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New Insights into the Origin of Kabbaldurga Charnockites, Karnataka, South India

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Abstract

A detailed study of the structure and petrology of the rocks bordering the Kabbaldurga-type charnockites provides important constraints on the origin of these charnockites. The structural elements register three phases of deformation and show a uniform pattern in the larger area, a pattern consistent with the regional structure of the Precambrian of Southern Karnataka. In the Kabbaldurga area, however, some of the earlier structures are poorly preserved. Yet there are vestiges of early folds described by banded/layered charnockites as in the neighbouring Kodamballi area, and a consistent development of dilatant structures which can be related to the kinematics of deformation in the larger terrain. At Kabbaldurga the pegmatitic charnockites occur as veins of diverse orientation; but they rarely follow the shear – generated structures.

The metamorphic reactions invoked by previous workers to explain *in situ* transformation of gneiss to charnockite were based on chemical similarity of some close pairs. But the petrographic and chemical variations in the pegmatitic charnockites and the Peninsular gneisses at Kabbaldurga quarry are compelling features which cannot be explained by the hypothesis of *in situ* transformation. We have argued, on the basis of rock and mineral chemistry, that derivation of the pegmatitic charnockites by dehydration melting in metabasites offers a better explanation. Pressure-temperature values (at least 850° to 900° C, 7 kbar) obtained by us for the granulites of this area , viewed against the results of experimental dehydration melting in basic rocks with hornblende and /or biotite, provide strong support for this model. In the field leucosomes within the basic granulites of Kabbaldurga are not uncommon. The compositions of the pegmatitic charnockites (tonalitic and granitic) match those of the melts produced in experiments. Further, the pattern of variation in the composition of hornblende and plagioclase in the basic granulites of the Kabbaldurga area is compatible with extraction of melts. This alternative model for the origin of the Kabbaldurga charnockites is petrologically feasible and does not require either *in situ* transformation or structurally controlled growth, which, incidentally, are not ubiquitous at Kabbaldurga.

Key words: Charnockites, basic granulites, polyphase deformation, shear fractures, dehydration-melting.

Introduction

The Kabbaldurga (Kabbal hereafter) charnockite quarry in southern Mysore is a well known locality. Following the initial observation of Pichamuthu (1960) that Peninsular gneisses were being transformed to charnockites, a large number of publications have advocated the hypothesis of charnockitisation aided by fluid ingress (Janardhan et al., 1982; Friend, 1985; Hansen et al., 1987; Stahle et al., 1987). Several lines of evidence pertaining to field structures, petrography and geochemistry have been advanced to explain the mechanism of the assumed *in situ* transformation. The favoured mechanism was that of fluid ingress, styled carbonic metamorphism by Newton et al. (1980), through channelways created by deformation. However, the relation of these channelways to the kinematics of regional deformation was not explored by the earlier workers, who, incidentally, missed out on the presence of non-patchy charnockites and granulites further north.

A comprehension of the deformational and petrological setting in a larger canvas is badly needed because the Kabbal quarry is characterised by coarse grained charnockites, migmatites and gneisses with a complex deformation pattern and by a limited number of lithological varieties.

In this paper we have treated the structure and petrology of the Kabbal area in the light of the larger geological setup and for this purpose have mapped the Kodamballi area which is about 15 km north of Kabbal. This area was taken up for understanding how charnockites and granulites relate to the regional structures. Significantly, this structurally older charnockite – granulite suite can still be traced at Kabbal, though they are overshadowed by the new, structurally younger patchy charnockites. In addition, we have examined the Yelachipalyam quarry, 18 km north of Kabbal. Integration of the results obtained from these three locations (Fig. 1, inset A) throws new light on the origin of Kabbal charnockites in particular, as well as the relation between Peninsular gneiss and granulites – charnockites in general. We advance here an alternative model to that of Janardhan et al. (1982), a model that is petrologically feasible and does not require fluid streaming along preferred structures.

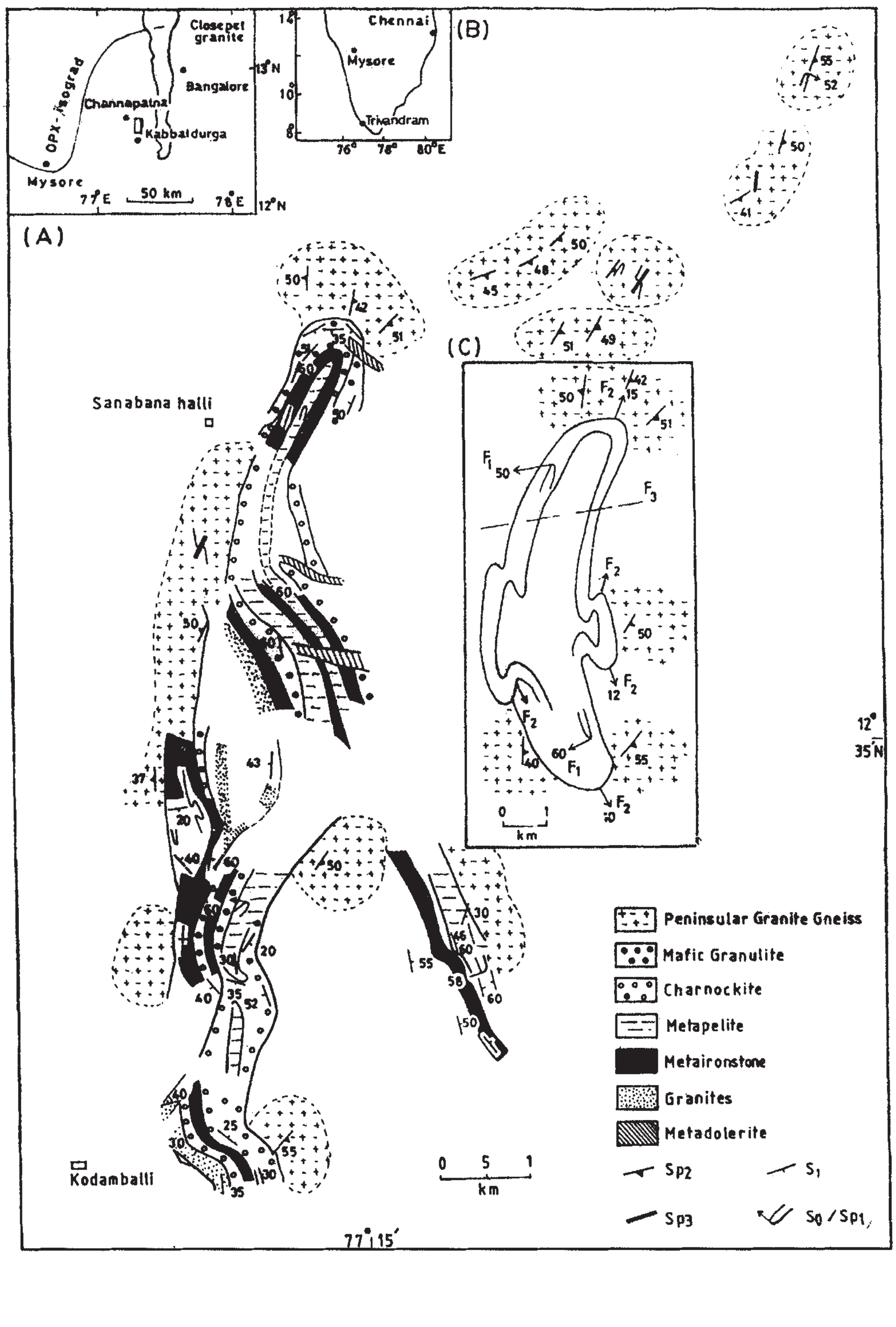

Fig. 1. Structural map of Sanabanahalli-Kodamballi area. Insets A and B : location map; A - Rectangle - Study area; Yelachipalyam quarry in figure 3A is located near Channapatna. C: idealized map depicting fold geometry.

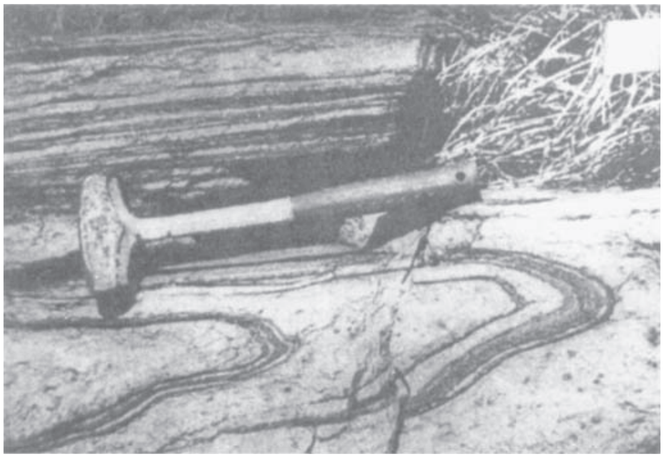

Fig. 2a. Intrafolial fold in meta-ironstone at Sanabanahalli. The main foliation (S_1) above the hammer is parallel to axial plane of fold; incipient S_1 at fold nose.

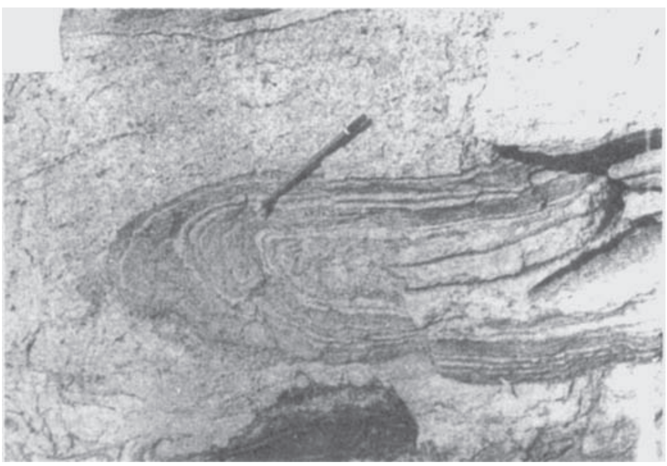

Fig. 2b. Intrafolial fold in metapelite at Sanabanahalli; the axial planar foliation is the most pervasive, as seen in metapelite (with interbanded quartzite).

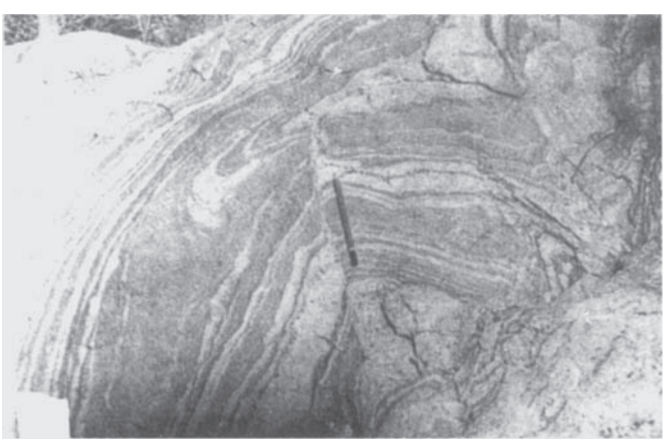

Fig. 2c. Banded charnockites doubly folded by F_2 and F_3 at Sanabanahalli; fracture and displacement parallel to F_3 axial plane, also marked by leucosomes.

