Mineral chemistry and reaction textures in metabasites from the Eastern Ghats belt, India and their implications

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Abstract

Three types of mafic granulites, namely two pyroxene–plagioclase granulite (MG), two pyroxene–plagioclase–garnet granulite (GMG) and spinel–olivine–plagioclase–two pyroxene granulite (SMG) are exposed at Sunkarimetta, Eastern Ghats belt, India. The mafic granulites exhibit a foliation concordant with that in associated granulite facies quartzofeldspathic gneisses. Textural characteristics and mineral chemical data suggest the following mineral reactions: olivine + plagioclase = spinel + orthopyroxene + clinopyroxene (SMG), orthopyroxene + plagioclase = garnet + quartz (GMG), clinopyroxene + plagioclase = garnet + quartz (GMG) and plagioclase + hemoilmenite + quartz = garnet + ilmenite + O_2 (GMG). Geothermobarometry indicates maximum *P–T* conditions of metamorphism at *c.* 8.5 kbar, 950 °C. The mafic granulites later suffered nearly isobaric cooling to *c.* 7.5 kbar, 750 °C. Bulk compositional characteristics suggest that SMG is of cumulate origin. The protoliths of the mafic granulites, emplaced at *c.* 32 km depth, are probably responsible for thermal perturbation causing granulite facies metamorphism of the enclosing rocks.

KEYWORDS: basite, granulite, texture, Eastern Ghats, India.

Introduction

THE Eastern Ghats granulite belt, occurring along the eastern coast of India, records an anticlockwise *P–T* trajectory of evolution, comprising a prograde path of high *T/P*, followed sequentially by nearly isobaric cooling and nearly isothermal decompression (Kamineni and Rao, 1988; Sengupta *et al.*, 1990). It has been argued that granulite production on an anticlockwise path is a consequence of magmatic accretion at the base and/or within the crust (Bohlen, 1987; Harley, 1989). Mafic granulites, occurring abundantly as conformable lenses in paragneisses in the Eastern Ghats, record maximum *P–T* condition of metamorphism of 8.5 kbar, 950 °C (Sengupta *et al.*, 1990; Dasgupta *et al.*, 1991). In a previous paper (Dasgupta *et al.*, 1991), we have reasoned that the mafic granulites represent intraplate magmatism and could be the potential energy source for the granulite facies metamorphism in the Eastern Ghats. In this paper, we provide mineral chemical data and rection textures of three different types of magmatic rocks from the Eastern Ghats granulite belt which bear the imprints of cooling from abnormally high temperature.

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Geologic setting

The Eastern Ghats granulite belt is characterised by the presence of several varieties of paragneisses (khondalite or garnet–quartz–perthite–sillimanite gneiss, calc granulites and sapphirine–spinel granulites), orthogneisses (plagioclase–clinopyroxene–orthopyroxene–garnet gneiss), alkaline rocks, anorthosites and orthopyroxene-bearing quartzofeldspathic gneisses (Naqvi and Rogers, 1987). Isotopic age determinations indicate at least two major phases of granulite metamorphism at *c.* 2600 Ma (Perraju *et al.*, 1979) and *c.* 1000–900 Ma (Grew and Manton, 1986; Aftalion *et al.*, 1988; Paul *et al.*, 1990). Basic magmatism in the Eastern Ghats has been dated at 2800–2600 Ma (Paul *et al.*, 1990). Deformational signatures in the mafic granulites indicate that these were emplaced syntectonically with the earlier phase of metamorphism (Dasgupta *et al.*, 1991).

