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Geochronological Constraints on Granulite Formation in Southern India: Implications for East Gondwana Reassembly

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(With 1 Table and 3 Figures)

Abstract

The granulite grade metamorphic terrains of southern India form an integral part of East Gondwana. The geochronologic data distribution in these terrains show granulite facies events at ca. 2500 Ma, 1000 Ma, and 500 Ma each marking the predominant latest granulite facies metamorphism in the Northern Granulite Segment (NGS), Eastern Ghats Granulite Segment (EGS), and the Southern Granulite Segment (SGS) respectively. These events have traceable counterparts in Sri Lanka and East Antarctica, which form the East Gondwanian assembly with southern India. Thus, the Napier Complex of the Enderby Land in East Antarctica is comparable with the Northern Granulite Segment in South India, because both these segments record sporadic precursory 3000 Ma and older events. The Rayner Complex of the Enderby Land has almost continuous geochronologic sequence from the Late Archean through Early Proterozoic to Pan-African. The EGS and SGS in Peninsular India preserve similar pre-1000 Ma geochronologic record, comparable to the Rayner Complex of Antarctica. The ca. 1000 Ma event is more predominant in EGS while the SGS largely correspond to Pan-African. The radiometric data distribution suggests repeated thermal reworking of once stabilized Archean crust in many segments of East Gondwana.

Key Words: Granulite, Geochronology, Pan-African, Precambrian, Peninsular India.

Introduction

The earth's middle to lower crust is thought to be predominantly of granulite grade. Hence, studies of granulite facies rocks exposed on the surface of the earth are fundamental to our understanding of the early evolutionary history of the earth. Deeper portions of the earth's crust are exposed in some Precambrian metamorphic terrains such as South India. Reliable radiometric dates for evaluating the complex history and different modes of charnockite occurrence are sparse from southern India. Most of the previous studies show the earliest granulite facies metamorphism to have been at ca. 2500 Ma. Recent geochronologic studies (UNNIKRISHNAN *et al.*, 1992, and in preparation) trace a pre-2500 Ma

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metamorphic event.

Peninsular India was an integral part of East Gondwana, interpreted to have been juxtaposed with Antarctica (YOSHIDA *et al.*, 1992). Reconstructions of Precambrian Gondwana as well as its amalgamation tectonics are still in a preliminary stage due to lack of geochronologic data, especially from the Indian subcontient; such data may provide a key to the evaluation of the tectenothermal history of East Gondwana. This work aims to determine the geochronology of the granulites in Peninsular India and to correlate the results with those of the other parts of East Gondwana.

Geological Setting of Peninsular India

Peninsular India comprises a granite-greenstone terrain in the north which grades into granulite terrain in the south, separated by an orthopyroxene isograd. The granite-greenstone terrain consists largely of tonalite-trondhjemite gneisses called the Peninsular Gneiss, associated with Archean supracrustals, granite gneisses and a number of post-kinematic granitic plutons. The high-grade terrain comprises granulite facies rocks, represented largely by charnockites (orthopyroxene-bearing rocks of acid to intermidiate compositions having greasy appearence) and minor supracrustals. This high-grade terrain is dissected by a number of mega-faults/lineaments which divide the terrain into different blocks (Fig. 1). All these lineaments are believed to be Late Proterozoic in age (DRURY and HOLT, 1980). The granulite terrain north of the Palghat-Cauvery Shear Zone and south of the orthopyroxene isograd is called the Northern Granulite Segment (NGS); it includes the Northern, Madras and Nilgiri bolcks. The Northern Block is bounded by a narrow transition-zone south of the orthopyroxene isograd and north of the Moyar Shear Zone, and includes the Coorg and Biligirirangan Hills. The high-grade rocks of the Nilgiri Block are juxtaposed with the Biligirirangan Hill massive charnockites of the Northern Block along the Moyar Shear Zone. Blocks of the Southern Granulite Segment (SGS) are the Periyar, Madurai and Trivandrum blocks. The Madurai Bolck is separated from the Periyar Block by a belt of NE-SW trending zone rich in metasupracrustals; and the above two are separated from the Trivandrum Block by the Achankovil Lineament, which is considered to be a major strike-slip shear system truncating the earlier structures (DRURY *et al.*, 1984). The Trivandrum Block is formed of the vast pelitic supracrustal sequence called the Kerala Khondalite Belt (KKB, CHACKO *et al.*, 1987). The extreme south of the Peninsular India comprises the Nagercoil Block largely represented by massive charnockites (SRIKANTAPPA *et al.*, 1985) where it is associated with syenite plutons. The relationship of this with the KKB has not been resolved. The arcuate belt of high-grade terrain along the east coast of India, which is separated from the granite-greenstone terrain to the west by a Proterozoic shear zone, and which merges with the Madras Block in the south, is called the Eastern Ghats Granulite Segment (EGS). It is often referred to as the 'coastal granulites'.