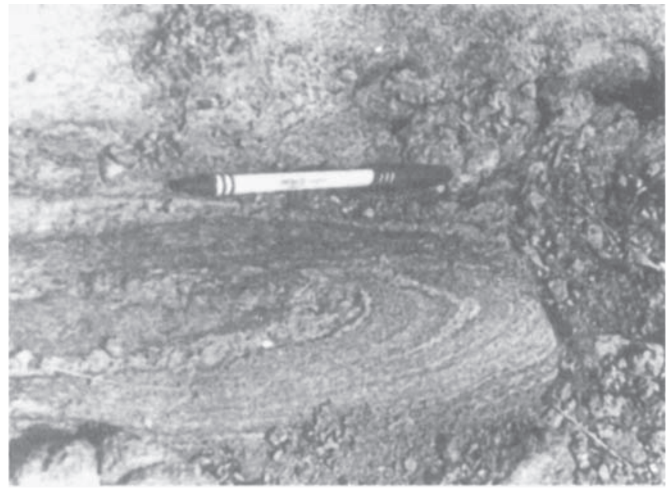

Fig. 2d. Intrafolial fold in Peninsular gneiss near Sanabanahalli; gneissic foliation S_{P2} parallel to the pen.

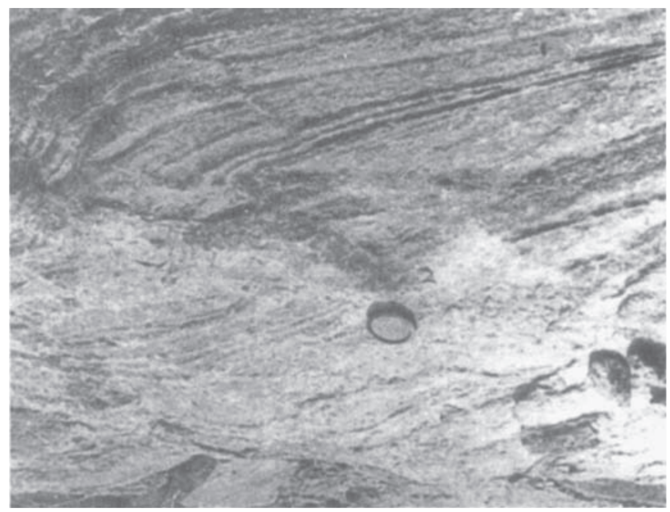

Fig. 2e. Dextral shear plane truncating and offsetting gneissosity in Peninsular gneiss.

Geological Setting and Deformation Pattern

Kodamballi area

Rama Rao (1927) described metasedimentary granulites and charnockites from the Kodamballi area and mapped the lithological variations in parts of the area. All the rocks here, except the granite gneisses, granitoids and metadolerites, show granulite facies assemblages. Gopalakrishna et al. (1986) stamped this area as a transition zone between amphibolite and granulite facies. The abundance of granulites and massive charnockites further south (B.R.Hills) and the interpretation of Kabbal charnockites as incipient ones must have suggested to these workers that the terrain surrounding Kabbal is transitional. We emphasise here that sizable bodies of granulites and charnockites are present in this area, and that there is nothing to suggest a transitional nature besides the assumption that the Kabbal charnockites are incipient.

We mapped the area between Sanabanahalli and Kodamballi, approximately corresponding to the area covered by Rama Rao (1927). In this linear belt, charnockites, basic granulites, metapelitic granulites and meta–ironstones are surrounded by Peninsular gneisses. Charnockites here are non-pegmatitic and occur as large massif type bands with an internal gneissic foliation. In addition, cross-cutting metadolerites, aplitic granites and leucogranite veins occur (Fig. 1).

The granulites of Kodamballi area record three phases of folding. The first folds on compositional banding (S_0) are intrafolial within the meta-ironstones (Fig. 2a). The pervasive gneissic foliation (S_1) is parallel to the axial plane of these folds. In the charnockites, basic granulites and metapelitic granulites, the compositional banding (S_0) could still be observed locally in the intrafolial folds (Fig. 2b). The pervasive gneissic foliation in them is axial planar to the intrafolial folds and parallel to the gneissic foliation (S_1) in the meta-ironstones. F_2 folds overprinting the pervasive gneissic foliation are tight to isoclinal and occur on mesoscopic (Fig. 2c) and map scale. The F_3 folds are open to close on mesoscopic scale with local fractures and displacement along the axial planes (Fig. 2c); they are present as broad warps on map scale (Fig. 1). It is important to note that though the deformation is polyphase, S_1 is always pervasive in the gneisses, while S_2 and S_3 could be recognised only locally on mesoscopic scales.

The Peninsular gneisses in this area record three episodes of penetrative deformation and development of pervasive foliations. The most pervasive gneissic foliation is axial planar to intrafolial F_1 folds (Fig. 2d) and is designated S_{P2}. The foliation which defines the intrafolial folds could have been an earlier gneissic foliation S_{P1}, which is also represented by the internal foliation of the amphibolite enclaves at places. S_{P2} is folded on various scales (Fig.1) and a gneissic foliation, S_{P3} is locally developed as axial planar to these folds. The third deformation is represented by small scale drag folds and dextral shearbands, S_{PS}, commonly filled by veins with an almost constant trend of N40° E (Fig. 2e).

Although polyphase deformation structures are observed in both the granulite – charnockite suite of Kodamballi and the surrounding Peninsular gneisses, the style and sequence are not the same. From the map (Fig. 1) it is clear that the pervasive gneissic foliation (S_{P2}) in the Peninsular gneisses is at high angles to the gneissic foliation (S_1) in the granulite – charnockite suite, especially near the fold hinge. S_{P2} is parallel to axial planes of folded S_1 in granulite – charnockite suite; thus S_1 is older than S_{P2}. However, Peninsular gneisses in this and other areas contain foliated amphibolite enclaves with intrafolial folds which suggest an earlier deformation. These intrafolial folds could have been produced by the pre- Dh_{F1} of Naha et al. (1990).

Yelachipalyam quarry

The Yelachipalyam quarry displays several field features which connect the well defined granulite – gneiss relations of Kodamballi with the irregular and fragmented manifestations observed at Kabbal. The Yelachipalyam quarry exposes discontinuous lenses and pods of basic granulites as against the continuous and mappable layers at Kodamballi, while the charnockitic rocks occur as thin interlayered bodies, small inclusions and pegmatite veins as at Kabbal.

The dominant gneissic foliation, S_{P2} in the Peninsular gneisses here displays small scale folds (F_2) with axial planar S_{P3} foliation (Fig. 3a). Basic granulite and charnockite-enderbite layers are concordant with S_{P2} foliation and cofolded by F_2 folds (Fig. 4a). However, basic granulite bodies can be shown to be older than S_{P2} gneissosity (Fig. 4b). It is noteworthy here that Naha et al. (1993) interpreted some minor patches of charnockitic rocks from a nearby quarry at Lakkojanahalli as transformed along DhF2 axial planes and shear zones in Peninsular gneisses. These authors have also described charnockitic patches from hinge regions of DhF2 folds at Kabbal. But our observations at Yelachipalyam and Lakkojanahalli show that many of these minor patches can be traced to dismembered folds now occurring as inclusions (Fig. 4c); disposition of some of the patches along fractures could be coincidental. More importantly, these bodies are non-pegmatitic, fine-grained, as

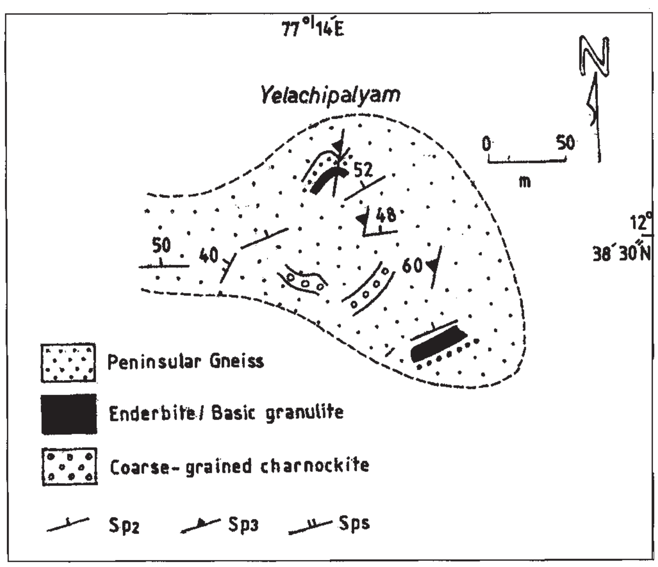

Fig. 3a. Structural map of Yelachipalyam quarry near Channapatna.

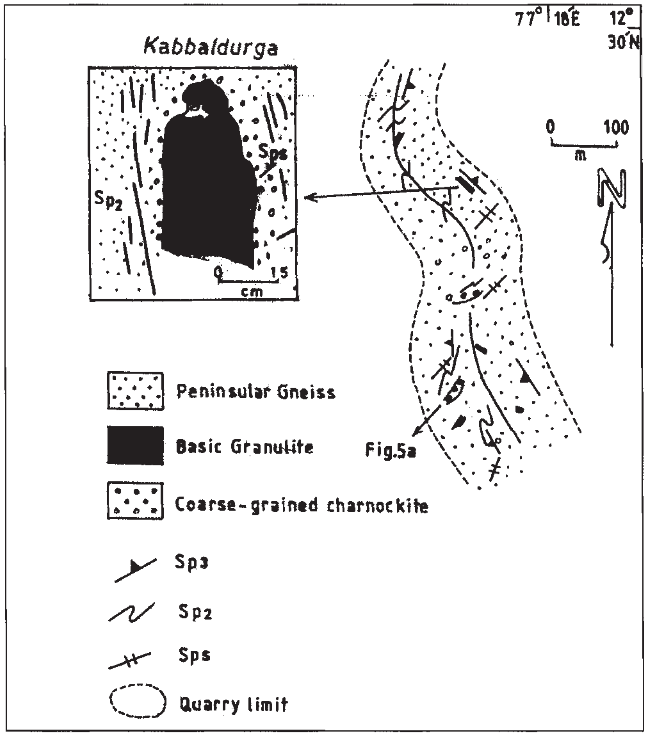

Fig. 3b. Structural map of Kabbaldurga quarry; inset shows a basic granulite enclave with coarse-grained leucocratic rind.