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The present study area is around Sunkarimetta, which is halfway between Araku and Anantagiri (see Fig. 1 in Dasgupta *et al.*, 1991). The area is characterised by linear patches of orthopyroxene granulite (orthopyroxene–plagioclase–garnet-perthite–quartz), khondalite and quartzite. Conformable lenses of mafic granulites are present throughout the area and are mostly hosted in orthopyroxene granulite. Based on the presence and absence of garnet, the mafic granulites can be divided into a garnetiferous (GMG) and a non-garnetiferous (MG) type. Field relationships between Mg and GMG is not clear, although it is evident that GMG has a distinct domainal occurrence within MG. Within the MG domains several irregular blocks (maximum dimension 8 × 5 m) of an unusual mafic rock containing spinel–plagioclase–olivine–pyroxene occur (SMG). All the types of mafic granulites show a weak foliation marked by parallel arrangement of prismatic pyroxenes and/or ilmenite. The foliation is conformable with the regional gneissic foliation in the associated rocks.

Petrography

SMG is characterised by the mineral assemblage spinel + plagioclase + clinopyroxene + orthopyroxene + olivine ± mica ± amphibole. The pyroxenes occur in two modes. Coarse subhedral grains of ortho- and clinopyroxene show interlocking texture. Orthopyroxene contains (100) lamellae and blebs of clinopyroxene and vice-versa. In the other mode, clino- and orthopyroxene contain vermicular intergrowths of green spinel (Fig. 1). In addition spinel locally forms coarser tabular grains, adjacent to the pyroxenes (Fig. 1). Olivine occurs as rare subrounded grains enclosed in the spinel–pyroxene intergrowths and grains are never in contact with plagioclase (Fig. 1). Plagioclase forms coarse xenomorphic grains in the rock. Both amphibole and biotite occur as patchy grains replacing the pyroxenes.

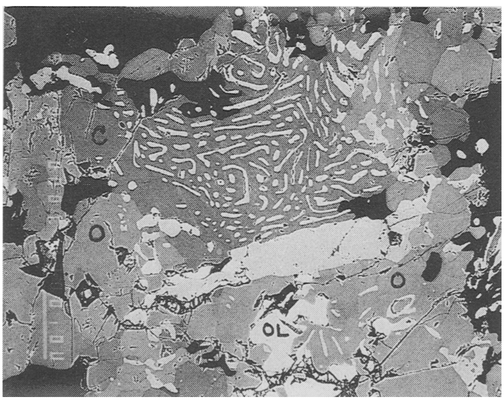


FIG. 1. Spinel (white) occurs as symplectitic intergrowth with clinopyroxene (C) and orthopyroxene (O). Note a coarse tabular grain of spinel. Olivine (Ol) occurs as relic grains in the intergrowth. Black phase is plagioclase. EPMA BEI, length of bar is 0.05 mm.

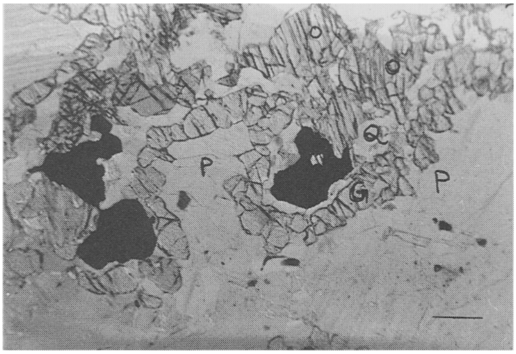
In both MG and GMG, ortho- and clinopyroxene occur as coarse subhedral grains, (100) lamellae and orthopyroxene in clinopyroxene and vice-versa are common features. In MG, plagioclase, pyroxene and ilmenite show mutual grain contact. In GMG on the other hand, plagioclase is separated from the pyroxenes as well as from ilmenite by thin rims of coronal garnet (with or without quartz) and garnet–ilmenite corona respectively (Figs. 2, 3). Tabular ilmenite grains in GMG separated from plagioclase by garnet corona are compositionally hemoilmenite (see later) and are distinct from nearly pure ilmenite involved in intergrowth with garnet. Other phases in MG and GMG are K-feldspar, biotite and apatite. Biotite is a late phase in the rocks, replacing garnet, pyroxenes and K-feldspar.