Charnockite studies in southern India are complex because of repeated events of charnockite-making, breaking and re-making (PICHAMUTHU 1953; YOSHIDA and SANTOSH

1987). Charnockites in all these blocks occur either as regional units or as incipient phenomena. The former are mappable; the latter are not mappable and develop as overp-

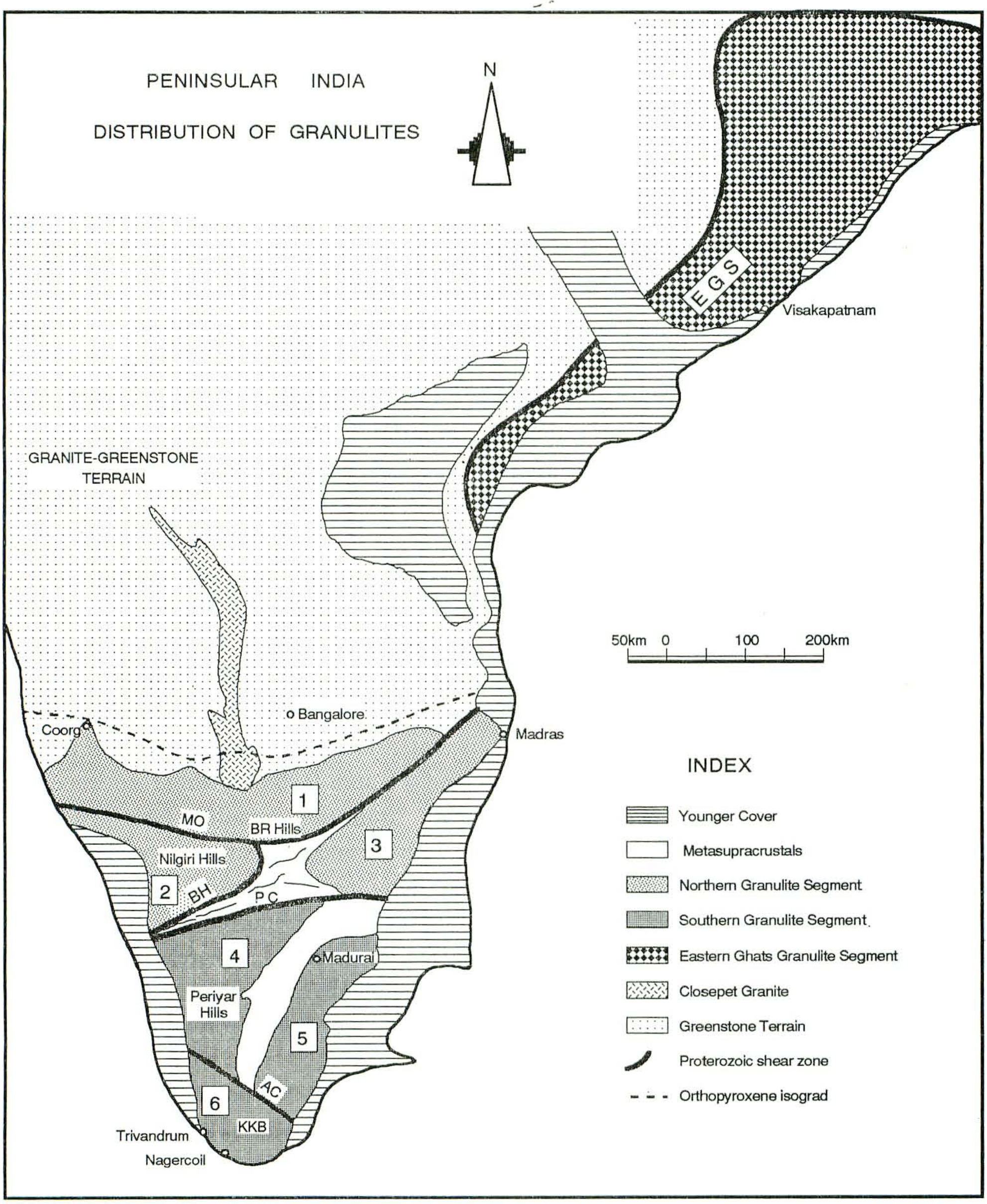

Fig. 1 Generalised geologic map of southern India showing the granite-greenstone terrain and the granulite terrain. KKB-Kerala Khondalite Belt, BR Hills-Biligirirangan Hills. The granulite blocks are (1) Northern Block, (2) Nilgiri Block, (3) Madras Block, (4) Periyar Block, (5) Madurai Block, and (6) Trivandrum Block. The Proterozoic shear zones are MO-Moyar, BH-Bhavani, P-C-Palghat-Cauvery and AC-Achankovil.

rints along small pods and shears within the precursor geniss. Both froms may also be present.

Regional Geochronology

The list of published and unpublished geochronologic data from Peninsular India are given in Table 1, and some of the selected data are assembled in the form of a histogram (Fig. 2) to summarize the geochronologic data distribution.

Northern Granulite Segment (NGS)

Northern Block: In northern Peninsular India, the earlier continental nucleii are represented by the tonalite-granodiorite-trondhjemite gneisses and granodiorite-adamallite gneisses called Peninsular Gneiss, associated with Archean supracrustals. Both the gneisses and the supracrustals suffered greenschist to amphibolite facies metamorphism and are intruded by a number of post-kinematic granites. Towards the south, the amphibolite facies basement gneisses grade into orthopyroxene-bearing granulites which constitute the major portion of the Northern Block. Classical examples of *in situ* charnockite formation ('incipient charnockite') are also present in the Northern Block.

