

Domainal fabric development, associated microstructures and P – T records attesting to polymetamorphism in a granulite complex of the Eastern Ghats granulite belt, India

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The granulite complex around Jenapore, Orissa, Eastern Ghats granulite belt, bears the imprint of two episodes of strong deformation (D_1 and D_2) attended with foliation (fabric) development (S_1 and S_2). Two distinct metamorphic events at P – T conditions of $\sim 900^\circ\text{C}$ at ~ 9 kbar and $\sim 600^\circ\text{C}$ at ~ 6 kbar are correlated with D_1 and D_2 respectively. The reaction textures in S_1 -microdomains are interpreted to be the product of near isobaric cooling at ~ 9 kbar from 950°C to 600°C , whereas those in the S_2 -microdomains are considered to be the result of an up-pressure trajectory from ~ 6 kbar at 600°C . The D_1 – M_1 high P – T granulite event is interpreted to be Archean in age (ca. 3 Ga) on the basis of the isotopic data obtained from the charnockite suite of the area. The later relatively low P – T granulite facies event, attendant to D_2 – S_2 is considered to be related to the Grenvillian orogeny as represented by the dominant isotopic record in the belt.

1. Introduction

Regional granulite terranes within Precambrian shield areas, with no record of gradual transitions to lower grade zones, are typified by the preservation of relatively uniform granulite assemblages, implying similar physical conditions over very large regions (Harley 1992). Moreover, many of these terranes record high-grade metamorphism and deformational events pre-dating major crustal episodes such as the Grenvillian. The metamorphic evolution of these belts is certainly very important and likely to be complex. The Eastern Ghats granulite belt of India, which records the imprint of both Grenvillian and pre-Grenvillian high-grade metamorphism (Mezger and Cosca 1999; Bhattacharya *et al* 2001), is one such polymetamorphic granulite belt that is of major importance in reconstructing past continental configuration.

During the last decade investigations in parts of the regional granulite belt of the Eastern Ghats

have revealed many complexities. Principal findings are:

- (a) the polyphase deformation (Sarkar *et al* 1981; Halden *et al* 1982; Bhattachayra *et al* 1994; Kar 1995; Bhattacharya 1996, 1997; Shaw 1996),
- (b) complex and multi-stage history of granulite facies metamorphism (Dasgupta *et al* 1994, 1995; Sen *et al* 1995; Shaw and Arima 1996a, 1996b, 1997, 1998; Dasgupta and Sengupta 1998; Rickers *et al* 1998; Bhattacharya and Kar 2002),
- (c) partial melting under granulite facies conditions (Dasgupta *et al* 1992; Sen and Bhattacharya 1997; Bhattacharya *et al* 2001; Bhattacharya and Kar 2002), and
- (d) diverse styles of melting (Mukhopadhyay and Bhattacharya 1997; Sen and Bhattacharya 1997, 2000).

Keywords. Eastern Ghats granulite belt; polyphase deformation; distinct fabrics; diverse P – T records; polymetamorphism.

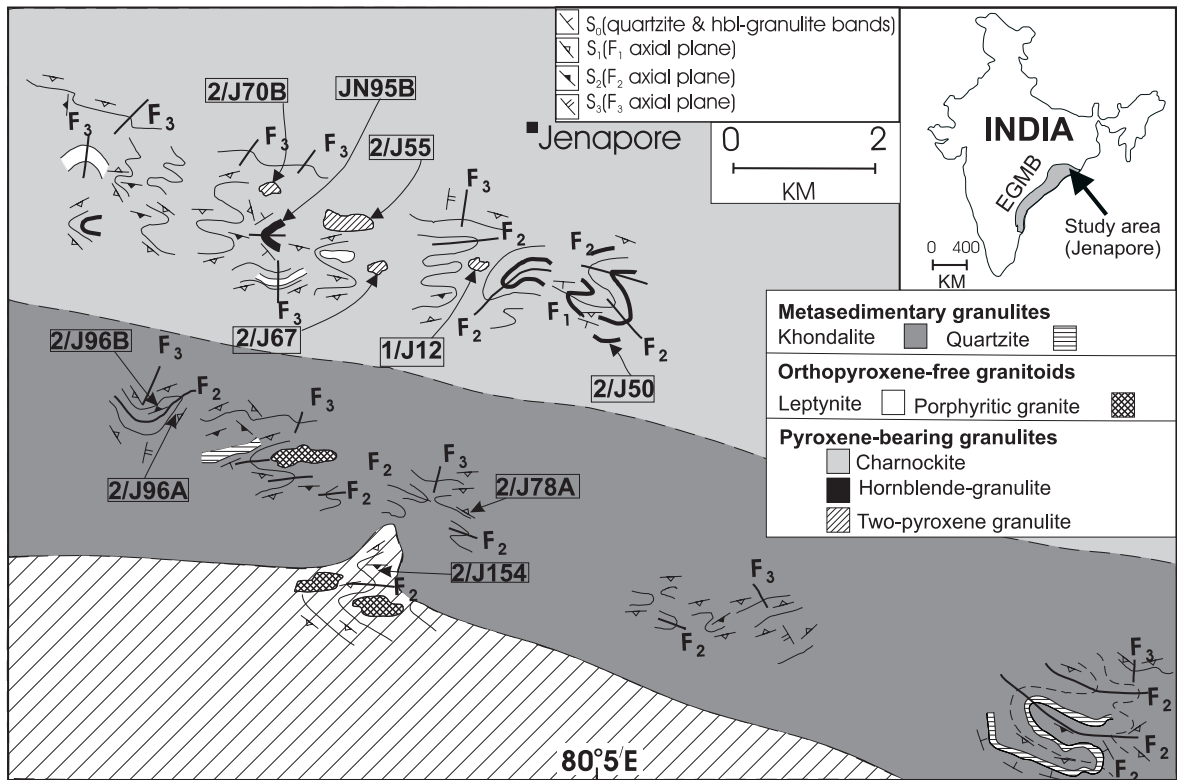


Figure 1. Simplified geological map of the area around Jenapore, Orissa. Inset shows the location map. Locations of the analysed samples are given in rectangular boxes.

From different parts of this large belt, different P - T estimates and P - T - t paths have been reported. Three common P - T clusters or domains can be identified: high P - T conditions of 9.5–10 kbar at 900–1000°C; intermediate P - T conditions near 700°C at 6–8 kbar; and lower pressure condition in the range of 4.5–6 kbar at 650–700°C. These sets of conditions are recorded in different rock samples from many localities (cf. Sen *et al* 1995 and references therein). Contrasting, post-peak isobaric cooling and isothermal decompression have been recorded from several areas in the Eastern Ghats granulite belt (Lal *et al* 1987; Sengupta *et al* 1990; Dasgupta *et al* 1991, 1993, 1994; Sen *et al* 1995; Bhattacharya 1996; Shaw and Arima 1996b; Mohan *et al* 1997). However, barring a few (Bhattacharya and Kar 2002), the prograde P - T trajectory is rarely documented. In addition, the significance of the extreme metamorphism, and the regional context of the post-peak P - T paths, is not clear as the ages of the assemblages is poorly constrained. Moreover, except a few, most of the studies lack integration between deformation history, metamorphic evolution and age data from the assemblages of a locality. Nevertheless, the possibility of polymetamorphism cannot be denied.

