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Eastern Ghats granulite terrain of India: an overview

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Abstract—The Eastern Ghats on the east coast of India is a largely granulite terrain but also exposes granites, migmatites, anorthosites and alkaline rocks. This granulite belt has had a prolonged history of mountain building from late Archaean to late Proterozoic. During this long period the Eastern Ghats mobile belt witnessed repeated folding and possibly polycyclic metamorphism. Some recent findings suggest breaks between orogenic cycles and a proterozoic reworking of Archaean granulites. Extreme-temperature crustal metamorphism under fluid-absent conditions and crustal anatexis in huge thickness of pelitic to psammitic protoliths producing leptynites are some of the important results of recent investigations of the Eastern Ghats mobile belt. Different generation of charnockites are present in the Eastern Ghats belt, but charnockitisation of granitic gneisses is yet to be documented. Some apparently nascent growths, the patchy charnockites in the Chilka area are shown to be relict of older charnockitic rocks that suffered granulite-facies metamorphism and attendant migmatisation.

Introduction

The Eastern Ghats terrain skirting the east coast of India has all the characteristics of a mobile belt, namely a linear disposition for over 900 km, granulite-facies metamorphism through the length and breadth of the belt (aptly described as a Granulite terrain), a prolonged history of mountain building spanning most of the Proterozoic era and orogenic activity continuing at least up to the Pan-African (*ca.* 500 Ma).

A comprehensive understanding of the evolution of this mobile belt in the light of the plate-tectonic theory is urgent at this time. Over the last two decades much has been published on different aspects of this granulite belt. But, unfortunately, multi-disciplinary studies are far from sufficient and it is an arduous task to integrate all the scientific inputs and thereby build a realistic story of this important mobile belt. In this context, some degree of bias is perhaps unavoidable in choosing the topics and/or aspects. The present communication focuses on the following aspects of the Eastern Ghats mobile belt:

(1) deformation history and its bearing on the tectonic regimes;
(2) boundary relations with adjoining cratons and its bearing on the efficacy of the plate boundary processes;
(3) nature of magmatic episodes and their bearing on the tectonic setting;
(4) petrologic and time relations between important lithologies—khondalites, charnockites and leptynites; and
(5) granulite-facies metamorphism and *P–T–t* paths and their implication on the tectono-thermal processes.

It is hoped that this exercise will also be useful for identifying specific problems that need further attention.

Deformation history

The granulite belt of the Eastern Ghats has the imprints of three major episodes of folding and associated metamorphic fabrics, developed on various scales (Sarkar *et al*., 1981; Halden *et al*., 1982; Bhattacharya S. *et al*., 1994; Chetty and Murthy, 1994).

The first episode of folding is represented by minor rootless folds of bedding S_0 in metapelites, with a strong and pervasive metamorphic foliation developed parallel to the axial planes of these folds. Although these are not common, the presence of major F_1 folds is indicated by several hook-shaped folds on a map scale (Bhattacharya *et al*., 1994; Chetty and Murthy, 1994; Bhattacharya, 1996) produced by coaxial refolding of F_1 folds by F_2 folds. The present attitude of these minor F_1 folds are reclined. Rootless and intrafolial F_1 folds are also observed in the bands of charnockites and mafic granulites (Bhattacharya *et al*., 1994; Bhattacharya, 1996). The most pervasive foliation—a gneissic foliation in the khondalites—corresponds to the F_1 fold axial traces and is broadly syntectonic with granulite-facies metamorphism.

The second-generation folds, which are common in most of the granulites and occur on various scales, are commonly overturned to isoclinal and are on a regional scale. F_2 axial planes are parallel to F_1 axial planes. In many areas, characteristic hook-shaped interference patterns are observed. However, in a number of localities F_1 and F_2 axes are at high angles in charnockitic rocks, resulting in arrow-head interference patterns (Rajib Kar, 1995). The S_2 foliation, axial planar to F_2 folds, is developed in most of the lithologies. Several small-scale shear zones marked by quartzite mylonites and pseudotachylites have developed parallel to S_2. One such shear zone in the Chilka area has S-C microfabric and a downdip stretching lineation. It is also important to note that steep plunges of S_2 is spatially associated with the shear zones and their downdip stretching lineation. Thus, the steep plunge of F_2 folds is a consequence of rotation of fold axes by progressive simple shear (Bell, 1978; Bhattacharya, 1989).

The third-generation folds, developed on various scales, are commonly open and upright with subhorizontal axes. The attitude of these folds on a mesoscopic scale is highly diverse. The diversity of F_3 axes can be a consequence of variously oriented F_2 limbs. But diversity of F_3 axial plane foliation, particularly in the eastern sector (Bhattacharya *et al.*, 1994), is evidently related to the melt-dominated rheology of the rocks, the migmatites. Locally developed shear cleavage, microfaults and shear bands are commonly associated with F_3 folding. The stretching lineation in the form of rod-like structures and quartz ribbons are parallel to the subhorizontal F_3 axes.

The NE–SW-dominant trend of the Eastern Ghats was correlated to F_1 folding and granulite-facies metamorphic fabric from the Chilka Lake area (Bhattacharya, *et al.*, 1994). Within the Eastern Ghats belt, deviations from this trend are noticed at several places and are clearly the effects of F_2 and F_3 folding. A few large-scale strike-slip shear zones could be recognised from the lineament maps (Chetty and Murthy, 1994; Bhattacharya, 1996) and are correlated with the third episode of folding and associated S_3 foliation (Bhattacharya, 1996).