Chemical characteristics

Three representative bulk chemical compositions of Mg, GMG and SMG, determined by XRF, along with the modal and normative compositions, are given in Table 1. SMG is chemically an olivine gabbro and is distinctly more magnesian and aluminous (reflected in the normative corundum content) than both MG and GMG. MG is again enriched in Mg compared with GMG. All the varieties have, however, hypersthene and olivine in the norm (Table 1).

The composition of the coexisting phases in these rocks were determined by JEOL–JXA 733 and 8600 EPMA, and representative data are given in Tables 2–4. In SMG, spinel is essentially hercynite–spinel solid solution with X_{Mg} [= Mg/(Mg + Fe^{2+})] close to 0.5 (Table 2). Recalculated Fe_2O_3 content in spinel varies between 2.69 and 3.38 wt.%. Olivine is Fo_{66} Fa_{34} and the composition of plagioclase is close to An_{70} (Table 2). Both types of pyroxene are more aluminous than those in MG and GMG; Al_2O_3 wt.% in orthopyroxene varies within the range 2.91–3.35 and in clinopyroxene 4.05–3.03. Lower range values are recorded when these are intergrown with spinel. Orthopyroxenes are enstatitic (X_{Mg} = 0.71), while clinopyroxenes are essentially diopside–hedenbergite solid solutions with X_{Mg} = 0.8 (Table 2).

Orthopyroxenes in MG have higher X_{Mg} (0.58–



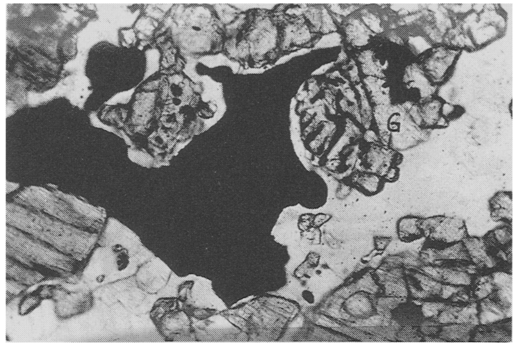


FIG. 2 (*left*). Garnet (G) - quartz (Q) symplectite in between orthopyroxene (O) and plagioclase (P). Length of bar is 0.05 mm. FIG. 3 (*right*). Garnet (G) - ilmenite (black) symplectite around hemoilmenite (black) in presence of plagioclase (P) in GMG. Length of bar is 0.025 mm.

0.61) than those in GMG (X_{Mg} = 0.37–0.39) (Table 3). Octahedral aluminium content in the orthopyroxenes varies in the range 0.01–0.04. Chemical composition of coarse subhedral orthopyroxene and that occurring as (100) lamellae in clinopyroxene are generally comparable. Clinopyroxenes in both MG and GMG are essentially solid solutions of diopside—hedenbergite with low jadeite (1.7–2.8 mol.%), Ca-Tschermak (max. 3.96 mol.%) and TiO_2 content (Table 3). However, these are more magnesian (X_{Mg} = 0.71–0.74) in MG as compared to in GMG (X_{Mg} = 0.56–0.53). Compositions of coexisting clino- and orthopyroxenes, when plotted in the pyroxene quadrilateral (Fig. 4), clearly show that X_{Mg} increases in the order GMG–MG–SMG.

Coarse subhedral ilmenite defining the weak foliation in MG and GMG are hemoilmenite with 3–4 wt.% Fe_2O_3 (calculated after Bohlen and Essene, 1977) (Table 4). On the other hand, ilmenite intergrown with coronal garnet in GMG is nearly pure $FeTiO_3$ (Table 4). Plagioclase in GMG shows sharp zoning, with higher albite towards the rim (X_{Ab} in the core is 0.29 and in the rim adjacent to coronal garnet is 0.47; Table 4). Zoning is less conspicuous in plagioclase of MG, nevertheless the same trend is noted (X_{Ab}^{core} = 0.28, X_{Ab}^{Rim} = 0.38). The composition of coronal garnet in GMG is nearly homogeneous ($Alm_{65}Gr_{20}Py_{13}Sp_2$) irrespective of the nature of the phase (platioclase, orthopyroxene, ilmenite or clinopyroxene) it rims (Table 4).