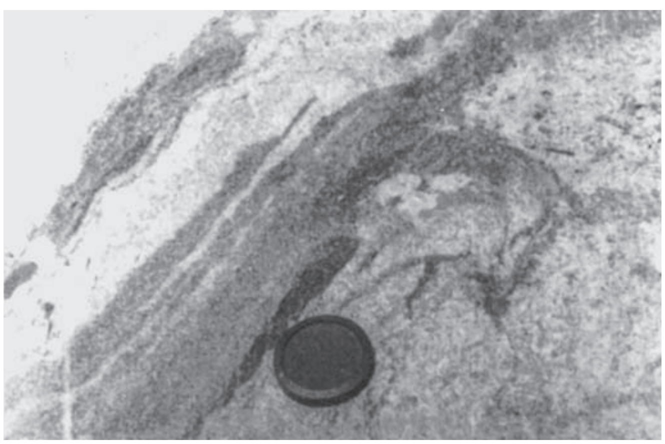

Fig. 4a. Cofolded charnockite-enderbite layers and enclosing Peninsular gneiss at Yelachipalyam quarry; note the tearing apart and dismemberment of the charnockite-enderbite.

contrasted with Kabbal charnockites. Pegmatitic charnockites also occur in the Yelachipalyam and Lakkojanahalli quarries, but they form veins of diverse orientations (Fig. 3a).

Kabbal quarry

Lithological variations within the granulite suite at Kabbal is limited when compared with the Kodamballi area. Highly migmatitic Peninsular gneisses are dominant. Charnockite and basic granulite are the two other rock types. It is intriguing that the presence of basic granulites

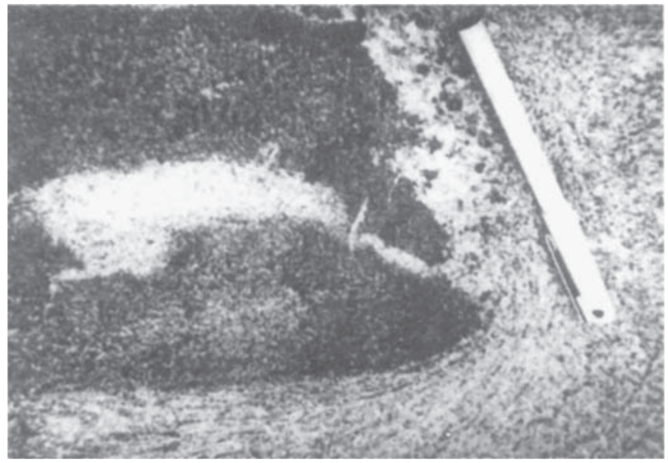

Fig. 4b. Basic granulite inclusion around which the gneissosity (S_{P2}) in Peninsular gneiss is seen to swerve (lower part of the photo) at Yelachipalyam quarry.

Fig. 4c. Basic granulite inclusion (marked with arrow) within folded Peninsular gneiss.

has been largely ignored in the publications on Kabbal rocks. Recognizing earlier granulite facies rocks would have demanded some explanation for the notion of a transition zone.

The early structures in both Peninsular gneisses (S_{P1}) and granulites–charnockites (S_1) are mostly erased at Kabbal. Late structures, particularly S_{PS}, are prominent. Leucosomes and migmatites are profusely developed here, and could be related to the Closepet granites nearby. The

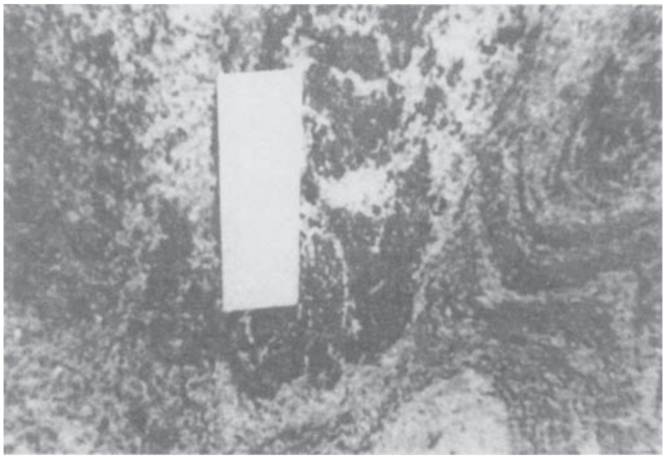

Fig. 4d. Drag folds in Peninsular gneiss terminated by a short shear running roughly NE-SW, and bordering a basic granulite inclusion (dark) at Kabbaldurga quarry.

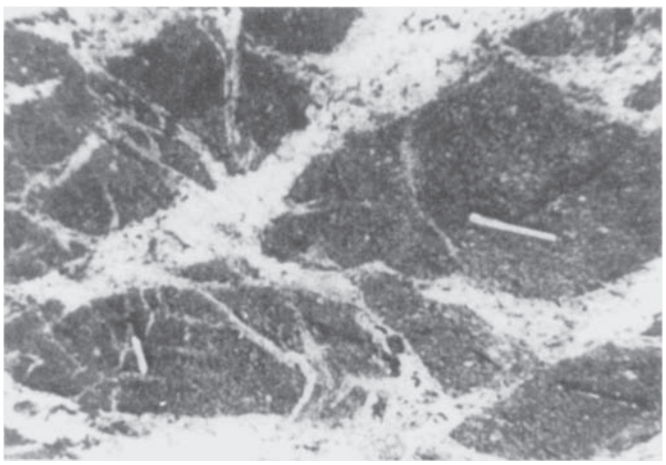

Fig. 4e. Basic granulite inclusions with their internal gneissosity diversely oriented (parallel to pencils) at Kabbaldurga quarry.

pervasive gneissic foliation S_{P2} in the Peninsular gneisses displays numerous small scale F_2 folds with axial planar foliation S_{P3}. S_{P3} describes broad warps throughout the

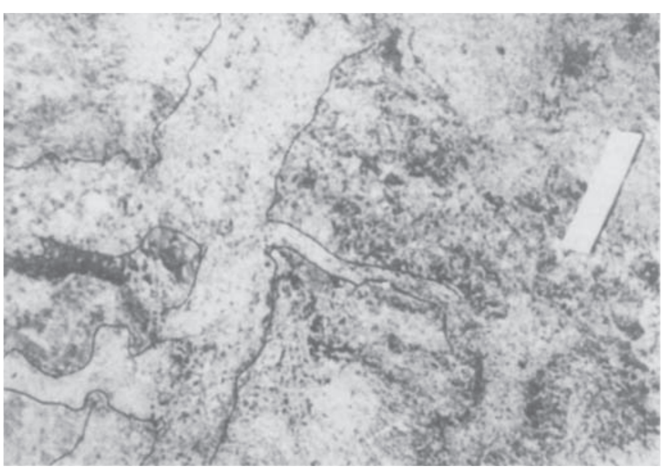

Fig. 5a. Pegmatitic charnockite veins branching in a tree-like fashion, at Kabbaldurga quarry.

quarry length, with axial planar fractures, S_{PS} developed locally (Fig. 3b). Shear bands and drag folds are common and they are usually filled with leucosomes and pink granites (Fig. 4d).

The basic granulite bodies display various orientations (Figs. 3b, 4e); S_{P2} foliation of Peninsular gneiss abutting against basic granulites is a common feature. Naha et al. (1993) described " pockets of charnockite formed in the hinge zones of DhF_2 folds" – but our observation suggests

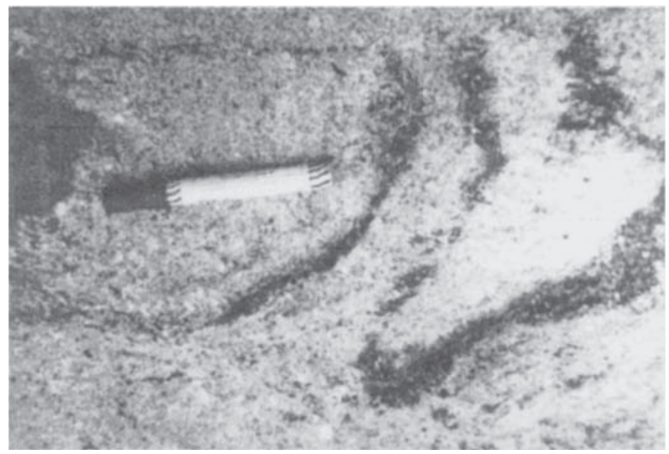

Fig. 5b. Non-pegmatitic fine-grained stringers of charnockite as folded inclusions within Peninsular gneiss, gneissosity of Peninsular gneiss aligned parallel to marker pen, at Kabbaldurga quarry.

that these are more likely to be dismembered inclusions of basic granulites as in the Yelachipalyam quarry (Fig. 4c).

The pegmatitic charnockites at Kabbal occur as diversely oriented, irregular and branching veins (Fig. 5a), at places in tree-like fashion (Friend, 1983). Some workers have suggested formation of charnockite patches along shear fractures, at some locales conjugate (Hansen et al., 1987; Naha et al., 1993). Note that in terms of deformation structures, including the shear fractures, Kabbal fits well in the regional framework. At Kabbal, shear fractures, S_{PS}, are developed along short limbs of F_3 folds at places (Figs. 6A, 6B). However, on regional scale, the axial planes of F_2 folds have a constant orientation (Fig. 6d), hence F_3 folds are not regional. More importantly, the different orientations of S_{P3} and S_{PS} suggest that they are unlikely to be related kinematically. We therefore consider S_{PS} as a regionally developed late deformation structure, manifested at Kabbal along short limbs of minor F_3 folds. Furthermore, though S_{PS} fractures have two different orientations in the whole area (Fig. 6d), they do not occur together as conjugate sets. At Kabbal only one orientation of shear fractures (S_{PS}) is represented (Fig. 6e). The shear fractures are commonly filled by non-charnockitic leucosomes while the pegmatitic charnockites are seldom found in these fractures (Fig. 6C). It is important to note that S_{PS} shear fractures can easily