Based on deformation structures, two different tectonic interpretations have been proposed. Chetty and Murthy (1994) proposed an early collisional regime and implied that crustal thickening, responsible for granulite-facies metamorphism, was achieved by thrusting. Thrust tectonics would require that early structures be subhorizontal, namely recumbent folds, subhorizontal stretching lineation and strike-slip displacements. However, most of the subhorizontal structures reported in the literature are late features superimposed on already over-thickened crust. Bhattacharya (1996) proposed an early compressional regime that resulted in early subvertical structures by homogeneous shortening across the belt.

Isoclinal and rootless F_1 with NE–SW-trending steep axial plane foliation S_1 (also representing granulite-facies event) and characteristic steep plunges of F_1 suggest a regional NW–SE-directed compression and shortening during the development of first-generation folds. Isoclinal to overturned F_2 folds on NE–SW-trending steep axial plane foliation, S_2 points to a continued compressional regime during the development of second-generation folds. Extensional structures are mostly associated with F_3 folds.

Detailed structural studies in many more areas are needed to clinch the issue. However, the structural data so far reported in the literature, namely the sequence of fold styles and major fabric development (foliations and lineations, do not corroborate an early thrusting event.

Boundary relations

The granulite terrain of the Eastern Ghats bordering the Dharwar, Bastar and Singhbhum cratons provide an excellent opportunity to study the granulite–greenstone contact relations.

However, opinion is sharply divided as to whether the granulite belt south of Godavari belongs to the Eastern Ghats or the South Indian granulite belt. The gravity discontinuity and −40 mGal contour, characteristic of the western boundary of the granulite belt of the Eastern Ghats, continues (with a few interruptions) up to the southern tip of India and shows a smooth NW bend to merge with the Western Ghats granulite belt (Subrahmanyam and Verma, 1986; Fig. 1). The NE–SW trend of the Eastern Ghats also follows the gravity contour (Drury and Holt, 1980). But, on the other hand, the granulite belt south of Godavari appears to be more akin to the South Indian granulite terrain in terms of dominant lithologies, petrological histories and isotopic ages (Ramakrishnan, 1993). To avoid confusion, therefore, the present communication deals with the granulite belt north of the Godavari river, and granulite–greenstone boundary relations are discussed with reference to the western boundary against Bastar Craton and the northern boundary against the Singhbhum Craton.

The western boundary of the Eastern Ghats mobile belt (EGMB) against the Bastar Craton is sharp and more or less linear with a NNE–SSW trend. A gravity survey (Subrahmanyam, 1983; Subrahmanyam and Verma, 1986) across this boundary shows a characteristic high gravity anomaly from the schist belt of the Bastar Craton. Interpretation of this gravity signature is problematic. This gravity contrast may simply indicate high density crust and/or thickened crust underneath the Eastern Ghats (Subba Rao, 1994). Early workers also considered a boundary fault on the evidence of crushed rocks in the boundary region. But the mylonites and crushed rocks appear to be restricted to the Eastern Ghats lithologies. Moreover, small-scale shear zones with NNE–SSW trends are common in the EGMB (Chetty and Murthy, 1994; Bhattacharya, 1996) and are broadly synchronous with the second deformation episode. It is important to note that anorthosite and alkaline complexes (taken to indicate rift tectonic setting) are not confined to the boundary and are broadly synchronous with F_2. From a detail field study of the border region in Jeypore, Crookshank (1938) described intrusive charnockites with tounges and apophyses of charnockites into the schist belt of Bastar Craton. Nanda (1995) emphasised that field evidences do not support the view of upliftment along a boundary fault. Nanda (1995) further described a transition zone between the granulite and greenstone terrains, characterised by coexistence of low- and high-grade rocks. However, intermingling of high- and low-grade rocks in this boundary region may also have resulted from tectonic movements and a transition zone cannot be postulated on this ground alone. However, the magmatic charnockites and other granitoids (Crookshank, 1938; Nanda, 1995) might have obliterated earlier tectonic imprints, but the time relation of this magmatic episode (no isotopic data so far) to the juxtaposition of the granulite belt against the greenstone belt is still not clear.

The northern boundary against the Singhbhum Craton is rather complex, and a host of granitoids separate the two geologic provinces of the EGMB and the Singhbhum Craton (Patra *et al.*, 1994; Moitra, 1995). Rao S. V. P., *et al.* 1964) proposed a boundary thrust, and later workers (Banerjee *et al.*, 1987) considered a faulted boundary on the evidence of crushed rocks and blastomylonites near this boundary. Also, Mahalik (1994) proposed recently a boundary fault, interpreted from Landsat imageries. Incidentally, the Sukinda ultramafics are generally taken to indicate a cryptic suture representing the 'Sukinda thrust' (Saha, 1994).

However, a crustal-scale shear zone or clear-cut fault zone is not recognisable in the Landsat imageries or aerial photographs. Mylonites with S-C fabrics are present on both sides of the boundary. This mylonitic fabric and the shear cleavage is post-kinematic to F_3 folds in the Singhbhum Craton and the EGMB. Thus, this late shear cleavage, which is restricted to the boundary region, may be correlated with the deformation accompanying juxtaposition of the two geologic provinces.

An analysis of the structures of different generations in the adjoining parts of the EGMB and the Singhbhum Craton does not indicate an extensional tectonic setting. The NE–SW Eastern Ghats trend is rotated to WNW–ESE near this boundary. Also, the NW–SE Singhbhum trend is rotated to N–S near the boundary. On the evidence of the aforesaid rigid body rotation and strike-slip shear cleavage of the boundary region, Bhattacharya (1994) postulated a transpressive tectonic regime during the juxtaposition of the two geologic provinces. Moreover, the granitoids, syn-kinematic with the shear cleavage, is suggestive of rapid uplift in a transpressive regime.

