Chapter 8
Pandyan Mobile Belt

8.1 Introduction: Geological Setting

Pandyan Mobile Belt (PMB) is the name given by Ramakrishnan (1993, 1988) to the Southern Granulite Terrain (SGT) situated to the south of the E-W trending Palghat-Cauvery Shear Zone (PCSZ) (Fig. 8.1). The name Pandyan is adopted after the legendary dynasty that ruled this part of South India in the historical past. Interestingly, the SGT has been defined variously by different workers. According to Fermor (1936), this terrain is a part of the large "Charnockite Province" located to the south of the orthopyroxene-in (Opx-in) isograd, delineated along a line straddling the join Mangalore-Mysore-Bangalore-Chennai (Pichamuthu, 1965). It would not be justifiable to encompass the entire granulite province under the Pandyan mobile belt since this would include both Archaean granulites (Northern Terrain, see below) and Neoproterozoic granulites (south of the PCSZ), each with their distinctive differences in geological setting (Ramakrishnan, 1998). Vemban et al. (1977) pointed out this difference which was later emphasized and elaborated by Drury et al. (1984).

A reference to Fig. 8.1 reveals that the SGT (south of Opx-in isograd) is dissected into different granulite blocks by structural discontinuities, lineament or shear zones which are taken as boundaries of the differerent granulite blocks. The most conspicuous is the E-W trending Palghat-Cauvery shear zone (PCSZ), first mapped as Cauvery Fault by ONGC and recognized by Grady (1971) and Vemban et al. (1977) as a boundary between two different geological domains. Drury and Holt (1980) established this boundary from Landsat imagery and named it as Noyil-Cauvery shear zone with Moyar Shear zone (MSZ) and Bhavani Shear zone (BSZ) as its subsidiary (Fig. 8.1). On this basis, the southern Indian granulite terrain to the south of the Opx-in isograd is divided into two distinct crustal blocks (Drury et al., 1984; see also Meissner et al., 2002), viz. the Northern Block (NB) or the Northern Granulite Terrain (NBSGT); and the Southern Block (SB) or Southern Granulite Block (SBSGT), separated by the Palghat-Cauvery Shear zone, PCSZ (see inset in Fig. 8.1). These two Blocks correspond to the Northern Marginal Zone and Central Madurai Zone of Ramakrishnan (1988).

Realizing the grand scale of this shear zone, the term Cauvery Shear zone (CSZ) system was used in maps by GSI and ISRO (1994; Gopalkrishnan, 1996 and

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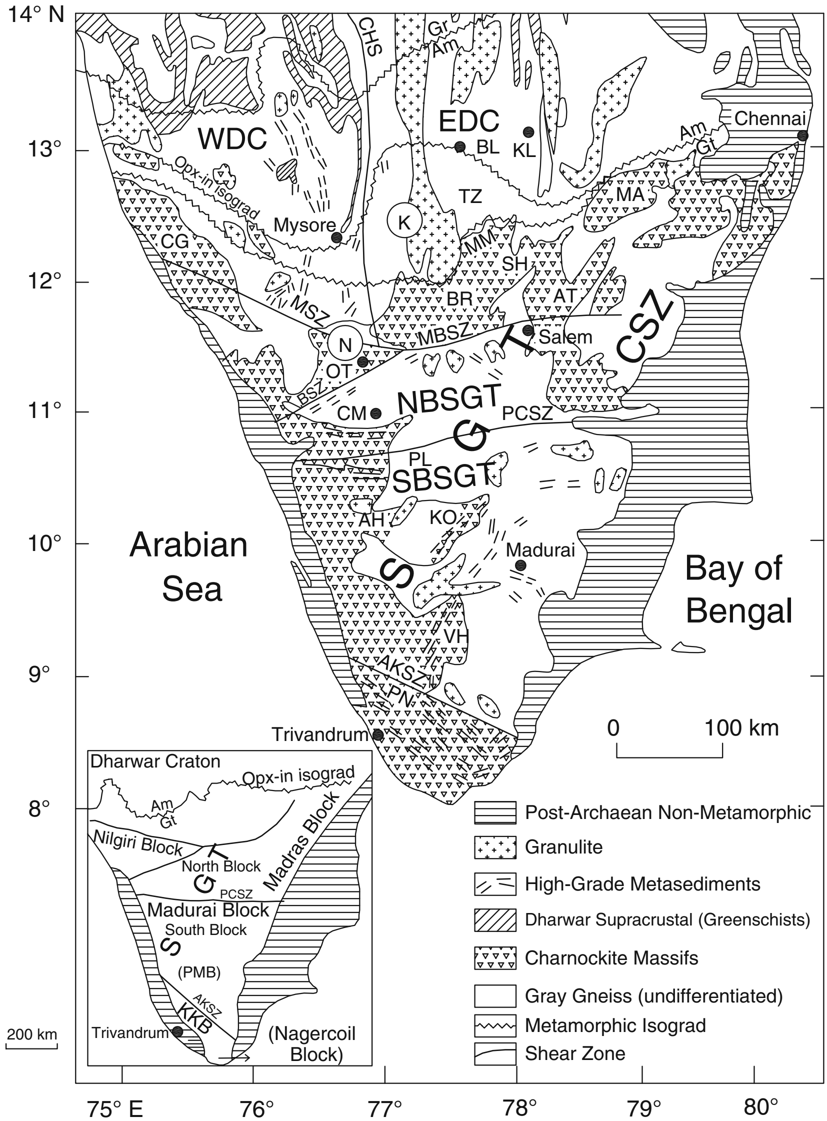

Fig. 8.1 Simplified Geological map of the southern India (after GSI and ISRO, 1994), showing the major geological domains, the Western Dharwar Craton (WDC), Eastern Dharwar Craton (EDC), and Southern Granulite Terrain (SGT) along with the Cauveri Shear Zone System (CSZ). Abbreviations: AKSZ = Achankovil Shear Zone; AH = Anamalai Hills; AT = Attur; BS = Bhavani Shear zone; BL = Bangalore; BR = Biligirirangan; CHS = Chitradurga Shear Zone; CG = Coorg; CM = Coimbatore; EDC = East Dharwar Craton; K = Kabbaldurga; KL = Kolar; KKB = Kerala Khondalite Belt; MS = Moyar Shear zone; N = Nilgiri; OT= Ooty; PCSZ = Palgahat Shear Zone; PL = Pollachi; PMB = Pandyan Mobile Belt; SGT = Southern Granulite Terrain; SH = Shevaroy Hills; WDC = West Dharwar Craton; GR-Am = Isograd between Greenschist and Amphibolite Facies; Am-Gt = Isograd between Amphibolite and Granulite Facies; TZ = Transition Zone of amphibolite and granulite facies. *Inset* shows various identified crustal blocks

references therein). The E-W trending crustal-scale shear zones, namely MSZ, BSZ, and PCSZ in Southern Granulite Terrain have been taken to represent major lineaments that are associated with significant regional strike-slip movements and delineated by major river valleys. The BSZ and MSZ enclose the *Nilgiri Block* or Nilgiri granulite massif. These two shear zones join near Bhavani Sagar and extend eastward as Moyar-Bhavani Shear Zone (MBSZ). The SBSGT is the Madurai Block of some workers (see Ramakrishnan, 1998). This block is separated on its south from another granulite block, the Kerala Khondalite Belt (KKB) or Trivandrum Block by the NW-SE trending lineament called the Achankovil Shear Zone (AKSZ) (Santosh, 1996) (see Fig. 8.2). The Madurai Block located between the PCSZ and the AKSZ was designated earlier by the name Pandyan Mobile Belt (PMB) by Ramakrishnan (1993). But the present nomenclature of the PMB is the granulite block south of the PCSZ, being Neoproterozoic in age (see in Ramakrishnan and Vaidyanadhan, 2008).

All these above-stated blocks of the SGT have granulite facies rocks but they differ in regard to their relative abundances of litho-units, deformational history, ages, character of magmatism and exhumation history. The following section gives a brief account of the geological attributes for each granulite blocks so that the reader can appreciate mutual relationship of the granulite blocks as well as the geological status of the Pandyan Mobile belt and its evolution in light of the temporal and spatial data of the SGT.

8.2 Geological Attributes of the Granulite Blocks

As mentioned earlier, the southern Indian granulite terrain occurs to the south of the Opx-in isograd. This terrain is dissected by Proterozoic shear zones that separate the granulite rocks into four regions or blocks, viz. Madras Block, Nilgiri Block, Madurai Block, and Trivandrum Block (se inset Fig. 8.1). In all these blocks of the SGT, charnockites are conspicuously exposed. Two distinct types of charnockites can be recognized in the SGT: (1) massive charnockite and (2) Incipient or arrested chatrnockite. The massive charnockite occurs in the Nilgiri and Madras Blocks.