Some earlier studies emphasized the repeated metamorphism in the Eastern Ghats granulite belt (Naqvi and Rogers 1987; Halden *et al* 1982). Especially, Grew and Manton (1986) dated the 1 Ga granulite-facies metamorphism in this belt, but had strongly opined the possibility of Archaean or early Proterozoic high-grade metamorphism. However, recent findings emphasized that Eastern Ghats belt possibly represents a collage of several crustal provinces (Chetty 2001; Rickers *et al* 2001; Bhattacharya and Kar 2002). Contextually, in his review on the Proterozoic granulite terranes, Harley (1992) also emphasized this possibility and stated that the pre-Grenvillian high-grade terrains not only consist of reworked older crustal material, but may also contain newly accreted materials. Moreover, Barton *et al* (1994) noted that in complex terrain the P - T loops might be apparent which may actually link P - T vectors of isotopically distinct metamorphic cycle. Hence, in complex terrain like Eastern Ghats belt, to interpret the retrieved P - T data one has to be very cautious. A more comprehensive approach, considering the all-round information from the local assemblages, is required and this is the major focus of the present communication.

2. Geological setting

2.1 Lithologic types and field relations

The granulite complex in and around Jena-pore, Orissa is primarily composed of suites of metasedimentary granulites and pyroxene-bearing granulites (figure 1). Different varieties of orthopyroxene-free granitoids namely, leptynite and prophyritic granite are also exposed. The metasedimentary granulites are of two types, namely, khondalite and quartzite, of which khondalite is the mappable unit. Pyroxene-bearing granulites are mainly charnockites, while enderbite, two-pyroxene granulite and hornblende granulite are minor but significant members.

Khondalite generally preserves the pervasive gneissosity defined by the alternate quartz-rich and ferromagnesian mineral rich layers. Quartzite mostly occurs as minor bands within the khondalite, concordant to the pervasive gneissosity. Locally, the quartzite bands define intrafolial folds; the gneissosity of the host khondalite is axial planar to these folds and is therefore termed S_1 .

Charnockite occurs as massif-type bodies characterised by the presence of pervasive, but streaky, gneissic foliation. The charnockite hosts the bands and patches of other varieties of pyroxene-bearing granulites. The hornblende-granulite mostly occurs as bands, also as discordant patches, as well as folded layers, with gneissic foliation of the enclosing charnockite axial planar to these folds. The enderbite and two-pyroxene granulite occur as small lenticular patches, disposed along the foliation of the host charnockite. Such a mode of occurrence of these members of the pyroxene-bearing granulites indicates that they may be genetically connected. Kar *et al* (2003) documented that the massif-type charnockite is a tonalitic magma, product of hornblende-dehydration melting in the protolith of hornblende-granulite; the hornblende-granulite occurring as xenolith in it.

2.2 Structural setting

Three phases of folding are recognised from the granulite complex of the area (Kar 1995). Quartzite bands in the khondalite host and hornblende-granulite bands in the massif-type charnockite host define the intrafolial, reclined F_1 folds. The pervasive gneissic banding of the khondalite and streaky gneissic foliation of the charnockite-massif are axial planar to these minor F_1 folds, and are designated as S_1 . F_2 folds are commonly tight, and have axial planar foliation, defined by alignment of ribbon-shaped and platy quartz, plattung structure, known as leptynitic foliation after Sen (1987),

and designated S_2 . These F_2 folds occur on regional scale and determine the map-pattern of the area (figure 1). F_3 folds are regional broad warps, developed on regionally parallel S_1/S_2 fabrics. Notably, S_1 and S_2 foliations also dominate both the lithologies at limbs and noses of regional F_2 folds respectively. Also, overprinting of the S_1 foliation by S_2 foliation and complete obliteration of the earlier foliation at places are commonly observed.

The F_1 - F_2 folds generate both hook-shaped and arrowhead shaped interference pattern on profile section on outcrop scale. The form surface of these refolded folds is represented by a quartzite band in the khondalite host and hornblende-granulite band in the charnockite host. Kar (1999, 2001) described the regional fold geometry and detailed structural analysis of the area, which reveals that the regional geometry could be the result of a break in the deformation history. Also, the S_2 foliation often crosscuts the S_1 foliation at the noses of the regional F_2 folds and the transposition of S_1 by S_2 at places certainly attesting to this break.

2.3 Microstructures

The two prime lithologies of the area, khondalite and charnockite preserve two deformation fabrics, S_1 and S_2 , on hand-specimen scale also.

2.3.1 S_1 fabric

Garnet-ilmenite-sillimanite segregations define the S_1 gneissic banding in the khondalite. Two domains are readily identifiable, felsic domains and mafic domains. In the felsic domains, evidence of crystal plastic deformation is very clear within quartz and feldspar. Large quartz grains often show undulose extinction and deformation banding; occasional subgrains are also observed. Although xenoblastic texture is apparent, close scrutiny reveals an aggregate of relatively coarse-grained quartz, having irregular grain boundaries; commonly interpreted to be the product of grain boundary migration (GBM) recrystallisation (Passchier and Trouw 1996). Moreover, typical granoblastic textures are observed at places, possibly a product of static recrystallisation. In the mafic domains, on the other hand, garnet porphyroblasts are generally undeformed. Ilmenite and sillimanite grains sometimes show wavy foliation; the fairly coarse tabular crystals of sillimanite show optical discontinuity.

Lenticular accumulations of orthopyroxene, plagioclase and Fe-Ti-Oxides within a quartz-feldspar groundmass define the S_1 streaky gneissic foliation in the charnockite. Two domainal divisions, namely, lenticular mafic domains and felsic domains could be identified on microscopic scale.

The felsic domains are characterised by typical granoblastic texture with triple point contacts of coexisting mineral phases. Signatures of crystal plastic deformation are preserved in large grains: undulose extinction and occasional sub-grain formation in quartz and bending of twin lamellae in plagioclase. In the mafic domains, on the other hand, recrystallisation of fine moats of orthopyroxene along the margin of the large orthopyroxene grains is indicative of high temperature recrystallisation (Passchier and Trouw 1996). Also, exsolution lamellae of clinopyroxene in the host orthopyroxene are suggestive of the possibility of high temperature microstructural readjustment (Passchier and Trouw 1996).

2.3.2 S_2 fabric

At F_2 fold noses, S_1 gneissosity is virtually obliterated. The S_2 fabric in the khondalite is defined by arrangement of plates of quartz. Relatively fine-grained, polycrystalline and lenticular quartz with irregular grain boundaries define the S_2 fabric, which is interpreted to be the result of sub-grain rotation (SR) recrystallisation (Passchier and Trouw 1996). Static recrystallisation on this resulted in the platy granoblastic textures. This is the microscopic manifestation of the typical plattung structure (Merh 1962; Sen 1987), the so-called leptynitic foliation. The garnet porphyroblasts are generally deformed and occasionally show sigmoidal grain shapes with tapering ends. Also, the sillimanite and feldspars show sigmoidal grain shapes. The tapering ends of these sigmoidal porphyroblasts commonly form an acute angle with the characteristic leptynitic foliation, indicating deformation-induced growth of the porphyroblasts.