Magmatic episodes bearing on the tectonic setting

The earliest magmatic rocks in the EGMB are represented by the precursors of mafic granulites, which occur in an interbanded fashion with the khondalites and charnockites. Two types of mafic granulites are described in the literature (Dasgupta *et al.*, 1991; Murthy *et al.*, 1994). One is a hornblende–pyroxene

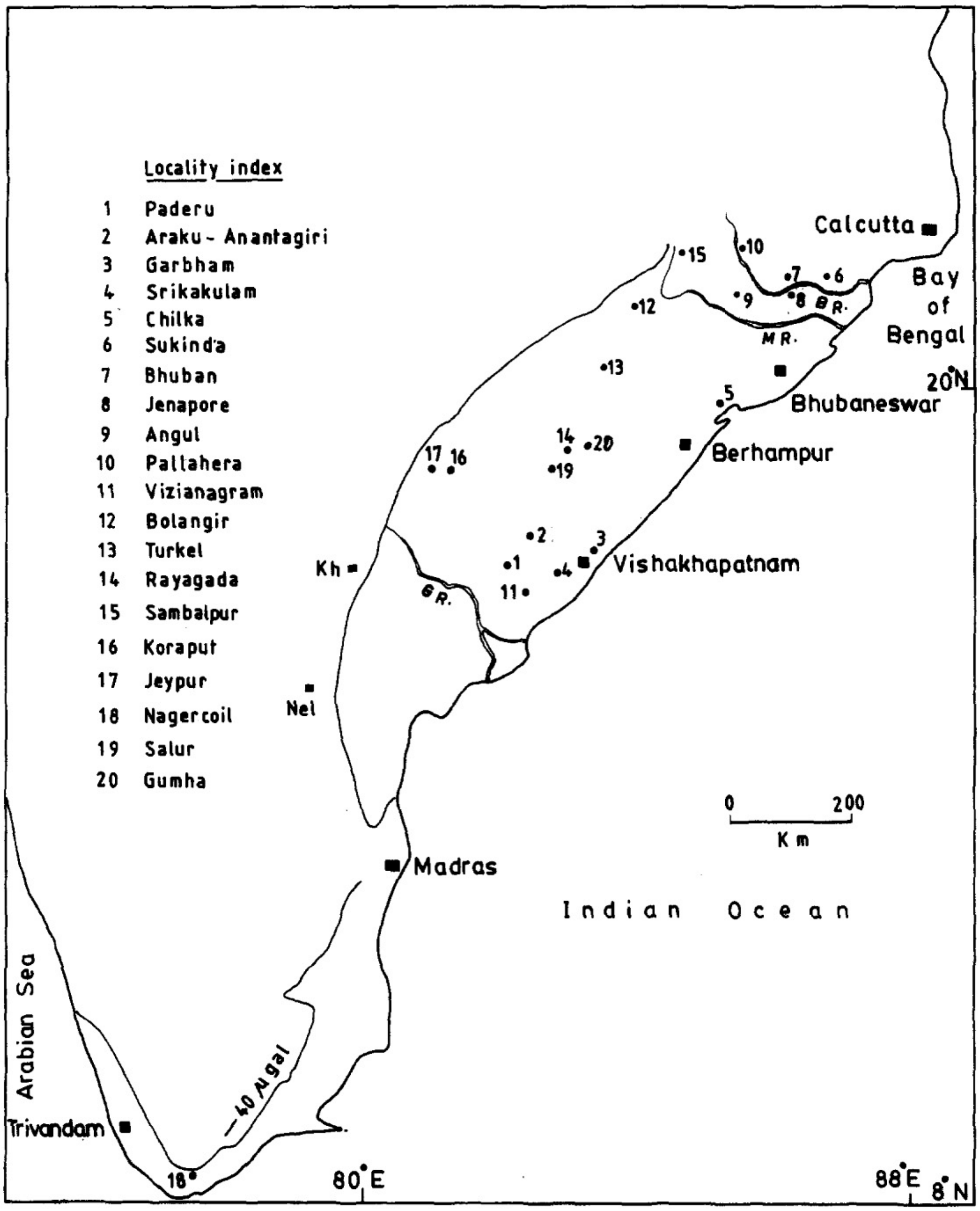

Fig. 1. Eastern Ghats granulite belt with studied localites: −40 mGal gravity anomaly contour marks the western boundary of the granulite belt.

granulite with a minor ultramafic component. These mostly occur as xenoliths in charnockitic rocks. The other variety of mafic granulite is a two-pyroxene granulite. From a number of localities in Orissa and Andhra Pradesh, two-pyroxene granulites are described as members of the magmatic suite with enderbite and charnockite (Mallikarjuna Rao *et al.*, 1994; Murthy *et al.*, 1994; Rao A. T. *et al.*, 1994). In the field, the two-pyroxene granulite occurs in an interbanded fashion with enderbite and charnockite.