Historically, the *Madras granulites* are significant, being the first to be investigated. However, the charnockites vary in composition from adamellite, monzonite, diorite to granite. These hypersthene-bearing rocks were used for the tombstone of Job Charnock, the founder of modern Kolkata (formerly Calcutta) and as a mark of respect to him, they were named Charnockite by Thomas Holland (1900). In the area around Madras, the charnockites are interbedded with garnet-cordierite-sillimanite gneisses, graphite-sillimanite gneiss, pyroxenite, and hornblende granulite and also contain intrusion of norite (hypersthene gabbro). The charnockites were first considered igneous origin but later they were found to be metamorphic, recrystallized in deep-seated conditions into granulite facies. The acid charnockites form St. Thomas Mount near Chennai (formerly Madras) yielded 2580 ± 45 Ma (Crawford, 1969; see also Bernard-Griffiths et al., 1987; Unnikrishnan-Warrior et al., 1995). The P-T

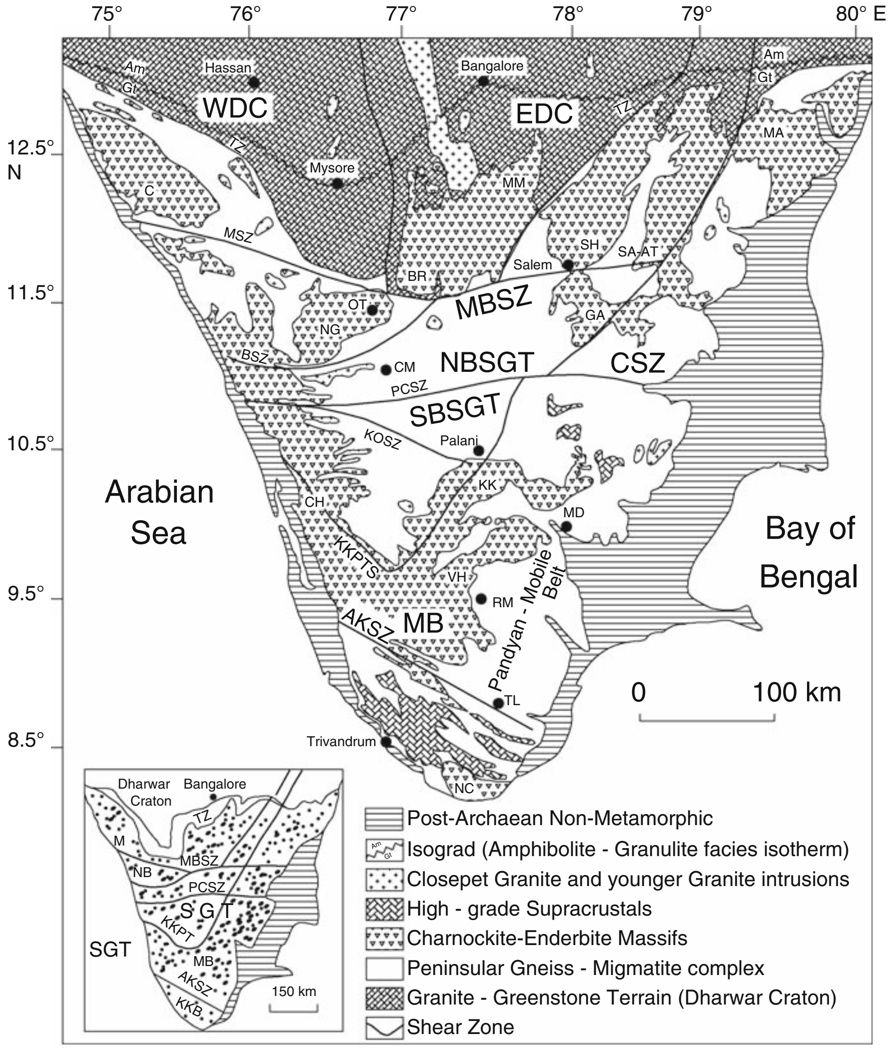

Fig. 8.2 Simplified Geological map of part of the southern Indian shield (based on GSI and ISRO, 1994), showing the location of the Southern Granulite Terrain (SGT) to the south of the Am/Gt (Amphibolite-granulite facies) isograd (drawn after Pichamuthu, 1965). To the north of the isograd are the Western and Eastern Dharwar Cratons (WDC and EDC). The Highland massifs are: Bilgirirangan (BR), Coorg (C), Cardamom (CH), Madras (MA), Kodaikanal (KK), Malai Mahadeswara (MM), Nilgiri (NG), Shevroy (SH), Varshunadu (VH). The prominent shear zones: The Cauvery Shear Zone System (CSZ), comprising Moyar (MS), Bhavani (BS), Palghat-Cauvery (PCS), Salem-Attur (SA-At). Others are: Gangavalli (GA), Karur-Kambam-Painvu-Trichur (KKPT) and Achankovil Shear Zones (AKSZ), Korur-Odanchitram Shear Zone (KOSZ). The different crustal blocks recognized in the SGT *sensu lato* are: the Northern Block (NBSGT) and Southern Block (SBSGT), Madurai Block (MB). The block between the Palghat Shear Zone (PCS) and the Achankovil Shear zone (AKS) is designated Pandyan Mobile Belt (PMB). To the south of the AKS is the Kerala Khondalite Belt (KKB). Other abbreviations are: CM = Coimbatore; NC = Nagercoil; OT = Ooty; RM = Rajapalayam; TL = Tirunelveli. *Inset* shows the SGT, the KKB and the different shear zones traversing the SGT. Other abbreviations as in Fig. 8.1

estimates by Weaver et al. (1978) for the charnockites from near Pallavaram gave 720–840°C and 9–10 kbar.

The charnockites of the *Transition zone* from southern Karnataka, especially at Kabbal quarry, are associated with gneisses. Pichamuthu (1953, 1960) observed this association of incipient charnockite-gneiss and proposed that the charnockites were the products of metamorphic recrystallization. Impressed by patches and streaks of charnockite, unchanged foliation from gneiss to charnockite, and by fluid inclusion studies, some workers (Janardhan et al., 1982; Newton, 1987; Santosh, 2003) suggested that the charnockites were formed by inlux of CO_2- rich fluids from mantle.

Another group of geologists, considered the presence of quartzo-feldspathic veins and pods at the site of gneiss-charnockite association, together with the results of experimental studies on granite system as well as P-T estimates and geochemical-geochronological data. On these considerations, a new model of dehydration melting was proposed for the origin of charnockite. According to this model, vapour-absent melting of biotite and/or hornblende is responsible to produce granite melt and hypersthene in rocks of suitable composition (e.g. tonalite gneiss). In general, all along the Transition Zone, the amphibolite facies gneisses (Peninsular Gneiss) have been transformed isobarically ($\sim$5 kbar/750°C) into foliated to massive charnockite. The incipient charnockites from Kabbal have been dated at 2500 Ma by zircon, monazite and allanite U—Pb geochronology (Buhl et al., 1983; Grew and Menton, 1986). Zircon ion probe studies from Kabbal indicate that the protolith is 2965 $\pm$ 14 Ma old, and was transformed into charnockite at 2500 Ma ago (Friend and Nutman, 1992; Hansen et al., 1987). Besides Kabbal, there are several incipient charnockite regions in this Zone (Fig. 8.1), for example around Krishnagiri-Dharmapuri area (Allen et al., 1983), northern part of the Malai Mahadeswara hills (MM Hills), Bilgiri Rangan hills (B-R Hills) (see Raith et al., 1990). In all these localities, the charnockites retain the dominant N-S to NNE-SSW structural trend that characterize the Dharwar craton located to the north of the Transition zone.

In the *Nilgiri Block*, the granulites are mainly enderbites, although minor charnockites are also found. The granulites are massive to foliated, and are characterized by hypersthene-plagioclase-quartz with or without garnet and relicts of biotite. The foliation trends about N65°E with steep dips. There are also numerous concordant lenses of pyroxenite and gabbro which are almost undeformed and show sharp contacts with the enderbitic granulites. Besides, a set of dolerite and picrite dykes are also found. The granulites of the Nilgiri have been sheared on its north and south by Moyar and Bhavani shear zones (Srikantappa et al., 2003). The shearing has developed mylonitic texture in these granulites, without affecting the granulite facies assemblages. However, minor hydration during shearing has developed greenish amphiboles and biotite from the breakdown of pyroxene. The general opinion about the Nilgiri granulite is that they represent deep crust and by their uplift the Nilgiri massif juxtaposed against the amphibolite facies terrain (DC terrain) in the north. The P-T data for the garnet-granulites from Nilgiri yielded 730°C/7 kb in SW part and 750°C/9 kb in the NE toward the Moyar shear zone, indicating a differential uplift of the Nilgiri massif (Raith et al., 1983). It has also been proposed by Raith et al. (1999), that the Nilgiri terrain is an allochthonous unit which was thrust upon the Dharwar craton in a Paleoproterozoic collision tctonics. On the other hand, Drury et al. (1984) correlated the Nilgiri charnockites with those of the Biligiri Rangan Hills (B-R Hills) across the Moyar shear zone. In contrast, Peucat et al. (1989) consider the Nilgiri granulites as syn-accretional type in contrast to the B-R Hills granulite massif which is presumed to be post-accretion. On the basis of geochemical characteristic, the charnockitic rocks of the Nilgiri are inferred to have igneous protoliths of tonalite to granodiorite composition (Condie and Allen, 1984; Srikantappa et al., 1988). The whole-rock Rb—Sr, Pb—Pb, Sm—Nd and U—Pb zircon ages for the enderbite granulites of the Nilgiri Hills suggest that the granulite metamorphism occurred at about 2.5 Ga. The granulite metamorphism, according to Buhl (1987) has closely followed the emplacement of the protolith. A four-point Pb—Pb whole-rock isochron for the Nilgiri charnockites yielded an age of 2578 ± 63 Ma (Peucat et al., 1989). The garnet-bearing charnockites from Ootacamund showed a Sm—Nd isochron age of 2496 ± 15 Ma (Jayananda et al., 1995, 2003). The BR-Hills charnockites have also been dated at 3.4 Ga by U—Pb zircon geochronology (Buhl, 1987), with protolith ages ranging from 3.0 to 3.4 Ga (Bhaskar Rao et al., 1993, Table 1). The 2.5 Ga old granulites with garnet-pyroxene-plagioclase assemblages are also found in Shevaroy hills and Bhavani Sagar. Large exposures of charnockites also occur east of Salem, particularly in the hills of Kollimalai and Pachaimalai hills where they occur amidst gneisses and metasediments (see Fig. 8.1).