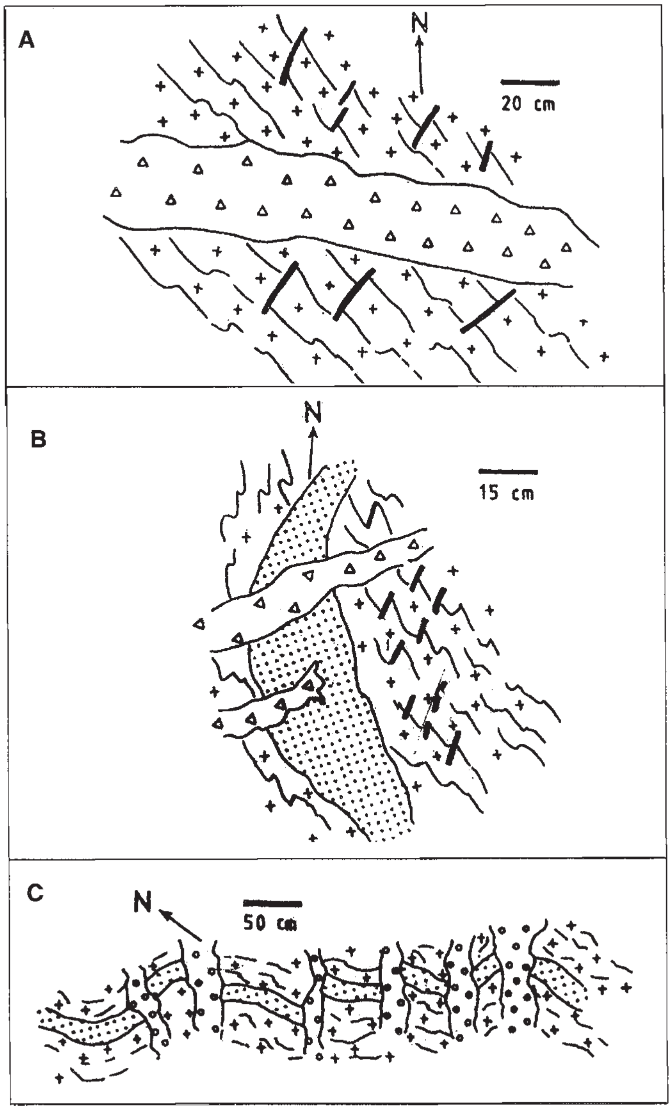

Fig. 6. Field sketches. A) Pegmatitic charnockite veins across a basic granulite band and Peninsular gneisses; shears along short limbs in folded Peninsular gneiss. Symbols: Pegmatitic charnockite-triangles, Basic granulite-stippled, Peninsular gneiss-plus sign. B) Numerous small scale folds (F3) in Peninsular gneiss with local shear fractures along short limbs of folds; pegmatitic charnockite vein at high angles to both dominant gneissosity and shear fractures in Peninsular gneiss. C) F3 folds in basic granulite and Peninsular gneisses; shearing and injection of pink feldspar granite veins along axial plane; granite veins-open circles, other symbols as in figure 6A.

be traced as a regionally developed structure, while "patchy" charnockites, thought to have grown along such dilatant structures are restricted to Kabbal and nearby quarries only.

It is highly significant that relatively fine-grained charnockites similar to those of the Kodamballi area also occur here, though as rare relics. Figure 5b shows a fold described by this variety of charnockites with the S_{P3} foliation of the enclosing Peninsular gneisses parallel to

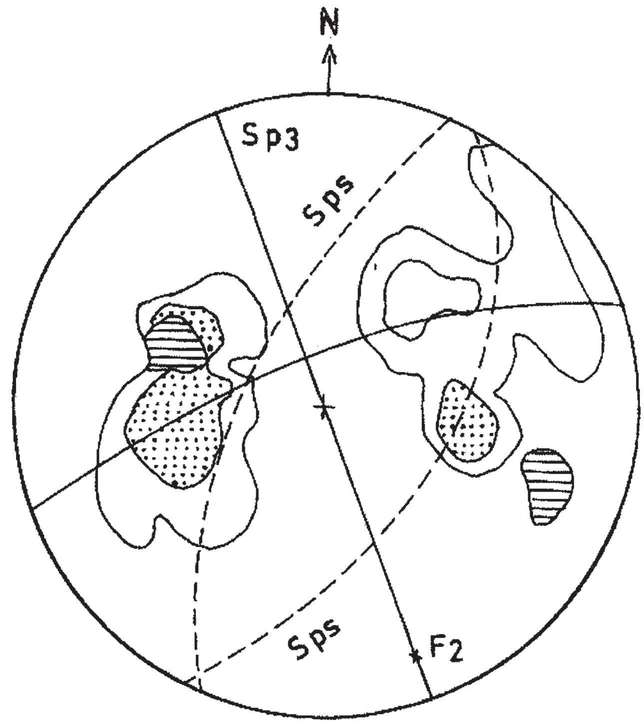

Fig. 6d. Stereoplots of the pervasive gneissosity (S_{P2}, n =63) and shear fractures (S_{PS}, n=17) in the Peninsular gneisses in the Kodamballi area; F_2 axis, axial plane (S_{P3}) and two orientations of S_{PS} corresponding to two point concentrations (marked by horizontal lines) also shown.

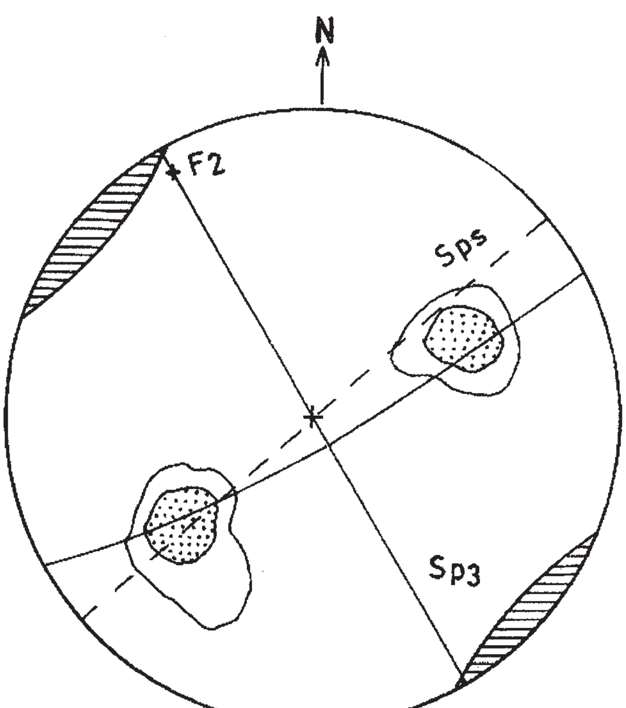

Fig. 6e. Stereoplots of S_{P2} (n=21) and S_{PS}(n=9) in the Kabbal quarry; F_2 axis, axial plane (S_{P3}) and mean orientation of S_{PS} also shown.

Table 1. Correlation of structures.

Lithology	Sanabanahalli – Kodamballi	Yelachipalyam and Kabbal
	S_{P1}- represented by intrafolial folds (F_1) and internal foliation in the amphibolite enclaves	Absent
Peninsular gneisses	S_{P2}- the pervasive gneissic foliation axial planar to intrafolial folds (F_1)	Present
	S_{P3} – locally developed gneissosity, axial planar to folded S_{P2} (F_2)	Present
	S_{PS} – shear bands	Present, also along short limbs of F_3 folds
	S_0 – compositional banding in meta – ironstones and metapelites	Absent
Granulites and non – pegmatitic charnockites	S_1 – pervasive gneissic foliation, axial planar to intrafolial folds	Present, as gneissosity in basic granulites, also rarely as minor folds in charnockites
	S_2, S_3 – locally developed gneissic foliations axial planar to F_2 and F_3 folds	Absent
Pegmatitic charnockites	Absent	Diversely oriented, veins unrelated to S_{PS} in Peninsular gneiss

the axial plane. Thus Kabbal charnockites are clearly of late origin with respect to both S_{P2} and S_{P3} and their irregular disposition argues against genesis by fluid ingress along dilatant structures such as shear fractures.

The correlation of structures in the three areas is shown in table 1.

Petrological Background

Petrography

In the Kodamballi area granulite assemblages are developed in a variety of chemical compositions. In addition to aplites and pegmatites (non-charnockitic in contrast to those at Kabbal) of granitoid composition, the following mineral assemblages are encountered .

a) quartz – plagioclase – garnet – cordierite – sillimanite – biotite – opaque (metapelitic)
b) quartz – magnetite – garnet – clinopyroxene and quartz – magnetite – clinopyroxene – orthopyroxene (meta – ironstone)
c) clinopyroxene – orthopyroxene – plagioclase – hornblende – quartz – opaque (metabasic)
d) K-feldspar – plagioclase – quartz – orthopyroxene – biotite (charnockite –enderbite, quartzofeldspathic)

The Peninsular gneisses have the general assemblage of : quartz – K-feldspar – plagioclase – hornblende – biotite – opaque

Also, boudins or larger inclusions of amphibolites within Peninsular gneisses have the assemblage hornblende – plagioclase – quartz – clinopyroxene.

Absence of feldspars and well developed exsolution lamellae in calcic pyroxenes are noteworthy features of the meta – ironstones.

In the Yelachipalyam quarry the Peninsular gneisses have occasional garnets. The meta–ironstones and metapelites are absent here; the basic granulites and charnockites (more commonly enderbites) show the same assemblages as in the Kodamballi area. Of significance is the presence of pegmatitic charnockites in this quarry; however, they are not as common as in the Kabbal quarry.

The Kabbal quarry is characterised by a plethora of pegmatitic veins containing orthopyroxene and occasional hornblende. Non–pegmatitic charnockites, in contrast to the medium-grained charnockites of Kodamballi area, are minor. One such small charnockite body is shown in Figure 5b. The Peninsular gneisses are migmatitic, at places the melanosome layers are dominant. The metapelites and meta – ironstones which are profusely developed in the Kodamballi area are absent in Kabbal.

Basic granulites with two pyroxene – plagioclase – hornblende – biotite ± K-feldspar ± quartz assemblages occur as small enclaves as well as layers of considerable dimensions (2 to 10 metres long and 0.2 to 0.5 metres wide) in Kabbal.Three of their notable features are as follows. There are hornblende–dominant (hornblende>biotite) and biotite–dominant (biotite>hornblende) varieties independent of the size of the bodies. Secondly, several basic granulite enclaves at Kabbal contain coarse–grained quartzofeldspathic leucosomes (Figs. 7a, 7b). Third, these basic enclaves are in places bordered by

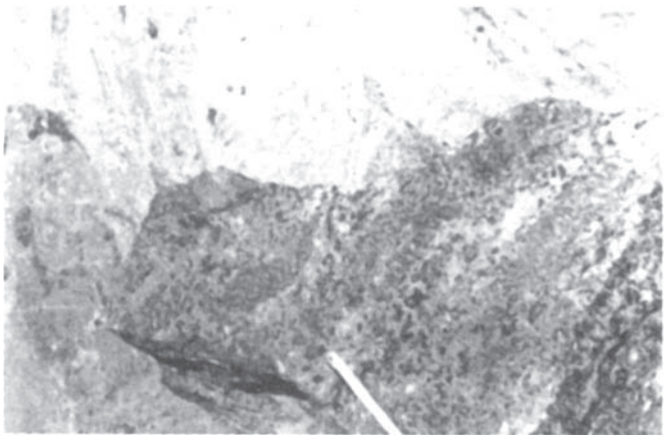

Fig. 7a. A sizable basic granulite enclave of migmatitic nature at Kabbal with coarse-grained quartzofeldspathic leucosomes.

rinds (Fig. 3b) , some of which can be demonstrated to be unrelated to interaction with the gneisses at their borders. As will be argued later, these features are of genetic significance, and were not explored by earlier workers. Concentrations of opaque oxides are found in a few of these rocks. Secondary hornblende and calcite grains are common, though insignificant in volume.