The Rb-Sr systematics of BECKINSALE *et al.* (1980) on Archean gneisses from the Gorur-Hassan area indicate that the gneissic precursors might have stabilized at about 3300 Ma. The oldest model Nd age (~3300 Ma) is reported from the Karnataka craton by DRURY *et al.* (1983). The older zircon components of the greenstone basement give 3300 Ma (BUHL, 1987). PEUCAT *et al.* (1989) reported a model Nd age of 2.8 Ga for the massive charnockites of Biligirirangan Hills and argued that this charnockite differs from other transition-zone charnockites. MAHABELESWAR and PECUAT (1988) reported an imperfect Rb-Sr whole-rock isochron age of ca. 2900 Ma from the granulite facies rocks of Satnur-Halagur area south-west of Kabbaldurga. Rb-Sr and Sm-Nd whole-rock isochron ages of VIDAL *et al.* (1989) indicate that the last dominant metamorphism in the transition-zone was at ~2500 Ma. GREW and MANTON (1984) reported that the incipient charnockites were formed at around 2500 Ma (U-Pb allanite), whereas BUHL (1987) reported ~3400 Ma for the zircon cores from the incipient charnockites. FRIEND (1981) suggested that the Closepet granite and the incipient charnockite formation were contemporaneous processes.

All these suggest that in the Northern Block the ~3300 Ma older crust had undergone regional metamorphism at ~3000 Ma, and that granulite facies metamorphism was associated with the incipient charnockite formation at ~2500 Ma.