All along the PCSZ, especially in the vicinity of the Moyar-Bhavani shear zones, the charnockite gneisses are associated with extensively developed supracrustals of Satyamangalam Group which consists of metapelites, calc-silicates, marbles, quartzites, amphibolites and granulites. Toward SE, the Satyamangalam rocks are associated with dismembered layered complex of anorthosite-gabbro-pyroxenite-chromitites, such as at Sittampundi and Bhavani complexes. U—Pb zircon geochronology (Ghosh et al., 2004) and Sm—Nd whole-rock isochron (Bhaskar Rao et al., 1996) gave coinciding ages of ca. 3000 Ma for the Satyamangalam layered complexes, suggesting their temporal equivalence with the Sargur Group rocks (see Chap. 2). The concordant charnockite gneisses within these supracrustals gave an age of 2.52 Ga (Ghosh et al., 1998, 2004), which indicates involvement of the Satyamangalam Group in the Early Proterozoic (or Late Archaean) charnockite event, so convincingly documented in the Transition Zone.

These data conclusively suggest that the granulite metamorphic event in the different sectors or Blocks to the north of Moyar-Bhavani shear zone occurred at about 2500 Ma (early Proterozoic).

The granulite area between the MBSZ and the PCSZ has charnockite-enderbite granulites interbedded with BIF, cal-granulites, quartzites and minor mafic to ultramafic rocks as at Chennamalai (Fig. 8.1), described already. South of Chennamalai, there are nepheline syenites of Sivamalai in which numerous enclaves of charnockites can be observed. In the vicinity of the MBSZ, there are pink granites (Sankari) which contain enclaves of rocks of Satyamangalam Group. Rb—Sr whole-rock age of 390 ± 40 Ma is obtained for pegmatoidal variety of the Sankari Granite.

The granulites of *Madurai Block* occur south of the PCSZ (Fig. 8.2). The block comprises the Annamalai-Kodaikanal ranges that are made up of massive to gneissic charnockites with minor bands of metasediments (mainly khondalites), conspicuously exposed between Dindigul and Madurai. In addition to these rocks, there are also gneisses, anorthosites Oddanchatran and Kadavur (Janardhan, 1996), and sapphirine-bearing granulites that occur at the margins of Palani-Kodaikanal Highlands (Lal, 1993; Mohan and Windley, 1993; Raith et al., 1997). Toward east, the basic granulites dominate as at Palani. The metasedimentary rocks of Annamalai-Palani ranges in the east are intruded by the Proterozoic anorthosites, mentioned above. The anorthosite intrusion contains large inclusions of deformed granulites and quartzites. The post-emplacement deformation is seen in the stretched and boudinaged inclusions. Symplectite minerals garnet-plagioclase-quart around pyroxene yielded 5–7 kb and 725°C (see Subramanian and Selvan, 1981).

South of Palani, the granulites are spinel-bearing metapelites that are interlayered with charnockite gneisses. These Al-Mg rich granulites are considered to have formed by anatexis at 5 kb/740°C under $P_{H2O} << P_{total}$ conditions (Harris et al., 1982). Some authors also consider that the magmatism of large anorthosites and ultramafic bodies and to some extent the abundant Late Proterozoic sodic- and potash–granites in the Madurai Block may have been responsible for causing the ultra high temperature (UHT) metamorphism, seen at places where sapphirine-bearing Mg—Al rich assemblages have formed (Braun and Kriegsman, 2002; Grew, 1982). In the southern Madurai Block, massive to streaky charnockites are found. The streaky appearance is attributed to volatile-deficient dehydration melting of biotite at high temperatures (Brown and Raith, 1996). The charnockites of Madurai Block yielded Sm—Nd ages in the range 2.2–2.5 Ga (Harris et al., 1994). The Kodaikanal charnockites gave model Nd ages of 2.2–3.0 Ga. The U—Pb zircon age from acid charnockite gave an age of 2115 $\pm$ 8 Ma for the core and 1838 $\pm$ 31 Ma for the rim of the mineral (Jayananda et al., 1995). Recently, Pan-African ages have been reported from the Madurai Block. Rb—Sr age of 550 $\pm$ 15 Ma is reported from Madurai gneisses (Hensen et al., 199), and Pb—Pb zircon age by evaporation method gave an age of $\sim$600 Ma (Bartlett et al., 1998; see also Bhaskar Rao et al., 2003). Mineral ages from the charnockites and Pb—Pb ages of zircon overgrowth are found to range between 550 and 500 Ma (Jayananda et al., 1995; Bartlett et al., 1998). U—Pb zircon geochronology from charnockites of Kodaikanal-Cardimom Hills gave 580 Ma (Miller et al., 1997). All these geochronological data convincingly show that the Madurai block has imprints of Pan-African tectono-thermal event (orogey), unlike the terrain located north of the PCSZ (see above).

Geothermobarometry data point to paleopressures of 4–5 kbar ($\sim$12–15 km depth) in the high-grade Karnataka craton; 9 kbar ($\sim$27 km depth) in the Nilgiri and the BR Hills; and 8 kbar ($\sim$24 km depth) in the Madurai block in an early phase followed by a 4.5 kbar and 700°C. P-T-t paths have a dominant isothermal decompresssive history in general (cf. Bhaskara Rao et al., 2003).

To the south of the Madurai Block and across the AKSZ is the *Trivandrum Block* (also called Kerala Khondalite Belt, KKB) of granulite facies rocks (Fig. 8.2). It is characterized by large exposures of folded khondalite and charnockite. The khondalites are predominant in the northern part, called the *Ponmudi Unit*, while charnockites are abundant in the southern part, called the *Nagercoil Unit* (Santosh, 1996). Both rock-types show migmatitic structures in which quartz-feldspar leucosome alternate with garnet-sillimanite bearing bands and hypersthene-plagioclase bearing bands or layers. The metasedimentary-dominated Ponmudi Unit shows spectacular in-situ charnockitization of gneisses and bleaching of charnockites. The arrested charnockites occur as patches, veins and rafts, all devoid of orientation. Arrested growth is identified by cross-cutting relation of charnockite with the gneissic foliation. The charnockitization seems to have been brought about by dehydration melting reactions, because granitic leucosome is always in proximity of the arrested charnockites and because inverse modal relationship is observed between biotite and hypersthene (Ravindra Kumar and Raghavan, 1992). In Trivandrum Block, anatexis of the gneisses is found to pre-date the charnockite formation since patches and veins of charnockites overprint both melanosome and leucosome as at Ponmudi (Santosh et al., 1990). P-T calculations showed that the incipient charniockitization at Ponmudi occurred at 5.5 kbar and 700–750°C (Santosh et al., 1990). The southern end of the Trivandrum Block (i.e. KKB) around Kanyakumari has migmatites, khondalite and charnockite. P-T data for charnockite and khondalite of Nagercoil massif are 670–720°C and 5 $\pm$ 1 kbar (Harris et al., 1982), while Srikantappa et al. (1985) report 750 $\pm$ 50°C and 6 $\pm$ 1 kbar. Nand Kumar et al. (1991) gave a variable range of 626–833°C and 4–6 kbar. All these values clearly suggest that the Trivandrum Block is formed of low- to medium-pressure granulites (see Chacko et al., 1987). There are also various stages of conversion of Opx-bearing charnockites to biotite gneisses (retrogression) which also occurred under low-pressure conditions (Ravindra Kumar, 2004). Other rocks in the Trivandrum Block are cordierite-gneisses and some calc-silicates with diopside-wollastonite-scapolite-garnet-quartz assemblages, often interleaved with charnockites and gneisses. At fringes of the Ponmudi Unit of the Trivandrum Block, there are massive charnockite-enderbites (Nagercoil Unit). Geochemically, the massive charnockites-enderbites resemble C-type magmas of Kilpatric and Ellis (1992). In contrast to the arrested charnockites whose composition is close to granitoids, Chacko et al. (1992) divided the massive charnockites of south Kerala into two types—felsic and intermediate—which are distinguishable by the contents of K-feldspar and mafic minerals. Chacko et al. argued that the massive charnockite varieties are the source of ultra high temperature (UHT) metamorphism. Like the Madurai Block, the Trivandrum Block hosts extensive alkali granite and granite/syenite of 550 Ma age, indicating anorogenic magmatism related to Pan-African event. In summary, the Madurai Block and Trivandrum Block have undergone similar tectono-thermal evolution in the Pan-African times (Jayananda et al., 1995). And this justifies to combine them as one terrain, or the Pandyan Mobile Belt after Ramakrishnan (see Ramakrishnan and Vaidyanadhan, 2008). Palaeoproterozoic ages of $\sim$2.0–1.8 Ga, obtained from single zircon Pb evaporation ages, CHIME zircon and monazite ages have been interpreted as maximum ages of sedimentation or high-grade metamorphism (Santosh et al., 2006).