Mineral reactions

In SMG relatively aluminous clinopyroxenes contain (100) exsolution lamellae of orthopyrox-

TABLE 1. Bulk chemical compositions, modal and normative compositions of MG, GMG and SMG

Bulk Composition				Modal Analysis				CIPW Norm			
	SMG	MG	GMG		SMG	MG	GMG		SMG	MG	GMG
SiO_2	46.03	48.80	47.92	Opx	28	25	20	Tl	2.73	4.70	7.48
Al_2O_3	21.93	7.63	6.64	cpx	25	18	15	Ap	0.03	.03	.03
TiO_2	1.43	2.48	3.94	ol	2	—	—	Kf	3.03	8.90	8.68
FeO	7.29	13.62	16.78	sp	6	—	—	Ab	7.76	9.17	10.28
MnO	0.06	0.05	0.04	Pl	40	35	38	An	46.23	11.48	8.32
CaO	9.34	9.81	11.14	Am	8	—	—	Co	2.85	—	—
MgO	11.06	14.34	9.39	Bi	1	2	1	Di	—	19.92	20.33
K_2O	0.63	1.51	1.47	gt	—	—	7	Hd	—	10.22	18.48
Na_2O	0.92	1.09	1.22	Il	—	2	5	Fo	5.32	11.62	5.33
P_2O_5	0.02	0.028	0.027	Kf	—	10	8	Fl	2.36	7.53	4.60
(H_2O)	0.18	—	—	Qtz	—	7	5	En	19.92	9.87	7.30
Total	98.90	99.35	98.54	Ap	—	<1	<1	F_3	8.04	5.80	7.66
								Total	98.57	99.23	98.57

TABLE 2. Composition of spinel, orthopyroxene, clinopyroxene, olivine and plagioclase in SMG

No.	1	2	3	4	5	6	7	8
SiO_2	0.01	0.05	36.88	50.54	52.32	52.48	52.43	51.87
TiO_2	0.06	0.01	–	–	0.07	0.03	0.05	0.06
Al_2O_3	62.37	61.81	–	31.09	2.91	3.35	3.03	4.05
Fe_2O_3	2.69	3.38	–	0.06	–	–	–	–
FeO	22.57	22.18	30.94	–	18.17	17.31	6.66	6.50
MnO	0.13	0.15	0.32	–	0.46	0.36	0.22	0.17
MgO	12.52	12.63	32.97	–	24.98	25.41	15.03	14.65
CaO	0.04	0.05	–	14.28	0.42	0.54	22.53	22.14
Na_2O	0.01	–	–	3.29	–	–	–	–
K_2O	–	–	–	0.10	–	–	–	–
Total	100.30	100.26	101.11	99.36	99.33	99.48	99.95	99.44
Oxygen Basis	4	4	4	8	6	6	6	6
Si	–	–	0.99	2.31	1.92	1.92	1.93	1.91
Ti	–	–	–	–	–	–	–	–
Al	1.94	1.93	–	1.68	0.13	0.15	0.13	0.18
Fe^{3+}	0.05	0.07	–	–	–	–	–	–
Fe^{2+}	0.50	0.49	0.69	–	0.56	0.53	0.20	0.20
Mn	–	–	0.01	–	0.01	0.01	–	–
Mg	0.49	0.50	1.32	–	1.37	1.38	0.82	0.80
Ca	–	–	–	0.70	0.01	0.02	0.89	0.88
Na	–	–	–	0.29	–	–	–	–
K	–	–	–	0.01	–	–	–	–