In the Chilka Lake area of Orissa, charnockite, enderbite and, rarely, two-pyroxene granulite occur as minor bands and patches (LC and SC in Sen *et al.*, 1995) within leptynites (garnetiferous quartzofeldspathic gneisses). Bhattacharya *et al.* (1994) suggested the possibility of an igneous protolith for the Chilka Lake charnockitic rocks, which have suffered granulite-facies metamorphism and migmatisation. Single zircon dating by $^{207}Pb/^{206}Pb$ systematics in a charnockite from the Chilka Lake area reveals three ages, 2.6, 1.7 and 0.9 Ga (Goswami, PRL, Ahmedabad, pers. comm., 1996). This is consistent with the proposition of Bhattacharya *et al.* (1994), and the three ages of equilibration may be correlated to F_1, F_2 and F_3, respectively. Moreover, pyroxene exsolution lamellae, indicative of magmatic temperatures, and zoning in plagioclase, indicative of crystallisation from melt, are recorded from the charnockitic rocks of the Chilka Lake area. The bulk composition of charnockitic rocks of the Chilka Lake area (Table 1) may be described in terms of a relic magmatic trend. Niggli c-al-alk diagram (Fig. 2(a)) depicts a bimodal distribution of charnockites and enderbites. However, a variation trend can be visualised in the $S'(SiO_2/Al_2O_3) - F'(Fe_2O_3/MgO) - A'(Na_2O/K_2O)$ diagram (Fig. 2(b)). Initially, at constant F', S' increases to peak value, and then at constant A', F' progressively increases. The variation trend is closely comparable to that of the Antarctican charnockites (Sheraton and Collerson, 1984), though the two parts are somewhat offset for the Chilka charnockites, particularly in the domain of high S' values. This may be interpreted as the effect of granulite-facies metamorphism and associated migmatisation, which tends to increase the silica content in the form of quartz-rich pods, commonly observed in charnockites.

A significant magmatism in the EGMB is represented by a large number of anorthositic rocks (Leelanandam, 1988). Some of these are massif type (notably Bolangir massif and Chilka massif), while some others are described as layered complex.

Bose (1979) considered the massif-type bodies as syntectonic emplacements. Sarkar *et al.* (1981) described the Chilka Lake anorthosite as massif type and part of a syntectonic (with F_2) plutonic complex that includes charnockitic rocks (acidic) and dated the complex (by Rb–Sr whole rock) as 1400 ± 100 Ma. However, Bhattacharya *et al.* (1994) argued on structural grounds that the charnockitic rocks of the Chilka Lake area are older than the anorthosite massif. Limited geochronological data (Aftalion *et al.*, 1988; Paul *et al.*, 1990) for metapelites and charnockites support the time relation enumerated by Bhattacharya *et al.* (1994).

Mukherjee (1989) proposed that at Bolangir the anorthosite magma ensued granulite-facies metamorphism of the enclosing rocks. In the absence of definite structural and/or geochronological evidence, this prop-

Table 1. Major-element composition of patchy charnockites (C) and leptynites (L) of the Chilka Lake area (analytical precision also given for all oxides)

	SD/2 (C)	G/1 (C)	DD/3 (C)	NA/2 (C)	KM/1 (C)	CM/4 (C)	SL-2 (L)	HD2/L (L)	H5 (L)	K10 (L)	DL1/A (L)	HD/1/L (L)	CD2/L (L)	Accuracy variation (%)	Precision SD (population)
SiO_2	46.26	67.05	67.71	47.03	62.41	54.18	69.85	69.31	67.04	72.18	78.86	70.66	73.05	0.33	3.26
Al_2O_3	17.02	14.46	17.03	15.41	17.41	16.42	14.29	14.15	15.25	13.81	11.01	14.70	13.12	1.55	1.20
Fe_2O_3t	13.79	2.46	3.59	14.73	5.66	8.65	2.43	4.34	4.19	2.54	1.12	4.15	2.41	0.19	1.13
MnO	0.19	0.02	0.25	0.25	0.10	0.15	0.04	0.06	0.04	0.04	0.03	0.08	0.06	20.00	0.02
MgO	8.83	1.39	0.54	6.74	3.50	6.86	0.79	0.79	1.40	0.29	0.00	0.58	0.71	19.20	0.37
CaO	6.91	1.91	1.87	10.82	3.54	6.69	2.80	3.03	3.35	1.34	1.13	2.92	2.89	2.39	0.78
Na_2O	1.06	4.07	1.79	2.54	3.59	4.04	3.92	4.01	3.79	3.81	3.45	3.59	3.67	7.48	0.18
K_2O	1.02	6.72	7.42	0.73	2.79	1.51	5.52	3.50	4.77	5.27	4.07	4.13	4.25	1.65	0.66
TiO_2	2.57	0.40	0.33	1.68	0.81	1.06	0.44	0.66	0.77	0.37	0.22	0.46	0.37	20.53	0.20
P_2O_5	0.68	0.70	0.55	0.09	0.02	0.39	0.34	0.37	0.38	0.21	0.02	0.31	0.17	10.04	0.16
Total	98.27	99.18	101.13	100.02	99.81	100.48	100.41	100.21	101.18	99.86	99.90	101.57	100.69		

osition cannot be substantiated. At least such a cause-and-effect relation between anorthosite and granulite-facies metamorphism on a vast scale cannot be valid for the EGMB as a whole.

Several alkaline complexes are reported from the EGMB and are mostly concentrated along the western and northern margins of the EGMB (Leelanandam, 1994). Petrological accounts of the different occurrences were given by several workers (Bose, 1979; Leelanandam and Krishna Reddy, 1981; Bose and Bose, 1982; Leelanandam, 1989; Madhavan *et al.*, 1989; Sarkar *et al.*, 1989). Many of these alkaline complexes have been dated by Rb–Sr whole-rock isochron as 1400 ± 50 Ma old (Clarke and Subba Rao, 1971; Sarkar *et al.*, 1994a, b). Alkaline complexes are generally believed to have been emplaced in rift tectonic setting; although these are concentrated along the western margin of EGMB, the structural setting around these complexes have not yet been worked out.