Deformation in the southern Indian granulite terrain as a whole records evidence of more than one fold phases and shear zones, particularly in the granulites of Karnataka and Tamil Nadu. The granulite massifs of BR-Hills, Shevaroy and Kalravan Hills to the north of the Moyar-Bhavani Shear zones are characterized by N-S to NNE-SSW trend (Dharwar trend). This trend is cut across by two distinct sets of lineaments—NNW and WNW. As a result, the NNE-trending foliation is rotated along the Moyar shear zone with E-W, ESE and ENE trends (Jain et al., 2003). According to the Geological Survey of India (Sugavanam and Vidyadharan, 1988), the granulite terrain is characterized by isoclinal and asymmetrical F1 folds with NNE-SSW axial planes, observed in both 2.6–2.5 Ga old charnockites and supracrustals. The superposed F2 folds with WNW-ESE trend affected migmatites, granulites and 2450 Ma old granites. The F3 are shear folds with N-S trend. Regional warps on WNW-ESE axis mark the F4 deformation and their interference with earlier folds produced domes and basin structures. In the southern extreme part of the Madurai Block, the deformation history involves an earlier folding (F1) about NW-SE axis. The F2 folds have refolded the F1 about NNW-SSE axis. The F2 generally plunges toward NW. Sometimes large folds are produced by the fold interference. Because of the cross folding the foliations show abrupt changes both in strike and dip (Narayanswami and Lakshmi, 1967). The superposed deformation is not observed in the granite intrusions that cut across the foliation and banding of the granulitic rocks and migmatites of the Madurai Block. Near the southern boundary of the PCSZ, the D1 deformation in granulites produced isoclinal folds (F1) and a regional foliation (gneissosity) as a result of the transposition of the original layering in the rocks. The second deformation (D2) in the granulites produced F2 folds with variable fold axes. Their axial planes are subvertical and strike E-W to ESE-WNW. The F2 folds are less tight than the F1 folds. According to Mukhopadhyay et al. (2003), the superposition of F2 on F1 folds produced interference patterns in the gneisses and granulites. The refolding has caused bending of mineral lineation which gave rise to different orientations on the two limbs—subhorizontal on the northern limb and northwesterly plunges on the southern limb. The sheared granulites are often retrograded to amphibolite facies gneisses with quartz-feldspar-hornblende-biotite assemblages. In these rocks, two sets of minor folds have formed wherein isoclinal minor folds with axial planes parallel to the regional gneissosity are refolded by later folds with N-S to NE-SW trending axial planes (cf. Mukhopadhyay et al., 2001, 2003). The sheared rocks are characterized by north-plunging folds with N-S axial trance. Shearing is characteristically seen in the Moyar and Bhavani shear zones. Here, the N-S fabric of the Dharwar craton (lower grade terrain) have been rotated to near E-W orientation along these shear zones which evidently developed later than the regional N-S fabric and granulite facies metamorphism of 2.5 Ga age.

Besides these shear zones, there are a few more shear zones, recently identified by the southern Indian workers (see Bhaskar Rao et al., 2003; Chetty et al., 2003). Amongst these are Karu-Kambam-Painvu-Trichur (KKPT) shear zone, Karur-Odanchatram shear zone (KOSZ), Salem-Attur shear zone (SASZ) can be mentioned (Fig. 8.2). In the SGT, some shear zones are located at the interface of two compositionally different rocks, for example charnockite and metasediments. The differing fabric and competence can facilitate rock-movement at the interface during any stage of deformation, developing a shear surface such as the curved KKPTSZ. Such shear zones do not have large-scale strike-slip movement. Attenuation of a limb of a regional fold could also give rise to a shear zone. The AKSZ may be cited as an example of this type of shear zone (cf. Ghosh and deWit, 2004).

8.3 Pandyan Mobile Belt

The Pandyan mobile belt (PMB), according to Ramakrishnan (1993), is the geological domain between the PCSZ in the north and the AKSZ in the south. Impressed by swirling structural pattern in the Madurai Block, Similar to Limpopo belt in South Africa, and by the general occurrence of fold belts either at the peripehery of a continent or sandwiched between two continents, Ramakrishnan carved out his Pandyan mobile belt from the segmented Southern Granulite Terrain. A few years later, Ramakrishnan (2003) enlarged the domain of his mobile belt and included areas of granulites on both north and south margins of his initially proposed Pandyan mobile belt, perhaps on the consideration of meaningful geochronological data available over almost entire SGT. Ramaskrishnan also incorporated the granulite region north of the MBSZ.

Ramakrishnan (2003) divided the enlarged Pandyan Mobile Belt into three zones, analogous to the division of the Limpopo belt. These zones are: (1) Northern Marginal Zone (NMZ), (2) Central Zone (CZ), and (3) Southern Zone (SZ). According to Ramakrishnan, the NMZ lies just north of the E-W trending Moyar-Bhavani Shear zone (MBSZ) into which the N-S cratonic grains abruptly swereve. This zone is characterized by the charnockite massifs of Shevaroy, Javada, BR-Hills and Nilgiri. The Central Zone, CZ (2) is located between the MBSZ and Noyil-Cauvery shear zone (i.e. PCSZ). This zone consists of mainly high-grade relics of older greenstone (Sargur Group), namely Satyamangalam Group, along with supracrustals enclaves (metasediments and carbonates of Sankari dome) and layered basic complex of Sittampundi. This layered complex has dismembered layered basic intrusions (layered gabbro and leucogabbro) within quartzo-feldspathic gneisses surrounding the Sankari (Sankagiri) dome. The gneisses contain enclaves of amphibolites, marble, calc-silicate rock and BIF. The complex is considered to have derived from LREE depleted mantle sources, by fractional crystallization. Sm–Nd whole-rock isochron gives 2935 ± 60 Ma for the complex. Still younger ages of $\sim$2000 and 730 Ma recorded in the complex are due to later thermal imprints (cf. Bhaskar Rao et al., 1996).

The area lying to the south of the PCSZ is the Southern Zone (SZ). It contains charnockite-khondalite rocks. The SZ of the PMB, according to Ramakrishnan (2003), contains two sub-units on either side of the AKSZ. First is the Kerala Khondalite Belt (KKB) to the south of the AKSZ and is predominantly formed of khondalite-leptynite suite with subordinate charnockite. Second sub-unit is the

Madurai Block to the north of the AKSZ. It consists of quartzo-feldspathic gneisses; and charnockites, like that of the central zone of the Limpopo belt. The Achankovil unit is characterized by the occurrence of cordierite gneisses, marbles and quartzites and pink granite—all of which are nearly absent in other units of the KKB (Cenki et al., 2004).

Age data on the charnockite and metasediments of the Southern Zone of the PMB unambiguously denote Pan-African tecto-thermal event. Jayananda et al. (1995) gave zircon evaporation ages of 652–560 Ma from charnockites near Palani area of the Madurai Block. U–Pb zircon geochronology from Varshanadu, Kodaikanal-Cardimom Hills gave 580 Ma (Miller et al., 1997). Also Madurai gneisses yield Rb–Sr ages of 550 ± 15 Ma (Hansen et al., 1995). The Pan-African event is also noticed in the carbonatites, syenites, and alkali granites of the Madurai Block (Deans and Powell, 1968; Subramanian, 1983; Santosh et al., 1989). More recently, Collins and Santosh (2004) showed from SHRIMP age data on zircons from Gangavarpatti quartzite (adjacent to sapphirine-bearing metapelites from Madurai Block), that zircon core gave age of 695 ± 16 Ma and zircon rim yielded 508 ± 9 Ma. The zircon rim age denotes the time of high-grade (granulite facies) metamorphism. A similar age is also obtained as the lower intercept age (550 Ma) of a zircon from felsic gneiss in the vicinity of the Cauvery Shear zone, giving upper U–Pb SHRIMP zircon age at 2600 Ma (upper intercept). Again, the biotites from Karur and Kodaikanal granulites in the domain of Madurai Block to the south of the PCSZ yielded 600–500 Ma age, although the granulite rocks gave T_{DM} age of 2.8 Ga or slightly less.