Madras and Nilgiri Blocks: The Madras and Nilgiri blocks have identical Archean histories. Lithological units in the Madras Block are the massive charnockites, khondalites, leptynites, and associated metagabbors and norites. The charnockites range from acid to basic varieties. The Nilgiri Massif consists predominantly of enderbitic charnockites, including garnetiferous and non-garnetiferous varieties, the former being

Table 1 List of radiometric ages from the granulite terrains of southern India.

AUTHORS	ROCK/AREA	METHOD	AGE
	TRIVANDRUM BLOCK		
Chacko (1987)	Metasediments/S.Kerala	Rb-Sr WR isochron	2100 Ma
Buhl (1987)	Ponmudi	U-Pb Zircon, Monazite	1970 & 550 Ma
Chaudhary et al. (1992)	charnockite/Ponmudi	Model Nd age	2500-2700 Ma
"	"	Sm-Nd (Ga-Wr)age	560 Ma
"	"	Rb-Sr Biotite	480±9 Ma
Santosh et al. (in press)	Charnockite/Nellikala	Sm-Nd Mineral isochron	~539 Ma
"	"	Rb-Sr Mineral isochron	505±41Ma
	MADURAI BLOCK		
Hansen et al. (1985)	B.Gneiss/Madurai	Rb-Sr WR isochron	550±15 Ma
	PERIYAR BLOCK		
Unnikrishnan-Warrier et al. (in Prep.)	Charnockite/Ottapalam	Rb-Sr Mineral isochron	~500 Ma
"	"	Sm-Nd Mineral isochron	~500 Ma
	NILGIRI BLOCK		
Crawford (1969)	Charnockites/Gneisses/Nilgiri	Rb-Sr WR isochron	2560±80 Ma
Buhl(1987)	Granulites/Nilgiri	U-Pb Zircon, Monazite	~2550 Ma
Spooner&Fairbairn (1970)	Charnockite/Nilgiri Mts.	Sr Model Age	~2500 Ma
	MADRAS BLOCK		
Crawford (1969)	charnockite/Madras	Rb-Sr WR isochron	2525±125 Ma
Bernard-Griffiths et al. (1987)	Granulites/Madras	Sm-Nd WR isochron	2555±140 Ma
Vinagradov et al. (1964)	Charnockite/Madras	U-Pb Zircon	2600 Ma
Ben Othman et al. (1984)	Charnockite/Madras,Mysore	Sm-Nd(TDM)	2723 Ma
Unnikrishnan-Warrier et al. (in Prep.)	Granulite/Madras	Sm-Nd Mineral isochron	~3000 Ma
"	"	Rb-Sr Mineral isochron	~2500 Ma

Table 1 (continued)

AUTHORS	ROCK/AREA	METHOD	AGE
	NORTHERN BLOCK		
Videl et al. (1986)	Granulites/Transition-zone	Sm-Nd & Rb-Sr WR isochron	~2500 Ma
Peucat et al. (1989)	Charnockite/S. of Krishnagiri	Rb-Sr WR isochron	2452±72 Ma
"	charnockites/BR Hills	Sm-Nd isochron	2440±155 Ma
"	"	Model Nd age	2800-2600 Ma
Grew & Manton (1984)	Granulite/Kabbal	U-Pb Allanite	2530 Ma
Mahabaleswar & Peucat (1988)	Granulite/Satnur-Halagur	Rb-Sr WR isochron	~2900 Ma
	EASTERN GHATS		
Vinagradov et al. (1964)	Khondalites/Puri	U-Pb Zircon	2600 Ma
Spooner & Fairbairn (1970)	Charnockites/Py.Granulites/E.Ghats	Rb-Sr Model Age	1938 &2424 Ma
Perraju et al. (1979)	Khondalites/Puri,Kasipatnam	Rb-Sr Model Age	3025 &2430 Ma
Aftalion et al. (1988)	Charnockites/Angul	U-Pb Zircon	1088 Ma
Rao et al. (1980)	charnockite/Visakhapatnam	Lead-Alpha Allanite	2000±100 Ma
Grew & Manton (1986)	Charnockites/Visakhapatnam	U-Pb Zircon	~1000 Ma
Paul et al. (1990)	Charnockites/Visakhapatnam	Pb-Pb isochron	1200±200 Ma
"	Charnockites/Phulbani	U-Pb Monozite	985±5 Ma
"	Charnockite/Visakhapatnam	Sm-Nd (TDM)	2600 Ma