Undoubted granite plutons are virtually absent in the EGMB (Leelanandam, 1994), although small stocks of porphyritic granite are common in some localities, namely Rayagada, Gumha, Salur and Jenapore (Fig. 1). These are mostly undeformed with euhedral feldspar phenocryst defining a subhorizontal layering. Around Gumha, one such granite is located in the nose of a large, upright, antiform (F_3). The only deformation imprint in these granites is local strike-slip shearing associated with F_3 folding. Veins of this porphyritic granite in the acid charnockite are observed around Salur and Jenapore, while xenoliths of metapelitic granulites, charnockites and mafic granulites are common within porphyritic granite around Rayagada. Petrological accounts of this granite variety are not available from published literature, although the common presence of garnet in them suggests a peraluminous composition and hence a probable anatectic history. It should be noted here that leptynites and other quartzofeldspathic gneisses (orthopyroxene-free) form an important component of EGMB and they are designated as S-type granites of anatectic origin (Sen, 1987).

Petrologic and time relations between important lithologies

Charnockites–leptynites

Besides the large bodies of massif-type charnockites at several localities (Jenapore and Jeypore in Orissa and

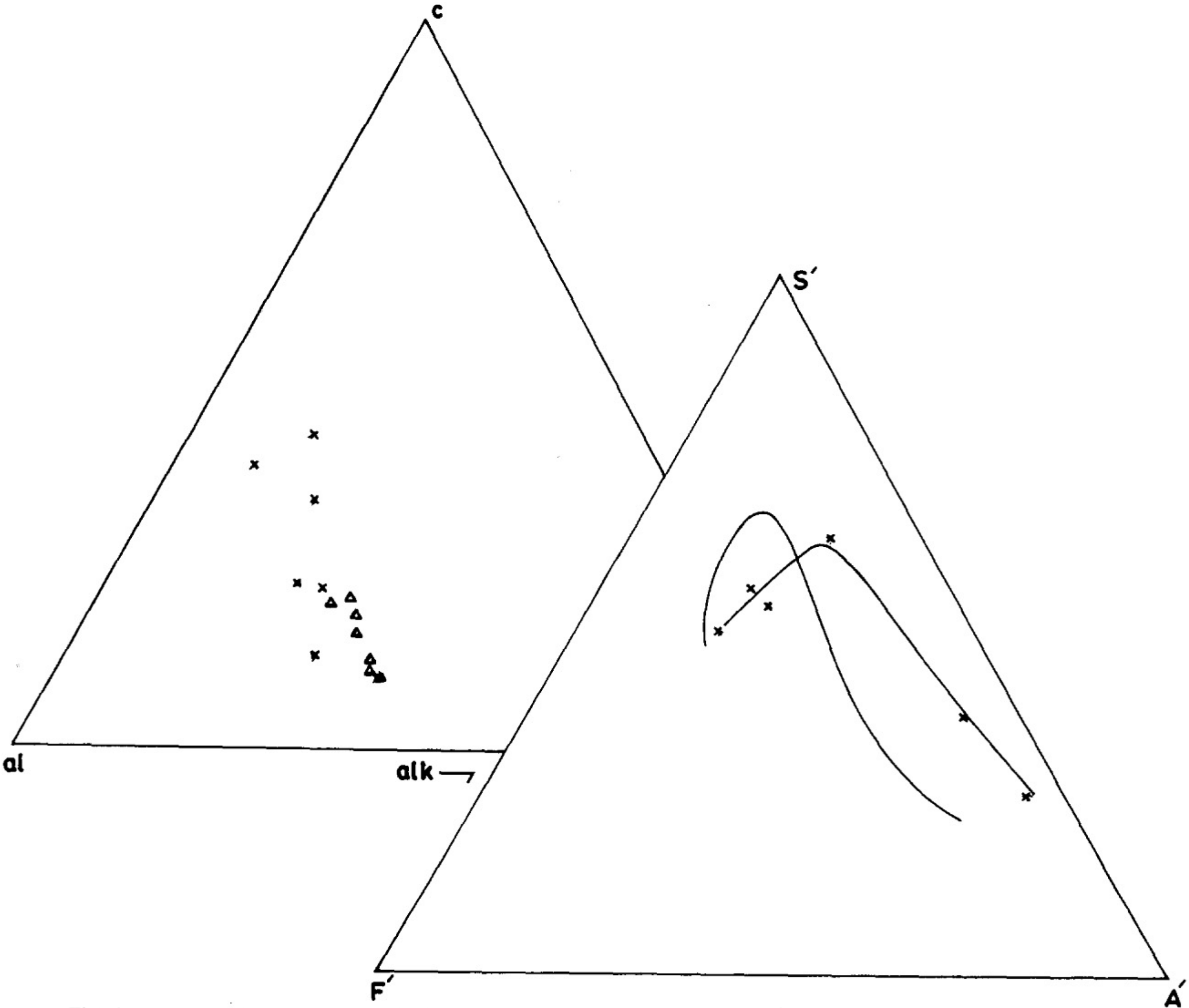

Fig. 2. (a) Niggli c-al-alk plots of Chilka charnockite suite (×) and leptynites (△). (b) S′(SiO_2/Al_2O_3) – F′(FeO_t/MgO) – A′(Na_2O/K_2O) plots of Chilka charnockite suite (×); variation trend for Antarctican charnockites (data source Sheraton and Collerson, 1984): bold line.