In the rocks of Trivandrum Block (i.e. KKB), no ages older than 1.8 Ga are recorded (Bartlett et al., 1995). Recent dating of zircons from granites affected by charnockitization in KKB yielded 548 ± 2 and 526 ± 2 Ma (Ghosh and de Wit, 2004). Also a monazite from a small khondalite enclave within a charnockite massif gave 525 ± 2 Ma (Ghosh and de Wit, loc. cit.). Again, the Sm–Nd isotopic data in minerals of cordierite-bearing charnockites in south Kerala yielded a mineral isochron age of 539 ± 20 Ma (Santosh et al., 1992).

These results clearly suggest that the entire region (Madurai Block and KKB) to the south of the PCSZ witnessed the charnockite formation during the Pan-African tectono-thermal event (see Bhaskar Rao, 2004). The charnockitization occurred in suitable compositions with variable prtolith ages. Based on these geochronological data, discussed above, Ramakrishnan defined his Pandyan Mobile Belt as the Southern Granulite Terrain lying south of the PCSZ (see Ramakrishnan and Vaidyanadhan, 2008). In other words, the Madurai Block and KKB (or Trivandrum Block) formed a single granulite terrain (The Pandyan Mobile Belt sensu stricto), despite the presence of the Achankovil shear zone between them. The AKSZ is not believed to be a shear zone but is considered to represent an attenuated limb of a large fold (Ghosh and de Wit, 2004). Within and across the AKSZ, both strike and dip of foliation are conformable. The isoclinal folding in the charnockite-khondalite rocks of the KKB together with the layer-parallel stretching and pinch-and-swell structure indicate that the AKSZ is an attenuated limb of a fold and not a simple shear. K–Ar date of ∼490 Ma on phlogopite from ultramafic rocks within AKSZ may suggest the age of AKSZ. This clearly shows that the AKSZ cannot be a terrane boundary. The record of the Pan-African event is also found in low-pressure granulite terranes in the Gondwanaland (see Harris et al., 1994).

Geochronological data do not support the amalgamation of the Pan-African terrain south of the PCSZ with the granulite terrain in the north. Age data indicate that the Northern Block (CZ and MNZ of Ramakrishnan, 2003) has undergone the granulite metamorphism in the Late Archaean/Early Proterozoic time (2.6–2.5 Ga). The high-grade rocks to the north of the Moyar-Bhavani-Attur shear zone (NMZ of Ramakrishnan, 2003) appear to be part of the Dharwar craton (Archaean age). This terrain contains granulite massifs of BR-Hills, Male Mahadeswara, Shevaroy and Kalravan Hills, and Coorg granulites—all characterized by NNE-SSW to N-S trend (Dharwar trend). All these areas preserve the 2.5 Ga old granulite metamorphism as documented in the Transition zone bordering the amphibolite facies rocks to the south of the Dharwar craton. The Nilgiri massif also consists of 2.5 Ga old granulites, although it is separated from the Dharwar craton (DC) by Moyar shear zone. The whole-rock Rb–Sr, Pb–Pb, Sm–Nd and U–Pb zircon ages for the enderbite granulites of the Nilgiri Hills suggest that the granulite facies metamorphism occurred at about 2.5 Ga ago. Also, a four-point Pb–Pb whole-rock isochron for the Nilgiri charnockites yielded an age of 2578 $\pm$ 63 Ma (Peucat et al., 1989). The BR-Hills charnockites have also been dated at 2.5 Ga by different isotopic methods, with protolith ages ranging from 2.9 to 3.0 Ga (cf. Bhaskar Rao et al., 2003, Table 1). A concordant charnockite gneiss within the supracrustals of Satyamangalam Group (at least 3.0 Ga old; Bhaskar Rao et al., 1996) gave an age of 2.52 Ga (Ghosh et al., 1998), indicating the involvement of these trocks in the Early Proterozoic charnockite event, coeval with that in the Transition Zone.

The above discussion conclusively suggests that the granulite metamorphic event in the terrane north of the MBSZ occurred at about 2500 Ma ago. It implies that the addition of this terrain (NMZ of Ramakrishnan, 2003) to the Pan-African terrane south of the PCSZ is geochronologivcally not valid. The continuation of the N-S fabric of the Dharwar schist belts beyond the Moyar-Bhavani shear zones (Naha et al., 1993) and the continuation of the pressure gradient for 7 kbar in the north near Dharmapuri and 10 kbar near the MBSZ (Raith et al., 1983) suggest that the Dharwar greenstone-granite terrane, the Transition Zone, and the Granulite terrane up to MBSZ (Northern Zone of the Pandyan Mobile Belt of Ramakrishnan, 2003) form a single terrane—the Dharwar Crustal Province. As such, the NMZ of Ramakrishnan (2003) has to be excluded from being a part of the Mobile belt. The continuity of DC (Dharwar craton) and granulite facies rocks north of the MBSZ is also supported by a continuity of the gravity anomalies across the Opx-in isograd (Reddi et al., 2003).

The N-S fabric of the Dharwar craton is rotated to near E-W orientation along the Moyar-Bhavani sheatr zones. Therefore, the MBSZ is certainly later than the 2.5 Ga old granulite metamorphism. The cross-cutting relationship between the N-S regional foliation and the E-W trending metamorphic isograds indicate that the regional metamorphism (related to 2.5 Ga old Dharwar orogeny) outlasted the major deformation that produced the regional fabric in the basement and cover rocks of the Dharwar Metamorphic Province. If the charnockite-granulites of 2.5 Ga age in the BR-Hills are considered to have been displaced dextrally in relation to the Nilgiri Hills (Drury et al, 1984; Chetty et al., 2003), the Moyar (Bhavani) shear zone has to be later than 2.5 Ga granulite event. Therefore, the MBSZ cannot be regarded as an Archaean Terrane boundary between the Dharwar craton and the Nilgiri granulite Block (cf. Raith et al., 1999). Again, there is a controversy in regard to the sense of shear. The Moyar shear zone is dextral, according to Drury et al. (1984), but Jain et al. (2003) show that the Bhavani shar zone is a sinistral shear zone. According to Naha and Srinivasan (1996), the Moyar shear zone has a predominant dip-slip transport rather than a strike-slip movement. But it seems, as shown by more recent studies, that the MBSZ has both steep and shallow plunging lineations and therefore both vertical and horizontal movements (cf. Chetty et al., 2003; Jain et al., 2003; D'Cruz et al., 2000).

The granulite domain between the MB shear zone and PCSZ is the Central Zone (CZ) of the Pandyan Mobile Belt of Ramakrishnan (2003). This zone contains migmatite gneisses that are structurally concordant with the 3.0 Ga old supracrustal rocks of (i) Sittampundi and Bhavani layered complexes, (ii) Satyamangalam Group metasediments, and (iii) Palaeoproterozoic charnockite gneiss. This zone also contains Neoproterozoic (700–550 Ma) mafic-ultramafic and granite intrusions (Bhaskra Rao et al., 1996). The granulites east of Sittampundi gave Sm–Nd whole-rock isochrones of 2935 $\pm$ 60 Ma, while Sm–Nd isochron for minerals (garnet and hornblende) and whole-rock yielded 730 Ma. In this terrane, there are several small domains that have preserved, although scantly, the Early Proterozoic granulite metamorphism (2.2–2.3 Ga; Bhaskar Rao et al., 2004), but biotites at other places and along the CSZ give Neoproterozoic ages. This suggests Late Archaean magmatic complex was overprinted by the Pan-African tectonometamorphic event (Bhaskar Rao et al., 1996; Meissner et al., 2002). The Pan-African ages in this zone are found all along the boundary shear zones—the MBSZ and PCSZ, except the domains around Salem and Dharmapuri. If the Sm–Nd model ages relate to the time of extraction of magmatic protolith from the mantle, then the charnockite parents here and across the Moyar-Bhavani shear zone (MBSZ) were formed nearly the same time. If the granulite metamorphism in the Central Zone and the Zone across the MBSZ also formed during Early Proterozoic, there is no justification to separate the two isogradic terrains, nothwithstanding the Pan-African overprinting in certain areas of the Central Zone. This means that the MBSZ is neither a Palaeoproterozoic terrane boundary nor a subduction zone, but is a shear zone that has developed after the 2.5 Ga-old granulite metamorphism during Dharwar orogeny. This is clearly manifested in the deflection of the N-S structural domain (Dharwar trend) and their alignment parallel to the MB shear zone.

The preceding discussion clearly rules out the extension of the Pandyan Mobile Belt beyond the Palghat Cauvery shear Zone. The PCSZ marks the craton-mobile belt boundary, and the Pandyan Mobile Belt occupies the entire granulite domain south of the PCSZ. This is the concept of the Pandyan Mobile Belt, according to the revised opinion of Ramakrishnan (2004).

