Mg-rich ($X_{\text{Mg}}=0.75\text{--}0.81$) and characterized by high Al_2O_3 content (14–20 wt.%). As shown in the figure, Na^{A} increases with increasing Al^{IV} . Such variations are responsible for substitution of $\text{Fe} \rightleftharpoons \text{Mg}$ and $\text{NaAl}^{\text{IV}} \rightleftharpoons \square \text{Si}$ (e.g. Robinson et al., 1971). Compositional zoning within single coarse-grained gedrite crystal is absent. Fine-grained (<0.05 mm) gedrite shows the highest Na content up to 0.59. The analytical totals of gedrite are less than 100% by a few wt.%. It is generally regarded that F and Cl could be incorporated in amphibole replacing hydroxyl. Our preliminary F and Cl analyses suggest that the anions total less than 0.2 wt.%.

Figure 4. Back scattered image photographs showing detailed textures of sapphirine-bearing gneisses from Paramati. (a) Sillimanite and plagioclase inclusions in subhedral sapphirine in sample KRR/P/1/2. (b) Spinel aggregates included in sapphirine in sample KRR/P/1/2. (c) Aluminum-rich domain of the rock composed of gedrite, cordierite, and corundum (sample KRR/P/1/2). Sillimanite inclusion in corundum is also seen. (d) Spinel included in cordierite in sample KRR/P/1/2. (e) Sapphirine + corundum aggregates in sample KRR/P/1/1b. (f) Elongated spinel scattered along grain boundary of plagioclase in sample KRR/P/1/1b.

Table 1. Representative electron microprobe analyses of minerals in aluminous gneiss from Paramati

Sample number	KRR/P/1/2												
Mineral name	Spr.1	Spr.1	Spr.2	Spr.2	Pl.1	Pl. 2	Pl.3	Sil.1	Sil.2	Crn.1	Crn.2	Spl.1	Spl.2
O*	20	20	20	20	8	8	8	5	5	3	3	4	4
	Core	Rim	Core	Rim	Matrix	In Spr.1	In Crn	In Spr.1	In Crn.1	With Crd.1	With Crd.1	In Spr.2	In Pl.1
SiO ₂	12.22	12.07	11.59	12.09	44.57	43.92	44.56	37.14	37.22	0.00	0.00	0.03	0.00
Al ₂ O ₃	65.61	65.38	65.91	65.18	35.26	35.51	35.28	62.02	62.44	99.21	98.99	64.14	61.13
TiO ₂	0.05	0.00	0.00	0.00	0.02	0.01	0.02	0.00	0.00	0.01	0.00	0.01	0.03
Cr ₂ O ₃	0.41	0.53	0.09	0.57	0.00	0.07	0.03	0.11	0.20	0.48	0.48	1.11	4.12
Fe ₂ O ₃ **												0.00	0.05
FeO	5.44	4.80	5.64	4.99	0.09	0.22	0.02	0.34	0.23	0.35	0.19	19.63	20.65
MnO	0.05	0.03	0.04	0.05	0.00	0.00	0.02	0.00	0.00	0.00	0.00	0.06	0.07
MgO	17.16	16.68	16.67	16.73	0.01	0.00	0.01	0.02	0.02	0.00	0.00	14.45	13.46
CaO	0.01	0.03	0.03	0.19	18.68	19.00	18.71	0.02	0.02	0.01	0.00	0.09	0.24
Na ₂ O	0.00	0.00	0.00	0.01	0.65	0.54	0.74	0.03	0.02	0.01	0.01	0.00	0.00
K ₂ O	0.00	0.00	0.00	0.00	0.00	0.01	0.02	0.00	0.00	0.01	0.02	0.00	0.01
ZnO	0.02	0.00	0.00	0.00	0.01	0.00	0.00	0.00	0.03	0.00	0.00	0.13	0.14
Total	100.97	99.52	99.97	99.81	99.29	99.28	99.41	99.68	100.18	100.08	99.69	99.65	99.90
Si	1.428	1.426	1.368	1.427	2.070	2.046	2.068	1.007	1.004	0.000	0.000	0.001	0.000
Al	9.035	9.104	9.170	9.067	1.930	1.949	1.930	1.982	1.985	1.990	1.991	1.977	1.911
Ti	0.004	0.000	0.000	0.000	0.001	0.000	0.001	0.000	0.000	0.000	0.000	0.000	0.001
Cr	0.038	0.049	0.008	0.053	0.000	0.003	0.001	0.002	0.004	0.006	0.006	0.023	0.086
Fe ³⁺	0.071	0.000	0.085	0.025								0.000	0.001
Fe ²⁺	0.460	0.474	0.471	0.468	0.003	0.009	0.001	0.008	0.005	0.005	0.003	0.429	0.458
Mn	0.005	0.003	0.004	0.005	0.000	0.000	0.001	0.000	0.000	0.000	0.000	0.001	0.002
Mg	2.987	2.936	2.932	2.942	0.001	0.000	0.001	0.001	0.001	0.000	0.000	0.563	0.532
Ca	0.001	0.004	0.004	0.024	0.929	0.948	0.930	0.001	0.001	0.000	0.000	0.003	0.007
Na	0.000	0.000	0.000	0.002	0.059	0.049	0.067	0.002	0.001	0.000	0.000	0.000	0.000
K	0.000	0.000	0.000	0.000	0.000	0.001	0.001	0.000	0.000	0.000	0.000	0.000	0.000
Zn	0.002	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.001	0.000	0.000	0.003	0.003
Total	14.031	13.997	14.043	14.014	4.993	5.003	5.000	3.002	3.002	2.002	2.001	2.999	3.000
Mg/(Fe+Mg)	0.87	0.86	0.86	0.86								0.57	0.54
Ca/(Ca+Na+K)					0.94	0.95	0.93						