Table 2. Representative modal composition of patchy charnockites and leptynites of the Chilka Lake area

	Charnockites					Leptynites			
Qtz	52	29	21	42	51	60	48	60	62
K-fs	16	18	16	14	32	22	29	22	22
Pl	20	20	25	18	7	7	9	7	7
Opx	4	27	19	8	8	—	—	—	—
Grt	8	—	—	tr	—	4	4	5	4
Bt	tr	—	19	18	2	4	7	6	4
Ilm	1	6	tr	tr	—	3	3	—	—

Vishakhapatnam in Andhra Pradesh), small bands and patches of charnockites are common within leptynites around the Chilka Lake area and Rayagada. In these localities the small patches of charnockitic rocks are often traceable to nearby bands that are torn and fragmented. Bhattacharya *et al.* (1993) argued on structural grounds that the patchy charnockites are older than the host leptynites, and they characterised the Chilka Lake patchy charnockites as migmatised relicts of loder charnockitic rocks. Later Sen *et al.* (1995) argued on the evidence of reaction textures that the small patches of charnockites are not related to the leptynites by any prograde or retrograde reaction. The bulk compositional data of Chilka Lake leptynites and patchy charnockites (Table 1, Fig. 2(a)) show that these are chemically distinct entities and cannot be related by any isochemical or even mildly alochemical transformation. Moreover, the modal composition (Table 2) and mineral compositional data (Table 3) of leptynites and patchy charnockites from the Chilak Lake area are also incompatible with any of the orthopyroxene-forming reactions proposed in the literature (Kumar and Chako, 1986; Hansen *et al.*, 1987).

It should be noted that different generations of charnockites are probably present in the vast granulite belt of the Eastern Ghats. But the propositions of charnockitisation in the Eastern Ghats by Halden *et al.* (1982) and Paul *et al.* (1990) cannot be verified, as these authors did not provide the necessary information—structural, petrographic and compositional.

Khondalites–leptynites

Early workers (Bhattacharya, 1973) considered leptynites as recrystallised khondalites. But Sen (1987) in a preliminary study showed from the chemical aspect that leptynites are anatectic granites. In a detailed field investigation in the Chilka Lake area, Bhattacharya *et al.* (1994) described leptynites at fold noses of khondalites and also sillimanite trails within the garnet of leptynites. Karmakar and Fukuoka (1992) also described the leptynites of Araku in Andhra Pradesh as anatectic granites from khondalites. From the Chilka Lake area, Sen *et al.* (1995) differentiated several types of metapelitic granulites on the basis of mineral assemblages and further emphasised that khondalites document evidence of dehydration melting reactions of the type

$$\text{biotite} + \text{sillimanite} + \text{quartz} \rightarrow \text{garnet} + \text{K-feldspar} + \text{melt}$$

Table 3. Representative mineral compositions of patchy charnockites and leptynites of the Chilka Lake area

	Charnockites			Leptynites			
	Grt	Opx	Pl	Grt	Bt	Pl	Ilm
SiO_2	37.41	49.30	55.89	38.02	37.732	62.595	—
Al_2O_3	21.91	0.72	27.34	21.211	14.971	23.031	—
TiO_2	0.03	0.11	0.17	—	4.367	—	52.578
FeO	32.22	39.15	0.16	34.586	12.615	0.086	51.586
MgO	2.71	10.53	0.01	5.798	16.078	—	—
CaO	4.85	0.61	8.72	1.531	0.002	4.519	—
MnO	1.43	0.56	—	1.258	0.008	—	0.362
Ma_2O	0.50	0.06	6.47	—	0.275	8.375	—
K_2O	0.17	0.07	0.32	—	9.867	0.140	—
Cr_2O_3	0.29	0.03	—	—	—	—	—
Cl_2O	—	—	—	—	0.019	—	—
FO_2	—	—	—	—	0.466	—	—
Total	101.52	101.14	99.08	102.586	96.198	98.745	104.526
Si	2.96	1.97	2.53	3.0249	5.5493	2.7970	—
Al	2.04	0.03	1.46	1.9797	2.5952	1.2130	—
Ti	0.01	0.01	0.01	—	0.4830	—	1.9294
Fe	2.13	1.31	0.01	2.0822	1.5516	0.0032	2.1051
Mg	0.32	0.63	0.01	0.6843	3.5249	—	—
Ca	0.41	0.03	0.42	0.1299	0.0003	0.2164	—
Mn	0.09	0.02	—	0.0844	0.0010	—	0.0150
Na	0.08	0.01	0.57	—	0.0784	0.7256	—
K	0.02	0.01	0.02	—	1.8513	0.0080	—
Cr	0.02	0.01	—	—	—	—	—
Cl	—	—	—	—	—	0.0046	—
F	—	—	—	—	0.2166	—	—
ΣCation	8.06	4.01	5.02	7.9853	15.8562	4.9632	4.0494

Table 4. Representative mineral compositions of calc-silicate assemblages of the Chilka Lake area

	R71 (Grt-Cpx-Pl-Scp-Wo-Qtz)				R20 (Cpx-Pl-Scp-Wo-Qtz)		
	Grt	Cpx	Pl	Scp	Cpx	Pl	Scp
SiO_2	38.11	47.92	42.11	43.17	48.72	42.27	40.12
Al_2O_3	17.73	3.11	34.76	27.96	1.59	34.46	29.56
TiO_2	0.81	0.21	0.00	0.00	0.00	0.00	0.00
FeOt	7.42	11.16	0.03	0.12	16.59	0.02	0.18
MgO	0.42	10.15	0.00	0.05	7.11	0.00	0.05
CaO	34.71	23.86	20.41	20.12	23.44	19.79	22.49
MnO	0.29	0.22	0.00	0.00	0.47	0.00	0.00
Na_2O	0.00	0.43	0.33	1.78	0.31	0.26	0.76
K_2O	0.00	0.00	0.00	0.03	0.00	0.00	0.08
Total	99.49	97.06	97.64	92.23	98.17	96.80	93.24
Si	5.92	1.89	1.98	6.73	1.95	1.99	6.37
Al	3.29	0.13	1.97	5.20	0.07	1.96	5.51
Ti	0.11	0.01	0.00	0.00	0.00	0.00	0.00
Fe^{2+}	0.571	—	0.00	0.00	0.57	0.00	0.03
Fe^{3+}	0.272	0.38	0.00	0.01	0.00	0.00	0.00
Mg	0.08	—	0.00	0.01	0.41	0.00	0.00
Ca	5.73	1.01	1.02	3.35	1.02	1.04	3.74
Mn	0.04	0.01	0.00	0.00	0.03	0.00	0.00
Na	0.00	0.03	0.02	0.71	0.01	0.03	0.38
K	0.00	0.00	0.00	0.00	0.00	0.00	0.02
ΣCation	16.14	4.06	5.02	16.04	4.03	5.04	16.07

or

$$\text{biotite + sillimanite + plagioclase + quartz} \rightarrow \text{garnet + K-feldspar + melt}$$