In the charnockite polycrystalline, relatively fine-grained and lenticular quartz-feldspar aggregates with irregular grain boundaries define the S_2 fabric. In extreme cases, this dynamic recrystallisation finally resulted in the formation of a mylonitic foliation. Sigmoidal orthopyroxene is also present.

Locally, in the felsic bands of the enderbite and two-pyroxene granulite typical platy granoblastic texture is common. This microstructural readjustment might have been related to the event responsible for the development of the S_2 fabric. Notably, hornblende-granulites never contain platy granoblastic texture. Mafic rich lithologies in them might have hindered such microstructural readjustment.

Thus the deformational regime and/or response during the development of S_1 and S_2 fabric in the similar lithologies might have been different. Simple shear component during the development of S_2 fabric was much higher. To summarize, structurally

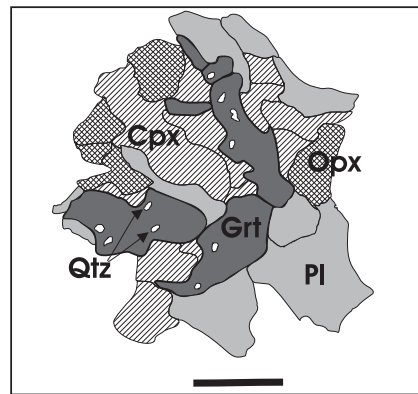


Figure 2. Sketch from photomicrograph showing garnet moat with occasional dactylitic quartz, separating clinopyroxene and plagioclase in hornblende-granulite. Scale bar: 5 μ .

there is convincing microstructural evidence for S_1 and S_2 , both characterised by high T minerals and with S_2 at an angle to S_1 . Also, almost complete obliteration of previous deformation fabric (S_1) and growth of new fabric (S_2) having distinct characteristic features indicate annealing during the latter fabric development.

3. Petrography

3.1 Mineral assemblages

Khondalite is characterised by the assemblage: quartz (60%) – K-feldspar (5%) – garnet (25%) – sillimanite (5%) – ilmenite (4%) – rutile (1%) \pm biotite. Notably, significant secondary biotite development, after garnet, is generally noticed in the samples having dominant S_2 -fabric. The members of the pyroxene-bearing granulites are characterised by the following primary assemblages. Charnockite: plagioclase (35%) – quartz (25%) – K-feldspar (25%) – orthopyroxene (10%) – Fe–Ti oxides (5%) \pm garnet \pm clinopyroxene \pm hornblende \pm biotite; hornblende-granulite: hornblende (35%) – clinopyroxene (20%) – orthopyroxene (15%) – plagioclase (27%) – quartz (2%) \pm garnet; two-pyroxene granulite: clinopyroxene (30%) – orthopyroxene (25%) – plagioclase (30%) – Fe–Ti oxides (5%) – quartz (8%) – K-feldspar (2%) \pm garnet \pm hornblende \pm biotite; enderbite: plagioclase (35%) – orthopyroxene (20%) – K-feldspar (17%) – quartz (15%) – clinopyroxene (13%) \pm garnet \pm Fe–Ti oxides \pm hornblende \pm biotite. Garnet, although one of the major mineral phases in all these lithologies, invariably preserves reaction relations, mostly rimming the pyroxenes or forming coronas on them (figures 2, 3 and 4). In some samples, garnet porphyroblasts are observed



Figure 3. Sketch from photomicrograph showing garnet-clinopyroxene-quartz intergrowth enclosing orthopyroxene with embayed grain boundaries in hornblende-granulite; note plagioclase inclusion within the intergrowth. Scale bar: $5\ \mu$.

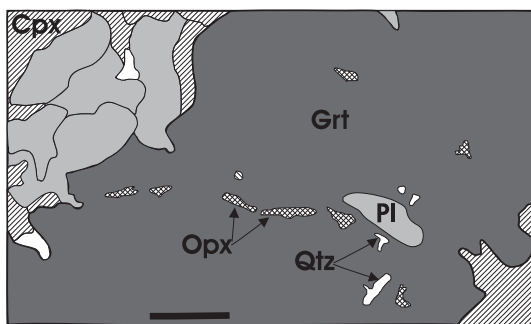


Figure 4. Sketch from photomicrograph showing xenoblastic garnet with inclusions of orthopyroxene and plagioclase in two-pyroxene granulite. Scale bar: $5\ \mu$.

enclosing the pyroxene and plagioclase. Pyroxenes in the two-pyroxene granulite assemblage occur in two distinct modes, one as inclusions within garnet and the other as matrix phases. Notably, they are compositionally distinct (section on mineral chemistry). Also, the abundant secondary growth of hornblende and biotite after pyroxenes is more pronounced in the samples with dominant S_2 -fabric.

4. Mineral chemistry

4.1 Analytical data

Mineral chemical data are obtained through Electron Probe Micro Analysis. EPMA work was carried out at the University Science Instrumentation Centre of Roorkee University and National Geophysical Research Institute, Hyderabad, using Jeol Jxa-8600M and Philips Camebax Microprobe Machine respectively. Operating conditions at Roorkee was 15 kV accelerating voltage, 0.5 nA sample current and $3\ \mu$ m beam diameter, while

those at Hyderabad were 15 kV and 20 kV accelerating voltage, 0.5 nA sample current and $2\ \mu$ m beam diameter. A few analyses were obtained from Yokohama National University, Japan using JEOL JSM-5300 electron microprobe and LINK QX2000J system (operating at 15 kV and 0.5 nA sample current).

4.2 Garnet

Mineral compositions of the garnet are presented in table 1. S_1 -garnets in the khondalite are almandine rich; X_{Gr} and X_{Sp} are insignificant. No compositional zoning is observed. However, some porphyroblasts show a marginal magnesian depletion towards the rim (sample no. 2/J96A, core: Py_{18} and rim: Py_{16}). S_2 -garnets are relatively magnesium rich (sample no. 2/J96B, $Alm_{76}Py_{21}$), although some relatively less magnesian garnet are also present along the S_2 fabric; these may represent relict S_1 -garnet. Notably, garnet overgrowths are more magnesian than idioblastic core (sample no. 2/J78A, core: $Py_{17}Alm_{78}$ and overgrowth: $Py_{20}Alm_{74}$).

Garnets in the hornblende-granulite are nearly homogeneous in composition, containing 54–55% almandine, 24–25% pyrope, 15–17% grossular, but slightly variable from sample to sample. Significantly, no marked distinction in composition is noticed when it rims different phases like orthopyroxene and clinopyroxene; although slight magnesium depletion towards rims in relatively thicker coronas is noticeable.

S_1 -garnets of two-pyroxene granulites are generally homogeneous, although markedly different from sample to sample. However, some large porphyroblasts show subtle iron enrichment towards the rim (core: $Py_{34}Alm_{48}And_1Gr_{15}$ and rim: $Py_{33}Alm_{49}And_5Gr_{12}$). On the other hand, S_2 -garnets are less magnesian but homogeneous with 57–58% almandine, 21–23% pyrope and 15–18% grossular contents. The most noticeable feature is the marginal subtle magnesium enrichment in thicker coronas, unlike the other coronal garnets in S_1 dominated hornblende-granulite and two pyroxene-granulites.