dominant in the Nilgiri Hills. These granulites record the highest P-T conditions in Peninsular India (HARRIS *et al.*, 1982). Lenses and pods of pyroxenite and gabbro are also present in this area. Charnockites of Madras give a model Nd age of 2600 Ma (BEN OTHMAN *et al.*, 1984) and a Rb-Sr whole-rock isochron age of 2525±125 Ma (CRAWFORD, 1969) identical to the Sm-Nd whole-rock isochron age (2555±140 Ma) obtained by BERNARD GRIFFITHS *et al.* (1987). VINAGRADOV *et al.* (1964) and BUHL (1987) reported U-Pb zircon ages of 2550 Ma and 2600 Ma for the Madras and Nilgiri charnockites, respectively. These dates suggest that initial crustal growth, including the charnockite formation and the regional granulite facies metamorphism took place at about 2550–2600 Ma. Our recent attempt on a sample collected from the Madras area give an Sm-Nd mineral isochron age of ~3000 Ma and Rb-Sr ages of ~2500 Ma (UNNIKRISHNAN-WARRIER *et al.*, in prep.); these suggest pre-2500 Ma event in the Northern Granulite Segment.

Southern Granulite Segment (SGS)

The Trivandrum Block of the Southern Granulite Segment is composed predominantly of a charnockite-khondalite-leptynite association, locally interlayered with basic granulites, calc-silicates and quartzites. Progressive (SRIKANTAPPA *et al.*, 1985) and retrogressive (SANTOSH and YOSHIDA, 1986; YOSHIDA and SANTOSH, 1987) transformations of the amphibolite facies gneisses to charnockites and vice versa are recognised in this block. Cordierite-bearing charnockites are reported proximal to the Achankovil Shear Zone (NANDA-KUMAR *et al.*, 1991). The Periyar and Madurai blocks are composed mainly of massive charnockites, with minor granites and pegmatites.

Geochronologic data from the southern blocks are broadly concentrated in the Trivandrum Block, and there are only a few published reports from the Periyar and Madurai blocks, including a Rb-Sr isochron by HANSEN *et al.* (1985). CHACKO (1987) described an ill-defined Rb-Sr whole-rock isochron age of about 2100 Ma from the metasediments of the Trivandrum Block. From the Ponmudi Quarry, BUHL (1987) reported zircon growth at 1970 Ma. CHOUDHARY *et al.* (1992) reported an older crustal component of 2500–2700 Ma (model Nd ages) from the incipient charnockites of Ponmudi. Cordierite-bearing charnockite from Nellikala, proximal to the Achankovil Shear Zone gave an Sm-Nd mineral isochron age of 539 Ma (SANTOSH *et al.*, in press). This, along with monazite and zircon growth ages of 550 Ma reported by BUHL (1987), as well as inclusion-free garnet ages of 560 Ma (CHOUDHARY *et al.*, 1992), reflect charnockite formation in the Southern Granulite Segment. Subsequent uplift is belived to have been at 480 Ma, from a Rb-Sr biotite age (CHOUDHARY *et al.*, 1992). The basement gneisses near Madurai provided an Rb-Sr whole-rock age of 550±15 Ma, isotope exchange is considered to have continued up to 425±55 Ma (HANSEN *et al.*, 1985). Charnockite from Ottapalam, Periyar Block, gives Sm-Nd and Rb-Sr mineral isochron ages of ~500 Ma (UNNIKRISHNAN *et al.*, 1992, and unpubl. data). These dates provide compelling evidence for the manifestation of Pan-African thermal event in the Southern Granulite Segment.