More recently, Sen and Bhattacharya (1996) from the chemical aspect revealed the link between khondalites and leptynites via dehydration melting of micas in pelitic and psammitic protoliths.

Granulite facies metamorphism and *P–T–t* paths

Some of the important aspects of granulite-facies metamorphism concern the *P–T*-fluid regime and sense of *P–T–t* path. Additionally, for the EGMB with polyphase deformation history, the possibility of polycyclic metamorphism or reworking should also be addressed.

P–T record from the EGMB varies substantially, although, the most pervasive *P–T* impress of 700°C and 6–8 kbar has been recorded from garnet–pyroxene–plagioclase–quartz assemblages in charnockites and mafic granulites. However, extremely high temperatures (1000°C and above) and peak pressure (10 kbar and above) have been registered from several areas: Angul (Bhattacharya and Sen, 1991), Chilka (Sen *et al.*, 1995), Bolangir (Mukherjee, 1989), Koraput (Bhattacharya and Sen, 1991), Paderu (Lal *et al.*, 1987), Anantagiri and Araku valley (Sengupta *et al.*, 1990, 1991; Dasgupta *et al.*, 1991), Garbham (Dasgupta *et al.*, 1992) and Vizianagram (Kamineni *et al.*, 1988a, b). These values are obtained from (i) orthopyroxene–garnet thermometry and peizionite exsolution in orthopyroxene, as in Koraput, Rayagada, Garbham and Araku; (ii) calc-silicate assemblages with grossular between wollastonite and plagioclase, as in Angul, Koraput and Chilka; (iii) stability relations of sapphirine as in Paderu, Araku valley, Vizianagram and Chilka.

Quantitative estimates of fugacities of H_2O and O_2 are available only for Angul, Koraput and Chilka granulites. a_{H_2O} is generally low (<0.3) and log f_{H_2O}–log f_{O_2} plots indicate fluid-absent metamorphism (Bhattacharya and Sen, 1991). Also, $C + O_2 = CO_2$ reaction in graphite-absent assemblages signify the absence of CO_2-rich fluids.

Both isobaric cooling and isothermal decompression paths have been recorded from several areas in the EGMB. The isobaric cooling paths are generally recorded from mafic granulites and charnockites (Sengupta *et al.*, 1990; Dasgupta *et al.*, 1991; Sen *et al.*, 1995). And isothermal decompression paths are generally recorded from sapphirine granulites (Lal *et al.*, 1987; Dasgupta *et al.*, 1994; Sen *et al.*, 1995). However, the relative chronology of these *P–T–t* segments still remains somewhat controversial, because they are recorded from different lithologies and because there is no unequivocal geochronological data so far.

Sengupta *et al.* (1990) proposed a counterclockwise *P–T–t* path defined by a prograde reaction in a metapelitic assemblage followed by isobaric cooling in pyroxene granulites and a late decompression in a metapelitic assemblage.

Lal *et al.* (1987) and Mohan (1995) described isothermal decompression paths from sapphirine granulites and emphasised that absence of early IBC path may be related to rapid uplift associated with rifting. Dasgupta *et al.* (1994) described an isothermal decompression path with a clockwise sense, from sapphirine granulites, but interpreted this as a Proterozoic reworking or a second cycle superposed on isobarically cooled granulite.

Bhowmik *et al.* (1995) reported extreme temperature and isobaric cooling from calc-silicate assemblages. However, the temperatures in excess of 950°C were estimated from associated mafic granulites and not from calc-silicate assemblages. Harley and Buick (1992) showed from calc-silicate assemblages of the Raur group, Antarctica, that calcite–plagioclase symplectitic intergrowth replacing scapolite is developed in the most meionitic scapolite (92% mei.) and they have placed this reaction at 920°C, 8 kbar.

In the Chilka area, calc granulites have high temperature assemblages, including scapolite, wollastonite and clinopyroxene (Table 4). Here, scapolite pseudomorph replaced by symplectitic intergrowths of calcite and plagioclase (Fig. 3) depict the vapour absent reaction:

$$\mathrm{Scp} = 3\,\mathrm{An} + \mathrm{Cc} \qquad (1)$$

This reaction defines the lower temperature stability of meionite, and in the Chilka area the scapolite is 90% meionite, particularly in the garnet-absent domains (sample R20), which gives a temperature in excess of 900°C. In the garnet-present domains (sample R71), the scapolite is 79–83% meionite. This further implies that grossular garnet is produced via several reactions upon cooling (Fig. 3). From the microtextures in the calc-silicate assemblages of the Chilka area, the following reactions are envisioned:

$$\mathrm{An} + 2\,\mathrm{Wo} = \mathrm{Gr} + \mathrm{Qz} \qquad (2)$$

$$\mathrm{Cpx} + \mathrm{An} = \mathrm{Gr} + \mathrm{Qz} \qquad (3)$$

$$6\,\mathrm{Wo} + \mathrm{Mei} = 3\,\mathrm{Gr} + \mathrm{Cc} + 3\,\mathrm{Qz} \qquad (4)$$