4.3 Pyroxene

Mineral chemistry of pyroxenes is presented in table 2. Clinopyroxenes of the hornblende-granulite are basically augites with low jadeite–acmite components (maximum 3.6 mol.%) and insignificant octahedral Al (maximum 0.05). However, in some samples the clinopyroxenes have quite higher jadeite–acmite component (maximum 5.4 mol.%) and markedly high octahedral Al contents (0.09

Table 1. *Representative garnet compositions from different lithologies.*

Rock type	Khondalite				Hornblende granulite				Two-pyroxene granulite						
	2/J96A S ₁		2/J78A S ₁		2/J96B S ₂		JN95B S ₁		2/J50 S ₁		2/J70B S ₁		2/J67C S ₁		2/J154 S ₂
Sample no. Fabric	Core 2/1	Rim 2/2	Core 2/3	Overgrowth 2/4	Core 2/5	Core 2/6	Core 2/8	Core 2/9	Core 2/10	Rim 2/11	Core 2/12	Core 2/13	Core 2/14	Rim 2/15	
Location Reference no.															
SiO ₂	37.08	37.82	39.09	38.34	38.85	37.32	39.52	39.17	39.49	39.55	37.42	39.04	38.40	38.64	
TiO ₂	0.00	0.00	0.00	0.00	0.00	0.02	0.03	0.00	0.05	0.11	0.00	0.05	0.02	0.09	
Al ₂ O ₃	21.26	21.47	21.69	21.95	21.69	22.63	21.95	22.12	21.96	21.19	20.69	22.39	21.19	21.73	
Cr ₂ O ₃	0.00	0.00	0.00	0.00	0.00	0.00	0.35	0.00	0.18	0.00	0.00	0.00	0.12	0.46	
FeO	34.49	34.30	33.84	32.23	34.19	33.96	24.75	23.29	22.42	24.25	27.36	24.41	27.27	26.69	
MnO	0.89	1.21	1.07	1.25	0.98	1.03	0.90	0.63	0.50	0.64	2.38	3.46	0.94	0.94	
MgO	4.35	3.89	3.98	4.84	4.46	5.27	6.37	7.54	8.87	8.43	4.37	5.20	5.48	5.93	
CaO	0.32	0.00	1.00	1.01	0.43	0.38	6.90	7.02	6.30	6.12	6.51	5.94	6.49	6.67	
Total	98.40	98.67	100.66	99.62	100.60	100.61	100.76	99.77	99.77	100.29	98.73	100.49	99.91	101.15	
Si IV	5.97	5.99	6.00	5.97	6.00	5.83	6.00	6.00	6.00	6.00	5.98	6.00	6.00	5.96	
Al IV	0.03	0.01	0.00	0.03	0.00	0.17	0.00	0.00	0.00	0.00	0.02	0.00	0.00	0.04	
Al VI	4.00	4.00	3.92	4.00	3.95	4.00	3.93	3.99	3.93	3.79	3.87	4.06	3.90	3.90	
Ti VI	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.01	0.01	0.00	0.01	0.00	0.01	
Cr	0.00	0.00	0.00	0.00	0.00	0.00	0.04	0.00	0.02	0.00	0.00	0.00	0.02	0.06	
Fe ⁺³	0.00	0.00	0.08	0.00	0.05	0.00	0.03	0.01	0.04	0.20	0.13	0.00	0.08	0.03	
Fe ⁺²	4.64	4.54	4.27	4.20	4.36	4.44	3.12	2.98	2.81	2.88	3.52	3.14	3.48	3.41	
Mn ⁺²	0.12	0.16	0.14	0.16	0.13	0.14	0.12	0.08	0.06	0.08	0.32	0.45	0.12	0.12	
Mg	1.04	0.92	0.91	1.12	1.03	1.23	1.44	1.72	2.01	1.91	1.04	1.19	1.28	1.36	
Ca	0.06	0.00	0.17	0.17	0.07	0.06	1.12	1.15	1.03	0.99	1.11	0.98	1.09	1.10	
Alm %	79.00	81.00	78.00	74.00	79.00	76.00	54.00	50.00	48.00	49.00	59.00	55.00	58.00	57.00	
Py %	18.00	16.00	17.00	20.00	18.00	21.00	25.00	29.00	34.00	33.00	17.00	21.00	21.00	23.00	
Sp %	2.00	3.00	2.00	3.00	2.00	2.00	2.00	2.00	1.00	1.00	5.00	7.00	2.00	2.00	
Gr %	1.00	0.00	1.00	3.00	0.00	1.00	17.25	18.75	15.50	12.00	13.75	17.00	16.50	15.25	
And %	0.00	0.00	2.00	0.00	1.00	0.00	0.75	0.25	1.00	5.00	3.25	0.00	2.00	0.75	
Uvr %	0.00	0.00	0.00	0.00	0.00	0.00	1.00	0.00	0.50	0.00	0.00	0.00	0.50	1.50	

Table 2. Representative pyroxene compositions from different lithologies.

Rock type	Hornblende granulite						Two-pyroxene granulite						
	S ₁			S ₁			S ₁			S ₂			
	JN95B		2/J50	2/J55		Matrix phase	1/J12		2/J70B	2/J67C		2/J154	
Location	Core	Included phase	Core	Matrix phase	Included phase	Core	Core	Core	Core	Core	Core	Core	
Reference no.	3/1	3/2	3/3*	3/4	3/5	3/6*	3/7*	3/8	3/9*	3/10	3/11	3/12	3/13
SiO ₂	50.86	51.98	52.54	51.42	53.58	52.12	52.88	51.90	51.47	53.06	51.27	53.02	52.37
TiO ₂	0.31	0.16	0.01	0.18	0.00	0.00	0.07	0.24	0.06	0.15	0.00	0.13	0.23
Al ₂ O ₃	3.18	2.47	1.85	3.34	4.16	0.43	1.71	3.63	0.51	1.97	3.09	2.93	2.39
FeO	8.12	7.04	21.50	8.59	7.24	21.70	23.07	8.48	25.67	8.85	11.39	11.59	9.33
MnO	0.17	0.16	0.31	0.15	0.00	0.31	0.58	0.19	0.68	0.24	0.00	0.22	0.04
MgO	14.76	14.84	24.37	13.80	13.10	25.31	21.84	12.77	21.90	13.52	10.95	11.52	15.18
CaO	21.08	21.43	0.38	21.16	21.23	0.41	0.40	21.73	0.37	21.18	19.80	18.77	20.76
Na ₂ O	0.76	0.82	0.00	0.93	1.48	0.03	0.00	0.67	0.23	0.94	1.78	1.58	0.36
K ₂ O	0.04	0.03	0.02	0.00	0.00	0.04	0.01	0.00	0.01	0.00	0.00	0.30	0.01
Total	99.28	98.92	100.97	99.57	100.78	100.34	100.56	99.61	100.90	99.89	98.27	100.06	100.67
Si IV	1.89	1.93	1.92	1.91	1.95	1.91	1.96	1.94	1.91	1.97	1.95	1.98	1.93
Al IV	0.11	0.07	0.08	0.09	0.05	0.02	0.04	0.06	0.02	0.03	0.05	0.02	0.07
Al VI	0.02	0.04	0.00	0.05	0.13	0.00	0.04	0.10	0.00	0.06	0.08	0.11	0.03
Ti	0.01	0.00	0.00	0.00	0.00	0.00	0.00	0.01	0.00	0.00	0.00	0.00	0.01
Fe ⁺³	0.13	0.00	0.00	0.00	0.02	0.17	0.00	0.00	0.17	0.03	0.10	0.03	0.00
Fe ⁺²	0.12	0.22	0.66	0.27	0.20	0.49	0.72	0.26	0.63	0.24	0.26	0.33	0.29
Mn ⁺²	0.01	0.01	0.01	0.00	0.00	0.01	0.02	0.01	0.02	0.01	0.00	0.01	0.00
Mg	0.82	0.82	1.32	0.76	0.71	1.38	1.21	0.71	1.21	0.75	0.62	0.64	0.83
Ca	0.84	0.85	0.01	0.84	0.83	0.02	0.02	0.87	0.01	0.84	0.80	0.75	0.82
Na	0.05	0.06	0.00	0.07	0.10	0.00	0.00	0.05	0.02	0.07	0.13	0.11	0.03
K	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.01	0.00
En %	41.60	41.80	66.00	39.20	38.20	69.00	62.00	37.40	64.00	38.70	32.50	34.20	42.10
Fs1 %	13.20	11.70	33.00	13.90	11.80	30.00	37.00	14.20	35.50	14.40	18.80	19.80	14.70
Wo %	42.60	43.40	1.00	43.30	44.60	1.00	1.00	45.80	0.50	43.30	41.90	40.10	41.60
Ac - Jd %	2.60	3.10	0.00	3.60	5.40	0.00	0.00	2.60	0.00	3.60	6.80	5.90	1.60