8.4 Agreed Observations and Facts

Before we discuss the evolutionary models of the Pandyan Mobile Belt (PMB), we summarize below the agreed observations and facts about the rocks of this Neoproterozoic belt. These are:

1. The Pandyan Mobile belt occurs to the south of the Palghat-Cauvery Shear Zone (PCSZ), including a large terrain comprising Madurai Block and Trivandrum Block (KKB). The PMB is made of granulite facies rocks of Pan-African age (700–500 Ma).
2. The PCSZ marks the Dharwar craton—Mobile belt boundary and hence is a Terrane boundary between Late Archaean terrain in the north and Neoproterozoic terrain in the south of PCSZ.
3. The Moyar-Bhavani shear zone (MBSZ) cannot be a terrane boundary because both Terrains on either side of it (North of the PCSZ) are isogradic (granulite facies rocks), have the same metamorphic age (2.5 Ga), excepting sporadic younger intrusives (Overprinting). Both Late Archaean terrains are characterized by N-S Dharwar trend that extend through the Transition Zone, MBSZ and further south up to PCSZ (Bhaskar Rao et al., 1996; Ramakrishnan, 2004).
4. The N-S structural grains (Dharwar trend) show E-W rotation along the MBSZ but Dharwar trend reappears across the shear zone and continue southward showing swirls within the Madurai sector of the PMB (Ramakrishnan, 2004).
5. As an orogenic belt, the PMB must have evolved by collision of an "unknown craton" against the Dharwar craton during Neoproterozoic time.
6. The charnockite protoliths of the PMB granulites are in the age range of 2.4–2.1 Ga but sometimes the granulites record Archaean ages (Bhaskar Rao et al., 2004).
7. Mineral and whole-rock isochron yield 700–500 Ma for the PMB granulites (Bartlett et al., 1998; Jayananda et al., 1995), indicating involvement of the PMB protoliths in a tectono-thermal event related to the Pan-African orogeny.
8. The Novil-Cauvery shear zone (i.e. PCSZ) appears to be a suture zone (? Subduction zone) and has southern dip, supported by seismic tomography (Rai et al., 1993).
9. The exhumation of the Southern Granulite Terrain (SGT) is post-PanAfrican, caused by northerly and also westerly tilt of the Indian Peninsula, perhaps episodically (Ramakrishnan, 2004).

8.5 Evolutionary Models and Discussion

With the basic informations given above, the different evolutionary models of the Pandyan Mobile Belt are discussed in the following pages.

Model 1. Subduction-Collision Model (Ramakrishnan, 1993, 2003, 2004)

This model is based on the consideration that the Neoproterozoic terrain south of the PCSZ is a fold belt and that the Dharwar craton is continuous with the 2.5 Ga old granulite facies terrains to the north of the PCSZ. The fold belt is constituted of both Madurai Block and Trivandrum Block (or KKB), having similar lithologies and Pan-African ages, revealed by the Sm—Nd and Rb—Sr whole-rock and mineral isochrons (Ghosh et al., 1998; Bhaskar Rao et al., 2004), from Pb-isotopes in zircons in leucosomes of the migmatite gneisses (603 ± 14 Ma), from newer zircon growth (560 Ma), from monazite in garnet-sillimanite gneiss (791 ± 1 Ma), and from charnockitization age of about 500 Ma given by a charnockite granite with protolith age of 800 Ma. The granulite facies metamorphism in the Kodaikanal and Palani areas also gave Pan-African ages around 560 Ma (Bartlett et al., 1995; Jayananda and Peucat, 1996). The Pan-African event is also documented in a series of intrusives of alkali granites, syenites and granites, as stated already.

Since the Sm—Nd isotope data on minerals of cordierite-bearing charnockite in southern Kerala yield mineral isochron of 539 ± 20 Ma (Santosh et al., 1992), similar to that in Madurai Block (Deans and Powell, 1968; Subramanian, 1983; Santosh et al., 1989), the Achankovil shear zone (AKSZ) occurring between the Madurai Block and Trivandrum block (i.e. KKB) does not represent a terrane boundary. According to Ghosh and de Wit (2004), the AKSZ represents an attenuated limb of a fold. This finds support from the lithotectonic map of the Pandyan Mobile Belt (Fig. 8.3), based on field data and interpretation of Landsat images that show coaxial folding of both granaulites and gneiss/migmatites, producing hook-shaped antiforms and synforms. This author has delineated the axial traces of the superposed folds, F1 and F2, which are cut across by the AKSZ (see Fig. 8.3). The migmatite outcrop (upper left part of Fig. 8.3) is parallel to the axial trace of F2 fold, indicating that migmatization was syn-F2 in the Pandyan Mobile Belt. The KKB rocks (Trivandrum Block) are seen oriented along this shear zone. The AKSZ is considered 550 Ma old ductile shear zone with left-lateral shear sense and occurring parallel to the Tenmalai-Gutan shear zone on the south of the belt. Contrary to the sinistral shear sense, Sacks et al. (1997), who mapped a part of this shear zone, suggest dextral movement. On the other hand, Radhakrishna (2004, p. 116) does not recognize any shear features along this lineament. To sum up, the AKSZ is not a suture zone or a discrete surface to mark a tectonic break between the blocks across it. Both Madurai and Trivandrum Blocks, south of the PCSZ are therefore part of a single terrain of Neoproterozoic age.

In contrast, the domain to the north of the PCSZ is clearly Late Archaean to Early Proterozoic granulite facies terrain. This terrain, especially north of the MBSZ is undisputedly a Late Archaean terrain, characterized by granulite massifs of Nilgiri, BR-Hills, Shevaroy Hills etc., as discussed earlier. The terrain between the MBSZ and the PCSZ also contains migmatite gneisses, structurally concordant with the supracrustals as well as with the Palaeoproterozozic charnockite gneiss, as stated already. However, there are a few small domains, although preserving Late Archaean or Palaeoproterozoic Rb—Sr ages, which show Pan-African overprinting

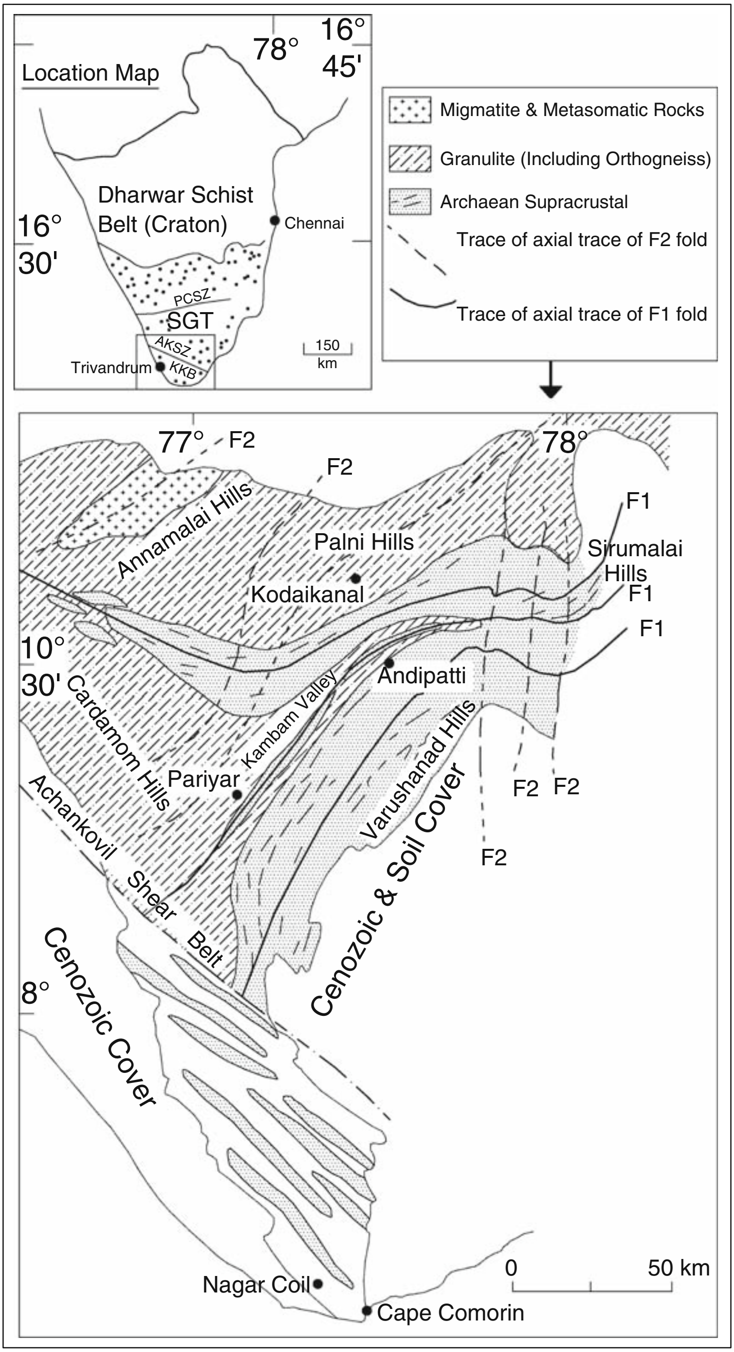

Fig. 8.3 Litho-tectonic map of the Kerala Khondalite Belt (KKB) and a part of the Southern Granulite Terrain (i.e. Madurai Block), redrawn from T. Radhakrishna, 2004. Note that the gneiss/migmatite and granulite are cofolded by superposed deformation F1 and F2 with axial traces (delineated by the writer) which are cut across by the Achankovil shear zone, see text for details