* Number of oxygens.

** Fe₂O₃ of spinel was calculated based on stoichiometry.

Coarse-grained gedrite in sample KRR/P/1/1b (e.g. Fig. 2h) is slightly magnesian ($X_{Mg}=0.80-0.81$) than that of cordierite-hosted gedrite in sample KRR/P/1/2 ($X_{Mg}=0.75-0.77$), probably because of lack of cordierite corona around gedrite or slight difference in bulk rock chemistry.

Other minerals

Compositions of sillimanite (Al₂SiO₅), corundum (Al₂O₃), and rutile (TiO₂) are close to the ideal chemistry, although

sillimanite and corundum contain small amounts of Fe₂O₃ as 0.36–0.37 and 0.22–0.41 %, respectively. Rutile occasionally contains up to 0.7 wt.% Cr₂O₃.

P–T conditions

Due to the absence of garnet and orthopyroxene in the examined samples, we could not apply some of the common geothermometers (e.g. garnet–orthopyroxene method) to estimate the peak metamorphic conditions of the Paramati rocks. In this study, we adopted sapphirine–spinel and

Table 1. (continued)

Sample number	KRR/P/1/2					KRR/P/1/1b							
Mineral name	Ged.1	Ged.1	Ged.2	Crđ.1	Crđ.2	Spr.1	Spr.1	Pl.1	Pl.2	Crn	Spl	Ged.1	Ged.2
O*	23	23	23	18	18	20	20	8	8	3	4	23	23
	Core	Rim	Fine-grained	With Ged.1	With Ged.1	Core	Rim	With Spr.1	With Ged.2	With Spr.1	With Spr.1	With Pl.1	Coarse
SiO ₂	43.80	43.75	42.02	49.93	49.68	12.46	11.78	43.85	43.85	0.01	0.03	43.92	47.71
Al ₂ O ₃	18.25	18.79	19.92	33.66	33.90	64.70	64.59	35.50	35.50	99.58	59.02	20.00	14.08
TiO ₂	0.28	0.28	0.18	0.04	0.00	0.05	0.05	0.00	0.00	0.02	0.00	0.24	0.23
Cr ₂ O ₃	0.92	0.84	0.88	0.00	0.00	0.59	1.73	0.01	0.01	0.17	6.87	0.94	0.16
Fe ₂ O ₃ **			0.00								0.30		
FeO	11.21	10.95	11.48	2.07	2.18	4.77	4.62	0.01	0.01	0.24	18.17	9.53	9.27
MnO	0.21	0.18	0.15	0.01	0.03	0.08	0.03	0.00	0.00	0.00	0.07	0.17	0.15
MgO	19.83	19.73	19.53	12.26	12.08	17.22	16.90	0.00	0.00	0.00	14.80	20.75	22.58
CaO	0.65	0.63	0.59	0.07	0.06	0.03	0.08	19.28	19.28	0.04	0.14	0.44	0.84
Na ₂ O	1.85	1.93	2.16	0.12	0.26	0.04	0.02	0.63	0.63	0.00	0.00	1.85	1.39
K ₂ O	0.01	0.00	0.01	0.00	0.00	0.00	0.00	0.00	0.00	0.01	0.02	0.01	0.01
ZnO	0.05	0.00	0.00	0.01	0.00	0.00	0.05	0.04	0.04	0.00	0.27	0.03	0.03
Total	97.06	97.08	96.92	98.17	98.19	99.94	99.85	99.32	99.32	100.07	99.69	97.88	96.45
Si	6.181	6.159	5.962	5.004	4.984	1.467	1.394	2.042	2.042	0.000	0.001	6.086	6.665
Al	3.035	3.117	3.330	3.975	4.007	8.978	9.004	1.948	1.948	1.994	1.848	3.266	2.318
Ti	0.030	0.030	0.019	0.003	0.000	0.004	0.004	0.000	0.000	0.000	0.000	0.025	0.024
Cr	0.103	0.093	0.099	0.000	0.000	0.055	0.162	0.000	0.000	0.002	0.144	0.103	0.018
Fe ³⁺						0.032	0.047				0.006		
Fe ²⁺	1.322	1.289	1.362	0.173	0.183	0.438	0.410	0.000	0.000	0.003	0.404	1.104	1.083