1,2 Spinel; 3, Olivine; 4, Plagioclase; 5, Orthopyroxene with intergrown spinel; 6, Primary orthopyroxene; 7, Clinopyroxene with intergrown spinel; 8, Primary clinopyroxene.

ene. Similarly, aluminous orthopyroxene contains lamellae of clinopyroxene. Reintegration of the pyroxene compositions following the method of Sandiford and Powell (1986) show that prior to exsolution, subcalcic augite and pigeonite were present in the rock. Textural features indicate that these, together with olivine and plagioclase, constitute the primary assemblage in the SMG. Textural relations (Fig. 1) and the compositional plots in the CA (FM) system (Fig. 5) (suggest that the spinel – OPX – CPX intergrowth originated via the mineral reaction,

Olivine + plagioclase = clinopyroxene + orthopyroxene + spinel. (1)

Reintegration of pyroxene compositions in MG and GMG also show that subcalcic augite and pigeonite existed prior to exsolution. It is evident from the textural relations that these, together with hemoilmenite and plagioclase, constituted the primary assemblage in both these rocks. Coronal garnet subsequently appeared in iron-rich GMG through several reactions. Development of coronal garnet–quartz symplectite around ortho- and clinopyroxene and plagioclase can be attributed to the reactions,

Orthopyroxene + plagioclase = garnet + quartz, (2)

Clinopyroxene + plagioclase = garnet + quartz. (3)

On the other hand, formation of garnet–ilmenite symplectite around plagioclase and hemoilmenite is due to the deoxidation equilibria,

Plagioclase + hemoilmenite + quartz = garnet + ilmenite + O_2 (4)

Compositional homogeniety of garnets rimming orthopyroxene, clinopyroxene, plagioclase and ilmenite suggests that the reactions (2), (3) and (4) occurred simultaneously.

All the rocks suffered late hydration which resulted in the appearance of amphibole and biotite. It may be recalled here that late hydration and K-metasomatism are the features common to other Eastern Ghats rocks (Sengupta *et al.*, 1990; Dasgupta *et al.*, 1991).

Geothermobarometry

Compositions of coexisting primary ortho- and clinopyroxenes in the SMG give a temperature of 940 °C following Kretz (1982), while the pyroxene intergrown with spinel record temperatures in the range 800–830 °C. There is no well calibrated barometer appropriate for the SMG. The empiri-

TABLE 3. Composition of orthopyroxene, clinopyroxene in MG and GMG

No.	1	2	3	4	5	6	7	8
SiO_2	52.68	51.20	50.09	50.17	52.26	51.62	51.45	51.19
TiO_2	0.16	0.10	0.13	0.07	0.28	0.35	0.14	0.17
Al_2O_3	1.07	2.52	1.05	0.43	1.50	2.62	1.25	1.26
FeO	23.53	25.25	35.74	35.44	8.52	9.24	15.05	14.96
MnO	0.68	0.64	0.42	0.60	0.25	0.17	0.26	0.14
MgO	21.42	19.82	11.92	13.24	13.79	12.84	9.73	10.53
CaO	0.64	0.64	0.83	0.58	22.08	21.84	21.56	21.36
Na_2O	—	—	—	—	0.22	0.35	0.26	0.28
Total	100.18	100.17	100.18	100.53	98.90	99.03	99.70	99.89
Oxygen Basis	6	6	6	6	6	6	6	6
Si	1.971	1.933	1.987	1.983	1.967	1.946	1.978	1.964
Ti	0.005	0.003	0.004	0.002	0.008	0.010	0.004	0.005
Al^{iv}	0.029	0.067	0.013	0.017	0.033	0.054	0.022	0.036
Al^{vi}	0.018	0.045	0.036	0.003	0.034	0.062	0.035	0.021
Fe^{2+}	0.736	0.797	1.186	1.171	0.268	0.291	0.484	0.480
Mn^{2+}	0.022	0.020	0.014	0.020	0.008	0.005	0.008	0.005
Mg	1.194	1.116	0.705	0.780	0.774	0.721	0.558	0.602
Ca	0.026	0.026	0.035	0.025	0.891	0.882	0.888	0.878
Na_2O	—	—	—	—	0.016	0.026	0.019	0.021
X_{Mg}	0.618	0.583	0.372	0.399	0.742	0.712	0.535	0.556
X_{Fe}	0.381	0.416	0.627	0.600	0.257	0.287	0.464	0.443
CaTs mol%					1.98	3.96	1.76	—
Jd mol%					1.76	2.86	2.09	2.33