Rock chemistry

The chemical variations within the three groups of rocks – Peninsular gneisses, charnockites and basic granulites

Table 2. Bulk composition of Peninsular gneisses.

Sample No. Oxides%	K4A	K4C	K6gn	E4B	Melanosome KB2D	Leucosome KB2L
SiO_2	75.25	70.32	70.27	71.24	51.26	71.65
TiO_2	00.28	00.60	00.67	00.42	01.02	00.66
Al_2O_3	13.28	14.20	14.55	14.77	15.00	13.85
Fe_2O_3	01.49	03.34	03.58	02.43	10.84	03.27
MnO	00.02	00.06	00.06	00.04	00.20	00.05
MgO	00.15	00.59	00.91	00.91	06.13	00.65
CaO	01.10	02.24	03.17	03.72	08.63	02.42
Na_2O	03.17	04.01	03.67	04.02	03.78	03.47
K_2O	04.71	03.26	02.73	01.32	02.21	03.52
P_2O_5	00.09	00.25	00.33	00.14	00.52	00.28
LOI	00.20	00.23	00.15	00.40	00.64	00.22
Total	99.74	99.10	100.09	99.41	100.23	100.04
Mg.no.	29	41	50	60	69	44
			CIPW Norm			
Q	35.69	27.89	29.19	32.79	02.60	26.48
Or	28.05	19.60	16.23	07.92	03.20	20.28
Ab	26.98	34.43	31.15	34.43	23.45	35.21
An	05.17	09.86	13.96	17.90	20.43	10.42
Cor	01.11	00.53	00.49	00.26	—	00.60
Di	—	—	—	—	19.85	—
Hyp	02.24	05.78	06.78	05.43	26.13	05.17
Mgt	00.11	00.25	00.26	00.18	11.24	00.14
Ilm	00.53	01.16	01.28	00.81	03.10	00.82
Ap	00.22	00.61	00.79	00.34	—	00.53

Note: Sample nos. with K are from Kabbal, E from Yelachipalyam and S from Kodamballi.

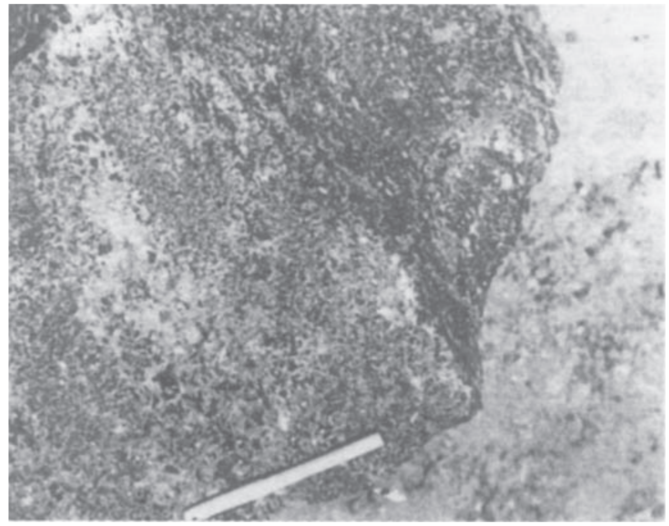

Fig. 7b. Basic granulite enclave at Kabbal with orthopyroxene-bearing coarse-grained leucosomes.

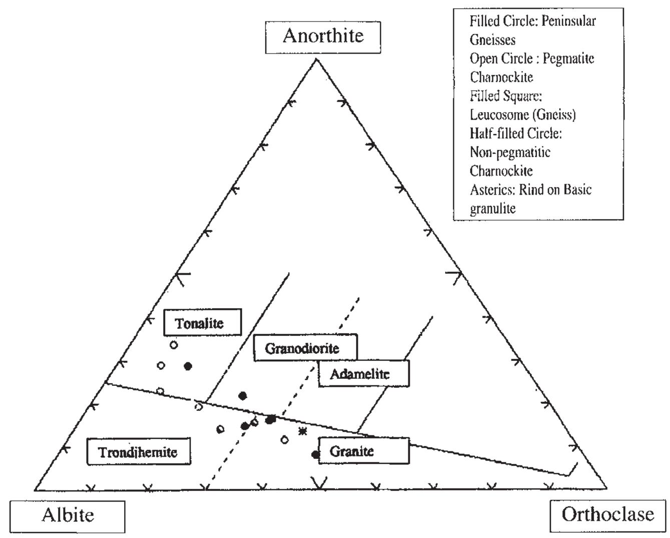

Fig. 8a. Composition of Kabbaldurga and Yelachipalyam pegmatitic charnockites compared with Peninsular granite gneisses of these quarries, in normative An-Ab-Or diagram of O'Connor, 1965.

– have to be understood before enquiring into the origin of Kabbal charnockites. We report here major element data on twentyfour (24) rock samples analysed by X-Ray fluorescence spectrometry (Tables 2, 3 and 4). These include analyses of some rocks from Kodamballi and Yelachipalyam for the sake of comparison.

Thin section studies indicate that the Peninsular gneisses which do not have overrepresentation of leucosome or melanosome layers vary in composition mostly from granite to tonalite in all the three areas. The chemical analyses of four representative Peninsular gneisses have been presented in table 2. In the normative diagram of O'Connor (1965), while the separated leucosome is of granitic composition, Peninsular gneisses

Table 3. Bulk composition of charnockites.

Rock type	Pegmatitic		Charnockite		Non-pegmatitic			Charnockite	
Sample No.	K40/8A	K9	K7A	K10	E1A	E25/3A	K6R	KB3	S-33
Oxides %									
SiO_2	61.91	69.21	64.27	74.65	73.31	70.54	68.62	63.43	70.76
TiO_2	01.73	00.98	00.32	00.38	00.13	00.43	00.44	00.75	00.67
Al_2O_3	12.84	14.46	13.32	13.59	15.52	14.61	15.49	14.98	14.04
Fe_2O_3	07.26	04.26	05.77	02.19	01.14	04.00	02.98	05.49	03.88
MnO	00.16	00.08	00.19	00.02	00.01	00.06	00.06	00.11	00.04
MgO	03.11	01.10	02.50	00.23	00.15	00.79	00.74	01.92	00.79
CaO	05.58	02.89	06.92	01.67	03.70	03.91	02.77	04.08	02.10
Na_2O	04.12	04.20	04.38	03.50	04.44	03.75	03.83	04.22	03.19
K_2O	02.68	02.01	01.07	04.05	00.84	00.75	05.12	03.70	03.20
P_2O_5	00.41	00.39	00.38	00.17	00.01	00.01	00.24	00.66	00.20
LOI	00.22	01.53	00.70	00.37	00.70	01.10	00.47	00.63	00.50
Total	100.02	101.13	99.82	100.82	99.95	99.95	100.76	99.97	99.37
Mg.no.	63	51	63	30	34	44	50	58	45
				CIPW Norm					
Q	11.43	27.16	16.15	33.83	36.15	32.10	26.21	18.12	32.82
Or	16.07	12.05	08.25	23.93	04.96	18.43	13.10	16.21	19.24
Ab	35.32	35.97	36.14	29.56	37.57	26.53	34.70	30.40	27.40
An	08.74	14.77	16.21	07.49	18.29	12.21	15.10	12.21	09.90
Cor	—	00.05	—	00.72	00.61	01.20	—	—	01.83
Hyp	08.49	07.88	07.90	03.42	00.37	06.30	08.12	06.70	06.98
Di	16.12	—	14.21	—	—	—	—	13.16	—
Mgt	00.53	00.31	00.13	00.16	01.14	00.13	00.21	00.21	00.29
Ilm	03.33	01.88	00.50	00.61	00.14	01.40	01.10	01.70	01.29
Ap	—	—	00.20	00.41	00.02	00.42	00.30	00.30	00.50

Table 4. Bulk composition of basic granulites.

Sample No.	K15	K6	K7	K8	K19	E25/3	E25/2	E5	S-9
Dominant Mineral	Hbl	Hbl	Hbl	Bio	Bio	Hbl	Bio	Hbl	Hbl
Oxides%									
SiO_2	51.66	47.82	51.63	53.23	52.55	51.66	59.36	49.04	50.90
TiO_2	00.63	00.69	00.74	01.06	01.13	01.27	00.95	01.44	00.49
Al_2O_3	08.81	11.93	10.37	15.39	14.44	12.96	16.42	13.91	15.64
Fe_2O_3	09.82	10.72	10.32	09.57	10.29	15.40	08.44	17.60	10.11
MnO	00.19	00.23	00.33	00.13	00.20	00.23	00.14	00.21	00.16
MgO	08.04	08.59	08.89	05.46	05.40	05.69	04.06	05.33	07.78
CaO	15.89	16.49	12.45	07.46	06.76	09.13	06.00	09.75	11.88
Na_2O	02.77	02.43	02.88	04.85	03.46	02.38	02.75	01.50	01.55
K_2O	01.21	00.66	01.13	02.24	03.58	00.62	01.08	01.11	00.50
P_2O_5	00.38	00.42	00.34	00.24	00.83	00.17	00.37	00.14	00.09
LOI	00.58	01.30	01.00	00.52	00.60	00.60	00.40	00.70	00.90
Total	99.98	101.28	100.08	100.15	99.24	100.11	99.97	100.73	100.00
Mg.no	77	76	77	69	68	60	66	55	75
				CIPW norm					
Q	—	—	—	—	—	02.57	16.17	00.48	—
Or	07.30	03.95	06.81	13.40	21.67	03.74	06.64	06.68	02.10
Ab	14.50	06.02	24.58	33.60	29.98	20.54	23.55	12.90	06.40
An	08.20	19.90	12.27	13.80	13.62	23.31	27.68	28.42	27.13
Di	57.50	49.50	39.58	18.30	12.58	18.27	—	16.80	38.10
Hyp	—	—	—	—	03.55	27.57	21.97	30.34	—
Ol	04.90	09.60	13.62	13.30	13.68	—	—	—	12.23
Mgt	00.72	00.79	00.76	00.70	00.76	01.1	00.62	01.30	01.10
Ilm	01.20	01.32	01.43	2.00	02.20	02.46	01.83	02.78	01.30
Apt	00.92	01.01	00.82	00.58	02.01	00.41	00.89	00.34	00.20
Nep	05.00	08.00	00.14	04.30	—	—	—	—	05.30
Cor	—	—	—	—	—	—	00.68	—	—

Hbl – and Bio- represent hornblende-dominant and biotite-dominant varieties respectively.