* Orthopyroxene.

to 0.13). This sample (no. 2/J50) is orthopyroxene-free and has euhedral garnet. Interestingly, clinopyroxene included in garnet and as matrix phase are markedly different in composition, the matrix phase being more iron rich (sample no. JN95B, included phase: $\text{En}_{42}\text{Fsl}_{11}\text{Wo}_{43}$ and matrix phase: $\text{En}_{39}\text{Fsl}_{14}\text{Wo}_{43}$). Orthopyroxenes are typically hypersthene with 66 mol.% of enstatite with very low Al_2O_3 content (up to 1.85 wt.%).

The S_1 -clinopyroxenes in the two-pyroxene granulite are also augites. Marked compositional difference is noticed from sample to sample, especially in terms of jadeite–acmite contents and octahedral aluminium contents. Two groups are noticed, one having relatively high jadeite–acmite component and octahedral Al contents (maximum 6.8 mol.% and 0.12 respectively) compared to the other (Jd–Ac: maximum 3.6 mol.% and octahedral Al: 0.06). Orthopyroxenes are hypersthene with slight variation in composition from sample to sample. Octahedral Al content is very low, varying between 0.02 and 0.04. The orthopyroxene occurring as an included phase within garnet is more magnesian than matrix one (sample no. 2/J55, included phase: $\text{En}_{69}\text{Fsl}_{30}$ and matrix phase: $\text{En}_{62}\text{Fsl}_{37}$). S_2 -Clinopyroxene in the two-pyroxene granulites is also a solid solution of diopside–hedenbergite and contains low jadeite (1.6 mol.%) and octahedral Al (0.07).

4.4 Ilmenite

Ilmenite in both the S_1 and S_2 dominated samples of khondalite are almost pure variety; X_{Ilmenite} is 98–99 mol.%. However, a slight variation of composition is also noticed; the included ilmenite in garnet is marginally less magnesian (table 3).

4.5 Feldspar

Plagioclase feldspars of hornblende-granulite are mostly oligoclase-andesine variety with 29–32% of anorthite. On the other hand, the plagioclases of two-pyroxene granulites are strictly andesine and are fairly rich in anorthite content: 36–38% (table 4).

4.6 K_D values

K_D values are provided in table 5. In hornblende-granulite, $K_D^{\text{Cpx–Grt}}$ $[(\text{Fe}/\text{Mg})^{\text{Cpx}}/(\text{Fe}/\text{Mg})^{\text{Grt}}]$ values of six coexisting pairs vary within a short range (0.15–0.19). The rim compositions for the same pairs show either similar or marginally lower K_D values. Coexisting pyroxenes have high $K_D^{\text{Cpx–Opx}}$ $[(\text{Fe}/\text{Mg})^{\text{Cpx}}/(\text{Fe}/\text{Mg})^{\text{Opx}}]$ value, 0.71, indicating a high temperature record.

Table 3. Representative ilmenite compositions from khondalite.

Fabric	S_1		S_2	
	2/J96A		2/J96B	
Sample no.	Inclusion	Inclusion	Matrix	
Location	4/1	4/2	4/3	
Reference no.				
SiO ₂	0.42	0.04	0.01	
TiO ₂	52.76	49.94	49.36	
Al ₂ O ₃	0.00	0.00	0.00	
Cr ₂ O ₃	0.00	0.06	0.06	
FeO	44.69	49.27	48.96	
MnO	0.00	0.37	0.10	
MgO	0.50	0.00	0.99	
CaO	0.00	0.00	0.00	
Total	98.37	99.68	99.48	
Si	0.01	0.00	0.00	
Ti	1.01	0.95	0.93	
Al	0.00	0.00	0.00	
Cr	0.00	0.00	0.00	
Fe ⁺³	0.00	0.10	0.13	
Fe ⁺²	1.01	0.94	0.89	
Mn	0.00	0.01	0.00	
Mg	0.02	0.00	0.04	
Ca	0.00	0.00	0.00	
Ilmenite %	98.00	99.00	96.00	
Geikelite %	2.00	0.00	3.00	
Phanite %	0.00	1.00	1.00	

In two-pyroxene granulite, K_D values of two spatially separated clinopyroxene–orthopyroxene pairs are also high (0.62 and 0.69) in one sample (no. 2/J55), thereby suggesting a high temperature signature. In another sample (1/J12), two orthopyroxene–clinopyroxene pairs register lower K_D values, 0.58 and 0.54, for the core–core and rim–rim compositions. Notably, the latter samples are more magnesian (#Mg no. 62) than the former (#Mg no. 55), thereby conclusively indicating the temperature dependence of the K_D values. $K_D^{\text{Cpx–Grt}}$ values for the core compositions are almost constant (0.15–0.17) with marginal changes towards the rim. In another sample, three coexisting but spatially separated clinopyroxene–garnet pairs show similar K_D values (0.14, 0.15, 0.19) for the core compositions. Coronal garnet on clinopyroxene, records higher K_D value (0.16) for composition of the points away from the contact than that of the points near the contact (0.11), thereby indicating substantial cooling.

Table 4. Representative plagioclase composition from different lithologies.