In contrast to the Northern Granulite Segments, several alkaline and sub-alkaline granites and syenites of 500–750 Ma are reported from Kerala (SANTOSH and DRURY, 1988) and from near Madurai (DEANS and POWELL, 1968).

Eastern Ghats Granulite Segment (EGS)

The Eastern Ghats form an arcuate belt of high-grade terrain parallel to the east coast of India. This belt is composed of metamorphosed supracrustals, mainly khondalites (granet-sillimanite gneiss), charnockites and migmatitic gneisses, with minor amounts of calc-silicates, marble and quartzite. Anorthosite and alkaline intrusions represent a younger phase (SARKAR *et al.*, 1981). Charnockites occur in these areas as massive bodies, and also as patches developed across the foliation of the gneiss. A U-Th-Pb age of 2600 Ma (VINAGRADOV *et al.*, 1964), and a model Nd age (TDM 2600 Ma) for the charnockites of Visakhapatnam and 2350 Ma for Phulbhani (PAUL *et al.*, 1990) indicate the incorporation of Archean components into this mobile belt. SPOONER and FAIRBAIRN (1970) reported a Sr model age of ~2000 Ma from the charnockites/pyroxene granulites of Eastern Ghats, whereas RAO *et al.* (1980) reported ~2000 Ma for Allanites from apatite veins and charnockite pegmatites from Visakhapatnam. The Chilka Lake Anorthosite is belived to have been formed at ca. 1400 Ma (SARKAR *et al.*, 1981).

AFTALION *et al.* (1988) summarized the polyphase history around Angul, Orissa, into four phases of deformation (D_1, D_2, D_3 and D_{late}) and three phases of metamorphism (M_1, M_2, and M_3). The D_{late} phase is correlated with local charnockite formation and granite pegmatite intrusion. The charnockite is dated between 1100–950 Ma (U-Pb Zircon) and the granite emplacement at 957 Ma.

GREW and MANTON (1986) report 979 Ma for zircon from charnockites of Visakhapatnam and a similar age for the sapphirine-bearing granulites from Anakapalle. This, together with zircon (U-Pb) and monazite (U-Pb) ages of 990~950 Ma from the charnockites of the Visakhapatnam and the Phulbani areas respectively (PAUL *et al.*, 1990), correspond to the charnockite formation event for the Eastern Ghats.

Discussion

The radiometric data distribution in different granulite segments of southern India is shown in Fig. 2, which shows three dominant events each predominent in every segment.

The Northern Granulite Segment is characterised by dominant ca. 2500 Ma crust formation and granulite facies metamorphic event having precursors of ca. 3000 Ma~3300 Ma granulites.

The Eastern Ghats Granulite Segment is characterised by charnockite formation at ca. 1000 Ma over precursor granulites of 2000 Ma and/or 2500 Ma. The Southern Granulite Segment is supposed to be similar in geochronologic sequence to that of the Eastern Ghats Granulite Segment with regard to its pre-1000 Ma history. But the Southern Granulite Segment lacks an ca. 1000 Ma event, but is characterised by