Table 5. Representative compositions of hornblendes.

Rock type	Basic granulites										Gneiss	Rind
Sample No.	K6-1	K6-1	K6-2	K6-2	K15-1	K15-1	E1-1	E1-1	K19-1	K19-1	K46-1	K6-1
Oxides%	Core	Rim	Core	Rim	Core	Rim	Core	Rim	Core	Rim	Core	Core
SiO_2	42.08	41.59	41.41	44.45	46.58	47.83	44.53	44.37	40.91	44.69	42.03	44.04
TiO_2	01.04	1.11	1.24	1.01	0.80	0.66	01.47	01.41	01.56	01.56	1.44	1.48
Al_2O_3	13.37	13.43	13.53	11.47	09.10	008.62	12.21	12.06	10.03	10.48	11.96	10.81
FeO	13.29	13.03	12.88	12.01	16.35	15.71	15.03	14.61	16.57	16.81	19.79	19.41
MnO	00.28	0.20	0.20	0.29	00.27	00.37	00.11	00.22	00.45	00.36	0.51	0.68
MgO	13.03	13.97	13.60	13.81	12.05	10.22	11.50	11.91	11.85	11.53	9.89	9.61
CaO	11.06	11.26	11.04	10.85	10.66	10.22	10.26	10.55	10.07	10.63	10.28	10.31
Na_2O	01.83	01.75	01.98	01.73	01.41	01.41	01.49	01.31	01.85	01.95	1.35	1.86
K_2O	01.65	01.74	01.68	01.25	01.14	01.03	0.83	0.91	01.37	01.43	1.60	1.38
Total	97.70	98.28	97.75	96.91	98.39	98.59	97.43	97.40	94.75	99.61	98.99	99.58
					Formula unit on 23 Oxygen basis							
Si	6.29	6.20	6.20	6.60	6.90	6.90	6.58	6.56	6.39	6.59	6.34	6.73
Al^{IV}	1.71	1.80	1.80	1.40	1.10	1.10	1.42	1.44	1.61	1.41	1.66	1.27
Al^{VI}	0.65	0.56	0.59	0.61	0.53	0.48	0.71	0.66	0.24	0.41	0.47	0.55
Ti	0.12	0.12	0.14	0.12	0.09	0.08	0.16	0.16	0.18	0.17	0.16	0.20
Fe^{2+}	1.66	1.63	1.61	1.49	1.78	1.69	1.86	1.81	2.16	2.07	2.50	2.32
Mn	0.04	0.03	0.03	0.04	0.03	0.04	0.01	0.03	0.06	0.05	0.07	0.08
Mg	2.91	3.11	3.04	3.06	2.81	2.99	2.53	2.63	2.76	2.53	2.23	2.05
Ca	1.77	1.80	1.77	1.73	1.63	1.69	1.63	1.67	1.69	1.68	1.66	1.58
Na	0.53	0.51	0.58	0.50	0.41	0.32	0.43	0.38	0.56	0.56	0.40	0.52
K	0.21	0.23	0.21	0.16	0.22	0.20	0.16	0.17	0.27	0.27	0.31	0.25
Cation	15.89	15.98	15.96	15.69	15.50	15.49	15.48	15.50	15.92	15.74	15.78	15.55
X_{Mg}	0.64	0.66	0.65	0.67	0.61	0.64	0.58	0.59	0.56	0.55	0.47	0.47

Table 6. Representative pyroxene compositions.

Rocktype	Basic granulite					Charnockite			Metaironstone		
Mineral	cpx	cpx	cpx	opx	opx	opx	opx	opx	cpx	cpx	opx	opx
Sample no.	K8	K6	K19	Kl9	El	K8	K5	S-36	30A	34	34	34/1
Oxides %												
SiO_2	52.20	52.83	52.86	50.21	52.18	51.24	51.01	49.82	51.99	52.29	52.23	50.17
TiO_2	00.20	00.17	00.13	00.05	00.07	00.12	00.12	00.08	--	--	0.01	--
Al_2O_3	01.64	01.79	01.38	00.56	00.93	00.41	00.48	00.65	00.80	00.13	--	00.81
FeO	12.62	07.19	12.78	28.21	26.41	29.21	30.97	29.62	15.48	14.46	32.83	38.64
MnO	00.64	00.33	01.05	03.11	00.61	01.48	02.06	03.63	02.97	00.20	00.54	00.81
MgO	11.13	14.74	12.33	17.23	20.76	17.21	15.84	15.16	09.52	11.57	15.80	10.81
CaO	20.10	21.81	19.09	00.63	00.43	00.58	00.60	00.68	19.95	21.90	00.46	00.54
Na_2O	00.65	00.49	00.72	00.04	--	--	00.05	00.03	00.20	00.38	--	--
K_2O	00.06	00.10	00.08	00.05	00.06	00.03	00.05	00.06	--	--	--	00.02
Total	99.25	99.50	100.43	100.09	101.45	100.28	101.19	99.15	100.90	100.91	101.86	101.07
					Formula unit on 6 Oxygen basis							
Si	1.99	1.97	1.99	1.95	1.95	1.98	1.97	1.97	1.99	01.98	2.00	2.00
Al^{IV}	0.01	0.03	0.01	0.02	0.04	0.02	0.02	0.03	0.01	00.02	--	--
Al^{VI}	0.06	0.05	0.05	--	--	--	--	--	0.04	--	--	0.04
Fe^{2+}	0.40	0.22	0.40	0.96	0.83	0.94	1.00	0.98	0.50	00.46	1.05	1.29
Fe^{3+}	--	--	--	--	--	--	--	--	--	--	--	--
Mn	0.02	.01	0.03	0.10	0.02	0.05	0.09	0.10	0.10	00.01	0.02	0.03
Mg	0.63	0.82	0.69	0.99	1.16	0.94	0.91	0.89	0.54	00.65	0.90	0.60
Ca	0.82	0.87	0.77	0.02	0.02	0.02	0.03	0.03	0.82	00.89	0.02	0.02
Na	0.05	0.04	0.05	0.005	--	--	0.004	0.002	D.01	00.03	--	--
K	0.003	0.005	0.004	0.005	0.003	0.002	0.002	0.003	--	--	--	--
Ti	0.006	0.005	0.004	--	0.002	0.003	0.003	0.002	--	--	--	--
Cation	3.99	4.02	4.00	3.95	4.03	4.01	4.01	4.01	4.00	4.03	3.99	3.98
X_{Mg}	0.61	0.78	0.63	0.51	0.53	0.51	0.48	0.48	0.52	0.59	0.46	0.32

Table 7. Representative compositions of plagioclase feldspar.

Rock type		Basic granulites						Gneisses		Charnockites		
Sample No.	K15	K19	K8	K17D	E1	K6	K6(O)	K46	K4A	S-36	K5	E1A
Oxides%												
SiO_2	63.04	63.11	61.34	61.30	57.28	55.92	53.09	59.99	63.69	61.94	60.91	59.37
TiO_2	00.03	—	—	—	00.03	—	00.02	00.13	—	—	00.04	00.02
Al_2O_3	24.23	21.98	24.26	23.98	28.84	29.11	31.13	26.63	22.29	24.96	23.68	25.36
FeO	00.11	—	—	00.03	00.20	00.04	00.09	00.08	—	—	00.45	—
MnO	—	—	00.05	00.03	—	—	00.08	—	—	—	—	00.02
MgO	00.01	—	—	—	—	—	—	—	—	—	00.12	—
CaO	03.95	03.92	04.03	04.25	08.34	08.12	10.19	05.18	04.07	05.56	03.82	05.38
Na_2O	08.66	08.41	08.89	08.82	06.13	06.94	04.99	08.09	08.73	08.35	09.03	08.11
K_2O	00.45	00.17	00.42	00.16	00.13	00.10	00.07	00.80	00.22	00.32	00.16	00.39
Total	100.48	97.67	98.99	98.59	100.99	100.29	99.73	100.89	99.03	101.13	98.20	98.69
					Formula unit on 8 Oxygen basis							
Si	2.77	2.84	2.74	2.75	2.54	2.50	2.40	2.65	2.83	2.72	2.75	2.68
Al	1.26	1.17	1.28	1.27	1.50	1.54	1.66	1.39	1.17	1.29	1.26	1.35
Fe	0.00	—	—	0.00	0.01	0.00	0.00	0.00	—	—	0.02	—
Mn	—	—	—	0.00	—	—	0.00	—	—	—	—	—
Mg	—	—	—	—	—	—	—	—	—	—	0.01	—
Ca	0.19	0.19	0.19	0.20	0.40	0.39	0.49	0.24	0.19	0.26	0.19	0.26
Na	0.74	0.73	0.77	0.77	0.53	0.60	0.44	0.69	0.75	0.71	0.79	0.71
K	0.03	0.01	0.02	0.01	0.07	0.01	0.00	0.05	0.01	0.02	0.01	0.02
Ti	—	—	—	—	—	—	—	—	—	—	—	—
Cation	4.99	4.95	5.00	5.00	5.05	5.04	4.99	5.03	4.96	5.00	5.03	5.02
X_{an}	0.20	0.21	0.20	0.21	0.43	0.39	0.52	0.26	0.20	0.27	0.19	0.26

Table 8. Representative compositions of biotites.