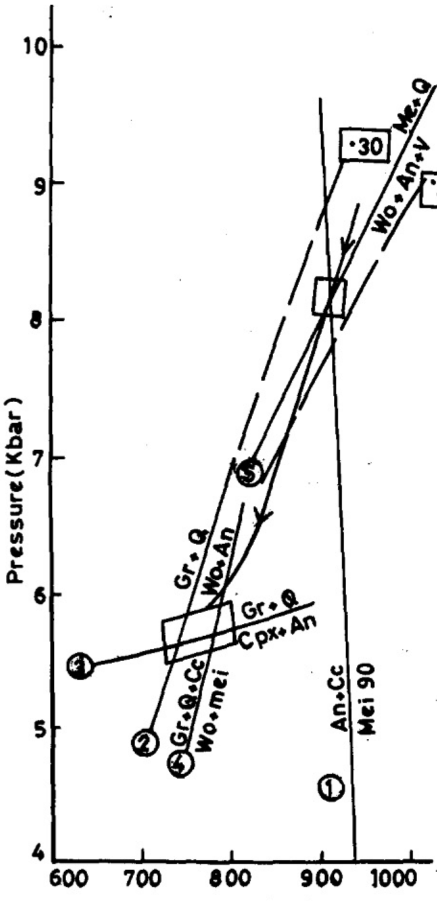

Fig. 3. *P–T–t* path from Chilka calc-granulites. Dashed lines for reaction scp + qtz → wo + pl + CO_2 at $aCO_2 = 0.30$ and 0.40.

Moreover, in the garnet-absent domains, microtextural evidence, namely moats of wollastonite and plagioclase partially enclosing coarse scapolite (Fig. 3), as well as symplectitic intergrowth of plagioclase–wollastonite suggest the reaction (5) advancing to the right-hand side on decompression at 8 kbar, 850°C and aCO_2 of 0.30:

$$\text{scapolite} + \text{quartz} = \text{wollastonite} + \text{plagioclase} + CO_2 \qquad (5)$$

Thus, cooling and grossular-producing reactions (2), (3) and (4) appear to have occurred at lower pressure.

From the Chilka granulite suite, Sen *et al.* (1995) described a high-temperature decompression from above 10 kbar to 8 kbar at 1100°C and emphasised that this sector is compatible with a clockwise trajectory, though it could not be ascertained whether this represents the complementary arm of a prograde loop.

Recently, the question of polycyclic metamorphism in the EGMB has been addressed by several workers (Dasgupta *et al.*, 1994; Dasgupta and Sengupta, 1995; Sen *et al.*, 1995). Dasgupta *et al.* (1994) and Dasgupta and Sengupta (1995) argued on the evidence different *P–T–t* loops and tentatively correlated the high-temperature decompression event to a late Proterozoic reworking. Sen *et al.* (1995) argued on the evidence of multi-state *P–T–t* path with a high-temperature decompression and two separate phases of cooling that different segments of the *P–T–t* path was separated by breaks between orogenic cycles.

It is evident from the foregoing that a strong possibility of reworking in the EGMB exists and the details can only be ascertained from structural–petrological and geochronological investigations in many more sectors.

Discussion

During the last decade some significant data pertaining to deformation history, *P–T*–fluid regime and *P–T–t* paths have been published. Although, far from sufficient, with particularly inadequate geochronological data, the relation between granulite-facies metamorphism and tectonics can be addressed, at least in a preliminary fashion.

Geophysical criteria and geobarometric estimates suggest that the Eastern Ghats granulite terrain represents an over-thickened crust. However, the mechanism of thickening has not been addressed by most of the workers.

From petrological studies in the Araku–Anantagiri areas of Andhra Pradesh, Dasgupta *et al.* (1993) proposed magmatic thickening by underplating or intraplating as the cause of granulite-facies metamorphism of the enclosing rocks. Although IBC paths and a counterclockwise sense of *P–T–t* path are consistent with this proposition, the lack of a significant volume of magmatic rocks and thermal model constraints (McKenzie and Bickle, 1988) argue against this proposition. Thus, this proposition appears valid for local contact metamorphic effects only.

From structural studies in the west-central sector of the EGMB, Chetty and Murthy (1994) proposed collisional tectonics and early thrusting as the cause of crustal thickening. The proposition of early thrusting should be viewed with scepticism because published structural data pertaining to thrust tectonics are scarce, to say the least (Bhattacharya, 1996).

From structural studies in several sectors, Bhattacharya (1996) proposed that crustal thickening was achieved by homogeneous shortening and folding in response to compression. Some petrological constraints, e.g. the high-temperature decompression vector (in the Chilka granulite suite) and the lack of a significant volume of magmatic rocks predating or at least synchronous with huge thickness of metapelitic granulites, are compatible with this proposition.

Finally, a strong case exists for correlation of the Eastern Ghats with the granulite terrains of East Antarctica. A multi-stage *P–T–t* path in the Chilka granulites is closely comparable to those from Forefinger Point (Harley *et al.*, 1990), The Raur Islands (Harley and Fitzsimons, 1991) and Sostrene Island (Thost *et al.*, 1991) in East Antarctica. Also, late Archaean granulites (Aftalion *et al.*, 1988; Paul *et al.*, 1990) and Proterozoic reworking (Dasgupta *et al.*, 1994; Sen *et al.*, 1995) in the Eastern Ghats belt have their analogues in the Archaean Napier complex and reworked Proterozoic Rayner complex in East Antarctica.

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