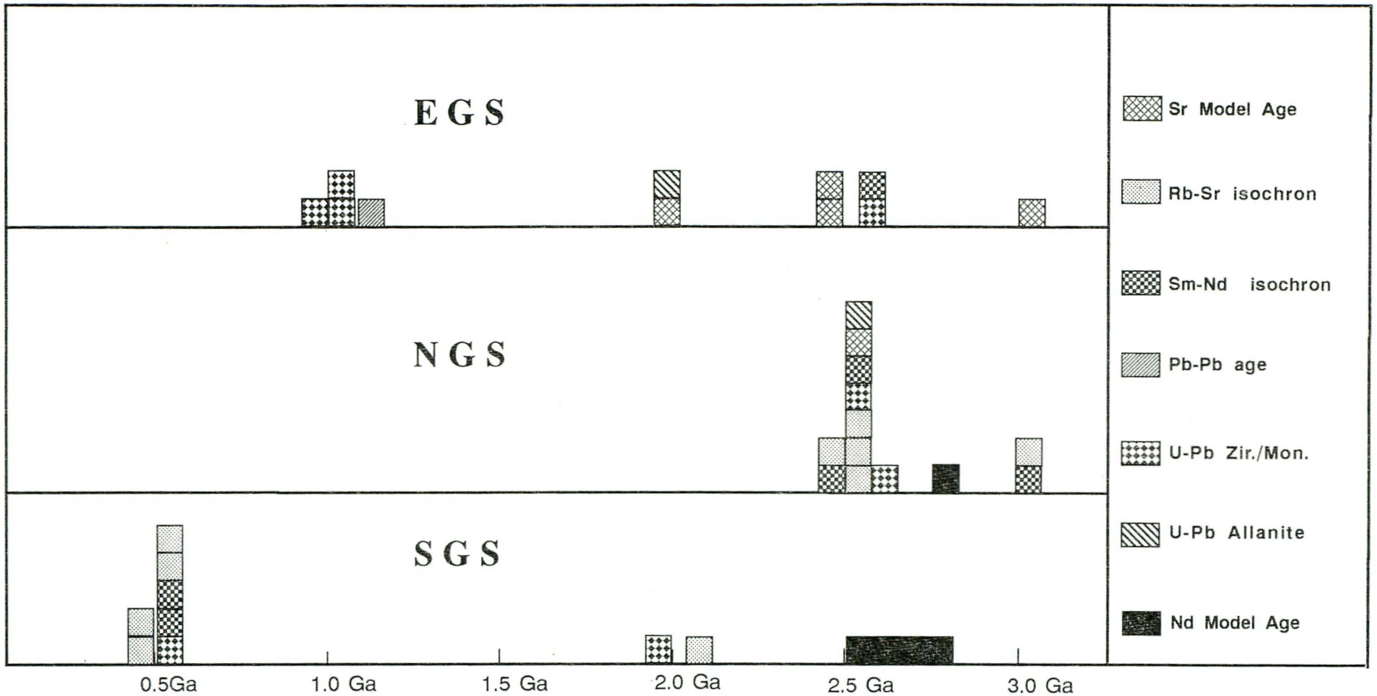

Fig. 2 Histogram showing the geochronologic data distribution in different granulite segments in southern India.

ca. 500 Ma charnockite formation over the precursor granulites of ca. 2000 Ma and/or 2500 Ma. It is suggested that the granulite terrains of Peninsular India are composed of successively reworked crustal fragments which suffered regional metamorphism during Archean and Early Proterozoic times.

These granulite segments with characteristic geochronologic imprints have common features with some other geologic units in Gondwanian fragments surrounding India (Fig. 3). The Napier Complex of Enderby Land in East Antarctica is characterized by a granulite facies events at ca. 3000 Ma on which was superimposed amphibolite to granulite facies events at ca. 2500 Ma (SHERATON *et al.*, 1987). This complex is thus comparable