Rock type		Basic granulite					Charnockite		
Sample no.	K19-1	K19-1	E1-1	E1-1	E1-2	E1-2	K5-1	K9-1	S-36
Position	Core	Rim	Core	Rim	Core	Rim	Core	Core	Core
Oxides%									
SiO_2	37.66	37.17	36.89	37.12	36.36	36.08	38.47	37.80	37.04
TiO_2	04.35	04.00	02.95	03.23	03.94	03.78	04.03	04.54	03.98
Al_2O_3	14.02	13.93	16.80	16.19	16.18	16.41	15.14	15.22	14.86
FeO	18.23	17.01	13.33	13.61	17.21	17.27	17.16	20.05	19.33
MnO	00.30	00.21	00.05	—	00.27	00.15	00.21	00.30	00.43
MgO	12.84	13.01	15.79	15.66	12.69	12.28	12.29	11.88	11.00
CaO	—	0.05	—	—	—	—	—	—	-
Na_2O	00.02	00.11	00.06	0.11	00.23	—	0.11	—	-
K_2O	09.65	09.52	08.55	08.68	08.81	08.64	09.76	10.11	09.53
Total	97.07	95.01	94.49	94.86	96.08	94.65	97.17	99.89	96.34
				Formula unit on 20 Oxygen basis					
Si	5.11	5.13	4.98	5.01	4.96	4.97	5.17	5.02	5.13
Al^{IV}	2.24	2.26	2.67	2.58	2.60	2.66	2.40	2.38	2.65
Fe	2.07	1.96	1.51	1.54	1.96	1.99	1.93	2.23	2.15
Mn	0.03	0.03	0.01	—	0.03	0.02	0.02	0.03	0.06
Mg	2.60	2.68	3.18	3.15	2.58	2.52	2.46	2.35	2.28
Ca	—	0.01	—	—	—	—	—	—	-
Na	0.00	0.03	0.02	0.03	0.06	—	0.03	—	-
K	1.67	1.68	1.47	1.50	1.53	1.52	1.67	1.71	1.84
Ti	0.44	0.42	0.30	0.33	0.40	0.39	0.41	0.45	0.41
?Cation	14.16	14.18	14.13	14.13	14.13	14.07	14.08	14.19	14.52
X_{Mg}	0.56	0.58	0.68	0.67	0.57	0.56	0.56	0.51	0.50

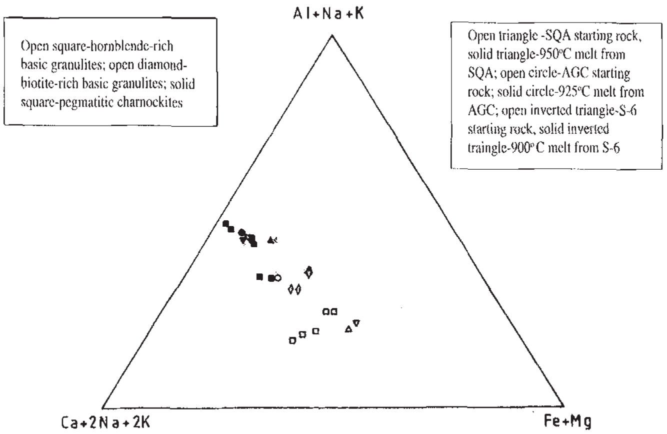

Fig. 8b. ACM deluxe projection for pegmatitic charnockites and basic granulites viewed against experimental source rocks and melts; Symbols: open triangle-SQA starting rock, solid triangle - 950°C melt from SQA; open circle-AGC starting rock, solid circle-925°C melt from AGC; open inverted triangle - S-6 starting rock, solid inverted triangle-900°C melt from S-6; open square -hornblende-rich basic granulites, open diamond-biotite-rich basic granulites; solid square-pegmatitic charnockites.
SQA refers to experiments of Patino Douce and Beard, 1995, AGC to that of Skjerlie and Johnston, 1993, and S-6 to that of Springer and Seck, 1997.

are tonalitic, trondhjemitic and granitic in composition (Fig. 8a).

Bulk chemical data on eight charnockitic rocks and one rind on basic granulite are presented in table 3. Six among these are pegmatitic charnockites from Kabbal and Yelachipalyam, they correspond to tonalite, trondhjemite and granite (Fig. 8a). Non-pegmatitic charnockite, one each from Kabbal and Kodamballi, fall in the field of tonalite in figure 8a. Analyses of nine representative basic granulites are given in table 4. Three of these are biotite – rich (K8, K19 and E25/2), while the rest are hornblende – rich basic granulites. All of them are broadly olivine normative basalts. Three basic granulites from Yelachipalyam, one of which is biotite – rich (E25/2), are somewhat different. They are hypersthene normative and one of them (E5) approaches the chemistry of diorite in several respects. The basic granulite of S-K area (S9) is of olivine normative basalt composition.

Mineral chemistry

Fortyfour EPMA analyses of major silicates are presented in tables 5 to 8. Apart from chemical characterisation of the solid solutions, the analytical data serve two purposes. First, they provide the basis of geothermobarometric estimates. Second, they constrain the metamorphic and melting reactions.

Hornblende

In general hornblendes have moderately high Al^4 and low Al^6 and Ti. The Mg : Fe ratios of hornblendes in basic granulites of Kabbal vary from 0.55 to 0.67, they are magnesio-hornblendes and alumino-magnesio-hornblendes in Leake's (1978) nomenclature. The hornblendes from the Peninsular gneisses are alumino-ferro-hornblendes. Higher X_{Mg} values in the margins of hornblende grains are common.

Pyroxenes

Orthopyroxenes are alumina-poor hypersthenes. In general, the spread in X_{Mg} is low if the orthopyroxene from the meta – ironstones is excluded. The X_{Mg} of orthopyroxene from Kabbal charnockite is 0.48, which is lower than those in the basic granulites of Kabbal. Calcic pyroxenes are also poor in alumina but they show a much wider variation in X_{Mg} values from 0.61 to 0.78.

Plagioclase

The compositions of plagioclase in Peninsular gneisses and charnockites are in the range An_{19} to An_{27}. In some basic granulites andesine – labradorites occur and within this group there are rocks which contain plagioclase grains of different compositions. Table 7 gives an example of such variation where the extreme values are An_{39} and An_{52}.

Biotite

The variability of biotite composition, in terms of major components, from similar assemblages is moderate. In the basic granulites X_{Mg} values show considerable variation from 0.56 to 0.68.

Pressure – temperature estimates

Temperature estimates were obtained from coexisting garnet – clinopyroxene, orthopyroxene – clinopyroxene, and orthopyroxene – biotite pairs from the meta-ironstones and charnockites of Kodamballi area and from basic granulites and pegmatitic charnockites of Kabbal (Table 9).

There are difficulties in obtaining dependable pressure estimates from the rocks of the area. Absence of garnet in basic granulites and charnockites, and of plagioclase in meta – ironstones preclude the use of the widely endorsed garnet – orthopyroxene/clinopyroxene – plagioclase barometers. The cordierite – garnet – sillimanite – quartz barometer and cordierite – garnet thermometer have been avoided because these assemblages generally stabilise during later decompression and hence are unlikely to record peak pressures and temperatures. An approximate pressure estimate is available from plagioclase bearing meta – ironstone from the neighbouring Satnuru area, where according to Bhattacharya et al. (1990) the pressure is around 7 kbar. A similar value, though not precise, is obtained from hornblende – plagioclase pairs in basic granulites of Kabbal from the barometer of Blundy and Holland (1990).

Table 9. Pressure – temperature estimates.

Thermometer/ Barometer	Metaironstone(S-K) Opx-Cpx	Basic(Kabbal) Opx-Cpx	Metaironstone(S-K) Grt-Cpx	Basic(Kabbal) Hbl-Plag	Basic Charnockite (Kabbal) Opx-Biot	Charnockite(S-K) Opx-Biot
Fe-Mg (Kretz,1982)	920°C (S 34)	870 -900°C (K 6,19)				
Ca-Mg (Kretz,1982)	890°C (S 34)	1000 –1020°C (K 6,19)				
Bhattacharya et al. 1990			760°C(7kbar) (S 30A)			
Ganguly et al. 1996			930°C (S 30A)			
Berman, 1991	1030°C (S 34)	960 –980°C (K 6,19)	780°C (S 30A)			
Blundy and Holland, 1990				5.7-7.8 kbar (K 6,19)		
McMullin et al. 1991					870, 840,820° C (K 19,5,9)	850° C (S 36)
Patino Douce et al. 1993					880,850,840° C (K 19,5,9)	850° C (S 36)

The preferred estimate of temperature from the present rocks is in the range 850 to 900° C, and most likely around 900° C in view of the values obtained from the improved calibration of garnet – clinopyroxene thermometer by Ganguly et al. (1996) and of two – pyroxene temperatures (Table 9).

Discussion

Pichamuthu (1960) first reported extensive veining of Peninsular gneisses by charnockites in the Kabbal area; he styled the phenomenon as " charnockites in the making". Several workers have interpreted "patchy" or "incipient" charnockites from several South Indian and Sri Lankan locales as *in situ* transformation of granite gneisses by ingress of CO_2 which caused lowering of a_{H2O} required for formation of charnockites (Janardhan et al., 1982; Hansen et al., 1987; Stahle et al., 1987; Hansen et al., 1995). Note that the pegmatitic charnockites at Kabbal are demonstrably younger than the enclosing rocks, but in some other Indian locales displaying "incipient" charnockites, such as Chilka Lake and Kerala, the charnockitic patches can be proved to be older than the enclosing rocks (Bhattacharya et al., 1993; Sen and Bhattacharya, 1993). Furthermore, there are non – pegmatitic charnockites in the neighbouring Kodamballi area which occur as large bodies interbanded with other granulites as well as in at least one instance at Kabbal (Fig. 5b).

The two important lines of evidence advanced in support of the hypothesis of transformation of granite gneisses to charnockites are: presence of structurally controlled channelways such as fractures, and chemical similarities between close pairs of gneisses and charnockites. We have pointed out earlier that charnockite veins at Kabbal are usually not emplaced along the system of fractures that are common in this region. Moreover, these fractures are present throughout the area, for example in S-K, where pegmatitic charnockitic veins are absent. Regarding chemical similarities of close pairs, the first point to note is that according to our findings, there are four varieties of gneisses – granitic, trondhjemitic, granodioritic and tonalitic (excluding the varieties showing concentrations of melanosomes) and three varieties of charnockites – granitic, trondhjemitic and tonalitic (Fig. 8a). Second, the pegmatitic charnockite veins occur within Peninsular gneisses of all varieties. Given the broad compositional spread of the Peninsular gneisses, it is not unnatural that pegmatitic charnockites of granitic to tonalitic compositions were found to be close to the composition of the host gneisses by earlier workers (Hansen et al., 1987). A full understanding requires consideration of petrographic and chemical variations of the Peninsular gneisses, basic granulites plus their rinds, and the charnockites.

In trying to explain the transformation of gneiss to charnockite, Hansen et al. (1987) considered derivation of orthopyroxene – bearing assemblages by breakdown of hornblende and biotite. As Stahle et al. (1987) noted, there is no textural evidence supporting this contention. Stahle et al. (1987) and Hansen et al. (1987) advocated open system reactions to explain away the discrepancies evident in closed system reactions. Inspite of the chemical similarities, the modal plagioclase contents of the two pairs of Kabbal samples given in table 2 of Hansen et al. (1987) show comparable or even lower amounts of plagioclase in the charnockites, while the reactions dictate an opposite trend. Moreover, discordant chemical observations, such as depletion in Rb by Stahle et al. (1987) and enrichment in Rb by Hansen et al. (1987), render the hypothesis of *in situ* transformation weak. An important question can be raised here – why did not the metasomatising fluids, which were evidently pervasive in Kabbal area, affect the basic granulites?

Petrographic indication of prograde reactions are absent in thin sections of Kabbal charnockites. On the other hand, "retrograde" reactions are common and evident in secondary biotites (replacing orthopyroxene) and hornblendes. Diffuse boundaries around charnockite bodies can be produced by these later reactions and do not necessarily constitute evidence for gneiss to charnockite transition via fluids as interpreted by Newton (1992).