Rock type Fabric Sample no.	Hornblende-granulite S ₁ JN95B		Two-pyroxene granulite S ₁ S ₂ 2/J55 2/J154	
	Inclusion 5/1	Inclusion 5/2	Inclusion 5/3	Inclusion 5/4
SiO ₂	61.64	62.23	60.68	59.90
Al ₂ O ₃	24.63	25.38	25.25	25.50
CaO	6.19	5.87	6.90	7.38
Na ₂ O	7.24	7.53	6.40	6.51
K ₂ O	0.26	0.33	0.25	0.22
Total	99.95	101.34	99.47	99.51
Si	2.76	2.74	2.74	2.70
Al	1.30	1.32	1.35	1.36
Ca	0.30	0.28	0.33	0.36
Na	0.63	0.64	0.56	0.57
K	0.02	0.02	0.02	0.01
Anorthite %	32.00	29.50	36.70	38.00
Albite %	67.00	68.50	61.70	60.60
Orthoclase %	1.00	2.00	1.60	1.40

Table 5. K_D values of different co-existing mineral phases.

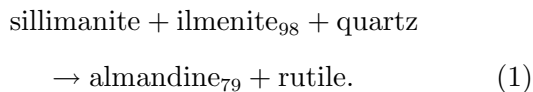
Rock type	Sample no. (fabric)	Pair no.	K_D (Cpx-Opx)		K_D (Cpx-Grt)	
			Core-core	Rim-rim	Core-core	Rim-rim
Hornblende-granulite	JN95B (S ₁)	Co-existing pair 1	0.71			
	2/J50 (S ₁)	Co-existing pair 1			0.18	0.18
		Co-existing pair 2			0.18	0.16
		Co-existing pair 3			0.15	0.15
		Co-existing pair 4			0.19	0.19
		Co-existing pair 5*			0.18	0.15
		Co-existing pair 6			0.16	0.15
Two-pyroxene granulite	2/J55 (S ₁)	Co-existing pair 1	0.57			
		Co-existing pair 2	0.62			
		Co-existing pair 3	0.69			
	1/J12 (S ₁)	Co-existing pair 1	0.58	0.57		
		Co-existing pair 2	0.54	0.57		
	2/J70B (S ₁)	Coronal garnet*			0.16	0.11
		Co-existing pair 1			0.16	0.15
		Co-existing pair 2			0.17	0.18
		Co-existing pair 3			0.15	0.15
		Co-existing pair 1				
	2/J67C (S ₁)	Co-existing pair 1			0.14	
		Co-existing pair 2*			0.19	0.16
		Co-existing pair 3			0.15	0.16

* P , T estimates of these mineral pairs are provided in table 6.

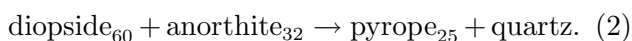
5. Reaction textures and metamorphic reactions

5.1 S_1 -microdomains

S_1 -garnet porphyroblasts in khondalite generally contain inclusion trails of sillimanite and/or ilmenite and/or quartz, indicating their appearance from an early ilmenite–sillimanite–quartz assemblage.

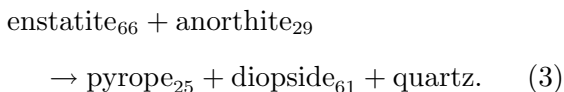


Common garnet–quartz symplectite with inclusions of clinopyroxene and plagioclase in hornblende–granulite is suggestive of the reaction



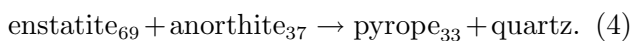
Garnet moats separating clinopyroxene and plagioclase (figure 2) also support this reaction.

The intergrowth texture involving garnet, clinopyroxene and quartz enclosing relict orthopyroxene and plagioclase (figure 3), possibly indicates a reaction of the type:



Notably, Harley (1989) pointed out the possibility of this reaction from quartz bearing mafic granulites. Dasgupta *et al* (1991) also noted this reaction from the mafic granulites of the Eastern Ghats belt.

Xenoblastic garnet in two-pyroxene granulite with inclusion of orthopyroxene and plagioclase is frequently noticed (figure 4), and this is suggestive of the reaction:



As the matrix also contains the included phases, especially orthopyroxene, the definite indicator of this reaction should be their compositional difference (Vernon 1996); the matrix phase here is less magnesian (En_{62}). Also, inclusion-free coronal garnet occurs on clinopyroxene, definitely suggesting their formation on cooling.

5.2 S_2 -microdomains

Although S_2 -garnet porphyroblasts with inclusion trails are rare, the commonly observed reaction texture is the relict sillimanite–ilmenite association separated from quartz by garnet, and

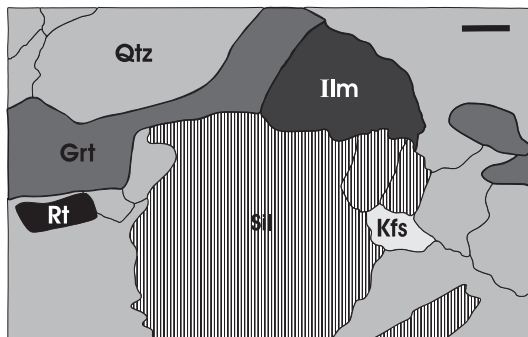


Figure 5. Sketch from photomicrograph showing neoblastic garnet separating sillimanite–ilmenite association from quartz in khondalite; note presence of rutile in the vicinity. Scale bar: 10 μ .

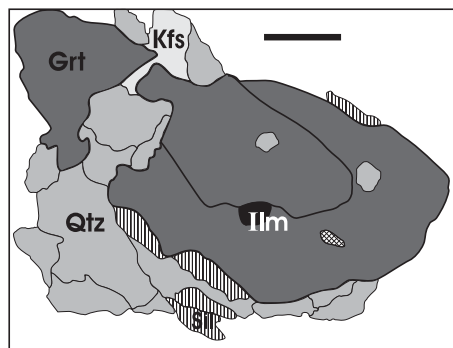
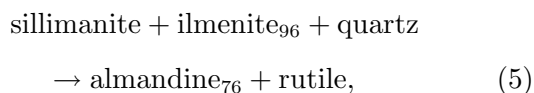


Figure 6. Sketch from photomicrograph showing garnet overgrowth on early euhedral garnet in khondalite. The early garnet is less magnesian (Py_{17}) than overgrowth (Py_{20}). Scale bar: 5 μ .

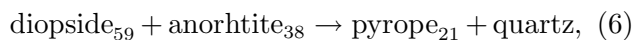
occurrence of rutile in the vicinity (figure 5), indicating that the garnet is mostly the product of reaction:



similar to reaction (1), but with different compositions.

The development of garnet overgrowth on early idioblastic garnet (figure 6), is consistent with this later garnet growth. The euhedral core is relict porphyroblast and is less magnesian ($\text{Py}_{17}\text{Alm}_{78}$ – against $\text{Py}_{20}\text{Alm}_{74}$ of the overgrowth).

Most of the S_2 -garnet xenoblast in two-pyroxene granulite contains inclusion of clinopyroxene and plagioclase (figure 7), which is suggestive of the garnet forming reaction:



similar to reaction (2), but with different compositions.