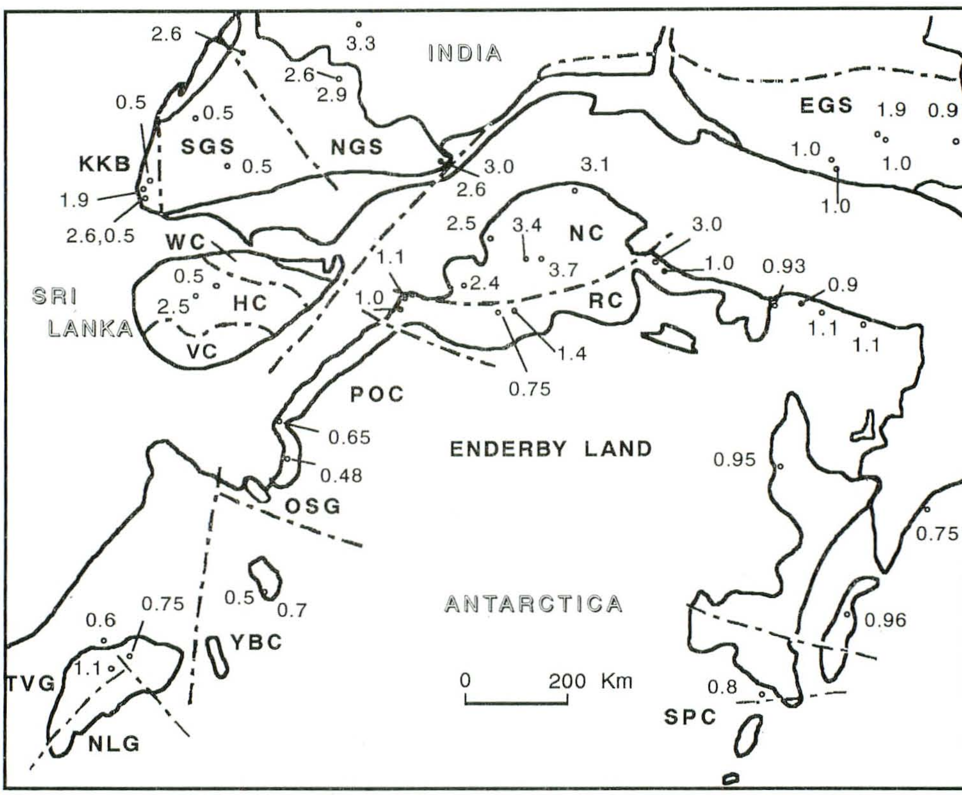

Fig. 3 The juxtaposition of India-Sri Lanka-Antarctica in East Gondwana showing the geochronologic data distribution. Abbreviations are EGS-Eastern Ghats Granulite Segment, NGS-Northern Granulite Segment, SGS-Southern Granulite Segment, KKB-Kerala Khondalite Belt, WC-Wanni Complex, HC-Highland Complex, VC-Vijayan Complex, NC-Napier Complex, RC-Rayner Complex, POC-Prince Olav Complex, OSG-Ongul and Skallen Group, YBC-Yamato Bulgica Complex, TVG-Teltet Vengen Group, NLG-Nils Larsenfjellet Group, SPC-Southern Prince Charles Mountains. Broken lines show estimated fault boundaries. The framework of the juxtaposition of the continents is after YOSHIDA *et al.* (1992). The geochronologic data presented are compiled from Table 1, YOSHIDA *et al.* (1992): and the geology of Enderby Land and Western Kemp Land, Australian Antarctic Territory (SHERATON, 1985).

to the Northern Granulite Segment of southern India.

The Rayner Complex of Enderby Land in East Antarctica has sporadic precursors of ca. 2000–2500 Ma and suffered mostly the ca. 1000 Ma granulite facies event, with later modifications during the Pan-African period (SHERATON *et al.*, 1987). A broadly similar sequence is reported from the Highland Complex of Sri Lanka as well as the Ongul and Skallen groups of the Lützow Holm Bay area of East Antarctica (YOSHIDA *et al.*, 1992). It is pointed out that the Eastern Ghats Granulite Segment (EGS) and the Southern Granulite Segment (SGS) may have pre-1000 Ma histories broadly similar to these areas. But in India the ca. 1000 Ma event affected only the Eastern Ghats Granulite Segment and the ca. 500 Ma event took place only in the Southern Granulite Segment.

YOSHIDA and SANTOSH (in press) stressed the geochronologic-tectonic division of the formation of incipient charnockites in East Gondwana. Incipient charnockite formation took place at ca. 2500 Ma, 1000 Ma and 500 Ma and the principal characteristic is that there was thermal reworking at every stage in already stabilized metamorphic belt. A polarity in age, with younging outwards from the core of the Archean nucleii of Peninsular India can be noticed. This study supports their view.

It is pointed out that the correlation of the younger Pan-African events in crustal fragments from East Gondwana are commanly been accepted, but that of the earlier events are not well constrained. Detailed metamorphic, structural and geochronologic studies are needed to resolve this aspect.

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