in the mineral of the Archaean protoliths (Bhaskar Rao et al., 1996; Ghosh et al., 1998) could be a thermal overprinting, presumably due to heating by numerous Neoprotoerozoic plutonic rocks (alkali granites, syenites and even carbonatites) that intruded the terrain during the globally recognized Pan-African orogeny. However, the charnockite gneisses of this domain (Central Zone of Ramakrishnan, 2003) are coeval with the 2.5 Ga old granulite belt to the north of the MBSZ, which was recrystallized 2.5 Ga ago during the Dharwar orogeny (Late Archaean/Early Proterozoic). The late Achaean charnockites are characterized by positive Eu anomalies, HREE depletion and near chondritiic values of $\Sigma_{Nd(O)}$ and $^{87}Sr/^{86}Sr$ at 2.5 Ga (Tomson et al., 2006), suggesting their derivation by partial melting of garnet-hornblende bearing mafic parent (mantle component or amphibolite). On the other hand, sources of Neoproterozoic charnockites (south of PCSZ) show greater recycling of crustal components, i.e. intracrustal melting as revealed by negative Eu anomalies, lower degree of HREE depletion and undepleted Y (cf. Tomson et al., 2006).

From the above discussion, it is suggested that the PCSZ is a major terrain boundary separating the charnockite region of Palaeoproterozoic in the north from the Pan-African (Neoproterozoic) charnockite domain (Pandyan Mobile Belt) in the south (Drury et al., 1984; Harris et al., 1994; Jayananda and Peucat, 1996; Yoshida and Santosh, 1995, and others). Since the PMB is located at the southern margin of the Dharwar craton, it is considered to have formed by collision tectonics, involving two oppositely converging plates. The continental block which is assumed to have collided against the Dharwar craton, to raise the Pandyan mobile belt, could be Mozambique craton from South Africa or some uncertain region of Antarctica (Ramakrishnan, 2004).

The present disposition of the metamorphic isograd suggest that in the Dharwar orogeny, the Dharwar craton with its cover sediments subducted southward under an "ancient continent". The southward subduction is also supported by seismic tomography (Srinagesh and Rai, 1996). In the subduction-collision process, the Dharwar crust was thickened and both Archaean basement and its supracrustals were deformed. The resulting increase of temperature as a consequence of crustal thickening gave rise to the progressive regional metamorphism from greenschist facies to amphibolite facies and finally to granulite facies. The cross-cutting relationship between the N-S regional foliation and the E-W trending metamorphic isograds indicates that the regional metamorphism (related to the 2.5 Ga old Dharwar orogeny) outlasted the major deformation that produced the Dharwar trend in the basement and cover rocks of the Dharwar Metamorphic Province. During the progressive metamorphism, the rocks at depth also underwent partial melting and generated granites (Closepet and other coeval granite plutons) of the same age. During this decompressive stage, charnockitization of Peninsular gneiss occurred, spectacularly seen at Kabbal and other places.

Besides metamorphism and magmatism, another internal process that occurred late in the ascending crustal segment of the Dharwar Province has been the development of post-metamorphic E-W shears or lineaments (e.g. Moyar, Bhavani shear zones) in the granulite terrain. Not only is the Dharwar trend deflected but the 2.5 Ga old granulites have also been retrograded and mylonitized to varying degree along these shear, developing shear fabric parallel to the above mentioned shears (cf. Jain et al., 2003). The deep-seated granulite rocks are inferred to have been uplifted along these shears. The P-T data for the garnet-graulite from Nilgiri yielded 730°C/7 kbar in the SW and 750°C/9 kbar along the NE toward the Moyar shear zone. These results suggest that the Nilgiri massif tilted northward during its differential uplift along these shears. It is perhaps this tilting deduced from the P-T data that led Raith (2004) to conceive the Nilgiri massif as an allochthonous massif, thrust northward onto the Dharwar terrain during Palaeoproterozsoic (2.3–2.1 Ga). The northward tilting of the Nilgiri massif could be associated with the northward tilt of the southern Indian shield during Neoproterozoic. It is indeed a matter of enquiry whether the tilting was during Palaeoproterozoic or Neoproterozoic time. The available evidence is taken by Raith et al. (1983) to suggest a differential uplift of the Nilgiri massif. From the proposition that the BR-Hills granulites have a correlation with the Nilgiri granulites (Drury et al., 1984; Chetty et al., 2003), a strike-slip movement is implied along the Moyar shear zone. If the Dharwar crust was segmented by these shears, different granulite blocks may have uplifted differentially from same or different depths. In this situation, the shears need not be of the same age, but necessarily developed in post-granulite metamorphic event, in view of their geological setting, described earlier. Drury and Holt (1980) considered the MBSZ as a part of the major Palghat-Cauvery shear zone system. Considering that the Palghat-Cauvery shear zone (PCSZ) separates the Late-Archaean granulite terrain from the Neoproterozoic Pandyan Mobile Belt, the PCSZ cannot be as old as the Moyar-Bhavani shear zones that separate the 2.5 Ga old granulites on its either side and affected them soon after their metamorphism. Recent geochronological work has given an age constraint on the shearing event. Rb—Sr dating of micas and Sm—Nd dating of garnet from mylonites of the MBSZ (Bhaskar Rao et al., 2003; Meissner et al., 2002) suggest that these shears are Neoproterozoic (700–500 Ma). But laser probe $^{40}Ar/^{39}Ar$ age data of 1250 Ma on pseudotachylites from the MBSZ indicate a Mesoproterozoic and hence older age than the PCSZ. As suggested by the age data of minerals from mylonites, these shear zones (MBSZ) have been reactivated during Neoproterozoic when the Pandyan mobile belt evolved.

Subsequent to the 2.5 Ga old Dharwar orogeny, there are ample evidence for the occurrence of Pan-African tectono-thermal event (orogeny) during which the PMB is considered to have evolved. The Pan-African orogeny was a global event and nearly all the continents of a supercontinent manifest its record in their rocks. The Indian shield also preserves the Pan-African related tectono-thermal event. The best example is the Pandyan Mobile Belt at the southern border of the Dharwar craton. Based on geometric configuration and best-fit of continents, the Pandyan Mobile belt appears to intersect the Grenville-type belt in Antarctica and may even be truncated by the Mozambique belt of eastern Africa (cf. Ramakrishnan, 2003). According to this configuration in the supercontinent (Rodinia), the "ancient continent" that may have collided with the Dharwar craton during the Pan-African time orogeny was Kalahari in Africa or one in Antarctica.

During continental collision, it is believed that the Dharwar craton subducted southward under the "ancient continent". This is inferred from the southern dip of the PCSZ which may represent a surface expression of continental subduction and collision of 2.5 old Dharwar Metamorphic Province against a southern continent in the pre-Neoproterozoic continental assembly. The subduction was in all probability an A-subduction in which crust-mantle delamination (or crustal decoupling) occurred whereby hot mantle magma (formed as a result of decompression melting) underplated the crust to generate high and also ultra high temperature metamorphism, seen in several areas of PMB (see Grew, 1982; Mohan and Windley, 1993). The clockwise decompression path with ITD (isothermal decompression) loop found in Gangavarpatti and Kodaikanal (Mohan and Windley, 1993) does not, however, support the underplating model for the evolution of the PMB. The emplacement of plutons of alkali affinity during the Pan-African event in southern India indicates a period of extensional tectonics in Gondwanaland at that time. Such a tectonic setting could have provided an appropriate stress regime for channelized influx of CO_2- rich fluid during incipient charnockitization and for enrichment of carbonic fluids (Santosh, 2003). The exposure of the rocks of the Pandyan Mobile Belt is the outcome of northerly and westerly tilt of the Indian peninsula, perhaps during India-Asia collisional events.

Model 2. Accretion Model (Radhakrishna and Naqvi, 1986)

One group of geoscientists believes that the southern Indian shield, particularly the Southern Granulite Terrain (SGT), resulted from accretion of two crustal blocks along the PCSZ. The PCSZ is considered to represent a cryptic suture or collision zone (Gopalkrishnan, 1996) or an accretion zone along which two blocks/cratons have been welded (Radhakrishna and Naqvi, 1986). The model considers welding of the once far-off located SGT with Dharwar craton. To the background of this model is the division of the Dharwar Metamorphic Province into charnockitic and non-charnockitic Provinces by Fermor (1936). This dividing line is the present Opx-in isograd which is also known as the Fermor Line. Although the charnockite/non-charnockite division is germane to the idea of Terrane Accretion Model, the emphasis shifted to the shear zones as the possible site of the terrain accretion. In this model, the shear zones are considered sutures along which continental blocks are assumed to have welded or fused.