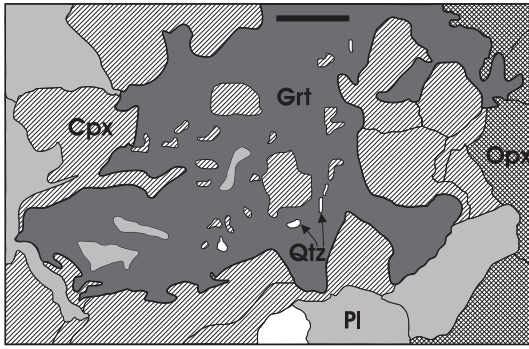


Figure 7. Sketch from photomicrograph showing garnet xenoblast with inclusions of clinopyroxene and plagioclase in two-pyroxene granulite. Scale bar: 5 μ .

The enhanced degree of reaction and new garnet formation in S_2 is a consequence of moving to lower T - P with increasing facilitation of reaction. The equilibrations are at least divariant. Notably, the aluminosilicates in the S_2 samples are more abundant, thereby suggesting relative lower temperature of the assemblage, although garnet breakdown reaction is not noticed.

6. Metamorphic evolution

Thermometric and barometric calculations have been made using TWEEQU (Berman 1991) approach. Berman (1991) has shown that with the proper choice of solution models, this technique may estimate temperature and pressure with uncertainties less than $\pm 40^\circ\text{C}$ and less than ± 0.5 kbar respectively. Thermodynamic parameters of different minerals are taken from the internally consistent data set of Berman (1988 and updated database of 1992). Additionally, the activities of the mineral phases like quartz, rutile, sillimanite are taken to be unity (assumed to be pure phase).

For precise thermobarometric analysis, a proper choice of solution model for interacting phases is necessary. For garnet, the quaternary solid solution of Berman (1990) is adopted as the garnets of the present assemblages contain fairly high grossular contents. For plagioclase, the solution model of Fuhrman and Lindsley (1988) is used in view of the high anorthite content of the plagioclase. For pyroxenes, the ideal on-site solution model is adopted here as inconsistent results are reported by Bhattacharya *et al* (1991) and Bhattacharya *et al* (1993) when using binary solution models of Wood and Banno (1973). Further, Bhattacharya *et al* (1993) also noted that the internally consistent database, used here, does not fit to the solution model of Wood and Banno (1973).

6.1 P - T record

6.1.1 S_1 dominated samples

No independent Fe-Mg exchange thermometer is available for the khondalites, due to the absence of suitable Fe-Mg phase other than garnet. However, good barometry is available from the garnet-ilmenite-rutile-sillimanite-quartz assemblage (GRAIL). The GRAIL barometer yields a pressure estimate of 8.5 kbar, estimated from reaction (1) at a temperature of 850°C (table 6).

In the hornblende-granulites, coexisting pyroxene pairs yield temperatures of the order of 950°C . Six pairs of coexisting clinopyroxene-garnet yield temperatures between 660°C and 800°C . Garnet moats separating clinopyroxene and plagioclase, indicating reaction (2), register a variation of temperature between 740°C and 640°C at 8.6 kbar for the core and rim compositions respectively. Formation of garnet-clinopyroxene-quartz symplectites from orthopyroxene and plagioclase, indicating reaction (3), is estimated to have occurred at 9 kbar, 770°C (table 6). The peak P - T conditions retrieved from the sample no. JN95B using the convergence method is given by the intersection of Opx-Cpx thermometer and GOPCQ barometer as 950°C and 9.0 kbar.

The highest temperatures of the order of 900°C and 800°C are recorded from two-pyroxene granulite, using coexisting orthopyroxene-clinopyroxene pairs. On the other hand, coexisting garnet-clinopyroxene pairs yield temperatures in the range of 750°C - 800°C and 650°C - 800°C in different samples. However, coronal garnet on clinopyroxene yields temperatures of 800°C and 600°C from the points away from the contact and points adjacent to the contact respectively; thus a 200°C cooling is indicated. The different estimated temperatures for different coexisting pairs might thus represent 'frozen' temperatures of microdomains (Frost and Chacko 1989).

Garnet - orthopyroxene - plagioclase - quartz (GOPQ) barometry applied to a garnet-bearing two-pyroxene granulite yields pressure estimate 9.5 ± 0.5 kbar, consistent with garnet-clinopyroxene-plagioclase-quartz (GCPQ) barometry of 8.9 ± 0.5 kbar on the same sample. The peak P - T conditions retrieved from the sample no. 2/J55 using the convergence method is given by the intersection of Opx-Cpx thermometer and GOPQ barometer as 900°C and 9.5 kbar.

6.1.2 S_2 dominated samples

The GRAIL barometer, applied in garnet forming reaction (5), yields a pressure values of

Table 6. P - T estimates from different rocks.

Rock type	Sample no./fabric	Thermometer	Location	$T(^{\circ}\text{C})$	
Hbl-granulite	JN95B/S ₁	Opx-Cpx	Core	950	
	2/J50/S ₁	Grt-Cpx	Core	800	
			Rim	660	
Two-px-granulite	2/J55/S ₁	Opx-Cpx	Core	900	
	1/J12/S ₁	Opx-Cpx	Core	800	
	2/J70B/S ₁	Grt-Cpx	Core	800	
			Rim	750	
			Core (c)	800	
			Rim (c)	600	
			Core	800	
	2/J67C/S ₁	Grt-Cpx	Rim	650	
Rock type	Sample no./fabric	Barometer	Location	P (kbar)	$T(^{\circ}\text{C})$
Khondalite	2/J96A/S ₁ (-)	GRAIL	Core	8.5 (Fe)	
	2/J96B/S ₂ (*)	GRAIL	Core	6.2 (Fe)	
Hbl-granulite	JN95B/S ₁ (#)	GCPQ	Core	8.6 (Mg)	740 (Grt-Cpx)
			Rim	8.6 (Mg)	640 (Grt-Cpx)
	JN95B/S ₁ (\$)	GOPCQ	Core	9.0 (Mg)	770 (Grt-Cpx)
Two-px-granulite	2/J55/S ₁ (+)	GOPQ	Core	9.5 (Mg)	750 (Grt-Opx)
	2/J55/S ₁ (#)	GCPQ	Core	8.9 (Mg)	825 (Grt-Cpx)
	2/J154/S ₂ (^)	GCPQ	Core	6.3 (Mg)	600 (Grt-Cpx)

(-) – reaction 1 (#) – reaction 2, (\$) – reaction 3, (+) – reaction 4, (*) – reaction 5, (^) – reaction 6,
(c) – coronal garnet on Cpx, core and rim are points away from and adjacent to contact respectively
Opx – Orthopyroxene, Grt – Garnet, Cpx – Clinopyroxene
GCPQ – garnet-clinopyroxene-plagioclase-quartz barometer
GRAIL – garnet-aluminosilicate-ilmenite barometer
GOPQ – garnet-orthopyroxene-plagioclase-quartz barometer
GOPCQ – garnet-orthopyroxene-plagioclase-clinopyroxene-quartz barometer
(Fe) – Calculation based on Fe-end members
(Mg) – Calculation based on Mg-end members
Hbl-granulite – Hornblende bearing mafic granulite
Two-px-granulite – Two-pyroxene granulite

6.2 ± 0.5 kbar. GCPQ barometry, applied to the reaction texture showing clinopyroxene and plagioclase inclusions in the garnet porphyroblasts (reaction 6) registered a pressure estimate of 6.3 ± 0.5 kbar at 600°C .