1, Orthopyroxene porphyroblast of MG; 2, Orthopyroxene exsolved in clinopyroxene of MG; 3, Exsolved orthopyroxene in clinopyroxene of GMG; 4, Orthopyroxene porphyroblast of GMG; 5, 6, Porphyroblastic clinopyroxene of MG; 7, Porphyroblastic clinopyroxene of GMG; 8, Clinopyroxene exsolved in orthopyroxene porphyroblast of GMG.

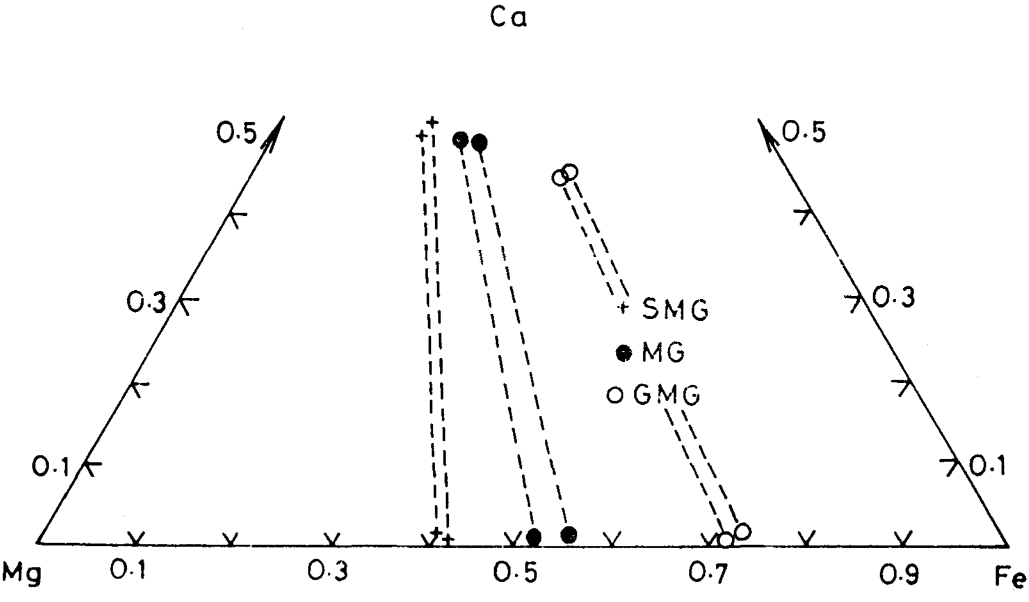


FIG. 4. Plots of Orthopyroxene and clinopyroxene in SMG, MG and GMG in pyroxene quadrilateral.

TABLE 4. Composition of ilmenite, plagioclase (MG and GMG) and Garnet (GMG)