Mn	0.025	0.021	0.018	0.001	0.003	0.008	0.003	0.000	0.000	0.000	0.002	0.020	0.018
Mg	4.168	4.138	4.127	1.830	1.805	3.021	2.978	0.000	0.000	0.000	0.586	4.283	4.699
Ca	0.098	0.095	0.090	0.008	0.006	0.004	0.010	0.962	0.962	0.001	0.004	0.065	0.126
Na	0.506	0.527	0.594	0.023	0.051	0.009	0.005	0.057	0.057	0.000	0.000	0.497	0.376
K	0.002	0.000	0.002	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.001	0.002	0.002
Zn	0.005	0.000	0.000	0.001	0.000	0.000	0.004	0.001	0.001	0.000	0.005	0.003	0.003
Total	15.475	15.469	15.602	11.018	11.038	14.016	14.022	5.012	5.012	2.001	3.000	15.454	15.332
Mg/(Fe+Mg)	0.76	0.76	0.75	0.91	0.91	0.87	0.88	0.00	0.00		0.59	0.80	0.81
Ca/(Ca+Na+K)								0.94	0.94				

* Number of oxygens.

** Fe₂O₃ of spinel was calculated based on stoichiometry.

cordierite-spinel geothermometers to infer temperatures of metamorphism.

Owen and Greenough (1991) proposed a geothermometer based on the following Fe-Mg exchange reaction between sapphirine and spinel.

The method is based on empirical determination of entropy and enthalpy of the reaction. For the regression

analysis, Owen and Greenough (1991) adopted available natural pairs of sapphirine ($X_{\text{Mg}}=0.72-0.98$) and spinel ($X_{\text{Mg}}=0.49-0.92$) in silica-deficient granulite-facies rocks ($T=775-1050^\circ\text{C}$). As our sapphirine and spinel compositions are within the compositional ranges of their regression, we applied the method to inclusion spinel and host sapphirine assemblage in sample KRR/P/1/2 (Fig. 4b). The results yielded a temperature range of 930–950°C, which is likely to indicate the near-peak metamorphic condition. If we consider the effect of Fe³⁺ in sapphirine, the above estimate would be enhanced by about 40°C in-

Figure 5. Compositional diagram showing sapphirine chemistry. 7:9:3 and 2:2:1 in the figure imply end member compositions of $\text{Mg}_{3.5}\text{Al}_9\text{Si}_{1.5}\text{O}_{20}$ and $\text{Mg}_4\text{Al}_8\text{Si}_2\text{O}_{20}$, respectively.

Figure 6. Compositional diagram showing spinel chemistry.

indicating that the Paramati rocks were subjected to ultra-high temperature conditions. Das et al. (2003) formulated a new sapphirine-spinel geothermometer using their experimental data at 9–12 kbar and 850–1100°C. Application of the method yielded almost consistent results as 940–960°C that further suggests very high- T conditions.

Vielzeuf (1983) calibrated cordierite-spinel geothermometer based on empirical estimates of entropy and enthalpy of reaction (5) below using available data from natural mineral pairs.