Thus, a significant difference of pressure of equilibration, namely ~ 8.5 – 9 kbar and ~ 6 kbar is noted between S₁ and S₂. Also, high-pressure samples generally register higher temperature of the order of 900°C or more. Notably, this P difference of ca. 2.5 kbar is not related to the dP/dT of the barometer and the ΔT (ca. 800°C vs. 600°C) involved.

6.2 P - T - t path

Although strong S₁ fabric is recorded from the khondalites and pyroxene bearing granulites,

a more complete record of changing pressure-temperature conditions during F₁ deformation is preserved in the pyroxene bearing granulites only. The khondalites only record near peak P estimates of 8.5 kbar. Pyroxene bearing granulites record cooling of about 350°C from peak temperatures of more than 950°C . This cooling vector is nearly isobaric at pressures between 9.5 kbar and 8.5 kbar and possibly triggered the reactions (1), (2), (3) and (4) (figure 8). Subtle magnesian depletion of the garnet in relatively thicker coronas within hornblende-granulite, two-pyroxene granulite and khondalite is also consistent with this cooling (sample nos. 2/J96A and 2/J55 in table 1).

On the other hand, the S₂-garnet of the khondalites, documenting reaction 5, yield a pressure estimate of 6.2 kbar, using GRAIL barometer (table 6). In the two-pyroxene granulite, a pressure

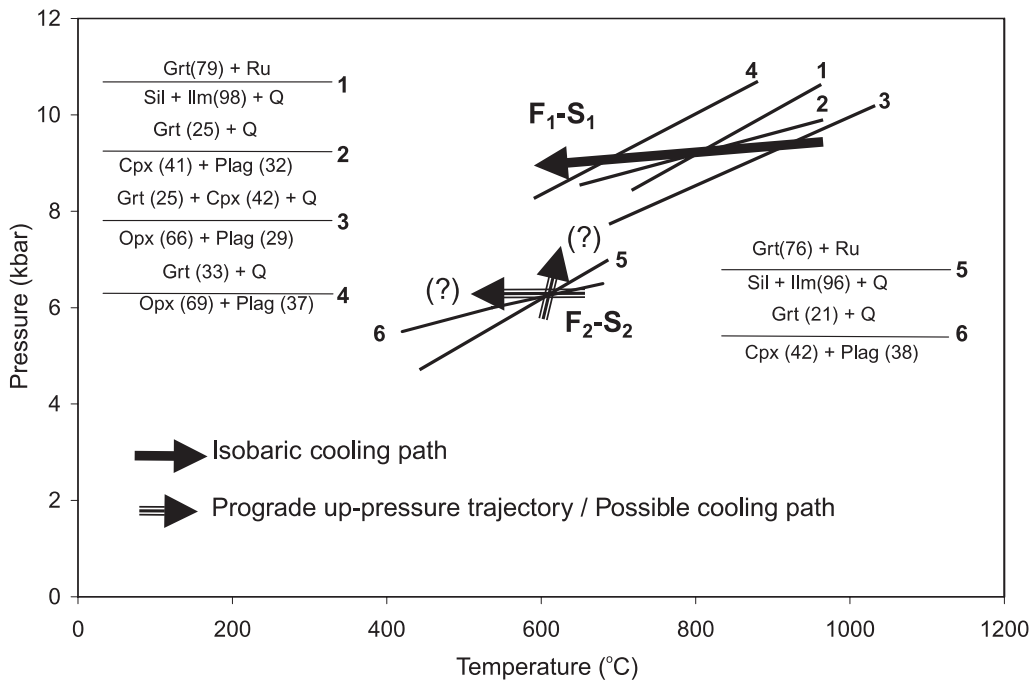


Figure 8. Pressure–temperature diagram showing the univariant lines for the studied metamorphic reactions with actual mineral compositions. Also shown are the possible P – T paths, associated with two deformation episodes.

estimate of 6.3 kbar at 600°C, from GCPQ barometer for the reaction (6) is noted. The sense of these reactions suggests cooling at ~ 6 kbar pressure or a prograde pressure-increase. Formation of magnesium rich garnet overgrowths on early garnet in khondalite and marginal magnesium enrichment in relatively thicker garnet coronas on pyroxene in two-pyroxene granulite collectively point to this possible up-pressure trajectory (figure 8). An alternative interpretation, that of cooling, may still be valid. Nevertheless, there is a distinct pressure difference between the S_1 and S_2 metamorphic conditions. This provides strong evidence for a break in the P – T evolution in this granulite complex.

7. Discussion

A regional granulite terrain, having the imprints of both Grenvillian and pre-Grenvillian thermal events is likely to have newly accreted crustal materials along with older reworked crustal components (Harley 1992). Another important finding regarding these terrains is that both these crustal components are typified by similar mineral assemblages, attesting to similar physical conditions over very large regions. These pose a serious problem regarding the derivation of P – T loops; the different segments of the loop may link isotopically distinct P – T vectors (Barton *et al* 1994).

The Eastern Ghats granulite belt, India is no exception; the belt contains all these general characteristics. Petrological evidence of polymetamorphism in the Eastern Ghats belt were presented by Grew and Manton (1986) and Sen *et al* (1995) from different parts of this regional granulite terrain; however, this could not be established with isotopic data. Some recent studies have pointed out the existence of several distinct crustal domains with unconnected pre-metamorphic histories (Rickers *et al* 2001; Bhattacharya and Gupta 2001). It is desirable, therefore, that polymetamorphism and/or reworking should be documented from the individual granulite suites in the different crustal domains in the Eastern Ghats. Note that the present area of interest is included in the domain IV (2.5–2.9 Ga) of Rickers *et al* (2001).

The arguments for polymetamorphism in the present study can be summarised as follows. Firstly, the geometry of the regional F_1 and F_2 folds suggests a break in the deformation history (Kar 1999, 2001), with the late deformational fabric (S_2) completely obliterating the early fabric (S_1) on local scale. Secondly, generally the mineral assemblages of S_1 -domains reflect a relatively high peak P – T regime of 9.5 kbar at 950°C, whereas the P – T regime of the assemblages of S_2 -domains is generally lower, 6.3 kbar at 600°C. Thirdly, the reaction textures in the assemblages of S_1 fabrics indicate post-peak cooling through 200–350°C at 9.5–8.5 kbar, while the reaction textures in the assemblages of the S_2 fabrics results

either from cooling or an increase in pressure at 600°C from 6 kbar (figure 8). The two distinct P - T - D regimes are considered to reflect the overprinting of an Archaean high-grade metamorphism (F_1 - S_1), as documented by Bhattacharya *et al* (2001), by an unrelated F_2 - S_2 event, most likely of Grenvillian age. The possibility of reworking of the Archaean crust during Grenvillian orogeny is interpreted from the Pb isotopic signatures of the Domain IV (Gupta 2004).

8. Concluding remarks and implications

- In regional granulite terrains with evidence of different crustal domains interpretation of geochronological data from different parts in terms of polymetamorphism is at best speculation.
- Even in the absence of isotopic data, polymetamorphism in a granulite complex may be indicated petrologically in terms of break in the P - T record.
- Polymetamorphism and reworking, when established from several sectors of the regional Eastern Ghats granulite belt, will lead to better understanding of the East Gondwana correlation, especially with the Antarctic granulite belt.

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