No.	1		2		3	4	5	6	7
	Core	Rim	Core	Rim					
SiO_2	50.89	55.84	50.70	54.05	38.27	38.41	—	—	—
TiO_2	—	—	—	—	0.03	0.05	51.26	51.03	51.96
Al_2O_3	30.47	27.67	30.85	29.10	21.17	21.37	—	—	—
Fe_2O_3	0.24	0.32	0.50	0.18	0.20	—	3.73	2.98	1.20
FeO	—	—	—	—	29.09	29.61	43.76	44.75	46.10
MnO	—	—	—		1.06	1.13	0.62	0.36	0.22
MgO	—	—	—	—	3.29	2.70	0.82	0.44	0.24
CaO	13.72	10.19	13.68	12.02	7.23	7.27	—	—	—
ZnO	—	—	—	—	0.20	0.04	—	—	—
Na_2O	3.15	5.15	3.07	4.25	—	—	—	—	—
K_2O	0.12	0.20	0.22	0.25	—	—	—	—	—
Total	98.59	99.37	99.02	99.85	100.54	100.58	100.19	99.56	99.72
Oxygen basis	8	8	8	8	12	12	12	12	12
Si	2.243	2.523	2.326	2.443	3.015	3.027	—	—	—
Ti	—	—	—	—	0.002	0.003	3.849	3.882	3.951
Al	1.653	1.474	1.668	1.550	1.966	1.985	—	—	—
Fe^{3+}	0.008	0.011	0.017	0.006	0.012	—	0.280	0.227	0.092
Fe^{2+}	—	—	—	—	1.917	1.951	3.653	3.786	3.897
Mn	—	—	—	—	0.071	0.075	0.052	0.031	0.019
Mg	—	—	—	—	0.386	0.317	0.112	0.066	0.036
Ca	0.677	0.493	0.672	0.582	0.610	0.614	—	—	—
Zn	—	—	—	—	0.012	—	—	—	—
Na	0.281	0.451	0.273	0.373	—	—	—	—	—
K	0.007	0.012	0.013	0.014	—	—	—	—	—
X_{an}	0.701	0.515	0.701	0.600					
X_{ab}	0.291	0.471	0.284	0.384					
X_{alm}					0.642	0.659			
X_{spess}					0.023	0.025			
X_{pyr}					0.129	0.107			
X_{gros}					0.204	0.207			
$X_{Fe_2O_3}$							0.068	0.055	0.022
X_{FeTiO_3}							0.891	0.921	0.963

1, Plagioclase in GMG; 2, Plagioclase in MG; 3, Coronal garnet in between plagioclase and ilmenite; 4, Coronal garnet in between plagioclase and orthopyroxene; 5, Ilmenite in MG; 6, Ilmenite in GMG; 7, Ilmenite intergrown with coronal garnet in GMG.

cally formulated anorthite–Ca-Tschermak–quartz barometer (Wood, 1977; Ellis, 1980) gives 'maximum' pressure of 9.5 kbar at the recorded T_{max} of 940 °C. Comparison of X^{cpx}_{CaTs}–X^{Pl}_{Al} with those in other granulite terranes (cf. Martignole, 1979) indicates pressures in the range 8–8.5 kbar. Early stabilisation of olivine–plagioclase–cpx–opx assemblage in the SMG and late appearance of spinel set an upper pressure limit of 8.5 kbar according to the data of Herzberg (1978) in the system $CaO–MgO–Al_2O_3–SiO_2$. The presence of iron in the system will further lower this pressure maxima. Similar estimates are obtained from the experimental data of Kushiro and Yoder (1966) and Emslie (1970) on reaction (1).

The compositions of coexisting pyroxenes devoid of exsolution lamellae in MG give a maximum temperature of 850 °C (after Kretz, 1982), while the host-lamellae compositions in the same rock record $T_{max.}$ of 780 °C. Simultaneous solution of garnet–orthopyroxene thermometer (Lee and Ganguly, 1988) and GOPS barometer (Perkins and Chippera, 1985), as well as GCPS barometer (Moecher *et al.*, 1988) and garnet–clinopyroxene thermometer (Ellis and Green, 1979) in the GMG give concordant results of 7.5 kbar, 760 °C. These *P–T* values can be taken to represent the condition of formation of coronal garnet in the GMG.