It is obvious that the pegmatitic charnockites of Kabbal cannot be derived by metamorphic – metasomatic transformation in the solid state from the basic granulites, the other rock type, because of the contrast in compositions. However, the presence of quartzo-feldspathic leucosomes within the basic granulites (Figs. 7a, b) suggests that derivation of pegmatitic charnockites by partial melting of basic granulites is a possibility. If the development of pegmatitic charnockites is a local phenomenon, we should consider the possibility of their origin by melting. The transgressive nature of these charnockites, and their distribution pattern as manifested in branching in diverse directions and cutting across the planar fabrics of the Peninsular gneisses, are highly suggestive of their emplacement as melts. The geothermobarometric results, which in view of resetting of elemental exchange are unlikely to record peak temperatures, yield values in the neighbourhood of 900 ° C and 7 kbar. In the light of recent experimental studies (Rushmer, 1991; Skjerlie and Johnston, 1993; Rapp and Watson, 1995; Patino Douce and Beard, 1995 and Springer and Seck, 1997) these P-T conditions are adequate for substantial melting in basic rocks. The occasional presence of nearly euhedral orthopyroxene in charnockites is also indicative of emplacement as melts.

Because of the relative closeness of the compositions of charnockites and Peninsular gneisses, the Peninsular gneisses should first be considered as the source rocks for the melts. A difficulty in assessing this possibility is that both Peninsular gneiss and charnockites have granitic to tonalitic variants (Tables 2, 3) and in view of the "mobility" of the pegmatitic material, comparison of the adjacent gneiss – charnockite pairs has little meaning. But the overall similarity of these two rock types makes it unlikely that charnockites are derived by partial melting of the gneisses. In other words, for generating charnockites by melting, the Peninsular gneisses will have to be completely melted – an unlikely proposition. Also, the leucosomes within Peninsular gneisses, best interpreted as anatectic products, are quite different in composition than charnockites. The leucosomes are alkali-feldspar granites, whereas the pegmatitic charnockites are granites, trondhjemites and tonalites (Fig. 8a). Moreover, the leucosomes within Peninsular gneisses are lacking in orthopyroxene and are practically free of ferromagnesian minerals.

A series of controlled dehydration melting (of hornblende and/or biotite) experiments on basic rocks combined with the record of 850° C or higher temperatures in many granulite terranes have strengthened the possibility of melting of basic rocks with hornblende and biotite during granulite metamorphism.

In Patino Douce and Beard's (1995) experiments, melting started at 850° C, 3 kbar in a quartz amphibolite and strongly peraluminous granodioritic melts with two pyroxene – plagioclase – quartz residue (at 10 kbar) were generated from amphibole dehydration melting at just below 20% melting. A notable aspect of this study is the low dP/dT of the solidus, namely approximately 6.6°C per kbar. Earlier, Rushmer (1991) reported tonalitic melts generated by dehydration melting of hornblende in an amphibolite corresponding to meta–island arc tholeiite at 950°C, 8 kbar. Skjerlie and Johnston (1993) investigated combined hornblende – biotite melting and produced granitic melts at 875° C, 10 kbar.

From basaltic composition, Rapp and Watson (1995) produced melts ranging in composition from high K – granite to low – Al trondhjemite at 1000° – 1075°C, 8 to 16 kbar. At about 20% melting between 1000° and 1075° C, granodioritic to dioritic melts were produced and the residue at lower pressures (~ 8 kbar) corresponded to mafic granulite assemblages of hornblende – two pyroxene – plagioclase. Springer and Seck (1997) carried out partial melting experiments with basic granulites and obtained tonalitic melts between 850°C and 950°C in the pressure range of 5 to 15 kbar.

Several chemical features of plagioclase, hornblende and biotite of the basic granulites are indicative of partial melting in these rocks (Tables 5, 7 and 8). For example, in two of the Kabbal basic granulites, sample K8 shows plagioclase with An_{20} while in K6 plagioclase composition varies from An_{39} to An_{52}. In E1 from Yelachipalyam plagioclase grains varying from An_{35} to An_{47} were measured. Such disequilibrium with respect to plagioclase composition in residues has been observed in the experimental work referred to above. Importantly, during dehydration melting of hornblende in these rocks the residual plagioclase gets enriched in anorthite, till the stage when garnet is stabilized and anorthite molecule starts entering garnet. In the biotite – dominated basic granulites, (such as K19,K15,K17), on the other hand, composition of plagioclase is virtually constant : An_{20-21}. Skjerlie and Johnston (1993) found that when hornblende and biotite melt together the anorthite content of residual plagioclase remains unchanged. Hornblende grains with different X_{Mg} have been found in the same rock (Table 5). It is significant that virtually all of the analysed hornblendes of basic granulites show rims richer in magnesium. Both the features are compatible with the interpretation that partial melting of basic granulites took place. Further in line with the findings of Skjerlie and Johnston (1993) on melting of hornblende plus biotite, basic granulite E1 from Yelachipalyam shows hornblendes of fairly constant X_{Mg} and biotites with widely varying X_{Mg} values (Tables 5 and 8). It is important to note here that the biotite – rich basic granulites were not metasomatically derived from hornblende–rich two pyroxene granulites : the biotites are euhedral to subhedral and show no textural evidence of secondary development, phases like sphene which are commonly observed as products of hornblende to biotite transformation, are rare. In other words, there is a case for assuming two broadly different protoliths, distinguished mainly by their potassium contents. In the field, the biotite – rich variety occurs as separate bodies.

We interpret the pegmatitic charnockites of tonalitic composition (K40/8, K7a , E1a, E25/3a) as products of dehydration melting of hornblende in hornblende – dominated basic granulites and those of granitic composition (K9, K10) as products of dehydration melting of biotite in biotite – dominated basic granulites. Note that the volume of basic granulites at Kabbal is substantial. Figure 8b shows the correspondence of the Kabbal rocks with the compositions of starting materials and melts as given in the relevant experimental investigations. Incidentally, orthopyroxene bearing leucosomes, of tonalitic to granodioritic composition , within mafic bodies of granulite facies rocks have been reported from California by Hansen and Stuk (1993), and interpreted as products of partial melting.

In this context the significance of leucocratic rinds separating the basic granulite enclaves from Peninsular gneisses, as in figure 3b (inset), is noteworthy. Comparison of the chemistry of the gneiss, rind and the basic granulite core reveals that first, the rinds on metabasic rocks are not an intermediate product of interaction between gneiss and metabasites, as evident from their concentrations of Fe_2O_3, CaO and MgO. Second, they have a sharp contrast in composition with the adjoining gneiss; K_2O% of 5.12 is much above the highest value recorded in the Peninsular gneisses. Elimination of these two possibilities leads us to conclude that the best interpretation of the rind is that, in view of the local extent of their occurrence, it is a melt phase derived from the metabasite, frozen at the border while migrating. A few hornblende grains are present in the rind, they are less magnesian than the hornblendes in the basic granulite core. On the other hand, they are similar in Mg:Fe ratio to the hornblendes of Peninsular gneisses (Table 5). Incorporation of parts of Peninsular gneisses in melt offers a reasonable explanation.

The petrology and structure of the rocks of Kabbaldurga and its neighbouring areas are complex. There are several varieties of granitoids, gneissic and non – gneissic, which form large bodies to small aplitic–pegmatitic veins. The migmatitic granitoid gneisses show considerable variation in the relative proportion of leucosomes and melanosomes. The charnockites encountered in this area are also varied, there are massif – type charnockites in the Kodamballi area, pegmatitic charnockite veins in Kabbal and Yelachipalyam area and a medium to fine-grained charnockite in Kabbal which is evidently earlier than the pegmatitic variety. In an area displaying such a complex interplay between granulite metamorphism, deformation, melting and migmatisation, it is but natural that attempts at nailing down the origin of Kabbal-type charnockite will encounter several difficulties. This was evident, for example, in the attempts of Hansen et al. (1987) and Stahle et al. (1987) to find proper reactions explaining the gneiss to charnockite transformation. We have emphasised the role of basic granulites which occur not only in Kodamballi area but also in Yelachipalyam and Kabbal, and have advanced an hypothesis which is capable of explaining, within limits, the origin of Kabbal charnockites by partial melting of these basic rocks. As all of the metabasites in the Kabbal quarry are restitic in varying degrees, the protoliths could have been granulite facies metamorphites whose original characters are no longer preserved or their amphibolite facies equivalents as represented by small to large amphibolite enclaves in the Sanabanahalli – Kodamballi area.

Incidentally, the isotope ages recently published by Hansen et al. (1997) do not show any difference between the two types of charnockites. The explanation could very well lie in resetting of Rb-Sr systematics. It is interesting that these authors' report a distinctly higher initial $^{87}Sr/^{86}Sr$ ratio in the "incipient" charnockites which suggests a longer crustal residence and reworking.

Conclusion

In conclusion we would like to emphasise two important aspects which are of general import to the origin of charnockites on the one hand and to the evolution of the high grade rocks of south India on the other. The Kabbal type pegmatitic charnockites are special and have been observed mainly in some locales in Karnataka. By no means can the Kabbal patchy charnockites be taken as prototypes of incipient development of charnockites; for instance, patchy charnockites seen at Kerala and in the Eastern Ghats are mostly non-pegmatitic; they could be pegmatitic only in very small patches, and certainly not as extensive pegmatitic bodies traversing and branching as in the Kabbal area (Bhattacharya et al., 1993, Sen and Bhattacharya, 1993). The presence of earlier structures, if found, demonstrates that they are earlier and the coarser-grained patches could very well be modified versions of the smaller patches. In other words, the pegmatitic charnockites of Kabbal are demonstrably later but many other so-called incipient charnockites reported from India are basically earlier than the enclosing gneisses (Bhattacharya et al., 1993, Sen and Bhattacharya, 1993). It is unfortunate that all of these have been clubbed together and explained in a similar fashion disregarding these differences. From a structural geology approach, Naha et al. (1993) concluded that there are two kinds of charnockites in the southern Karnataka, distinct in time signature and possible mode of formation.

It can also be questioned whether the terrain around Kabbaldurga is transitional or not. First, the presence of sizable exposures of mafic and pelitic granulites, along with layered charnockites in the Kodamballi area, clearly shows that this is a granulite terrain and not an amphibolite facies terrain transitional to granulite grade. Second, Kabbal quarry has exposures of basic granulites and non-pegmatitic charnockites. Third, patchy charnockites, evidently the main proof for such transition, are distinctly later than basic granulites. Fourth, "arrested" charnockites have been reported from areas further south of this transition zone (Hansen et al., 1987). The most that we can say, on the basis of Kabbal rocks, is that this part of Karnataka is a granulite-migmatite terrain where pegmatitic charnockite veins are spectacularly developed at places.

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