We attempted to apply their method to inclusion spinel and host cordierite assemblage in sample KRR/P/1/2 (Fig. 4d) because distribution coefficient (K_D) of our cordierite-spinel pairs (0.093–0.099) is within the K_D range of their calibration (0.074–0.179). The results show 610–640°C, which are considerably lower than the temperature estimates from sapphirine-cordierite assemblage.

There are two possibilities to explain the low- T results. The first is that, although the cordierite + spinel formed at prograde or peak events, they experienced retrograde Fe-Mg re-equilibrium. This would mean that the ca 600°C temperatures indicate a closure temperature of cation exchange between cordierite and spinel. The second possibility is that cordierite formed later during uplift. This possibility is consistent with the evidence that cordierite does not show any variation in composition. This aspect remains to be resolved in our further study.

Discussion

This is the first report of sapphirine-bearing Mg-Al rocks from Paramati within the northern domain of the Palghat-Cauvery Shear System. Sapphirine in our samples occurs as euhedral to subhedral crystals in plagioclase aggregates, and contains inclusions of plagioclase, sillimanite, and spinel. Numerous types of reaction textures involving sapphirine have been reported in previous works from the Madurai Granulite Block. These include, (a) sapphirine + cordierite symplectite after sillimanite + orthopyroxene (Grew, 1984; Brown and Raith, 1996; Sajeev et al., 2001; Prakash and Arima, 2003), (b) sapphirine + cordierite symplectite after sillimanite + gedrite (Ackermann et al., 1981; Lal et al., 1984), (c) sapphirine + cordierite symplectite after corundum + gedrite (Lal et al., 1984), (d) sapphirine + cordierite corona (with or without melt) after sillimanite + biotite (Lal et al., 1984; Prakash and Arima, 2003), (e) sapphirine + cordierite + orthopyroxene ± spinel symplectite after garnet (e.g. Mohan et al., 1985b; Mohan and Windley, 1993; Brown and Raith, 1996), (f) sapphirine + orthopyroxene intergrowth after high-Al orthopyroxene and spinel (Sajeev et al., 2001), (g) spinel + cordierite corona between isolated sapphirine and orthopyroxene (e.g. Mohan et al., 1985b; Mohan and Windley, 1993; Sajeev et al., 2001), (h) orthopyroxene + sillimanite + cordierite after sapphirine + garnet (Sajeev et al., 2001), (i) sapphirine + orthopyroxene + cordierite replaced by kornepurine (Sajeev et al., 2001), (j) sapphirine + cordierite + corundum symplectite patch in biotite aggregate (Tsunogae and Santosh, 2003), (k) sapphirine inclusion in

Figure 7. Compositional diagrams showing gedrite chemistry.

garnet (Mohan and Windley, 1993), and (l) sapphirine inclusion in plagioclase (Tsunogae and Santosh, 2003). The Paramati samples discussed in this paper appear to be unique among the sapphirine-bearing rocks reported so far from southern India in that sub- to euhedral sapphirine here occurs as intergrowth with corundum, it is totally surrounded by plagioclase, and reaction textures in silica undersaturated system. To the best of our knowledge, such sapphirine-bearing textures have not so far been reported in detail from southern India.

In this paper, we proposed two new reactions to explain textures of our samples; reactions (1) and (3). Dehydration reaction (3) probably marks a stage of prograde metamorphism. Figure 8 shows petrogenetic grid of silica-undersaturated MASH system including gedrite after Goscombe (1992). The grid is applicable to our rocks because they lack quartz. P - T array in the figure was deduced from the progress of the reaction (3). As we have no orthopyroxene, the reaction $\text{Ged} \rightarrow \text{Crd} + \text{En} + \text{Spr} + \text{V}$ did not take place. Therefore, we infer a decompressional P - T path after the reaction (3). According to the FMAS petrogenetic grid of Hensen (1987), sapphirine ($\text{Mg}_{2.66}\text{Fe}_{0.89}\text{Al}_{8.9}\text{Si}_{1.55}\text{O}_{20}$, $X_{\text{Mg}}=0.75$) + corundum can be produced from spinel and sillimanite (reaction (1)) by near isobaric cooling after peak metamorphism. However, our sapphirine is slightly rich in Mg ($X_{\text{Mg}}=0.84$ – 0.89) and poor in Al (1.35–1.48 pfu) than the composition adopted by Hensen (1987). If we adopt the ideal sapphirine chemistry of $\text{Mg}_{3.5}\text{Al}_9\text{Si}_{1.5}\text{O}_{20}$ and the thermodynamic data set of Holland and Powell (1998), the slope of the reaction (1) can be tentatively drawn as -11.6 kbar/100°C. Sapphirine and corundum appear in the high-temperature side of the