In summary, the studied rocks record $T_{max.}$ of metamorphism *c.* 950 °C, which is strikingly similar to the recorded temperature maxima in

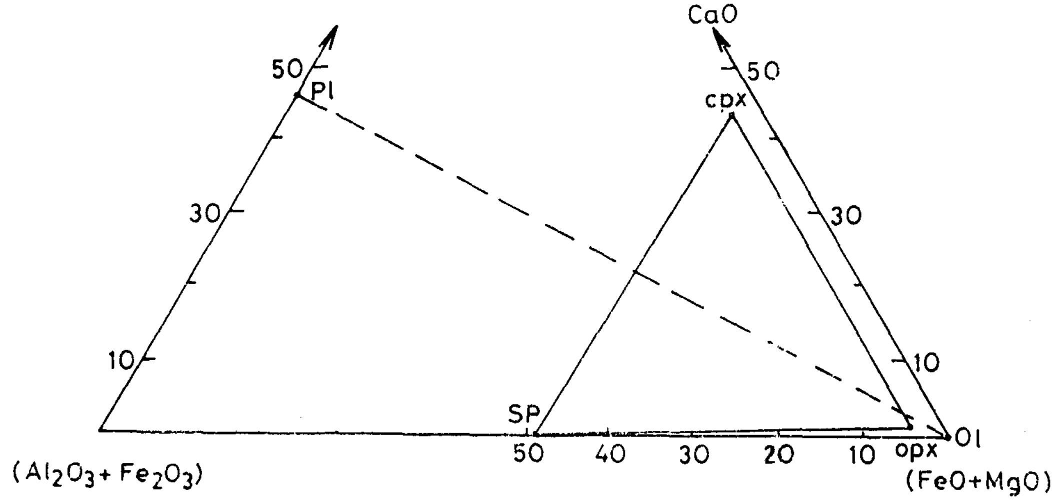


FIG. 5. Compositional plots of the phases in C (CaO) A (Al_2O_3 + Fe_2O_3) FM (FeO + MgO) space in SMG.

adjacent areas of the Eastern Ghats (Sengupta *et al.*, 1990; Dasgupta *et al.*, 1991). Pressure during the $T_{max.}$ cannot be calculated. However, it did not exceed 8.5 kbar as argued earlier. This is also consistent with the recorded $P_{max.}$ in the Eastern Ghats (Sengupta *et al.*, 1990). A $T_{max.}$–$P_{max.}$ of 950 °C and 8.5 kbar of metamorphism would imply that the complex subsequently suffered a nearly isobaric cooling to 750 °C, 7.5 kbar when coronal garnet appeared in the GMG. The formation of spinel–opx–cpx intergrowth via reaction (1) is usually attributed to cooling from igneous temepratures (Griffin and O'Reilley, 1987). Such textures have earlier been reported from lower crustal rocks (McBirney and Aoki, 1973; Francis, 1976). In the present situation, however, reaction (1) could additionally occur in response to cooling from peak metamorphic temperatures.

Discussion

The extremely high MgO and Al_2O_3 contents and insignificant K_2O content of the SMG are indicative of its cumulate origin (cf. Griffin and O'Reilley, 1987). Identical *P–T* history of SMG and the associated rocks corroborates with the contention that SMG does not represent xenoliths carried up from greater depths by the magma. The primary mineral assemblage of olivine–plagioclase–opx–cpx in the SMG constrain the emplacement of the magma occurred to a depth *c.* 32 km, corresponding to a pressure of 8.5 kbar. Cooling fo the magmatic complex at depth may have provided the heat source for thermal perturbation causing granulite facies metamorphism of the enclosing rocks (cf. Frost and Frost, 1987). Formation of spinel in SMG took place during cooling either from igneous temperatures or from peak metamorphic temperatures. Exsolution in pyroxenes and formation of garnet are the consequences of isobaric cooling of the complex subsequent to peak metamorphic conditions. Non-appearance of garnet in the SMG and MG is due to their relatively magnesian bulk composition at the ambient *P–T* conditions of metamorphism (cf. Green and Ringwood, 1967).

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