The accretion model is, however, beset with serious problems of uncertainty of the direction of crustal movement and the absence of squeezed (deformed) belt of supracrustals that may have been at the site of welding of the once far-off located continental mass. The model also appears weak if the recent conclusions on petrogenesis of the Late Archaean Closepet Granite (Friend and Nutman, 1991) are considered.

Moyen et al. (2001) recognized three zones in the Closepet Granite, which from north to south are: Intrusive zone, Transfer zone and Root zone. The Root zone granite extends from Palghat-Cauvery shear zone in the south up to Opx-in isograd in the north and shows a mixing of mantle-derived magma with the crustal-derived magma. These deep zone granites are heterogenous and contain enclaves and show migmatization at the contact with the Peninsular gneiss. The granites from the Transfer zone extend all through the amphibolite facies terrane from Kabbal to Kalyandungri and have similar granite type as that of root zone granite, except having fewer enclaves and less diffused contact with the country rocks of the Peninsular gneiss. The Intrusive zone granite has very few xenoliths but no thermal effects on the host rocks. These granite types from three zones show geochemical and isotopic similarity that led Moyen et al. (2001) to conclude that the Closepet granite is a continuous body from granulite facies to the greenschist facies (see also Jayananda et al., 1994). If so, the Model 3 is not supported by the Petrological-geochemical data on the Closepet Granite extending from Kabbal to Palghat. Furthermore, the petrological and geochronological data on the granulite massifs suggest uplift and not horizontal movement of the granulite blocks. The Nilgiris modeled as an upthrust-allochthonous terrain to be placed onto Dharwar craton (Raith et al., 1990). As stated earlier, there is no unanimity on the movement direction along the shear zones. Interestingly, the Palghat-Cauvery Shear zone is stated to be non-traceable to the east of the SGT (Mukhopadhyay et al., 2003). Recently, Chetty et al. (2003) consider that transpressional orogenesis (Dharwar) in the region was associated with thrusting and complex strike-slip movement, with a regionally consistent sense of shearing. This proposition explains the steep and gentle plunges of the mineral stretching lineations. But, here again, the shearing is not necessarily Dharwar age, in view of the arguments stated previously. In all probability, the shear zones are post-Dharwarian age but appeared to have played a significant role in causing differential movements of the crustal blocks, vertically as well as laterally. If the stated terrane-accretion model is accepted one needs to answer as to what happened to the intervening rocks (unmetamorphosed or already metamorphosed) that may have been there before the SGT moved from far off place and welded with the Dharwar craton. The problem of the SGT, whether an accreted block or a mobile belt formed due to the convergence of a “missing plate” with the Dharwar craton, can be solved by more geochronological and structural work in the critical areas of the southern Indian shield. It is a matter of debate as to how much geophysical investigations of the present crust-mantle configuration could help in unraveling the events that occurred around 2500 million years ago in this part of the Indian shield unless it remained completely inert since then.

The problem of the SGT terrain south of the PCSZ—whether an accreted block or a mobile belt formed due to the collision of “missing plate” against the Dharwar craton can be solved by more structural and geochronological work in critical areas of the southern Indian shield. It is also a matter of debate as to how much geophysical investigations of the present crust-mantle configuration would help in unraveling the events as old as 2500 Ma in this part of the Indian shield, even if the craton remained completely inert since that time.

Model 3. Reworked Ganulite Terrain Sans Mobile Belt

As an alternative to Models 1 and 2, this paradigm presumes that the granulite terrain was one single crustal block of granulite rocks, and the terrain south of the PCSZ is wholly re-Worked Archaean terrain by the superimposed Pan-African tectono-thermal event; i.e. PMB is not a mobile belt. The geological observation that the N-S fabric of the Dharwar craton extends through MBSZ up to PCSZ, and perhaps beyond the AKSZ where the fabric is deflected by post-metamorphic shearing in rocks of different competence. This Dharwar Crustal Province formed one large crustal unit during Late Archaean Dharwar orogeny (2.5 Ga ago). Both Archaean basement and suptracrustals (dominantly greenstones) were superposedly deformed and regionally metamorphosed, giving rise to the E-W trending isograds delineated between greenschist, amhibolite and granulite facies, so extensively developed at the southern margin of the Dharwar craton. Ramiengar et al. (1978) emphasized that the E-W trending belt of charnockites and granulites to the south of the Opx-in isograd does not have any lithostratigraphic significance because the unbroken greenstone and granulite transitions in southern India is orthogonal to the regional structural grain. This means that the SGT is a continuous terrain with the Dharwar craton *sensu stricto*. The regional N-S fabric in the affected rocks indicates that the compressive forces generated by the collision of lithospheric plates in the Archaean were in E-W direction. But the metamorphic isograds also trend E-W, implying that the compressive stresses due to subduction should be N-S and not E-W. This and other reasons require an alternative model for the evolution of SGT.

Considering the dominance of granulites to the south of Opx-in isograd and the southward progression of regional metamorphism in Dharwar orogeny (2.5 Ga), the granulites of the SGT do not seem to belong to a different Terrane, as they are believed to have been exposed by northward tilting of the Indian shield. This proposition of northward tilting finds support from the geophysical studies which show charnockite-granulite rocks (similar to those in the SGT) below the greenstone terrains of the Dharwar craton. This means that the SGT is not a laterally welded terrane, but a lower crustal component that got exposed through tilting of an Archaean continental crust. Conversely, it could be argued that if the northward tilting had not occurred, the SGT would not have such a vast exposure by erosion alone. Rifting of the various continents and related magmatic activities during the Pan-African orogeny are documented in the various regions globally. And its effects in the Indian shield are seen in a series of intrusions of alkaline granites, syenites and granites of 700–550 Ma age (including the Sankari Durg granite near the MBSZ) and also in the re-working of the terrain south of the PCSZ, which document wide spread Pan-African ages. It is interesting to note that the rocks of the Madurai and Trivandrum Blocks (both forming Pandyan mobile belt of Ramakrishnan, 2004), making up the terrain south of the PCSZ, have protolith ages of 3.0 and less, but not very different from the protolith ages from the terrain north of the PCSZ. The Neoproterozoic ages, given by the constituent minerals in rocks from the granulite terrain to the south of PCSZ may be taken to indicate a through rcrystallization during Pan-African overprinting. The tectno-thermal overprinting is also documented occasionally in the granulite facies domain between the MBSZ and PCSZ, although not convincingly in the terrain north of the MBSZ. This may be taken to infer that the Pan-African imprinting was weakening northward.

The PCSZ becomes a clear tectonic divide between the Archaean cratonic crust and the Neoproterozoic granulites of the Pandyan mobile belt. The PCSZ seems to have resulted by collision of a craton (Kalahari in Africa or one in Antarctica) with the Dhawar craton (including the Archaean SGT) during Pan-African time (550–700 Ma). Accordingly one cannot expect Late Archaean or Early Proterozoic deformation in the PCSZ (cf. Chetty and Bhaskar Rao, 2004). The PCSZ is the most plausible terrane boundary in the SGT. Earlier the PCSZ was also proposed as a zone of continental collision (Drury et al., 1984) in which the block south of PCSZ represents large stacks paragneisses, tectonically intercalated in between meta-igneous granulite massifs (represented by charnockite massifs). The first order assumptions of this tectonic model are: (a) magmatic origin of the charnockite massifs south of PCSZ, (b) tectonic contacts between the paragneisses and swathes and the charnockite massifs, and (c) charnockite emplacement pre-dating the tectonic stacking along shear zones. Principal support to this model comes from isotope data (Harris et al., 1994), magnetic anomaly data (Reddi et al., 2003), seismic tomography (Rai et al., 1993) and metamorphic P-T data (Ravindra Kumar and Chacko, 1994). The model of terrane boundary along PCSZ thus appears valid and any other terrane boundary such as along Karur-Kambam-Painvu-Trichur shear zone (KKPTSZ), proposed recently by Ghosh and de Wit (2004), lacks support from different aspects of geology and geophysics. A mere similarity or dissimilarity of lithology along a discrete surface cannot be regarded as convincing criteria of delineating terrane boundary as proposed recently by Ghosh and de Wit (2004). However, the PCSZ is in all probability a terrain boundary between the Dharwar craton (including the Archaean domain of SGT) and the Pandyan Mobile belt that may have accreted subsequent to its recrystallization in Neoproterozoic. The exhumation of the southern Indian shield should be post-Pan-African. The exposure of this vast granulite terrain owes largely to the northward and also eastward tilt of the Indian peninsula in different episodes (Mahadevan, 2004).

We have to collect more geological and geochronological data to accept or reject the proposition of the fold belt versus a cratonic terrain to the south of the Palghat-Cauvery shear zone.

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