Figure 8. Model petrogenetic grid for the silica-undersaturated system $\text{MgO-Al}_2\text{O}_3\text{-SiO}_2\text{-H}_2\text{O}$ after Goscombe (1992). Arrays indicate the P - T path of the Paramati area inferred from our petrographical observation.

reaction. To obtain the reaction (1) above, the temperature should increase at almost constant pressure, suggesting prograde sapphirine + corundum formation. This disagreement between Hensen's (1987) grid and our calculation will be discussed elsewhere (Tsunogae et al., in prep.).

The peak metamorphic temperatures of the Mg-Al rocks of Paramati locality is estimated as 930–950°C from equilibrium sapphirine-spinel assemblage in sample KRR/P/1/2, although the temperatures could have been still higher considering the effect of Fe^{3+} in sapphirine.

Our results are consistent with the UHT conditions recently obtained from Perumalmali (Brown and Raith, 1996; Raith et al., 1997), Ganguvarpatti (Sajeev et al., 2001; Tamashiro et al., 2004), and Karur (Tsunogae and Santosh, 2003) in the adjacent Madurai Block. Despite the evidence for UHT metamorphic conditions in Paramati, as obtained from sapphirine-spinel pairs, orthopyroxene, which is an index mineral for dry granulite facies rock, is absent in the examined samples. Also, the presence of coarse-grained gedrite can be taken to argue that the peak temperature of the Paramati area is less than *ca.* 800°C and that the rocks are within the amphibolite-facies. This temperature discrepancy could be explained by thermodynamic calculations by Lal et al. (1984) which point out that gedrite is more stable than orthopyroxene with increasing chemical potential of Na₂O. As shown in Table 1, gedrite in our samples contain up to 2.2 wt.% Na₂O. We therefore infer that the stability field of gedrite has been enhanced due to NaAl^{IV} $\rightleftharpoons$ □ Si substitution. As discussed above, fine-grained (<0.05 mm) gedrite shows higher Na content (up to 0.59) than coarse-grained ones. This evidence clearly suggests that, as Na-bearing gedrite breaks down to form cordierite + corundum assemblage, the remaining gedrite becomes enriched in Na as the hydrosilicate decreases in modal amount during the progress of the reaction (3). Such Na-bearing gedrite has been reported from several high-grade terranes. Hisada and Miyano (1997) reported gedrite (with up to 2.2 wt.% Na₂O) + cordierite + garnet assemblage from Limpopo Belt (Southern Africa), which has undergone *T*>850°C granulite-facies metamorphism. Harley (1985) also reported gedrite (with up to 1.8 wt.% Na₂O) + garnet + kyanite (or cordierite) + quartz assemblage in gneisses from the Napier Complex of East Antarctica. As the Napier samples are from the vicinity of shear zones, Harley (1985) concluded that the gedrite is a product during later shearing. Dasgupta et al. (1999) reported gedrite with up to 2.6 wt.% Na₂O in sheared rocks from the Eastern Ghats Belt (India). Since the Paramati rocks are also located within the northern domain of the Palghat-Cauvery Shear System, we do not rule out a similar possibility of gedrite formation during a retrograde event during shearing. Detailed petrological implication of the gedrite-bearing assemblages from Paramati and adjacent localities around Karur will be discussed elsewhere (Tsunogae et al., in prep.)

Our study on sapphirine-corundum gneisses indicates that rocks from Paramati experienced the peak metamorphism probably at *T*>900°C, translating to ultrahigh temperature conditions, within the stability field of sillimanite, similar to the UHT rocks in central part of Madurai Block. The results therefore confirm that the

Madurai Granulite Block as well as parts of the Palghat-Cauvery Shear System as a whole experienced similar UHT metamorphism and exhumation along a clockwise *P-T* path. The locality investigated in this study occurs within the northern domain of the Palghat-Cauvery Shear System, a major tectonic zone that defines the Archaean-Proterozoic collisional boundary in southern India, as well as an important transcrustal shear that figures in Gondwana reconstruction (Collins and Santosh, 2003). The UHT metamorphism reported in our study has important implications in understanding the tectonic framework of southern India as well as the history of amalgamation of Gondwana.

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